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Inter-firm exchanges, distributed renewable energy generation, and battery energy storage system integration via microgrids for energy symbiosis

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ABSTRACT

Policymakers and entrepreneurs are aware that reducing energy waste and underutilization are mandatory to actually foster the green transition. Nevertheless, small–medium enterprises usually meet technical and overwhelming financial constraints. They are unable to make profits, become less energy-sensitive, and cut down on their emissions simultaneously. Industrial districts are a source of both wealth and GHG (greenhouse gas) emissions. Eco-industrial parks (EIPs) supply a suitable strategy to ease symbiotic exchanges among various organizations. Surplus electricity from larger, energy-autonomous companies will be a new input for more vulnerable ones. This type of district is challenging, and it can provide an unexplored opportunity to cooperate, invest in renewable energy sources, and form alliances. To better exploit underutilized energy in industrial districts, it is essential to explore energy symbiosis (ES), i.e., an energy-based perspective of industrial symbiosis. This study presents an original mixed-integer linear programming (MILP) optimization model that aims to identify possible inter-firm exchanges and introduce microgrid-based support for distributed renewable-energy generators (DREGs) and battery energy storage systems (BESS) over a one-year simulation period. The model simultaneously targets economic and ecological objectives. The paper compares two case studies, one with battery support and one without. The optimization model was tested using a case study and found to improve energy efficiency (with a 43.46% saving in energy costs) and reduce greenhouse gas emissions (with an 84.59% reduction in GHG) by facilitating symbiotic exchanges among SMEs in industrial districts. The inclusion of BESS support further enhanced the model's ability to utilize green and recovered energy. These findings have implications for policymakers, entrepreneurs, and SMEs seeking to transition to more sustainable energy practices. Future work could explore the applicability of the MILP optimization model in other contexts and the potential for scaling up the model to larger industrial districts.

1. Introduction

1.1. Background and drivers

Due to emerging economies and future market electrification, which claim massive energy production, the green transition will become, and already is, a central topic for years ahead. It is mandatory to look at the most impactful and energy-consuming sectors to cut energy waste and underutilization. Recently in particular, geopolitical factors have pushed toward a recalibration of the European energy mix. In this way, it will be possible to enhance competitive advantage and partially decouple energy-type commodities' prices from oligopolistic orders.

Since the last century, modern industry has progressively tried to pivot away from unethical and unsustainable behaviours. Consumers are increasingly aware of the consequences of their purchases; thus, businesses need to be able to respond to and meet customer expectations. The United Nations started researching sustainability in the early 1980s by drawing up the idea of *sustainable development*, emphasizing intergenerational and intragenerational equality principles (Imperatives, 1987). In 1996, the World Bank suggested a triangular framework (Serageldin, 1996). The methodology helped to formalize solid procedures for evaluating sustainable proposals (Maes et al., 2011). Future

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companies of the 21st century should pursue success by looking at three specific and separate areas, also called the three ways of sustainability or 3 Ps: *profit* (economic goals), *planet* (environmental goals), and *people* (social goals) (Elkington and Rowlands, 1999). Furthermore, the most recent sixth IPCC assessment reiterates the need to stick to the targets of the Kyoto Protocol and COP21 by cautioning once more about the hazards connected with carbon dioxide emissions related to human activities (i.e., industrial activities). If resource usage continues along current trends, we will see a continuous degradation of the environment and the depletion of natural resources. Since the 19th century, carbon dioxide has constantly increased its atmospheric concentration due to the unregulated use of fossil fuels and industrial emissions (Kılkış et al., 2022) (Fig. 1).

The European Union (EU), referring to the problem of climate change, has been promoting various plans for emissions reduction and the clean use of natural resources. According to the 1990 baseline, the EU reduced its greenhouse gas (GHG) emissions by about 22% in 2017, with a 3-year delay. In addition, the EU increased the share of renewable energy use to 20% and improved energy efficiency by 20%. Recently, the commission adopted a bolder approach to climate action, setting a challenging target of 55% GHG reduction by 2030. Electricity generation needs to withstand continuous boosting to achieve the EU's renewable energy target. Overall, the European Commission fixed a long-term vision for its members. By 2050, the EU will reach net-zero emissions by implementing the European Green Deal: zero climate change-related emissions, safe/clean/interconnected transport, maximizing energy production technologies efficiency, safety infrastructures, sustainable agriculture, and new storage and disposal technologies for unavoidable GHG emissions. The EU's actions to fight climate change involve energy-intensive industries (EIIs). EIIs have widely reduced their emissions due to technical (innovation and energy-efficiency management) and nontechnical (2008 economic crisis) factors (Mendez-Alva et al., 2021). Despite significant enhancements, energy use in industry and buildings (electricity and heat) handles almost 42% of total GHG emissions. Even if we could fully decarbonize our electricity supply, we would also need to electrify all our heating and road transport. To reach net-zero emissions, we need innovations across many sectors. Single solutions will not get us there (Ritchie et al., 2020).

Next-Generation EU (NGEU) is a temporary means to ease flexibility measures in European members. Flexibility will enable states to face unpredictable circumstances generated by the ecological, digital, and resilient transition. NGEU boosts a long-term budget for 2021–2027 over 800 billion EUR. During the last 20 years, Europe has pursued its target (decarbonizing energy and electricity) by dramatically reducing coal consumption and expanding natural gas. Intermittency and non-programmability are obstacles to modern renewable energy sources, particularly solar and wind. The primary source of near-term flexibility for gas markets in Europe continues to be underground storage (Barbera et al., 2022). Reliance on inventory and supply efficiency (implicitly influenced by geopolitical circumstances) raises questions about pricing volatility and bargaining strength. Through Next-Generation EU, Italy, whose performance is comparable to that of the rest of Europe, expects to achieve carbon neutrality by promoting renewable energy, scalable-distributed solutions, and smart grid technologies. Higher independence may result from the switch to more ecologically friendly energy supply methods, according to three hypotheses:

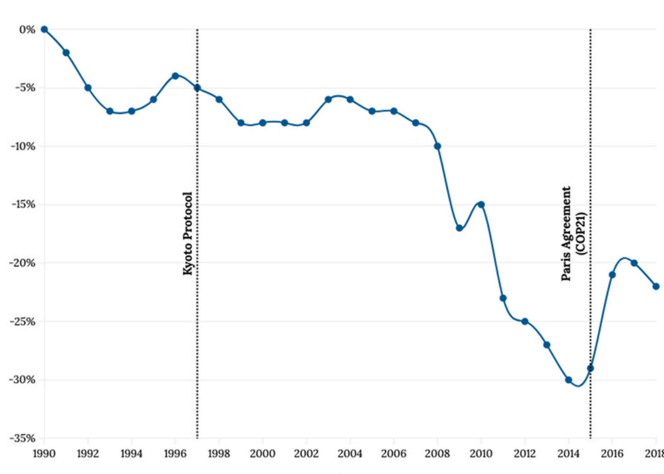

Fig. 1. Change in total European GHG (greenhouse gas) emissions (1990–2018) – author's reworking of data from CAIT source.

- Boosting renewable energy sources (RESs) will lead to the more restricted use of high-carbon sources (Merabet et al., 2022a,b).
- Battery energy storage systems (BESSs) will bring new flexibility tools (alongside old thermal plants), preventing demand and supply fluctuations (Dhundhara et al., 2018).
- The development of climate change mitigation strategies must be undertaken through an integrated, coordinated, and synergistic pathway (Kılkış et al., 2022).

IS focuses on business viability and operation while studying its environmental consequences, developing cooperative networks which reach competitive advantages through shared resources (Mendez-Alva et al., 2021). It seems to be a possible practice to achieve European goals. Matching the input and output of underutilized resources can lead to new business model opportunities (Lombardi and Laybourn, 2012). This system could steer toward a sustainable path for a circular economy (CE) among different actors (various sectors and dimensions) via mutually beneficial transactions. Thus, this paper presents a novel energy-based industrial symbiosis model, integrating both RESs and BESSs, to outline a pathway to take advantage of through energy cooperation.

The remainder of this work is structured as follows: Section 1.2 reviews the evolution of classical IS and EIP concepts to the energy-based symbiosis, focusing on barriers and enabling technologies; Section 1.3 underlines the innovative content of this work. Section 2 presents the novel approach mathematically, while Section 3 tests the approach on a realistic case study (the input data deduction process is explained in Appendix A); Section 4 concludes the paper with a synopsis and future research suggestions. Table 1 contains a summary of acronyms.

1.2. Theoretical background

Waste flows from firms in a traditional industrial district generally have separate disposal (Fig. 2). Each actor in the park wants to independently optimize by-product disposal. Systemic vision has no chance because every production process has its cycle. Generalized municipal

Table 1
Table of acronyms.

Acronyms	
BESS	Battery Energy Storage System
CE	Circular Economy
DEG	Distributed Energy Generation
DREG	Distributed Renewable Energy Generation
EII	Energy-Intensive Industry
EIP	Eco-Industrial Park
ES	Energy Symbiosis
EU	European Union
GHG	Greenhouse Gas
HRES	Hybrid Renewable Energy Systems
IE	Industrial Ecology
IS	Industrial Symbiosis
MILP	Mixed-Integer Linear Programming
NGEU	Next Generation EU
RES	Renewable Energy Source

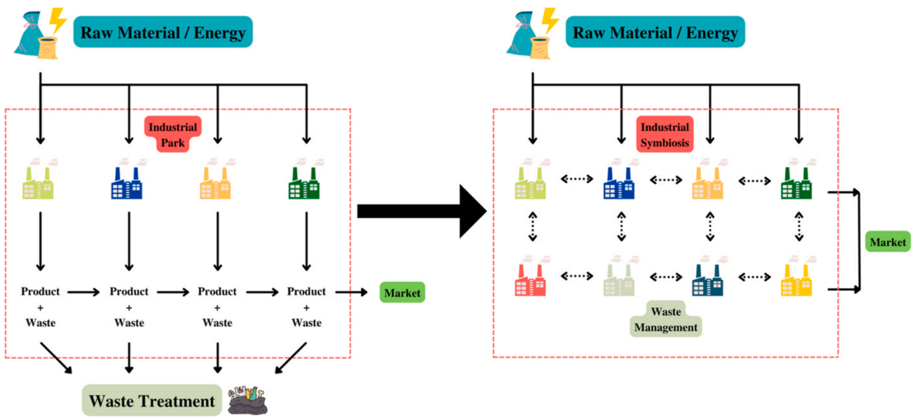

Fig. 2. From industrial park to industrial symbiosis.

systems take charge of the waste and transfer it to specific treatment facilities (Kastner et al., 2015). The end-of-pipe control no longer has a satisfactory marginal benefit. Emission sources are widespread over the supply chain, notably if strongly interconnected (Anderberg, 1998).

By taking advantage of physical closeness, new between-firm contacts (or, in large-scale organizations, within-firm relationships) are often more easily discovered and created (Fig. 2). Proximity eases transportation and trust, reducing resource use, waste, and GHG emissions, and obtaining environmental targets and economic benefits (Neves et al., 2020). The benefits of closeness and collaboration in the workplace are the foundation of so-called industrial symbiosis (IS). Chertow (2000) considers industrial symbiosis a field of industrial ecology (IE), which studies the flow of resources by focusing on the exchange between companies. The earlier definition is more than 20 years old, and it is still the most used; however, it does not consider the new perspectives of modern industry. Lombardi and Laybourn (2012) proposed a contemporary definition entangling aspects such as mutual learning, life-cycle thinking, and best practices. Despite shifts in company commitment and culture, the environment continues to be pervasive. In this updated version, the authors bear in mind every possible exchange (physical and nonphysical) so that a firm can consider the use of alternative materials. IS drives new business opportunities through a value-added combination of external by-products and technical innovations.

To better understand the genesis of a symbiosis, it is valuable to take advantage of a parallel from the natural world, in which there is a seed and fertile soil. Initially, the former (if active) enters the mitosis phase to produce a root in the latter (Frosch and Gallopoulos, 1989). Exogenous and endogenous factors enable plant growth (unique inclination and ground features); in an industrial setting, the company structure and district qualities underlie the success of symbiosis. Therefore, the process described above can be divided into three stages according to Mortensen and Kørnøv (2019). Firstly, firms explore several exchange relationships (Chertow and Ehrenfeld, 2012). This communicates the randomness (or serendipity) which drags development. In this stage, companies study easy-to-implement cooperation opportunities. No constraints or legal bounds are supposed. This involves both material exchange potential and a promising scenario. The next stage is critical and influences success and failure. This process is divided into three phases: awareness and interest, exploration, and organization (which can be generated by proactive business initiatives or government initiatives). In the end, symbiosis achieves tangibility. Funds and investments get placed for facility exchanges. Growing the sphere of influence represents the most significant goal in an IS. Increasing redundancy (e.g., exchange density or number of links connected to a node) boosts supply chain resilience, since disruption comes from the variability of output quality and quantity, reductions in waste disposal costs, and increases in waste exchange prices (Turken and Geda, 2020).

The eco-industrial park (EIP), a new way of considering an industrial district, stems from the IS concept (Neves et al., 2020). Usually, IS network design matches EIP design (Turken and Geda, 2020). This concept encompasses a cluster of manufacturing and service companies looking to collaborate in managing resource challenges, including energy, water, and materials, to improve economic and environmental performance. Collective benefit should be greater than the individual (Lowe, 1997). Sometimes, due to strict climate change regulations or industrial district requalification, an EIP may result from an external promoter called the initiator. Political strategy is mandatory to support the park's development. Business diversification reduces the risk of failure since sector variety means diverse processes, boosting material flow (Bellantuono et al., 2017). Firms linked by joint efficiency and sustainability goals will find new opportunities to strengthen network resilience (Lombardi and Laybourn, 2012). Promoting active involvement via stakeholder engagement must foresee information system integration and sharing of technologies (Chertow, 2007). An EIP cannot handle internal demand-and-supply fluctuation without a proper information system to share by-product types, quantity, quality, and time (Bellantuono et al., 2017). Formal contracts specifying relationship rules and benefits lead to strong partnerships. When facing uncertain demand, even the most straightforward agreements might be helpful (Turken and Geda, 2020).

1.2.1. *Energy symbiosis modelling*

The literature is particularly rich in contributions regarding EIP designing models for by-products, water, and steam, especially for network design (Fraccascia and Giannoccaro, 2020). Designing an ideal energy network layout while generally taking economic and environmental factors into consideration is the main goal of maximizing industrial and energy symbiosis. It is necessary to consider a variety of parties with possibly conflicting goals, including the specific businesses situated inside the park, local authorities, and citizens (Kuznetsova et al., 2016).

The problem of ES modelling is closely connected to the modelling of multi-energy systems (MES), integrating different and complementary energy conversion technologies within a network approach (Mancarella, 2014). Thus, exploring the modelling of MES integrating renewable technologies (also called HRES - Hybrid Renewable Energy Systems) can inform the design of ES networks by providing insights into the optimal configuration and operation of the system, even if it does not consider the EIP network configuration. Some relevant examples are shown below, including the modelling of different HRES configurations, and the integration and management of BESS.

Roth et al. (2019) developed a metamodel capable of handling various hybrid system configurations for different types of usage, while Kumar and Channi (2022) used a multi-criteria decision-making approach to select the optimal HRES configuration based on a set of parameters. Graça Gomes et al. (2021) developed an optimization model that sizes the most cost-efficient renewable power capacity mix of an autonomous microgrid supported by storage technologies, considering operational, technical, and land-use constraints. Merabet et al. (2022a, b) propose an innovative energy management system for a hybrid solar and wind microgrid with battery storage that reduces energy and battery degradation costs while increasing battery lifespan. Dhundhara et al. (2018) performed a techno-economic analysis of battery storage systems in microgrids with renewable energy sources. They compared the performance of lead-acid and lithium-ion batteries under different microgrid configurations, load profiles, and resource data. They show that lithium-ion batteries are more viable and efficient for energy storage and are expected to play a significant role in future electric power systems. In addition, the multi-objectives optimization techniques planning, designing and operation of distributed energy resources are reviewed by Naz et al. (2017); the authors analyse the application area of the considered optimization techniques and present some mathematical formulations for commonly used objectives relating to resource management in microgrids.

The previous brief literature overview highlights some of the key issues that can support the ES modelling, however the studies focusing on MES and HRES do not consider the EIP technical and organizational structure as an enabler of energy exchanges. A critical review focused on the optimization of the ES within EIPs is presented below.

According to the review performed by Kastner et al. (2015), the energy exchange networks (mostly heat) has typically been based on pinch analysis and MILP. In addition, according to Boix et al. (2015), the ES within EIPs is a large-scale problem requiring a multi-objective optimization, and he only method that can be used to address the problem is mathematical programming since the energy balances need to be resolved precisely by a MILP or linear programming.

ES models primarily seek to maximize energy efficiency while minimizing costs and emissions associated with energy exchanges (Kuznetsova et al., 2016). Chae et al. (2010) introduced a mathematical model to establish a waste to heat network aiming at minimizing the cost of energy exchanges.

To develop a low-carbon energy system inside EIPs, Timmerman et al. (2014) recommended a comprehensive techno-economic modelling strategy. The following are some characteristics that a good energy system model should assess: an adequate temporal information (to show availability trends and peaks), energy demand flexibility and energy storage technologies, and a system superstructure open to any kind of energy service demand or production technology. Meneghetti and Nardin (2012) developed an optimization model for CHP (Combined Heat and Power) systems and district heating design, able to differentiate among available technologies in terms of economic and technical performances. Afshari et al. (2018a,b) presented a model that minimizes the total cost and environmental impact of an energy based IS using technical constraints in the temperature and length of networks. Butturi et al. (2020) developed an optimization model for the evaluation of ES integrating RES, considering the collective point of view of the EIP's participants. Boix et al. (2023) have developed a new optimization procedure for designing flexible networks that promote the development of industrial symbioses, considering possible deviations from nominal conditions due to environmental problems, sanitary crises, or geopolitical conflicts. The dedication of Afshari et al. (2020) is noteworthy in developing a multi-objective model for the optimal design of waste heat energy exchange. The innovative approach considers all three pillars of sustainability (economic, social, and environmental) while studying a multiperiod horizon.

Table 2 presents the critical review of the recent literature on optimization of the ES within EIPs based on MILP, considering the following criteria: type of objectives, type of energy exchanged, technical features involved, i.e., renewable energy technologies and storage devices, the time horizon, and the consideration of companies belonging to different industries. The contribution of this study is shown in the last line of the table.

The present study aims at optimizing the EIP network configuration in terms of energy exchanges, including the sharing of renewable units and storage devices, considering the interactions of industrial partners belonging to different industries with different load profiles. Within this approach, the network is optimized using MILP programming, considering both the profits and the reduction of the emissions related costs in a shared environment-oriented vision.

1.2.2. Technological barriers and enablers

Until a few years ago, it seemed challenging to exchange electricity because of dissipation and the lack of storage systems (Fichtner et al., 2004). However, power-exchange networks are currently achievable. The RESs that fit industrial processes include biomass, solar radiation (thermal or photovoltaics), ground heat, and wind. Low-carbon energy production costs are getting closer to the fossil fuel range baseline (Butturi et al., 2019) (Fig. 3).

As pointed out before, the microgrid fits well with the mentioned symbiosis model as it allows interconnecting different energy production plants and sources (Maes et al., 2011). An integrated configuration includes a centralized or decentralized microgrid controller, optimizing energy efficiency. A less probable point-of-failure makes decentralization recommended (small-scale networks are vulnerable to defections that throw off the supply chain (Lehtoranta et al., 2011)). This system comes before a more comprehensive foundation, i.e., the energy hub (Fig. 4), a configuration consisting of energy carriers (electricity or heat), converters (transformers and gas turbines), and storage devices (Butturi et al., 2019).

One of the main technological barriers to this model is geographical limitation. Organizations that run an energy cascade symbiosis need to be sufficiently close to allow economic and technical viability (Fraccascia et al., 2021). It is necessary to consider the BESS for decoupling demand and supply in complex and multisource systems. Nevertheless, since storage technologies are highly priced and immature, building and running large-scale microgrid systems are demanding tasks (Butturi and Gamberini, 2020). The price of lithium-ion battery cells, used in applications ranging from mobile phones to grid storage, has drastically declined in the last three decades. Today, a 1 kWh battery costs about 181 USD (7500 USD in 1991) (Ritchie et al., 2020).

Table 2
Summary of studies on the ES.

Authors	Objective function (s)			Energy carrier (s)		RES integration	Storage devices integration
	Economic	Environmental	Social	Power	Heat		
Chae et al. (2010)	X				X		
Meneghetti and Nardin (2012)	X			X	X		
Afshari et al. (2016)	X				X		
(Afshari et al., 2018a,b)	X	X			X		
Butturi et al. (2020)	X	X		X			
Boix et al. (2023)	X			X	X	X	
Afshari et al. (2020)	X	X	X		X		
This paper	X	X		X		X	X

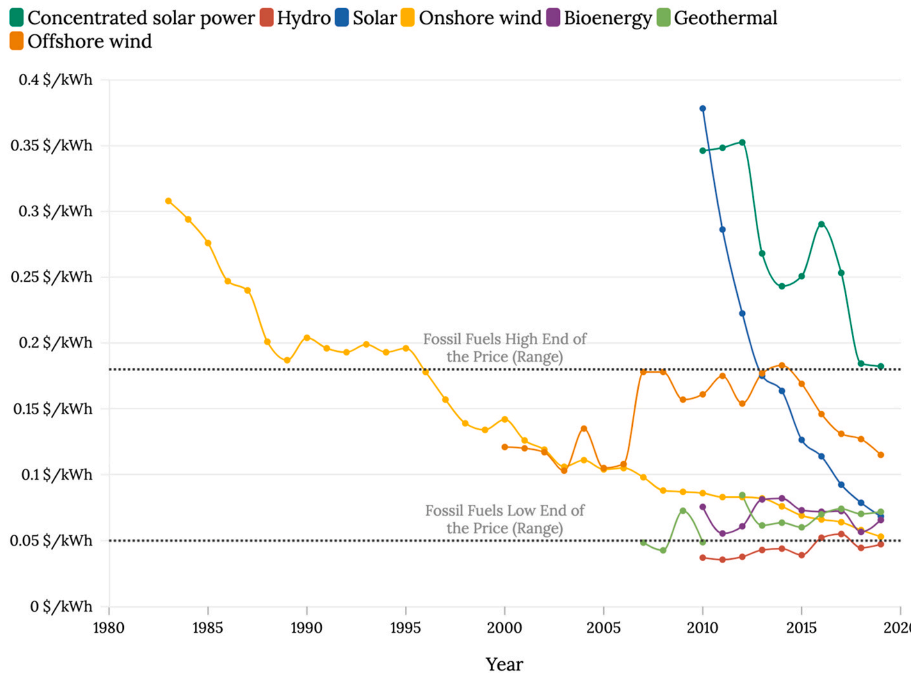

Fig. 3. World levelized cost of energy by technology (1983–2018) - author's reworking of data from IRENA source.

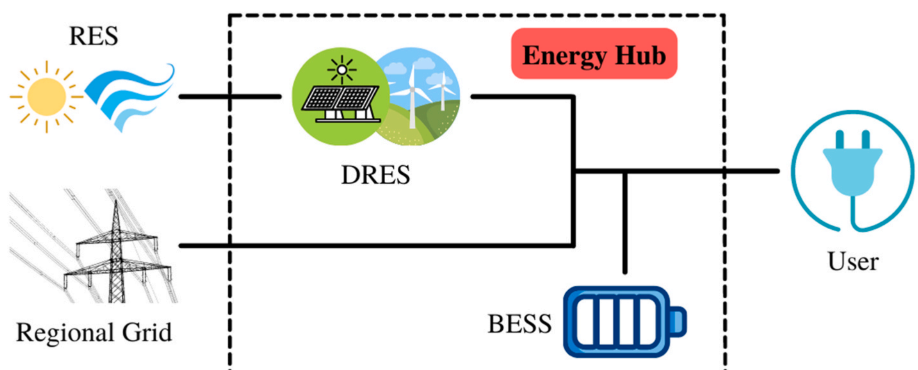

Fig. 4. Energy hub model.

1.3. Goals and contribution

As Knöttner et al. (2022) pointed out, referencing our previous study (Butturi et al., 2019), there is a need for deeper studies on the ES networks. As far as the authors are aware, a mathematical model has never been used to construct and assess an EIP for energy exchange supported by shared DREG facilities and BESSs. The optimal research should manage energy exchange within a specific timeframe and generates the best configuration for an eco-industrial park featured by DREG and BESS. The base hypothesis is that, if we introduce batteries into energy accounting, the park will have better use of resources and consequent economic savings.

Hence, this study's contribution extends beyond the state of the art. The most significant contributions are the following:

- A model to set up a novel park that connects businesses with power surpluses and businesses with energy deficits while also setting up new renewable facilities for decarbonization.
- Model improvement by using batteries to decouple the various energy sources.
- Optimization technique proofing through a case study application, demonstrating the effectiveness and practicality of the proposed approach, addresses the identified research gap of limited empirical evidence on the application of optimization techniques in real-world scenarios. By providing a detailed case study, this research work not only contributes to the existing literature but also provides a practical guide for practitioners and researchers in implementing optimization techniques in their respective fields.

Since the model is a reframing of a formerly published model focused on broad perspective investment decisions involving symbiosis and RESs (Butturi et al., 2020), it will be tested with and without BESS support. The present study aims to move forward, exploring electricity symbiosis via common facilities. DREG technologies for energy production and BESSs (lithium-ion batteries) will juxtapose direct exchange via a symbiotic relationship.

2. Problem statement

The model aims to minimize the overall costs of the electricity trade and related GHG emissions. All the players involved in the symbiosis will benefit from sharing surplus (by suppliers), stored (by BESS), and new power (by DREG). The study presents an original mixed-integer linear programming optimization model executed on Xpress Workbench. This tool reveals possible inter-firm exchanges and introduces renewable and battery energy storage systems during a 1-year simulation. It does this by concurrently targeting economic and ecological goals. Research on the Sicilian electrical market and an Indian photovoltaic system was carried out to test the model.

In this research work, two scenarios are studied in addition to the baseline scenario that represents the current state of the industrial district. The first scenario involves the use of distributed renewable energy generators (DREGs) without battery energy storage systems (BESS), while the second scenario involves the use of DREGs with BESS. The aim of these scenarios is to assess the impact of different energy storage systems on the exploitation of green and recovered energy in industrial districts. The setup of the optimization model used to decide on the best industrial energy-based symbiosis system design and operation is discussed in the sections below. Fig. 5 illustrates the optimization procedure.

2.1. Base model

To meet time-varying electricity demand and supply, the most cost-efficient ES setup is chosen using a mathematical model [35]. The energy exchange network optimization problem involves determining the optimal configuration and operation of a network of interconnected energy conversion and storage units, such as power plants, batteries, and renewable energy sources, to minimize the overall cost or maximize the system's efficiency while meeting energy demand requirements. To solve this problem, it is common to use mathematical models that represent the network's behaviour and use optimization algorithms to find the optimal solution. MILP models are widely used in optimization problems where there are discrete or binary decision variables, such as network design, scheduling, and resource allocation problems. They can capture the complex interdependencies between different components of the system, handle large-scale optimization problems, and provide insights into trade-offs between different objectives. Table 3 depicts a summary of the model's sets, parameters, and decision variables.

Energy balances, which guarantee that the demand is satisfied in every timestep, are the model's main constraints. Some important assumptions are considered:

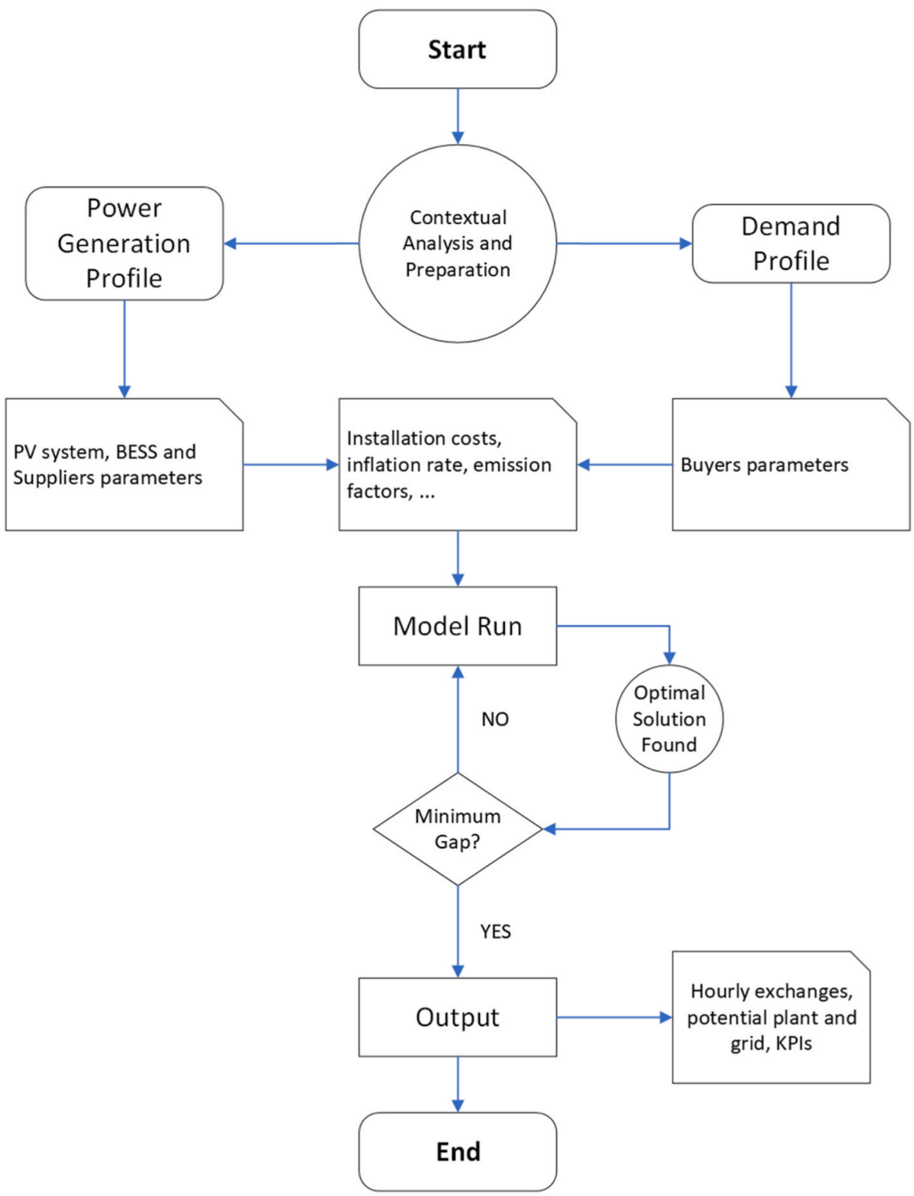

Fig. 5. Model testing workflow.

Table 3
Set of indices, parameters, and decision variables.

Sets and indices	
B	Set of buyers, indexed by b
V	Set of vendors (supplier and DREGs), indexed by v
S	Set of candidate BESS, indexed by s
T	Set of time frames, indexed by t
Input parameters	
D_b^t	Demand by industry b in period t (kWh)
EA_v^t	Available electricity by v in t (kWh)
VV_v	Variable cost by v (€ /kWh)
VF_v	Fixed cost by v (€)
PE_v	Electricity price by v (€ /kWh)
BF_s	Fixed cost by b (€)
$SOEmax_s^t$	Maximum state-of-energy by s in t (kWh)
$SOEmin_s^t$	Minimum state-of-energy by s in t (kWh)
η_s	Charging/Discharging Rate by s (%)
φ_s	Self-Discharging Rate by s in period t (%)
MP	Standard electricity price
$L_{a,b}$	Location distance $a \leftrightarrow b$ (km)
CC	Grid fixed cost standard factor (€ /km)
EI_k	Emission factor by $k \in \{B \cup V \cup S\}$ ($kgCO_2eq$ /kWh)
CT	Carbon tax (€ /$kgCO_2eq$)
$shareR$	Share of demand satisfied by renewable sources (%)
Decision variables	
$x_{v,k}$	A binary variable, 1 if v and $k \in \{B \cup S\}$ connected; 0, otherwise
$x_{s,b}$	A binary variable, 1 if s and b connected; 0, otherwise
z_k	A binary variable, 1 if $k \in \{V \cup S\}$ is established; 0, otherwise
$h_{v,s}^t$	A binary variable, 1 if partition v of s is charging at t; 0, otherwise
$y_{v,k}^t$	Energy (kWh) produced by v and supplied to $k \in \{B \cup S\}$ in t
$ydec_{s,b,v}^t$	Energy (kWh) (produced by v) supplied from s to b in t
$e_{v,s}^t$	Energy (kWh) produced by v, stored in s in t

- All input data are deterministic: the model uses discrete time periods to represent energy conversion and storage units' behaviour and includes constraints for demand and supply. Binary variables can ensure the system operates within capacity limits and meets demand. So, the model assumes that technology and market factors (e.g., electricity costs by standard energy supply or DREG power load) are uncertainty-free and use fixed values for these parameters.
- Economic criteria guide investments and supply decisions. Intents other than profit, unless they link costs, are not addressed. This means that non-economic factors like social and environmental impacts are not considered unless they can be directly linked to cost savings. The model's output is optimized based on economic criteria, which may not take into account non-economic factors relevant to stakeholders. Therefore, the model's output is useful for making economically efficient decisions, but it may not be the most socially or environmentally responsible choice.
- Carbon taxes influence the preferred source of energy. Carbon pricing tools help guide immediate investment and spending decisions with the long term in mind (Re et al., 2020). Accordingly, it can be assumed that status quo inertia against new investments will be, where applicable, broken by sustainability leverage.
- The choice of BESS is discretized among three predefined levels (low, medium, and high) based on the cost-benefit analysis. The MILP model developed does not consider any capacity dimension decision for BESS, meaning that the model assumes that the size of the battery is fixed and predefined. This could limit the flexibility and adaptability of the system to changing energy demand and supply patterns, as the model cannot optimize the size of the BESS in response to changing circumstances. However, the model can still provide insights into the most economically efficient BESS choice given the predefined levels.

2.2. Superstructure

The baseline scenario includes two active players (buyers and suppliers) and two types of facilities (DREGs and BESSs) (Fig. 6):

- Buyer, i.e., a firm with a power deficit. It must outsource its power demand relying on the municipal grid.
- Supplier, i.e., a firm with electricity surplus. It autonomously produces energy from indoor plants. Usually, wind turbines and PV panels on rooftops are the most exploited systems.
- DREGs, i.e., new facilities for EIP energy production (consumed by the park). Those plants could arise in locations decided by the regional administration or within large anchor/tenant companies.
- BESSs, i.e., storage systems used for decoupling demand and supply in complex interconnected grids. Lithium-ion batteries will be considered for higher efficiency, higher energy density, shorter charging time, and lower maintenance costs (Yaldız et al., 2021).

The ES configuration within the modelled EIP enables not only energy exchanges in a two-players scheme but also multiple exchanges and collective energy production. In this enhanced version, including also DREG and BESS, the network gains strategic means, demonstrating the shared commitment to reducing the environmental impact of electricity consumption and joining municipal power production.

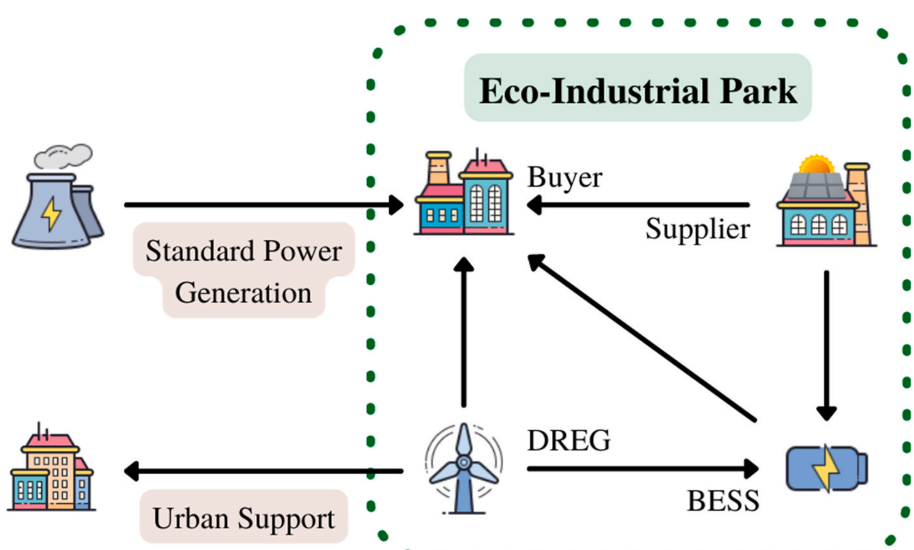

Fig. 6. EIP superstructure.

Looking at the park, summarizing all costs despite the owner, allows us to assess it without weighing up its participants. Since the model takes inspiration from a supply chain field class of problems known as multi-echelon supply chain configuration (i.e., supply chain that consists of multiple levels or tiers of distribution, production, and inventory control) (Fig. 7), the model has four sets: vendor (including all the nodes that are producing and supplying energy), buyer, storage, and time. The goal of this configuration is to optimize the flow of products and information across the supply chain, while minimizing inventory levels and transportation costs.

B is a set that holds every firm in an energy deficit (electrical), while V aggregates every possible source. It counts firms with electricity surplus and new potential RES plants. This assumption is linked to a vendor–buyer relation, as we can see in a manufacturing supply chain. S, i.e., a set of batteries, introduces the multilevel characteristic which desynchronizes production and consumption. Lastly, T, i.e., the time horizon, sets the wanted period. The calculation is executed for every hour in an entire year (8760 h) (Ren and Gao, 2010).

The input data for the model can be divided into the following categories: buyer information, vendor and storage information, and financial and policy information.

2.2.1. Buyer information

Since maintenance costs for batteries and energy production are associated with energy storage and dispatch, the hourly rate in kWh is considered rather than the power rating (kW) (Chen et al., 2012). In other papers, academics used tools such as simulations, machine learning, or surveys (Ren and Gao, 2010). Here, we use a dataset to extract plausible load distribution.

2.2.2. Vendor information

The vendor set V collects every potential supplier in the park. Supplier firms or a potential plant could set up new connections with a buyer or a battery. The yearly fixed cost VF_v has three elements: purchase, installation, and average maintenance (*kWp* dependence) costs. In this work, the model computes the total cost in an 8760-h time range. Thus, the investment cost IC_v must be annualized, increased by maintenance MC_v (Equation (1)) (Graça Gomes et al., 2021).

$$VF_v = \frac{r(1+r)^l}{(1+r)^l - 1} \cdot IC_v + MC_v. \qquad 1$$

It is used l as the plant lifetime. The variable r translates the annual real interest rate of the system and is calculated using Equation (2), which considers f as the inflation rate.

$$r = \frac{j - f}{1 + f} \qquad 2$$

BESS parameters focus approximately on the same issues as vendors. There are only fixed costs involving installation and maintenance, which follow the same assumptions as before. Incorporating battery aging into multi-energy EIP configuration problems affects both the state of energy and the charging/discharging rate (Cardoso et al., 2018).

2.2.3. Financial and policy information

In this section, some other contextual parameters are reported. They register general information: the players' positions, the economic/energy scenarios, and the national/regional policy objectives to satisfy.

Since we consider the transition phase to wider use of renewable energy sources, the modelled EIP is still connected to the distribution grid, and it can receive electricity from the outside when electricity produced within the EIP is insufficient to satisfy the load. Those outsourcing plants (coal or gas), which we call standard, compensate for any lacking indoor production. The park ought to set a competitive price. Emissions related to energy production are calculated in kg CO_2 eq. The carbon emissions for the different technologies have been extracted from Schlömer et al. (2014). The government sets the emission cost; hence, it is the same for each plant. A more in-depth LCA (Life Cycle Assessment) analysis of the electrical devices would give a more complete picture of the environmental impact of the whole system, but this analysis would require a more precise definition of the technologies involved in the study, here described mainly by their renewable sources and energy supplying.

Linking the grid investment cost follows the same assumptions for DREGs and BESS (annualization approach). This is used as a standard factor.

shareR is a project parameter that directly alters the park's geography. It is a parameter that measures the amount of electricity demand that is met by RES, expressed as a percentage of the total electricity demand. Thus, it provides insight into the level of reliance on renewable energy sources in meeting electricity demand. For example, if the parameter is 30%, it means that 30% of the electricity demand is met by renewable energy sources, while the remaining 70% is met by non-renewable sources such as fossil fuels. This parameter is important because it reflects the progress towards a more sustainable and climate-friendly energy system. A higher percentage of renewable energy in the electricity mix can lead to reduced GHG emissions, improved air quality, and increased energy security.

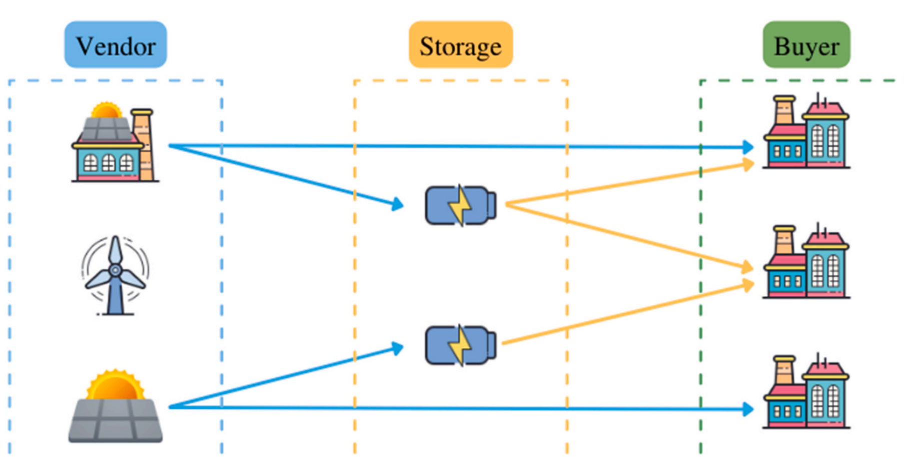

Fig. 7. Multi-echelon supply chain configuration.

2.3. Variables

The investigation carried out was aimed at uncovering possible company–company, company–BESS, and company–plant networks. The focus was on the existence and quality of the connection. Therefore, the variables reflect the presence or absence of links, cost centres, and dependency relationships. The model must consider a sort of memory for energy storage into the batteries.

The first element to consider should be the continuous variable that manages the energy transfer between one company and another or between a facility (plant and batteries) and a company in a specific period (Equation (3)). BESS accounts for the outgoing flow to the buyer but keeps the information about the energy source (Equation (4)). In the model, this pair of variables will be helpful to calculate energy-related costs (operations and emissions).

$$y^t_{v,k} = \text{Energy from } v \text{ to } k \in K = \{B \cup S\} \text{ in } t \tag{3}$$

$$ydec^t_{s,b,v} = \text{Energy (by } v\text{) from } s \text{ to } b \text{ in } t \tag{4}$$

Consequently, Equation (5) defines if a link between two players exists. Equations (3)–(5) are deeply related; if, in any of the periods, energy flows between two nodes, then the linkage can be expressed as

$$\begin{matrix} x_{v,k} \\ x_{s,b} \end{matrix} = \begin{cases} 1 \text{ if a link between two nodes is built} \\ 0 \; otherwise \end{cases} \tag{5}$$

Like the case of connecting arches (Equation (5)), RES plants and BESS will possibly have a flag variable (Equation (6)).

$$z_k = \begin{cases} 1 \; if \; k \in K = \{B \cup S\} \; is \; built \\ 0 \; otherwise \end{cases} \tag{6}$$

Equation (7) indicates the *state of energy* of the battery during period t. The BESS is partitioned according to vendors. It is mandatory to control this value because it must be limited by technical parameters.

$$e^t_{v,s} = \text{Energy by } v \text{ stored in } s \text{ during } t \tag{7}$$

In the end, the model must make sure that, if a battery is charged by a vendor, the partition will not discharge in the same period. This is needed to assume the linearity of inputs and outputs (Equation (8)).

$$h^t_{v,s} = \begin{cases} 1 \text{ if partition of } v \text{ in } s \text{ is charging during } t \\ 0 \; otherwise \end{cases} \tag{8}$$

2.4. Objective function

The objective function tracks the benefits of all shareholders within the EIP: since the goal is to minimize costs, the objective function will be set to minimize the total cost of production, purchase of energy, and investments. This will ensure that the stakeholders benefit from reduced costs, which can be passed on to consumers in the form of lower prices or to investors in the form of increased profits, as presented in Equation (9). Therefore, both buyer and vendor companies' costs are assessed. Furthermore, since the investment costs cannot be linked to a single company, connections and facilities investments are considered overall.

$$\min Z = C_1 + C_2 + C_3 \tag{9}$$

The first part of the objective function sum supplies costs from standard energy conversion systems. If the park sustains itself through green energy, this part should be zero or near zero. C_1 (Equation (10)) includes the market price of electricity from the regional grid and corresponding taxes from carbon emission.

$$C_1 = \sum_{t \in T} \sum_{b \in B} (MP + CT \cdot EI_b) \left[D^t_b - \sum_{v \in V} \left(y^t_{v,b} + \sum_{s \in S} ydec^t_{s,b,v} \right) \right] \tag{10}$$

Below, the objective function considers the contribution margin from the vendor's energy selling (both direct and via BESS). C_2 (Equation (11)) encompasses variable costs and carbon taxes related to the energy production (facilities) or recovery (suppliers) minus selling price.

$$C_2 = \sum_{t \in T} \sum_{v \in V} (VV_v + CT \cdot EI_v - PE_v) \sum_{b \in B} \left(y^t_{v,b} + \sum_{s \in S} ydec^t_{s,b,v} \right) \tag{11}$$

In the end, annualized costs from connections and new plants investments are considered (Equation (12)).

$$C_3 = \sum_{v \in V} VF_v z_v + \sum_{s \in S} BF_s z_s + CC \cdot \sum_{v \in V} \sum_{k \in B \cup S} L_{v,k} x_{v,k} + \sum_{s \in S} \sum_{b \in B} L_{s,b} x_{s,b} \tag{12}$$

2.5. Constraints

Constraints (13) and (14) switch the flag variable according to the flow. If the flow between two nodes is positive, the connection is on. M is a big enough integer value.

$$\sum_{t \in T} y^t_{v,k} \leq M \cdot x_{v,k} \forall v \in V, k \in B \cup S \tag{13}$$

$$\sum_{t \in T} \sum_{v \in V} ydec^t_{s,b,v} \leq M \cdot x_{s,b} \forall s \in S, b \in B \tag{14}$$

An adequate energy flux must justify a new plant construction or between-firm agreement for energy production. Therefore, for each new system, the flag variable that distinguishes it is strictly bonded to the energy produced and dispatched. Constraint (15) bounds both the source flow (limiting the total) and the related flag-variable behaviour.

$$\sum_{k \in B \cup S} y^t_{v,k} \leq EA^t_v \cdot z_v \forall v \in V, t \in T \tag{15}$$

For each buyer (during any period), the total amount of input must not exceed the demand (Constraint (16)). The input can come from a supplier firm, a new plant, or a battery (decreased by a certain quantity, discharging efficiency).

$$\sum_{v \in V} \left(y^t_{v,b} + \sum_{s \in S} ydec^t_{s,b,t} \cdot \eta_s \right) \leq D^t_b \forall b \in B, t \in T \tag{16}$$

Batteries need some other constraints. Constraint (17) is the counterpart of the number of BESSs. If the battery is used in any used partition and any period, the flag variable switches on.

$$\sum_{t \in T} \sum_{v \in V} e^t_{v,s} \leq M \cdot z_s \forall s \in S \tag{17}$$

Constraint (18) sets the *state of energy* of each partition in every battery as null. Constraint (19) is useful to update the energy content, increasing according to inputs and outputs. Constraints (20) and (21) delimit the *state of energy*.

$$e^0_{v,s} = 0 \forall v \in V, s \in S \tag{18}$$

$$e^t_{v,s} \leq e^{t-1}_{v,s} (1 - \varphi_s) + \eta_s \left(y^t_{v,s} - \sum_{b \in B} ydec^t_{s,b,v} \right) \forall v \in V, s \in S, t \in T \tag{19}$$

$$\sum_{v \in V} e^t_{v,s} \leq SOEmax_s \forall s \in S, t \in T \tag{20}$$

$$\sum_{v \in V} e^t_{v,s} \geq SOEmin_s z_s \forall s \in S, t \in T \tag{21}$$

Since the model presents a particular issue about charging and discharging limits during the testing phase, it is necessary to specify how much energy to send in Constraint (22).

$$SOEmax_s z_s - \sum_{v \in V} e^{t-1}_{v,s} \geq y^t_{v,s} \forall s \in S, t \in T \tag{22}$$

The last two constraints mediate battery condition. If some energy comes from any of the vendors, Constraint (23) makes sure that the partition will not discharge Equation (24).

$$y^t_{v,s} \leq M \cdot h^t_{v,s} \forall v \in V, s \in S, t \in T \tag{23}$$

$$\sum_{b \in B} ydec^t_{s,b,v} \leq M \cdot \left(1 - h^t_{v,s}\right) \forall v \in V, s \in S, t \in T \tag{24}$$

The last constraint, Constraint (25), involves a designer aspect of the model and the incidence of energy produced through renewable sources (including any symbiosis between companies).

$$\sum_{t \in T} \sum_{b \in B} \frac{\sum_{v \in V} \left(y^t_{v,b} + \sum_{s \in S} ydec^t_{s,b,v} \cdot \eta_s \right)}{D^t_b} \geq shareR \tag{25}$$

The basic constraints refer directly to the implicated variable types; the binary variables will have 0 and 1 as the allowed values, while continuous ones can also assume a value greater than or equal to 0.

$$\begin{matrix} x_{v,b} & & \forall v \in V, b \in B \\ x_{v,s} & \in \{0;1\} & \forall v \in V, s \in S \\ x_{s,b} & & \forall s \in S, b \in B \end{matrix} \tag{26}$$

$$\begin{matrix} z_v & \in \{0;1\} & \forall v \in V \\ z_s & & \forall s \in S \end{matrix} \tag{27}$$

$$h^t_{v,s} \in \{0;1\} \quad v \in V, s \in S, t \in T \tag{28}$$

$$\begin{matrix} y^t_{v,b} & \geq 0 & \forall v \in V, b \in B, t \in T \\ y^t_{v,s} & & \forall v \in V, s \in S, t \in T \end{matrix} \tag{29}$$

$$ydec^t_{s,b,v} \geq 0 \forall s \in S, b \in B, v \in V, t \in T \tag{30}$$

$$e^t_{v,s} \geq 0 \forall v \in V, s \in S, t \in T \tag{31}$$

3. Use case

The earlier model was tested through a fictional case example, with data being gathered via public datasets. The proposed model was used to optimize a dummy but plausible EIP. The case was made up of three energy suppliers, three possible photovoltaic plants, and six energy buyers. Furthermore, three potential BESSs support the energy management of industrial area. In the case study data, an in-depth analysis of data exploration and pre-processing of input data is reported.

The developed model was coded using FICO Xpress and its FICO Xpress Optimization Suite for solving mixed-integer programming problems. Testing was conducted on a Windows 10 Pro Educational PC with an Intel i-7 (3,4 GHz) processor and 16 GB RAM. The explanatory model has 158′175 binary variables, 1′580′940 continuous variables, and 790′564 constraints.

3.1. Input data

The case study shows a district with heterogeneous sectors. Every firm must be supplied with electricity by standard energy conversion systems (high-carbon plants or national mix). There are six different buyers, each distinguished by the industrial sector: *Buy1* is a clothing company, *Buy2* is a food company, *Buy3* produces paper, *Buy4* produces plastic, *Buy5* produces steel, and *Buy6* produces wood. The results show the electricity consumption over 2020. The time horizon frames a 1-year demand with a 1 h timespan, this means that the entire year's demand is represented and analysed at a granularity of 1-h intervals. Since the objective function calculates the total costs over the entire time period considered, the optimal solution obtained is valid for all time intervals. This means that the optimal solution provides the optimal value for each time interval and not just for the last period of the year. In other words, the optimal solution found is applicable to all periods of the year and ensures the best possible result in terms of total costs over the entire time period considered. All data are extrapolated from the previously cited datasets. We take into consideration a one-year dataset since considering a more precise energy production forecasting, based on 5–10 years data, falls outside the scope of our investigation.

The distance matrix is given in Table 4. The linkage investment costs CC were derived through a multiplier (190 € $/km$) found in the literature (Vaillancourt et al., 2014). In Tables 5 and 7, the emission factors are reported based on technology.

There are three different suppliers, each distinguished by the industrial sector: *Sup1* is a chemical company, *Sup2* produces coke, *Sup3* water treatments. Each supplier applies a markup to the variable recovery cost PE_v, approximately 10% (Table 5). The variable recovery cost refers to the expenses related to the installation and maintenance of the equipment necessary for energy recovery, as well as the cost of converting and distributing the recovered energy.

There are three different DREGs and three photovoltaic systems distinguished by size, with *Res1* the biggest, *Res2* medium, and *Res3* the smallest.

There are three different Li-ion batteries: *Bat1*, *Bat2*, and *Bat3*. Each of them has an installation cost related to its capacity with a standard factor of 100 €$/kWh$ (Ritchie et al., 2020). In Table 6, we summarize the key data points that must be considered. These data include the nominal capacity of the battery, the state of charge maximum $SOEmax_s$ and minimum $SOEmin_s$, the charging/discharging rate η_s, and the self-discharging rate φ_s.

Table 7 presents data about the background scenario, which encompasses all factors outside the park and its components, such as electricity prices set by the local authorities. As an example, in the first quarter of 2022, the electricity price for non-households in Italy was 0.27 €$/kWh$ on average. This study assumes a fixed price and does not consider the variability of prices, instead using a standard price derived from the average price per energy consumption category of each company.

3.2. Methodology for results comparison

This model aims to solve a trade-off between two of sustainability's three pillars. Since social indicators are translated differently from environmental and economic ones and obtaining data for their measurement is more controversial (Neves et al., 2020), third pillar objectives are not directly engaged in the objective function. Three classes of KPIs (Key Performance Indicators) are considered to compare the scenarios: energy efficiency, environmental, and economic indicators. In this section, each KPI is covered in detail.

The ability of the system to exploit dispatchable electricity is handled. A greater incidence of exchanges within the park results in a more solid and resilient logistics system. Mangers of the park might find it interesting to know how the resources are used. For buyer-side companies, the focus is on the ratio of demand satisfied by the purchase from partner companies or ecological plants on the total. On the other hand, for suppliers and DREG plants, the focus is on how much energy is destined for the park and how much will remain unexploited (Afshari et al., 2018a,b). Furthermore, an interesting index for the organization of the park could be the quality of the installed batteries. The chosen indicators are listed below.

- Average demand met by internal sources *SD*.

$$SD = \sum_{t \in T} \sum_{b \in B} \frac{\sum_{v \in V} \left(y^t_{v,b} + \sum_{s \in S} ydec^t_{s,b,v} \cdot \eta_s \right)}{D^t_b} \tag{32}$$

- Energy by vendor usage rate US_v.

Table 4
Distance matrix.

	Buy1	Buy2	Buy3	Buy4	Buy5	Buy6	Bat1	Bat2	Bat3
Sup1	5	2	9	5	6	8	2	12	6
Sup2	6	15	14	4	12	9	4	12	4
Sup3	12	3	3	9	5	7	7	5	11
Res1	5	9	10	9	14	7	13	8	15
Res2	8	10	9	11	8	3	5	14	2
Res3	8	7	4	7	11	10	2	10	8
Bat1	12	3	11	15	6	6	–	–	–
Bat2	8	11	2	11	11	8	–	–	–
Bat3	13	10	8	4	14	14	–	–	–

Table 5
Electricity recovery and price for suppliers.

	Sup1	Sup2	Sup3	Res1	Res2	Res3	
VV_v	0.20	0.10	0.22	0	0	0	EUR/kWh
PE_v	0.25	0.20	0.26	0	0	0	EUR/kWh
EF	0.200			0.020			$kgCO_2eq/kWh$

Table 6
Storage-side parameters.

	Bat1	Bat2	Bat3	
Capacity	300	400	500	kWh
$SOEmax_s$	270	360	450	kWh
$SOEmin_s$	30	40	50	kWh
η_s	0.90	0.93	0.95	%
φ_s	0.03	0.04	0.05	%

$$US = \sum_{t\in T}\sum_{v\in V}\frac{\sum_{b\in B}\left(y^t_{v,b} + \sum_{s\in S} ydec^t_{s,b,v}\cdot\eta_s\right)}{EA^t_v z_v} \quad 33$$

- BESS usage rate UB.

$$UB = \sum_{t\in T}\sum_{s\in S}\frac{\sum_{v\in V} e^t_{v,s}}{SOEmax_s z_s} \quad 34$$

The environmental dimension assessment is here restricted to the quantities of $kgCO_2eq$ emitted the indicator typically correlated to energy consumption. This allows us to directly compare the baseline scenario to the scenarios integrating renewable energy.

- Emission reduction

$$V_1 = \sum_{t\in T}\sum_{b\in B} EI_b D^t_b \quad 35$$

$$V_2 = \sum_{t\in T}\sum_{b\in B} EI_b\left[D^t_b - \sum_{v\in V}\left(y^t_{v,b} + \sum_{s\in S} ydec^t_{s,b,v}\cdot\eta_s\right)\right] + \sum_{t\in T}\sum_{v\in V}\sum_{k\in B\cup S} EI_v\cdot y^t_{v,k} \quad 36$$

$$ER = \frac{V_2 - V_1}{V_1} \quad 37$$

Another key point to account for is regional rules to build new plants and connections. Given the evolution of industrial districts into social aggregation centres, the park must follow laws limiting noise, smell, and impact on biodiversity or the landscape. We do not deal with all these issues here, but it is essential to address them during the transition to more sustainable energy supply mechanisms (Bellantuono et al., 2017).

Yet, it is important to consider the economic aspect for an EIP assessment. The organization that controls the payments and exchanges of energy among players should aim to ensure the financial sustainability of the entire project. Since buyers should split new facility investments and an asset allocation was not hypothesized, a buyer cost reduction evaluation does not have any basis. Nevertheless, the carbon tax reduction quantification and levelized cost of electricity for hybrid systems can be assessed.

- Carbon tax reduction

$$tr_1 = CT\sum_{t\in T}\sum_{b\in B} EI_b D^t_b \quad 38$$

$$tr_2 = CT\sum_{t\in T}\left\{\sum_{b\in B} EI_b\left[D^t_b - \sum_{v\in V}\left(y^t_{v,b} + \sum_{s\in S} ydec^t_{s,b,v}\cdot\eta_s\right)\right] + \sum_{v\in V}\sum_{k\in B\cup S} EI_v y^t_{v,k}\right\} \quad 39$$

$$TR = \frac{tr_2 - tr_1}{tr_1} \quad 40$$

- Levelized cost of electricity for hybrid systems

$$LCOE = \frac{\left(\begin{array}{c}\sum_{v\in V} VF_v z_v + \sum_{s\in S} BF_s z_s + \\ +\sum_{t\in T}\sum_{v\in V} VV_v \sum_{b\in B}\left(y^t_{v,b} + \sum_{s\in S} ydec^t_{s,b,v}\right)\end{array}\right)}{\sum_{t\in T}\sum_{b\in B}\sum_{v\in V}\left(y^t_{v,b} + \sum_{s\in S} ydec^t_{s,b,v}\cdot\eta_s\right)} \quad 41$$

- LCOE (levelized cost of electricity) reduction

$$R_{LCOE} = \frac{LCOE - MP}{MP} \quad 42$$

3.3. Results and discussion

In this section, we study the analysed case results. The model was run with two similar datasets. One did not consider BESS support, while the other did.

Table 7
Non-household electricity prices by consumption class.

	Buy1	Buy2	Buy3	Buy4	Buy5	Buy6	
Batch	<20	20–500	<20	20–500	20–500	<20	$MWh/year$
Electricity Price	0.336	0.202	0.336	0.202	0.202	0.336	€/kWh
MP	0.270						€/kWh
EF	0.483						$kgCO_2eq/kWh$

Using the previously presented data on Xpress Workbench, we obtained an all-new scenario with specificity in 103.87 s (about 1 min 44 s). All three supplier firms were involved in the symbiosis, proving that the engagement is economically feasible. While only small-scale photovoltaic systems were chosen, this could mean that a well-tailored plant choice would lead to a more cost-effective configuration. Data show how the model found an even better energy mix.

Fig. 8 shows how one big plant can provide energy for every actor, while the supplier side only focuses on a few actors. The *Res3* plant at 79 *km* in network grid foresees a 600,000 € investment with 15,010 € in the grid network. The output relies on a 24.93% standard high-carbon source of energy. In Fig. 9, the buyer side supplies itself mainly through RES-side surplus. Renewable plants provide energy to the municipal grid with the buyback system. Via overall park cost optimization, considering any costs and savings for supplier companies in selling their surpluses, the choice of between-firm exchange is considered cheaper. On the contrary, unlike shared facilities, this exchange is profitable for both buyers and suppliers. Again, the old energy mix supplies the industrial park, but the new configuration achieves European targets (i.e., more than 55% of energy mix is supported by RES).

Despite the massive use of indoor energy, the park exploits only 74.93% of the total supplied energy. This leads to an 84.59% reduction in emissions and a resulting 68.09% saving in carbon taxes. The new energy mix allows the park another 43.46% saving; the LCOE of 0.1526 €/*kWh* is lower than the standard price for outsourced energy.

The second case study result requires a way more time-consuming process. After less than 4 h approximately, the model finds a fair enough solution with a 0.87% gap (compared to the relaxed solution). We obtained here a suboptimal solution. In general, a suboptimal solution may not be optimal for all decision-making situations, and further analysis may be required to determine the sensitivity of the results to changes in parameters or constraints. However, the obtained suboptimal solution still satisfies the constraints and objectives of the problem, making the assumptions and hypotheses of the model proven to be valid. Thus, the suboptimal solution is adequate for addressing the problem, and any potential limitations or uncertainties should be identified and addressed in future research.

Figs. 10 and 11, again, show how one smaller plant provides energy for every actor. Moreover, a medium-scale battery supports the plant with added storage. In this configuration, we find 95 km of grids taking 18,050 €. A 40,000 € battery is useful to supply both *Buy2*, a large-scale player, and *Buy4*, a smaller one. Compared to Case Study 1, this solution enhances the exchange density of suppliers. A firm vendor is more willing to share its excess energy with multiple buyers, as the central plant allows for better energy management efficiency. By satisfying the demand of multiple buyers through the shared plant, the supplier can avoid the cost and complexity of dealing with multiple individual energy buyers. Additionally, the use of a medium-scale battery with added storage can further support the plant and increase the exchange density of suppliers. The resulting optimization can lead to a more efficient and cost-effective energy distribution system for all parties involved.

The high-carbon sources of energy supply 17.69% of the total consumption, i.e., more than seven percentage points higher compared to the battery-free solution. The chosen battery only has a 41% mean usage

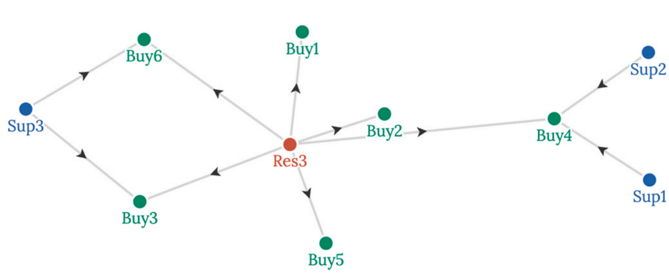

Fig. 8. EIP grid network, case 1: no BESS.

Fig. 9. Energy consumption and production, case 1: no BESS.

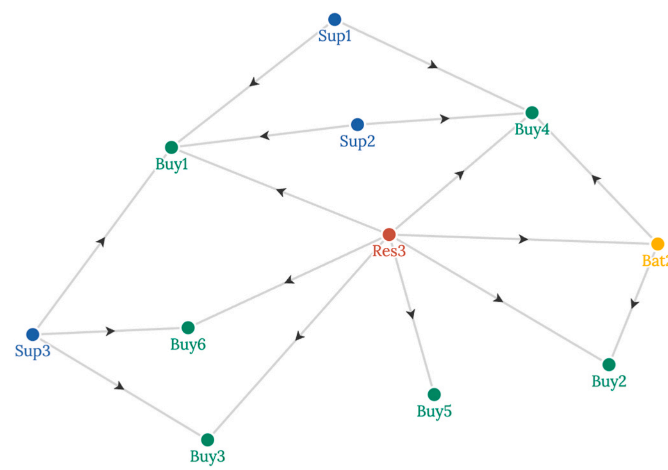

Fig. 10. EIP grid network, case 2: BESS.

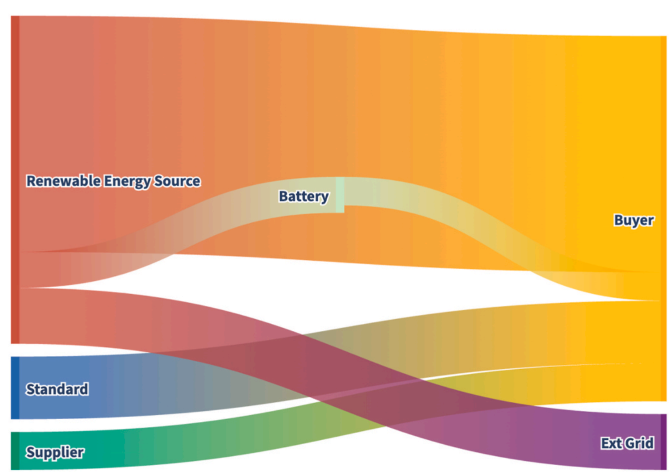

Fig. 11. Energy consumption and production, case 2: BESS.

ratio, with a state-of-energy peak of 345.01 *kWh*. A better BESS sizing phase could lead to higher usage and better-performing energy management, but it is good enough for our purposes. The inequality between the input and output of *Bat2* is explainable by structural battery inefficiencies (φ and η technical parameters). The proposed setup exploits 82.16% of the supplied energy. This does not reflect a significant improvement in emission reduction but tangible savings in carbon taxes. The energy mix reaches a drop to 0.1380 €/kWh.

Table 8 summarizes and compares the results.

SD, US, and UB summarize the results related to the use of energy produced and recovered. The second scenario shows a substantial improvement in energy efficiency management. Surprisingly, despite using its capacity (peak and discharged conditions), the chosen battery still has a low usage ratio. There are several possible explanations for such a result:

- A suboptimized set of potential batteries could prevent capacity saturation and efficiency. The model only suggests the best combination of factors and does not size them.
- Data inconsistency might lead to an already adequate solution. If demand data collected for the buyer-side were underestimated, the supplier-side energy production would be well-sized to exploit it without BESS (and vice versa).

In the violin plot showed in Fig. 12 presents the distribution of *Bat2* state-of-energy data, with a median value of 124.34 kWh and a mean value of 147.59 kWh. The quartile values indicate that 50% of the data falls within the range of 41.67 kWh to 245.11 kWh. This indicates that the network has a certain level of flexibility to handle variations in energy production and demand.

The under-utilization of the battery could allow for more flexibility in the network to handle any variations in demand and production. The excess capacity of the battery could be used to store any excess renewable energy generated during periods of high production, and then release that energy during periods of low production to meet demand. This would not only provide a more stable and reliable energy supply, but also increase the efficiency of the renewable energy sources by reducing wastage. Additionally, the unused capacity in the battery could be leveraged for ancillary services, such as frequency regulation, to further improve the stability and reliability of the network. Overall, while the battery usage may be low in this setup, it does provide an opportunity to enhance the flexibility and reliability of the network, and further optimize the use of renewable energy sources.

Regarding environmental benefits, there would be a significant reduction in CO_2 emissions in both cases. The data clearly shows that the second case study, which includes the use of BESS, outperforms the first case study in terms of several key metrics. For example, the percentage of demand satisfied by renewable sources SD increases from 75.07% to 82.31% with the support of BESS. Additionally, the percentage of energy by the supplier used in the park US also improves significantly, increasing from 74.93% to 82.16%. This indicates that BESS allows for better utilization of renewable energy sources and more efficient use of energy from the supplier. Moreover, the usage of the battery UB is also significant, reaching 41% on average. While there is still room for improvement in the BESS sizing phase to increase usage, this data shows that BESS can be an effective solution for managing energy supply and demand in an industrial park. In terms of economic savings, the total cost $Ctot$ of the second case study with BESS is lower than the first case study without BESS, resulting in a cost savings of approximately €54,000. This is reflected in the levelized cost of energy $LCOE$, which decreases from 0.1526 €/kWh to 0.1380 €/kWh. This indicates that BESS not only helps to reduce carbon emissions and increase resource efficiency, but also results in cost savings for the industrial park. Overall, the data strongly supports the hypothesis that the use of BESS can lead to better resource utilization, improved economic performance, and more sustainable energy management in industrial parks.

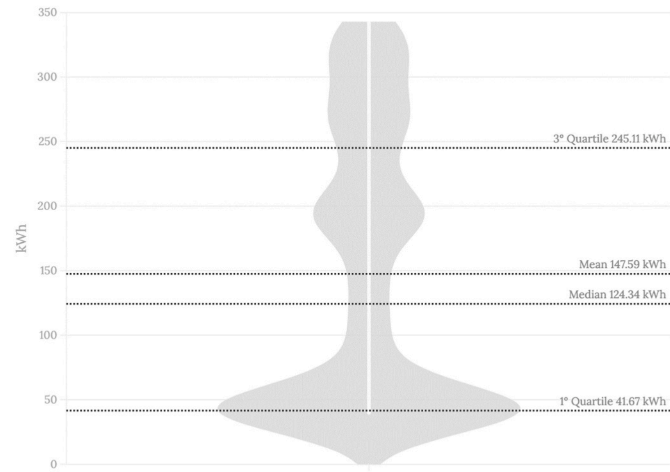

Fig. 12. Bat2 state-of-energy.

4. Conclusions

Eco-industrial parks and industrial symbiosis seem to be a valuable path to enhance competitive advantage and partially decouple the prices of energy-type commodities from oligopolistic orders. An environmental footprint cut in the industrial sector would provide benefits to nearby communities, but a lack of technical knowledge among companies generates friction. The IS is a model for fostering circularity even in the electricity sector. This study set out to define a mixed-integer linear optimization model that uncovers profitable energy exchanges supported by a cooperative investment in RES plants and BESSs. A plausible case study generated from Sicilian electricity production and consumption analysis showed how batteries effectively influence the economic and environmental performance of the park. While a non-supported RES limits energy efficiency, this approach provides new insights into decoupling demand and supply to enhance the usage ratio and lower external dependencies.

The main limitation of this study is the lack of real case studies to validate the proposed optimization model and clarify the hypothesis and results. Without validation, the model's applicability in other contexts may be limited. As the number of cases of introducing renewable energy is increasing, there is an opportunity to validate the proposed model with actual examples. This would not only provide evidence for the effectiveness of the model but also demonstrate the potential benefits of introducing renewable energy and batteries in industrial parks. By validating the model, the proposed optimization technique could be optimized and refined, leading to a better understanding of the factors influencing the economic and environmental performance of industrial symbiosis.

It is worth noting that the low mean usage ratio of the battery (below 41%) suggests that the network is not fully utilizing the potential of the battery to improve its flexibility. Therefore, further optimization of the battery sizing and usage may be necessary to fully leverage its potential benefits in handling variations in energy production and demand. One research gap that could be addressed in future work is the incorporation of stochasticity into the model. This would allow for a more realistic representation of the uncertainties present in energy production and

Table 8
Results comparison.

Case Study	*Ctot* [€]	*Computing Time* [s]	*Gap*	*SD*	*US*	*UB*	*ER*	*TR*	*LCOE*	*R_lcoe*
1 (no BESS)	572187.14	103.87	0.00	75.07	74.93	0.00	84.59	68.09	0.1526	−43.46
2 (BESS)	517978.35	13887.50	0.78	82.31	82.16	40.99	87.89	74.93	0.1380	−48.87

demand. Additionally, the current model assumes a fixed energy mix, but in reality, the energy mix can vary depending on market conditions and policy changes. Incorporating such dynamic features could lead to a more accurate representation of the energy system and its behaviour. Another potential future direction is to explore the impact of different battery chemistries and configurations on the performance of the energy system. For instance, lithium-ion batteries are currently the most commonly used battery technology, but emerging battery chemistries such as solid-state batteries and flow batteries could potentially offer higher energy density, longer lifetimes, and safer operation. Finally, the current model assumes a predetermined set of battery capacity levels. However, it may be more beneficial to optimize the battery capacity as a decision variable in the model. This would enable the model to determine the optimal size of the battery for a given set of operating conditions, rather than assuming a fixed capacity.

Moreover, further studies are needed to investigate whether correlations exist between the competitive structures of symbiotic relationships and political situations. The political environment can significantly impact the feasibility and success of implementing renewable energy projects in industrial parks. Therefore, understanding the influence of political factors on the optimization model is crucial to maximize the benefits of renewable energy and batteries in industrial symbiosis. Finally, the proposed model assumes that companies are willing to cooperate and exchange information for mutual benefits. However, in reality, there may be systematic distrust between firms, which can limit the success of symbiotic relationships. Therefore, a new research field could be considered for future development, focusing on information-exchange technologies that can overcome systematic distrust and create new concurrent business models to strengthen cooperation.

Nevertheless, electrification of industrial processes coupled with the use of renewable energy sources is widely acknowledged as a strategy supporting the transition to carbon-neutral industrial systems (Li, 2017). In this study, we only focused on the energy industrial symbiosis with regard to electricity consumption (Philibert, 2017). In this context, also a relevant share of thermal energy can be supplied using electric power (Bühler et al., 2019). Future research should consider the contribution of electrification of industrial processes to carbon emissions reduction.

Credit author statement

Alessandro Neri: Conceptualization, Methodology, Software, Investigation, Data curation, Validation, Writing – original draft, and Visualization. **Maria Angela Butturi**: Conceptualization, Validation, Writing – review & editing, Supervision, and Project administration. **Francesco Lolli**: Conceptualization, Writing – review & editing, Supervision, and Project administration. **Rita Gamberini**: Supervision and Project administration.

Declaration of competing interest

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

Data availability

As stated in the article, the data used in this analysis is fictional and sourced from open government sources

A. Case Study Data

A Terna dataset holding the Sicily aggregate power demand was used as the load dataset. The dataset consisted of five tables describing the power demand in *MW* measured every 15 min. For convenience, only the data on the hour are kept, thus eliminating data at 15, 30, and 45 min. The Sicily region was chosen because, being an island, the data were recorded separately from southern Italy (Figure A.1).

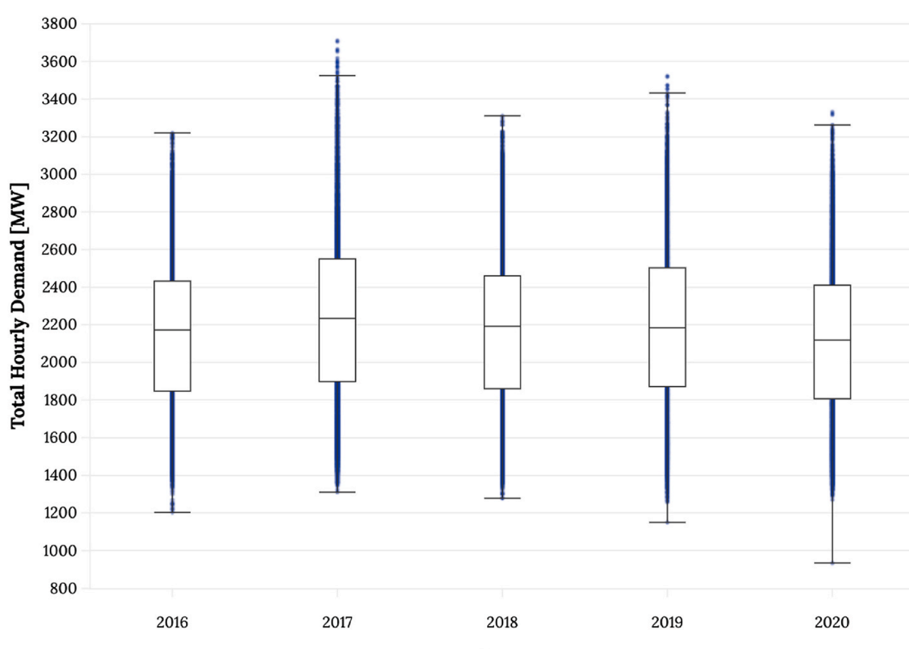

Fig. A.1. Sicily (2016–2020), electricity demand - author’s reworking of data from Terna source

Still working on the same dataset, the data relating to the annual energy destination in *MWh* were extracted. The industry annually absorbs about 30% of its energy needs (divided between domestic use and the services sector). Consumption in the agricultural sector is almost irrelevant

(Figure A.2).

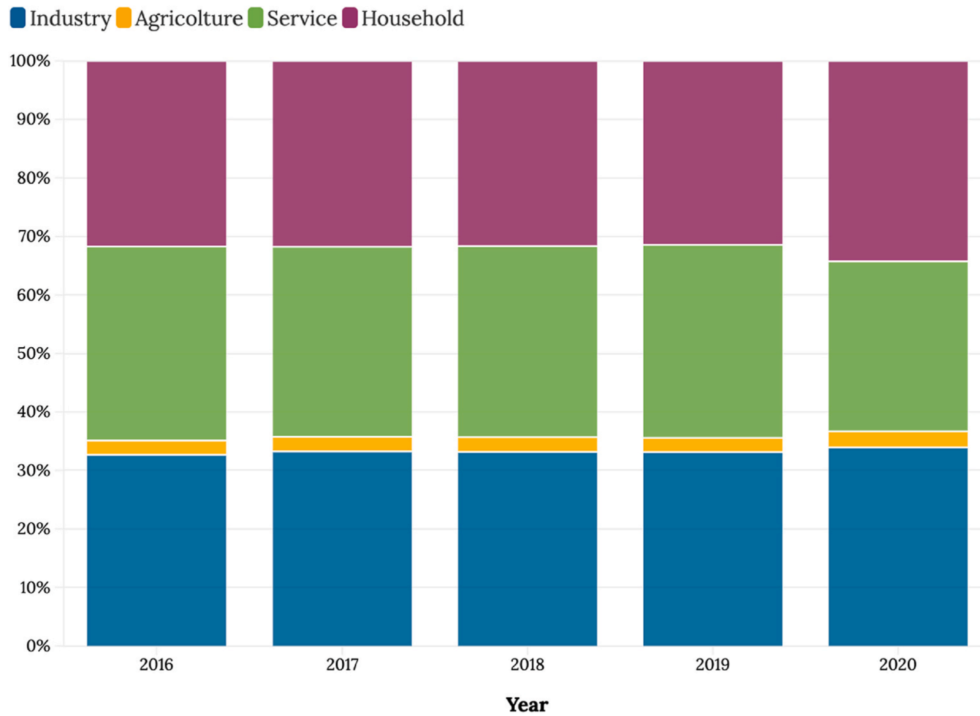

Fig. A.2. Sicily (2016–2020), energy consumption by sector - author's reworking of data from Terna source

After that, it must be studied how annual consumption is divided by business category. The manufacturing (aggregating basic and non-basic manufacturing) and the sectors that deal with the treatment of wastewater and the extraction of raw materials absorb most of the annual energy (Figure A.3).

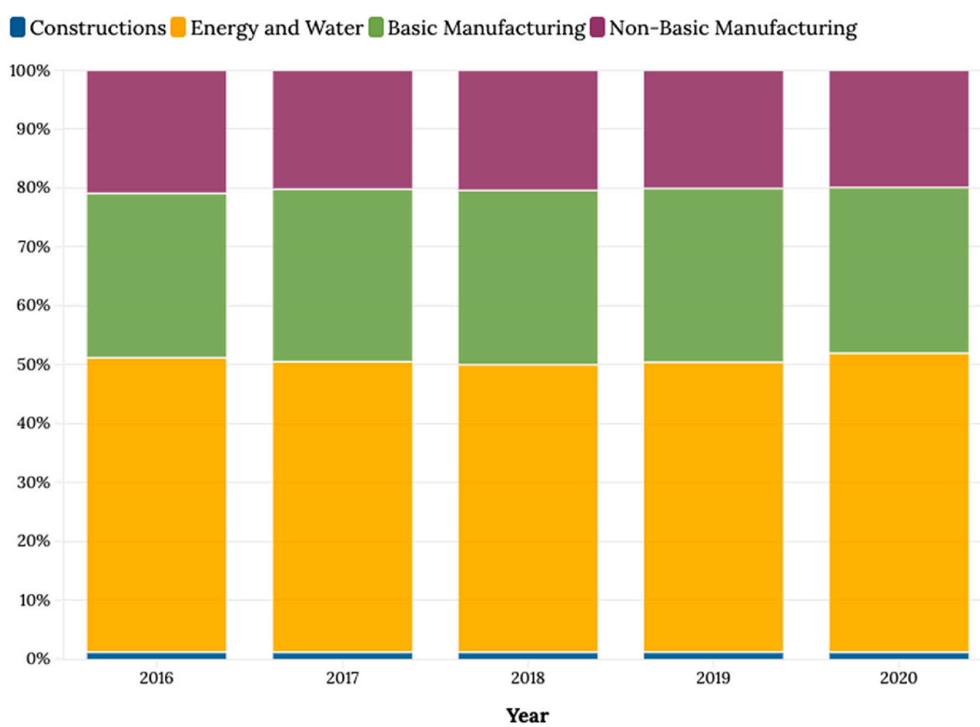

Fig. A.3. Sicily (2016–2020), energy consumption by industrial sector - author's reworking of data from Terna source

To a certain extent, a company in the pharmaceutical/chemical sector will be more energy-intensive than a textile company. In this section, we calculate a multiplier which is later used to deviate from the average figure. To do that, the next section is devoted to studying ISTAT Sicilian manufacturing numbers and dimensions. In Figure A.4, micro enterprises are the driving force, but large enterprises hire more employees. Manufacturing activities account for 12.7% of 7175 companies and 64,181 employees. From here, the average consumption of the company is calculated and, therefore, the dataset with the required hourly power is established.

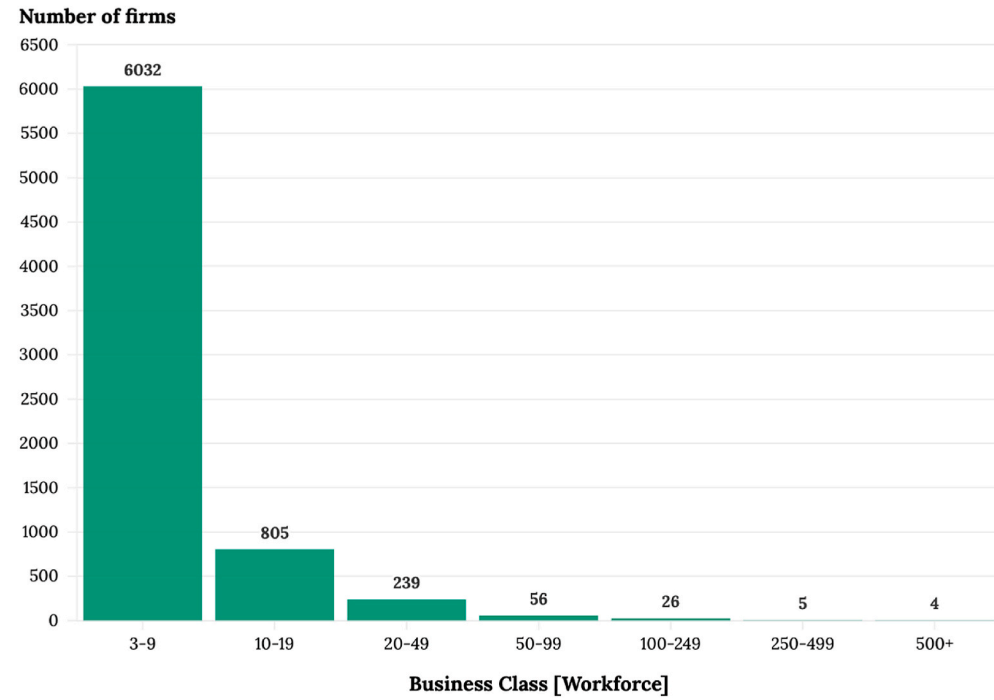

Fig. A.4. Sicily (2018), manufacturing firm number - author's reworking of data from ISTAT source

Firstly, the percentage of electricity dedicated to basic and non-basic manufacturing must be calculated each year. With this value, the demand in *MW* with an hourly timestamp is obtained, which is linked to the power demand of the manufacturing sector.

$$\widehat{D_j^{th}} = \frac{D^{th}_{man.\ sect.tot}}{\#\ Az.Man.} \cdot \varphi^t_{settore} \forall j, t, h. \quad 43$$

To calculate the power demand of company X, the sector to which it belongs is isolated to have the proper multiplier year by year. Finally, the power already calculated is divided by the number of manufacturing companies, and the multiplier is applied (Equation (43)).

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