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Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks

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Abstract: In order to evaluate the environmental benefits of energy industrial symbiosis networks with the inclusion of renewable technologies, a model that minimises greenhouse gases emissions has been developed. A validation of the model has been carried out comparing the results with those calculated with a life cycle assessment of a reference case. The study demonstrates that energy industrial symbiosis networks integrating renewable energy technologies have the potential to significantly reduce greenhouse gases emissions and suggests a methodology to optimise energetic symbiosis connections inside eco-industrial parks.

Keywords: Decision making, Energy dependence, Energy management system, Environments, Industrial production systems, Integration, Models, Performance analysis, Renewable energy systems.

1. INTRODUCTION

According to IRENA (IRENA Publications, 2018), the global industry sector accounts for almost 40% of final energy demand and is responsible for one-fifth of global energy-related CO_2 emissions. While greenhouse gas emissions (GHG) in the EU-28 are decreasing in line with the targets set by 2020 (EUROSTAT, 2018), a common effort is still needed to definitely continue the path towards reducing the carbon footprint of the industry sector. In the framework of the Industrial Symbiosis (IS) approach, energy symbiosis represents the viable path towards "carbon neutral industrial parks" (Maes *et al.*, 2011). Energy symbiosis within eco-industrial parks (EIPs) can promote the use of renewable energy sources (RES) at industry level, by means of inter-firm energy exchanges and the collective production and management of green energy (Butturi *et al.*, 2019). The evaluation of the environmental impact represents a key information for optimising the energy symbiosis solutions, with the aim of maximising the carbon emissions reduction. In this study, we compare the results obtained with two methods widely used for analysing environmental impacts in the field of the IS: the mathematical optimisation through mixed integer linear programming (MILP) and life-cycle assessment (LCA) method. Since the EIP design is typically a multi-objective problem, the mathematical optimization through MILP is one of the main methods used to design energy symbiosis networks considering both economic and environmental issues (Boix *et al.*, 2015). On the other hand, LCA is one of the most accepted and used methods for analysing environmental impacts related to products, processes or services (Wolf *et al.*, 2012).

We developed a mathematical model that optimises the environmental impact of energy symbiosis networks including renewable technologies. In order to validate the model, the results obtained by minimising the related objective function have been compared with those obtained by the environmental assessment study conducted with the LCA methodology. The results show that the calculated scenario, including symbiotic exchanges and renewable energy technologies, can led to a GHG emissions reduction of almost 97% when compared to a reference conventional scenario. The estimation is confirmed by the life cycle analysis with a total reduction of about 3000 $kgCO_2eq$. The study, even though at an initial stage, suggests a methodology to design strategic symbiosis connections inside EIPs and demonstrates that the integration of renewable energy in energy IS networks has the potential to significantly reduce GHG emissions in industrial districts. The paper is organised as follows. In section 2 the analysis methodology is presented, in section 3 the reference case is illustrated and in section 4 results are presented and discussed. Section 5 draws the conclusions and suggests future research directions.

2. METHODOLOGY

2.1 Energy symbiosis involving RES

The eco-industrial parks are industrial clusters based on the firms' cooperation and the efficient sharing of the resources. Energy exchange networks and collective energy approaches can contribute to significant park emissions reduction. In this study we focus on the integration of renewable energy technologies in the energy system of an EIP. In fact, while energy symbiosis modelling has been widely analysed, only few papers considers the RES integration (Butturi *et al.*, 2019).

A representation of the possible energy symbiosis involving RES that we considered is shown in Fig. 1. The EIP is connected to the main grid that can satisfy all the internal electrical energy demand, by means of standard power plants (fuelled by fossil sources). Among the EIP's participants, some firms buy the whole electricity needed to satisfy their demand (buyers), while others can deliver an amount of renewable excess energy (suppliers). In addition, the EIP organization may enable the joint installation and use of eco power plants. While inter-firm energy and materials supply requires dedicated infrastructure, electricity exchanges can rely on existing electrical connections within the EIP. The questions driving our research pertain to two levels. The first goal is to build a model that allows to analyse which energy symbiosis schemes including RES enable a greater carbon emissions reduction. The second target concerns the validation of the performed results with the use the well-known life cycle environmental assessment methodology. The need for dealing with multiobjective optimisation of an EIP sharing energy flows requires an approach based on mathematical optimisation through mixed integer linear programming (MILP), one of the main methods used to make energy exchange networks optimal. According to (Boix *et al.*, 2015), the development of an environmental objective function, aiming at optimising environmental impacts, combined with the evaluation of such an impact through LCA approach (that precisely assess the impacts, but does not improve the solution), can give key information to reach environmental optimal solutions.

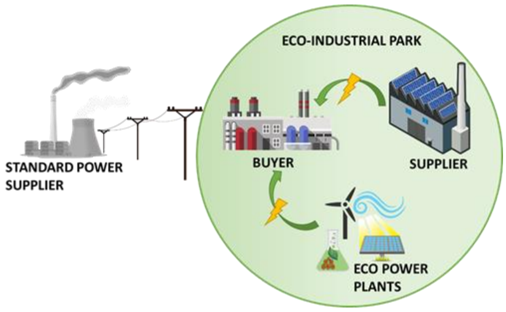

Fig. 1**.** Energy symbiosis network within eco-industrial park, as considered in this paper.

2.2 The mathematical model

Starting from the models proposed by (Afshari, Farel and Peng, 2018) and using the described configuration, we developed a mathematical model to investigate the environmental impact of the integration of RES in the energy system of an EIP. The model uses mathematical optimisation through mixed integer linear programming (MILP). The model aims at minimising the environmental impact, in terms of CO_2 emissions, due to the energy contribution within the EIP. The model objectives are summarised in Fig. 2.

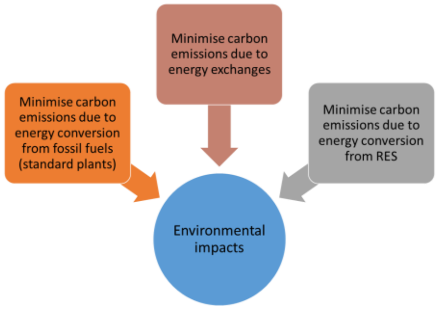

Fig. 2. The objectives of the model.

The objective function (1) includes three main blocks, according to the scheme depicted in Fig. 2. The first block represents the emissions due to the electricity supply from the public utility grid (considering plant fuelled by fossil sources);the second block represents emissions due to power generation by supplier firms within the EIP, and the third block accounts for the emissions generated by installed renewable plants as joint projects within the EIP.

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

Sets, parameters and variables are listed as follows.

Sets: $I = I.Sup \cup I.Eco$

This set includes both the renewable power generation units that could be installed (*I.Eco*) and the firms that can supply a surplus of power (*I.Sup*).

J	set of firms demanding energy
T	set of the time period (in years)

Parameters:

D_j^t [kWh]	Energy demand of firm j in year t
IP_j^t [kgCO_2/kWh]	Environmental impact due to standard power production
S_i^t [kWh]	Renewable energy amount converted to electricity by unit i in period t
EP_i^t [kgCO_2/kWh]	Environmental impact due to renewable power production in unit $i \in I.Sup \cup I.Eco$
Lij	*Distance between i and j*
γ	*Maximum distance between I and j*

Variables:

x_{ij}^t	Binary variable if symbiosis exists between i and j in the period t
y_{ij}^t	Amount of the energy demand of j satisfied by i in t

The constraints of the model are:

$$x_{ij}^t \in \{0,1\} \qquad \forall \;\; t,i,j \tag{2}$$

$$0 \le y_{ij}^{t} \le 1 \qquad \forall \; t, i, j \tag{3}$$

$$\sum_{i \in I} y_{ij}^{t} \le 1 \qquad \forall \; t, j \tag{4}$$

$$y_{ij}^{t} \le x_{ij}^{t} \qquad \forall \; t, i, j \tag{5}$$

$$D_{j}^{t} y_{ij}^{t} \le S_{i}^{t} x_{ij}^{t} \qquad \forall \; t, i, j \tag{6}$$

$$\sum_{j \in J} D_{j}^{t} y_{ij}^{t} \le S_{i}^{t} \qquad \forall \; t, i \tag{7}$$

$$\left(L_{ij} x_{ij} - \gamma\right) \le 0 \qquad \forall \; i, j \tag{8}$$

The constraints (2) and (3) defines the variables type in the model. Constraint (4) sets the satisfaction up to the whole energy demand: the sum of all the internal and external energy contributions does not exceed the whole energy demand. Constraint (5) guarantees that if symbioses are working an amount of energy demand is satisfied. Constraint (6) sets that only suppliers with the enough capacity can establish symbioses with demanding firms; constraint (7) that the total supplied demand should not exceed the supplier's supply capacity. Constraint (8) defines the geographical limits of the park dictating a maximum distance between buyer and supplier. The developed model has been coded and elaborated using MATLAB's *Optimization Toolbox*.

2.3 Life-cycle environmental assessment

The LCA analysis refers to the quantification of the environmental benefits (or impacts) associated to a product, a system or a service throughout its life cycle according to standards (ISO 14040, 14044) and guidelines (Guinéé, 2012; ILCD, 2010). The methodology provides four phases: 1. the goal and scope definition, in which the purpose of the study and the system boundaries (SB) are defined; 2. the inventory analysis (LCI) in which input and output data are collected and analysed with regard to the output of the product or system under study, called functional unit (FU); 3. the impact assessment, in which the environmental impacts of the product or the system are assessed and evaluated; 4. The interpretation step in which the results are evaluated in order to draw conclusions and formulate recommendations. In the IS field the LCA approach has been widely applied, mainly to measure environmental impacts of existing systems (Kim *et al.*, 2017).

In recent years several techniques have been developed to better describe the sharing of energy between firms (Mattila *et al.*, 2012; Liu *et al.*, 2019). The methodology applied in the present study is based on the approach outlined by Martin *et al.* (2015). It follows the system expansion method and employs the 50/50 allocation method, to avoid allocation (Weidema, 2001). Credits are shared by companies for the avoidance of energy in input for the buyer B (Energy B) from the utilization of by-product generated by the supplier S (RES Energy S) (Kim *et al.*, 2017). In addition, by reason of we focus on the integration of renewable technologies in the energy system of an EIP, the energy produced by eco-plants (photovoltaic and wind power) installed in the park enters the system, as energy in input for buyer B (RES energy) (Fig. 3).

In this study, the main products of the firms are set as FU, because of the industrial symbiosis network is viewed as a multi-functional system, producing several main products and by-products (Martin *et al.*, 2015). The energy produced by supplier firms S, is considered as by-products. Because of the study focuses to minimise the environmental impacts due to the energy contribution within the EIP, the SB include all the inputs for energy. Raw materials data, transports, maintenance operations and wastes are excluded.

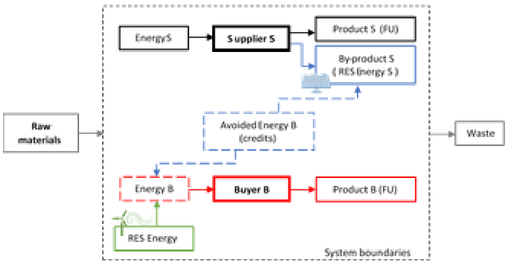

Fig. 3. The allocation method for exchanges between companies S (Supplier) and B (Buyer).

Modelling was performed using the *SimaPro* LCA software, including the LCI database Ecoinvent 3.4 (Wernet *et al.*, 2016). By reason of the main driver of the environmental objective function (1) is the reduction of CO_2 emissions, for this study we considered the following impact categories:

- the 20-year time horizon Global Warming Potential (GWP) based on the Intergovernmental Panel on Climate Change (IPCC) assessment method (Eggleston *et al.*, 2006);

- the carbon originated from fossil fuels, biogenic sources and land transformation and the carbon stored in plants and trees as they grow (carbon uptake) calculated with the Greenhouse Gas Protocol (GHG) assessment method (GHG, 2019).

3. THE REFERENCE CASE

To compare the two methods, a representative industrial park has been designed. It consists of 3 energy supplier firms (S1 to S3) and 6 energy buyer firms (B1 to B6). We consider also the possibility of installing 3 different technologies eco-plants: 3 biomass plants (M), 3 wind plants (W) and 3 photovoltaic (PV) plants. The Euclidean distances between facilities are shown in Table 5 in the appendix A.

3.1 Reference case data

According to (Afshari, Farel and Peng, 2018), the optimization has been launched over 10 years (T), fixing the maximum distance between two connected facilities to 20 km to avoid high costs for the connection infrastructures. Three energy consumption profiles have been chosen for the energy buyers, considering high (range 1000 MWh/year), medium (range 100 MWh/year) and small (range 10 MWh/year) industry energy consumers according to (Cialani and Mortazavi, 2018). The complete set of assumptions are presented in the appendix A

(Table 6). The capacity and carbon emissions for the eco-plants are presented in the appendix B (Table 7). The life cycle inventory (LCI) includes data from the Ecoinvent database. In Table 1 inventory input data are compiled with the indication of the selected datasets and the relative emission factors ($kgCO_2eq$), in comparison with those used in the environmental objective function (1) for each type of electric energy.

Table 1. Comparison of energy emission factors ($kgCO_2eq/kWh$)

Energy	Env. function	LCI	Ecoinvent dataset
Grid	$IP_j^t = 0.70$	0.7207	*Electricity, low voltage, production IT, at grid/IT*
PV	$EP_i^t = 0.07$	0.0689	*Electricity, production mix PV, at plant/IT*
Wind	$EP_i^t = 0.007$	0.0144	*Electricity, at wind power, offshore/OCE*

4. RESULTS AND DISCUSSION

4.1 Modelled energy symbiosis scenario

The optimisation of the environmental model provides a scenario outlining all the energy flows among facilities (buyers, suppliers and eco-plants) per year, on the total temporal range of 10 years. Since it does not include the minimization of infrastructure costs, the extension of the energy links increases to more than 260 km. For clarity, here we chose to refer to the scenario involving the buyer B6, the firm with the highest number of energy connections, to present the methods comparison. The modelled symbiosis scenario provides the input data for the LCI analysis: two photovoltaic plants (P1 and P2) and a wind plant (W1), supposed installed inside the park to supply the energy demand. For the symbiosis scenario it is assumed that the electric energy provided by the three suppliers (S1, S2, S3) is produced by photovoltaic plants installed on the firms' roof. In Table 2 the percentage of energy exchanges are listed.

Table 2. LCI of % energy changes associated with the symbiosis network

Firms	S1	S2	S3	P1	P2	W1
B1	0	0	0	3	4	93
B2	0	0	0	10	80	10
B3	0	0	0	30	0	70
B4	0	0	0	7	30	63
B5	0	0	0	80	20	0
B6	12	11	11	35	0	31

4.2 Reference scenario

To evaluate the potential benefits of the proposed symbiosis network, a reference scenario is created for comparison of the environmental impacts. A reference scenario is important in order to provide a robust comparison to review the potential benefits of a symbiotic network and, in the modelling of symbiosis networks, it is defined as the case in which there does not exist any exchanges (Martin, 2018; Mattila, 2012).

In this case, for the reference scenario, it was assumed no symbiotic links between the firms and no RES, therefore all the firms in the park are powered by traditional electricity from the national grid. The reference scenario is created to produce the same F.U. of the energy symbiosis scenario (the main products of the firms) in order to allow for comparisons.

4.3 Eco-industrial park assessment

In the framework of the MILP mathematical model, in order to analyse the obtained environmental benefits of the optimised symbiosis scenario, we defined an indicator that values the carbon emissions reduction from the collective point of view (9):

$$ER = 1 - \sum_{t \in T} \sum_{j \in J} \frac{\sum_{i \in I.Sup} EP_i^t D_j^t y_{ij}^t + \sum_{i \in I.Eco} EP_i^t D_j^t y_{ij}^t}{\sum_{i \in I} IP_j^t D_j^t y_{ij}^t} \tag{9}$$

The evaluation of the ER indicator shows a mean carbon emission reduction of the 97% respect to the reference scenario. The LCA results confirm the benefits that can be obtained from the energy symbiosis network. In fact, in comparison with the reference scenario a reduction of about 3000 $kgCO_2eq$ can be achieved (Table 3).

Table 3. LCA results of the system for the reference and the symbiosis scenario

Impact [$kgCO_2eq$]	Reference scenario	Symbiosis scenario	% reduction
Fossil CO_2eq	70410	2977.9	95.62
IPCC GWP 20a	76844	3360.7	95.77

4.4 Individual firm assessment

The LCA method used in this study allows for the review of benefits for the symbiotic network (as a whole) but also for the individual firms in the network (Martin, 2018). As shown in Fig. 4, the selected firm B6 receives energy from Supplier S1, S2, S3 and from the photovoltaic and the wind plants (P1, W1) supposed installed inside the park.

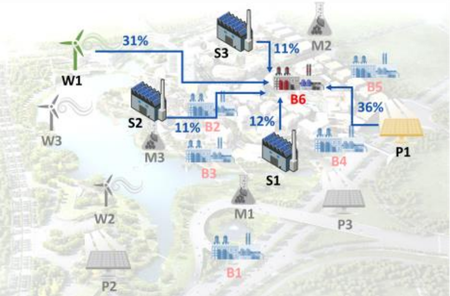

Fig. 4. Energy inputs for the firm Buyer B6.

The symbiotic scenario is compared with a reference scenario in which firm B6 uses only energy from the national grid, without any energy exchanges and RES energies. The results, listed in Table 4, show a reduction of almost 96% of $kgCO_2eq$.

Table 4. LCA results of the individual B6 for the reference and the symbiosis scenario

Impact [kgCO$_2$eq]	**Reference scenario**	**Symbiosis scenario**	**% reduction**
Fossil CO$_2$eq	13235	423.45	96.80
IPCC GWP 20a	14890	478.76	96.78

5. CONCLUSIONS

This study aims at investigating the environmental benefits achieved by energy symbiosis networks with the inclusion of renewable technologies. A model to minimise the GHG emissions have been developed and the results obtained have been compared with the LCA analysis. The results of the developed MILP mathematical model show that a reduction of about 97% of emissions can be obtained by the introduction of RES technologies and symbiosis connections. The LCA analysis confirms the environmental advantages both form the collective and the individual point of view. However, the study is at an initial stage and has several limitations. More comparison examples, including real case studies, will be provided to validate the model. Moreover, it focuses (only) on electricity exchanges, coming from grid or from renewable sources, and the system boundaries do not include raw materials, transportations or productive processes. 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 firms in an EIP. In future assumptions, it may be interesting to explore further synergies in order to optimise 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, by-products, etc.) and considering other significantly environmental impact categories.

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Appendix A. REFERENCE CASE DATA

Table 5. Euclidean distance between facilities

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

Table 6. Annual demand for the buyers

	Year									
	1	2	3	4	5	6	7	8	9	10
D^t_j	Annual demand (x 100 MWh)									
B1	30	30	30	40	40	30	30	30	40	30
B2	6	5	5	6	6	5	5	6	5	5
B3	0.2	0.3	0.1	0.3	0.3	0.3	0.2	0.3	0.1	0.2
B4	30	30	40	30	40	40	40	30	30	40
B5	5	6	6	5	6	6	6	6	6	5
B6	0.3	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.3	0.3

Table 7. Annual energy surplus and carbon emissions considered for the suppliers

	Year									
	1	2	3	4	5	6	7	8	9	10
S^t_i	Annual supply (x 100 kWh)									
S1	70	60	60	50	80	60	50	50	80	50
S2	50	70	60	70	60	70	60	80	50	80
S3	50	70	50	60	80	80	70	70	50	60
EP^t_i	Carbon emissions (kgCO$_2$/kWh)									
S1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
S2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
S3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Appendix B. ECO-PLANTS DATA

Table 8. Eco-plants capacity (*P*$_i$)

	Plant	**Capacity (kW)**
Wind	W1	2000
	W2	3000
	W3	4000
PV	P1	500
	P2	1000
	P3	2000
Biomass	M1	600
	M2	800
	M3	1000

The energy production S_i^t, over the period *t*, of *i-th* eco-plant is calculated as a function of the capacity factor (1):

$$S_i^t = P_i \cdot \phi_i^t \cdot (365\,days) \cdot \left(24\,\frac{h}{days}\right) \qquad \forall t, i \in I.Eco \qquad (1)$$

The capacity factors values are (IRENA, 2018):

$\phi_{Wind} = 0.30 \div 0.35$ %

$\phi_{PV} = 0.15 \div 0.25$ %

$\phi_{Biomass} = 0.67 \div 0.74$ %

Table 9. PV plants data

	Year									
	1	2	3	4	5	6	7	8	9	10
S^t_i	Annual supply (MWh)									
P1	1051	920	832	832	701	920	788	745	1051	1007
P2	1840	2102	1314	2015	2015	2102	1314	2015	1840	1577
P3	4380	4380	2978	4380	3329	4380	3154	4205	3504	4380
EP^t_i	Carbon emissions (kgCO$_2$/kWh)									
P1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
P2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
P3	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Table 10. Wind plants data

	Year									
	1	2	3	4	5	6	7	8	9	10
S^t_i	Annual supply (MWh)									
W1	5782	5606	5431	5957	5957	5256	5782	5957	5782	5606
W2	8935	8672	9198	8935	9198	8410	8935	7884	7884	8410
W3	11213	10512	11563	11213	10512	12264	12264	10512	10512	11563
EP^t_i	Carbon emissions (kgCO$_2$/kWh)									
W1	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
W2	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
W3	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007

Table 11. Biomass plants data

	Year									
	1	2	3	4	5	6	7	8	9	10
S^t_i	Annual supply (MWh)									
M1	3627	3784	3732	3837	3679	3522	3627	3732	3889	3574
M2	4695	5116	5186	5186	4765	4836	5186	4836	4695	5186
M3	6482	6220	5869	5869	5869	5957	6044	5957	5869	6220
EP^t_i	Carbon emissions (kgCO$_2$/kWh)									
M1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
M2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
M3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

The carbon emissions for the different technologies have been extracted from (Schlömer S. *et al.*, 2014).