Environmental benefits of the industrial energy symbiosis approach integrating renewable energy sources

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Abstract: Industry sector accounts for almost 40% of final energy demand and is responsible for one-fifth of global energy-related CO_2 emissions. A viable pathway to reduce the carbon footprint of the industry sector is represented by the industrial energy symbiosis, that promotes inter-firm energy exchanges and the sharing of energy-related resources. While a single firm comes across technical and financial barriers that often hamper the implementation of energy conservation projects, the cooperation between firms can enable energy saving measures and the use of renewable energy sources at industry level. Considering a case study involving an energy intensive industry, the study analyses the potential environmental benefits of the industrial energy symbiosis approach integrating renewable energy sources. The research suggests a methodology to design strategic energy symbiosis connections, advantageous for the involved firms, with the objective of reducing carbon emissions and economic costs. The methodology is based on the mathematical optimization through mixed integer linear programming. combined with the environmental analysis conducted with the life-cycle assessment method. The application of the methodology to the case study provides a scenario outlining all the potential energy flows, that are evaluated respect to the state-of-the-art (reference) scenario and alternative electrification strategies, showing the potential environmental benefits.

Keywords: Energy intensive industry; Industrial Symbiosis; Life-cycle assessment; Multi-objective optimization; Renewable energy

1. Introduction

Industry sector accounts for almost 40% of final energy demand and is responsible for one-fifth of global energy-related CO_2 emissions (IRENA Publications, 2018). Energy intensive industries (EIIs) account for about 15% of the total greenhouse gas (GHG) emissions in the European Union (EU) (IES, 2018).

Aiming at the EU targets by 2050 (European Commission, 2011), several possible emissions abatement solutions for the energy intensive industry have been investigated by the literature (Gerres *et al.*, 2019).

Low-carbon strategies should be based both on the sustainable transformation of production processes and the use of sustainable energy sources (UNIDO, 2018). 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 (IEA/OECD and Cédric Philibert, 2017). According to Timmerman *et al.* (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), that promotes inter-firm energy exchanges and the sharing of energy-related resources. So, a set of industrial companies located near each other, sharing a strong approach to environment preservation, can take advantage of their geographical proximity and decide to develop cooperation networks, realizing industrial symbiosis projects (Lambert, Boons, 2002).

In this paper, we present a model to design and optimize low-carbon energy synergies between neighbour firms, integrating RES. Since the integration of RES in creating energy synergies is still under-investigated (Butturi *et al.*, 2019), the study represents a step forward in bridging a gap in the industrial symbiosis (IS) related research.

The model is applied to explore the opportunities of carbon emissions reduction of an EII located in the Emilia Romagna region (Italy). The optimized scenarios outlined by the model are compared to a more common decarbonization strategy scenarios that consider the electrification of some processes, according to different alternatives.

To demonstrate the potential environmental benefits, the CO_2 emissions of both the electrification and the optimized scenarios are calculated and compared with the reference scenario, using the life-cycle assessment (LCA) method, one of the best tool for assessing the environmental performances of a product, a process or a system currently available (European Commission, 2003(302)), always more frequently used in decision making processes (Marinelli *et al.*, 2019) and required in Sustainable Consumption and Production (SCP) policies around the world (Sonnemann *et al.*, 2018).

2. Industrial energy symbiosis approach: an overview

The need to improve the sustainability of industrial areas is widely explored in the literature, to develop solutions aiming at reducing the environmental impact at the local level (Liu *et al.*, 2018). The IS approach establishes cooperation links among firms with the aim of increasing industry sustainability (Neves *et al.*, 2019). It involves the collective management and the exchange of resource flows—particularly materials, water, and energy (Chertow, Ehrenfeld, 2012). Within the IS framework, the industrial energy symbiosis considers the sharing of energy-related resources, facilities and infrastructures as an effective model to promote energy conservation measures and reduce the dependence from fossil fuels (Fichtner *et al.*, 2004). Energy (mainly heat and electricity) requires specific transportation infrastructures (e.g. pipes) and supply-demand balance or storing facilities (Maes *et al.*, 2011). Another peculiarity of IES is that, though the geographic proximity is not considered as a driver for IS projects (Lombardi, Laybourn, 2012), the distance between firms influences energy flows (Winans *et al.*, 2017): in EU, the IES projects are restricted to local areas, since the cost of energy exchange infrastructures limits the distribution distance (Domenech *et al.*, 2019). Moreover, the sharing of the same geographical and administrative conditions facilitates the implementation of common energy strategies aimed at rationalizing consumption and optimizing the energy supply (Horbach, Rammer, 2018). So, the local conditions influence and can support the uptake of industrial symbiosis projects (Yeo *et al.*, 2019).

Considering the location of the analysed case study, 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.

From a modelling point of view, energy symbiosis modelling has been widely analysed (Kuznetsova *et al.*, 2016). It is a multi-objective problem addressing techno-economic and environmental issues: energy symbiosis models mainly aim to simultaneously minimize costs and emissions related to energy exchanges (Afshari *et al.*, 2016), and to optimize energy efficiency. According to the review performed by Kastner *et al.* (2015), the main methods to optimize energy (mainly heat) exchange networks are pinch analysis and MILP methods.

IS initiatives, fulfilling circular economy principles, are mainly evaluated in the literature using LCA based analysis, focusing on resources and GHG emissions (Daddi *et al*, 2017; Kim *et al.*, 2018; Martin, Harris, 2018). The LCA technique has standards (ISO 14040; 14044) and guidelines (Guinéé, 2012; ILCD, 2010) developed in order to meet society's needs for credible and comparable environmental metrics at the product and organization level. However, no standardized guidelines are available to describe IS networks. In recent years, several different LCA approaches have been outlined to quantify the distribution of impacts or benefits between firms (Mattila *et al.*, 2012; Kim *et al.*, 2017; Liu *et al.*, 2019).

In the present study, the standard LCA technique is firstly applied to evaluate the environmental harmful gas emission mitigation benefits due to three alternative electrification strategies. Afterward, the LCA approach outlined by Martin *et al.* (2015) is used to analyse the implementation of energy symbiosis links between neighbour firms integrating RES, suggested by the mathematical model.

3. Methodology

The methodology combines the application of a mathematical model, developed to design and optimize energy exchanges between firms and the LCA analysis used to evaluate the environmental benefits of the symbiosis links.

Starting from the carbon emissions reduction strategy of the considered EII, that involves also the electrification of some processes, the model is applied to minimize both the costs and the environmental impact of the feasible energy exchanges between the EII and some neighbour firms. Some of them need to buy energy to satisfy their demand, while others can supply an amount of renewable excess energy. The model considers both the buyers' and the suppliers' benefits. The LCA based analysis is applied to the optimized scenarios to calculate the variation in CO_2 emissions respect to the reference and the electrification scenarios.

All the data used for the reference and modelled scenarios are available upon request.

3.1 The mathematical model

Starting from the models proposed by Afshari *et al.* (2018) we developed a mathematical model to investigate the advantage of electrical energy synergies, integrating RES, between firms. The model uses mathematical optimization through MILP, one of the main methods used to optimize energy exchange networks, since it allows to solve exactly energy balances (Boix *et al.*, 2015). Here we present an adapted version of the originally developed model, to fit the case study. So, we did not limit the distance among firms to keep costs down, as the distances are fixed. Moreover, we did not consider the possible installation of RES plants, due to spatial limits.

Model sets, parameters and variables are listed as follows:

J set of firms demanding energy
I.Sup set of firms that can supply RES energy
T set of the time period (in years)
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 the firm *i* in year *t*
FC_i^t [€] Fixed cost of recovering energy within the firm *i* in year *t*
PE_i^t [€/kWh] Selling energy price from supplier firm *i*
IC_i [€] Investment cost for renewable power unit *i*
P_i^t [kW] Nominal power for unit *i* in *t*
S_i^t [kWh] Energy converted by unit *i* in *t*
EP_i^t [$kgCO_2$/kWh] Environmental impact due to renewable power production in unit $i \in I.Sup$
CC_{ij} [€] Investment cost for the link between *i* and *j*
EC^t [€/$kgCO_2$] Emission allowance cost
PI^t [kWh] System peak load in year *t*

Variables (BV = binary variable):

x_{ij}^t BV if symbiosis exists between *i* and *j* in *t*
y_{ij}^t Amount of energy demand for *j* satisfied by *i* in *t*
h_j^t BV if *j* achieves the energy independence in *t*
wij BV representing the investment cost if symbiosis exists between i and j

The objective function (1) considers the optimization of both the costs and the environmental impact from a collective point of view. The blocks represent the sum of the fixed and variable cost of standard energy purchased by standard plants; the cost of the renewable energy delivered by supplier firms including the recovery cost; the CO_2 emissions allowance due to the standard energy and the exchanged energy. The last part considers the investment cost of new connections.

$$\min Z = \sum_{t \in T} \left\{ \sum_{j \in J} \left[FD_j^t \left(1 - h_j^t\right) + VD_j^t D_j^t \left(1 - \sum_{i \in I} y_{ij}^t\right)\right] + \right.$$
$$+ \sum_{j \in J} \sum_{i \in I.Sup} \left(FC_i^t x_{ij}^t + RC_i^t D_j^t y_{ij}^t\right) +$$
$$\left. + \sum_{j \in J} \left[EC^t IP_j^t D_j^t \left(1 - y_{ij}^t\right) - EC^t \sum_{i \in I.Sup} EP_i^t D_j^t y_{ij}^t \right] \right\} (1+s)^{-t} +$$
$$+ \sum_{j \in J} \sum_{i \in I} CC_{ij} w_{ij} \tag{1}$$

The constraints of the model are as follows. Constraint (2) further characterise variable y and (3) refers to satisfy up to the whole buyers' energy demand. Constraint (4) guarantees that, if symbioses are working, an amount of energy demand is satisfied and (5) guarantees that the cost of existing symbioses is considered.

$$0 \le y_{ij}^t \le 1 \qquad \forall \ t, i, j \tag{2}$$

$$\sum_{i \in I} y_{ij}^t \le 1 \qquad \forall \ t, j \tag{3}$$

$$y_{ij}^t \le x_{ij}^t \qquad \forall \ t, i, j \tag{4}$$

$$\sum_{t \in T} x_{ij}^t \ge w_{ij} \qquad \forall \ i, j \tag{5}$$

The next group of constraints manages the relation between demand and supply. Constraint (6) guarantees that suppliers can provide excess energy to support the exchanges and (7) controls that the energy supplied does not exceed the surplus availability.

$$D_j^t y_{ij}^t \le S_i^t x_{ij}^t \qquad \forall \ t, i, j \tag{6}$$

$$\sum_{j \in J} D_j^t y_{ij}^t \le S_i^t \qquad \forall \ t, i \tag{7}$$

Lastly, constraints (8) and (9) dictate the economic sustainability of the symbioses for the buyers and suppliers, respectively.

$$FD_j^t + VD_j^t D_j^t \sum_{i \in I.Sup} y_{ij}^t + IP_j^t D_j^t EC^t \sum_{i \in I.Sup} y_{ij}^t \ge$$
$$\ge \sum_{i \in I.Sup} \left[\left(PE_i^t - EC^t IP_j^t\right) D_j^t y_{ij}^t\right] \qquad \forall \ t, j \tag{8}$$

$$\sum_{j \in J} PE_i^t D_j^t y_{ij}^t \ge \sum_{j \in J} RC_i^t D_j^t y_{ij}^t +$$
$$+ \sum_{j \in J} FC_i^t x_{ij}^t - \sum_{j \in J} EC^t EP_i^t D_j^t y_{ij}^t \qquad \forall \ t, i \in I \tag{9}$$

3.2 Life-cycle environmental assessment

In the present study, the standard methodology outlined by ISO 14040 and 14044 is followed to compare the GHG emissions released by the reference scenario with those released by different scenarios: firstly three scenarios that considers the application of alternative electrification strategies and secondly three scenarios proposed by the mathematical optimization model characterized by the creation of the energy links between firms and the integration of RES..

The functional unit (FU) is the output of the main product of the firm under study (called B1-EII) and the input data is the total energy consumed divided for energy vectors, with a lifespan of 20 years. The life cycle inventory (LCI) includes primary data for energy consumptions and energy datasets from the Ecoinvent database (Wernet *et al.*, 2016).

Since the focus is on energy exchanges, the system boundaries (SB) include all the input of energy and fuels. Raw materials, maintenance operations and wastes are not included.

The environmental assessment of the modelled IS scenarios is based on the system expansion approach outlined by Martin *et al.* (2015) and applied by the same authors to study the urban IS network of the municipality of Sotenas, Sweden (Martin *et al.*, 2018).

The methodology employs the 50/50 method and credits are shared by companies for the avoidance of energy in input for the buyers Bn (Energy Bn) from the utilization of excess energy (co-product) generated by the supplier Sn (RES Energy Sn) (Kim *et al.*, 2017) (Figure 1).

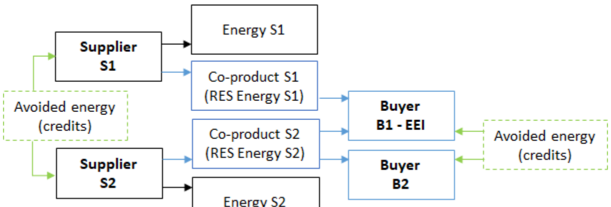

Figure 1: the allocation method for exchanges between Sn (Supplier) and Bn (Buyer)

FU, LCI and SB are equal to the reference, the electrification and the modelled scenarios. The LCA is performed using the SimaPro LCA software. Since the main driver of the strategy is the reduction of CO_2 emissions, for this study we considered the Global Warming Potential (GWP) impact category based on the Intergovernmental Panel on Climate Change (IPCC) assessment method (*Eggleston et al.*, 2006) with a 20-year time horizon.

4. Case study and decarbonisation strategies

4.1 Reference scenario

The case study involves an Italian EEI whose main consumptions are electric energy, natural gas and diesel due to activities that can be divided into the following three functional areas: I. Main activities; II: Auxiliary activities; III. General services. The main energy consumption is the natural gas that accounts for the 57% of the total, used in four industrial furnaces for main activities as 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, 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 2).

In 2018 the firm involved in the present work, approached an energy audit (diagnosis) to uncover the critical issues and plan strategies for improving the energy system. The study of the consumptions outlined two viable energy reduction strategies: (1) reduction of lighting energy consumption by the replacement of obsolete lamps with LED units and (2) optimization of auxiliary processes and plants that utilize electric energy by the installation of inverters able to regulate the energy absorption. The thermal recovery, since the intermittent use of the four furnaces, was not considered an advantageous strategy.

The results of the analysis of the two outlined strategies demonstrated an energy reduction of about 4% against a large investment. By this, the interest to consider different strategies: the electrification by the replacement of the equipment consuming gas and the IS network by creation of energy links with neighbour companies.

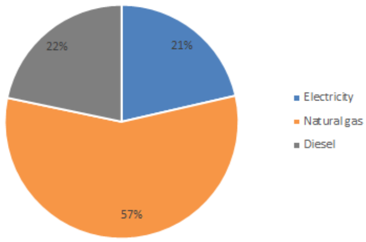

Figure 2: annual energy consumption for energy vector

4.2 Electrification strategies

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 only the four industrial furnaces. The electrification of the vehicles used for internal goods movement was not suitable because the vehicle fleet consists mainly of trucks.

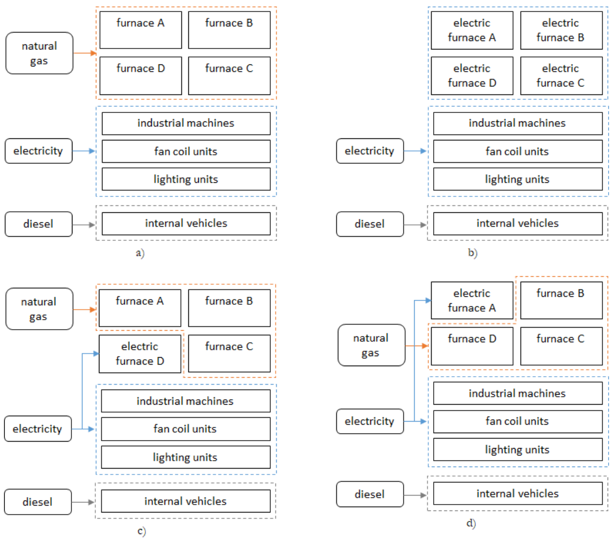

Figure 3: Reference (a) and electrification scenarios EL 0 (b), EL 1 (c), EL 2 (d)

For this reason, the evaluation of the electrification was performed for different furnaces electrification scenarios, starting from the reference scenario (Figure 3(a)):

- Electrification scenario 0 (EL 0): all the 4 furnaces are replaced by electric furnaces (Figure 3(b));
- Electrification scenario 1 (EL 1): the furnace with lower power (furnace A) is replaced by an electric furnace (Figure 3(c));
- Electrification scenario 2 (EL 2): the furnace with higher power (furnace D) is replaced by an electric furnace (Figure 3(d)).

All the strategies were considered for an assumed 20-year lifetime, with an estimation of energy consumption year by year based on previous trends.

The CO_2 emissions released by the three different scenarios were calculated with the LCA analysis and compared with the reference scenario.

4.3 Context and potential energy synergies

The considered company, B1-EEI, is located in the Emilia-Romagna region, in northern Italy. In the territory, with a primary agricultural vocation, farms coexist with a rich entrepreneurial fabric made up of many small and medium-sized businesses.

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. Two SME companies (B2 and B3) with medium and low electricity consumption profiles according to (Cialani, Mortazavi, 2018) (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. The five organisations can be viewed as an industrial district and the potential energy synergies can be evaluated.

5. Results and Discussion

5.1 Electrification strategies

The environmental impact of the reference scenario in terms of GWP is equal to 1.1E+08 $kgCO_2eq$, due for the 66% to natural gas, for the 28% to electricity and for the remaining 6% to diesel used by vehicles.

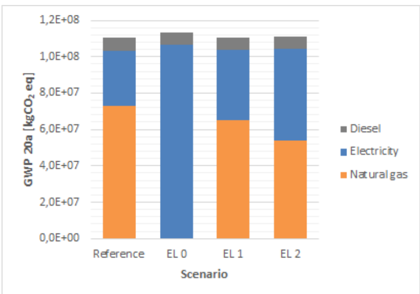

Figure 4: LCA results of the electrification scenarios

With respect to the reference scenario, the results of the analysis of the three electrification strategies show that the substitution of the four existing furnaces with electric units (EL 0) have the potential to increase the CO_2 emissions of the 3%, despite the zeroing of natural gas in input.

An increase of CO_2 emission can be observed also in the other scenarios. An increase of the 0.3% and of the 0.7% can be observed with the substitution of furnace A (EL 1) and of furnace D (EL 2), respectively (Figure 4).

5.2 Modelled scenarios

The developed 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 1) and the improved electricity demand due to processes electrification. Regarding the electrification, the scenarios EL 1 and EL 2 have been considered.

The model minimizes simultaneously the major costs and environmental impacts of the energy inter-firm exchanges including RES. It provides the optimized energy flows between supplying and buying facilities per year, on the total temporal range of 20 years. Figure 5 gives a representative picture of the results, showing advantageous energy connections from a collective point of view in the three different scenarios.

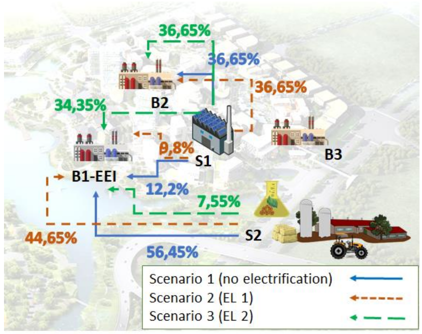

Figure 5: modelled advantageous energy connections

Overall, in the energy symbiotic scenarios 1 and 2, the biomass plant owned by S2 is the main supplier for B1, while in scenario 3, 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. The average amount of the energy demand satisfied over the entire period is shown in percentage. 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.

To analyse the environmental benefits provided in the modelled scenarios and support decision-making, we performed the LCA analysis of the resulting energy connections.

5.3 LCA evaluation

An environmental evaluation of the different modelled scenarios was performed to assess the change in CO_2 emissions respect to the reference scenario.

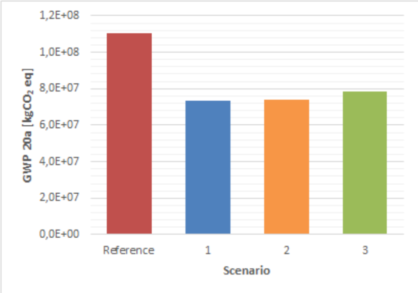

Figure 6: LCA results of the modelled scenarios

The largest reduction is illustrated when comparing the reference scenario with the scenario 1 and 2. The sharing of RES energy coming from S1 and S2 can lead to a reduction of roughly 3.65E+07 $kgCO_2eq$ corresponding to a decrease of GWP equal to the 33%. When reviewing the scenario 3, results show a reduction of GHG emission the 29% (3.21E+07 $kgCO_2eq$) (Figure 6).

The results suggest a significant CO_2 emissions reduction, despite an increasing of electricity consumptions.

6. Conclusion

This study investigates the potential environmental benefits achieved by means of IES initiatives integrating RES presenting a methodology that can support firms, energy managers and local authorities in taking decisions regarding energy efficiency and carbon emissions reduction projects. The methodology has been applied to the case of an energy intensive industry committed to the environment preservation.

The environmental analysis of the electrification strategies revealed that, for the electric standard Italian source, the electrification of the main energy intensive equipment (installation of electric furnaces) would not be beneficial in terms of CO_2 emissions. The mathematical optimization model, considering economic and environmental indicators, designed optimal energy synergy configurations among the EII and some of its neighbour firms. The LCA analysis of the energy symbiosis scenario shows that GHG emissions can be reduced approximately of the 30%, despite the increasing of energy consumptions. The results demonstrate that implementing a collective energy strategy including RES, from the district level, according to the developed mathematical optimization model, can allow to achieve a higher environmental benefit than operating at individual level, while keeping the costs down. Thus, both firms and local authorities should explore the opportunity of collective strategies aiming at reducing the industry footprint.

The research is at an initial stage and some several limitations. With regards to the environmental analysis, the study focuses to electricity exchanges, coming from grid or from renewable sources and the system boundaries do not include raw materials, maintenance operations and wastes. This assumption does not permit to quantify a complete environmental impact of a system and, in addition, hold to not taken into account all the feasible exchanges between involved firms. With regards to the mathematical model, it may be interesting to explore further synergies in order to optimize the symbiosis. As the system will be developed in the future, the assessment would be improved including all input and output data in the system boundaries (e.g. raw materials, etc.) and considering other significantly environmental impact categories.

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