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Optimal on-grid hybrid power system for eco-industrial parks planning and influence of geographical position

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Abstract

Nowadays, many Eco-Industrial Parks (EIP) are emerging all around the world. In these eco-industrial parks, industries gather to share several streams like energies, water, resources, and wastes in order to realise economic benefits while lowering their environmental impact. However, most of the time, these EIP are historically constituted and therefore sub-optimal. To really observe the sought gains, exchange networks need to be optimally designed. This article aims to develop a methodology for a grassroots design of hybrid power system (HPS) based on multi-objective optimization to supply an EIP. Overhang of this study is multi-objective (MO) approach which aims to minimize energy cost for project lifespan and to minimize environmental impact of energy production to supply EIP demand. This last criterion is evaluated by a life cycle assessment (LCA) on each sources. Another advantage is that geographical influence on HPS design is taken into account to evaluate climate effect on RE production and LCA impact depending on selected position for the EIP. A case study compares single objective and MO optimization and geographical influence on designed HPS for the same EIP, in two countries, Malaysia and in Germany. Results shows that a big reduction on environmental impact (above 70%) thanks to a little invest (cost increased about 10%) can be reached. Also, compared with different geographic positions, designed solution is really contrasted according to cost, environmental impact and selected RE sources.

Keywords: eco-industrial parks, renewable energies, multi-objective optimization, environmental assessment

1. Introduction

In recent years, at climate conference of the UNO (COP23 in 2017) important measures have been taken to fight against climate change and global warming, and to reduce human footprint on his environment. In this aim, to reduce extraction of raw materials and to limit amount of generated wastes, industrial ecology proposes to industries to gather within eco-industrial parks (EIP) to exchange energies and resources. Thereby, the main opportunity for companies is to reduce their environmental impact while increasing their competitiveness by making economic gains. In their review (Boix et al., 2015) have analysed methods applied to design and to optimize networks and streams in

EIP. Previous studies have been mainly focused on water and materials networks, while there is already a little number of publication dealing with energy networks for EIP. However to supply energy demand while reducing its environmental impact an EIP could produce its own local energy by using a renewable energy hybrid power system (HPS). An HPS is an energy network where several renewable energy sources are available also called RE-HPS. Lee et al. (2014) developed an LP optimization model to minimize energy loss of a RE-HPS. More recently, Theo et al. (2016) have completed this study by introducing an MILP model to minimize operating and investment costs and to select storage technologies.

The aim of this paper is to develop an on-grid HPS model to optimize energy planning to supply an EIP. MO optimization method is driven by both antagonist criteria: economic and environmental. To measure geographical impact of the location, the same HPS is optimized in different countries (Malaysia, Germany) using the same EIP demand, regardless of HPS technologies. Moreover, this model for the grassroots design of an EIP allows to optimize energy storage size, and renewable energy power rating (for wind Turbines, photovoltaic panels and biomass combustion) in order to provide known energy demand of EIP's processes.

2. Methodology and model formulation

The first step of this methodology is to delineate a model representing HPS. To this end, a superstructure has been developed, in which are represented links between sources and power demand (each company owns a number of process units representing sinks). Scheme of this superstructure is illustrated in figure 1.

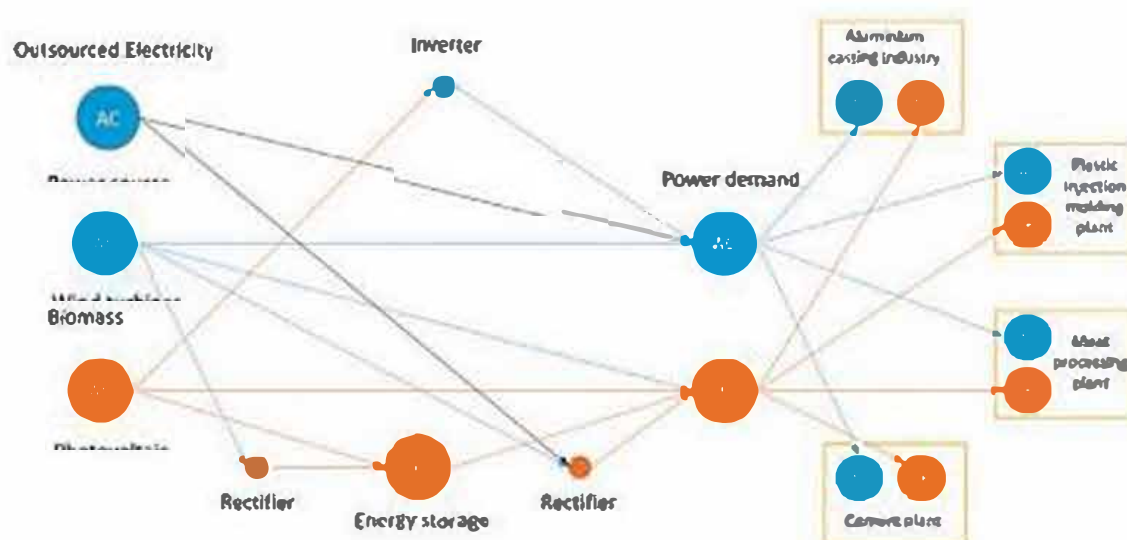


Figure 1: Superstructure of the HPS model

In this HPS, the renewable energy Alternative Current (AC) power sources are Wind Turbines, Biomass and Direct Current (DC) one is Photovoltaics panels. It is also possible to buy AC outsourced electricity (OE) from grid. To convert AC or DC electric current, rectifier and inverter are available. Due to the intermittency of renewable energy production, it is a dynamic model, in which time is discretized by hour, at any hour of the horizon time.

The EIP consists in 4 industries composed of AC or DC process to supply. While it is a theoretical EIP, energy demands are those of real process industries, in order to represent a complex demand, with many variations over time. Indeed in the aluminium casting industry works as a batch production (most of energy demand is between 7AM and 6PM) while the other industries works continuously. The cement plant is the biggest consumer (above 75% of the consumption) due to processes like raw-mill driver, cement mill driver and conveyor system. Moreover, renewable energy production can be stored in DC energies storage which is lead-acid batteries technology due to their best price capacity ratio to make profitable storage use.

The main mathematical constraints are energy balances at power source which is supplied directly to the power demand or charged into storage. This constraint is available for each power source and for each type of electrical current. Concerning the demands, the power demand must be satisfied by equivalent power of sources or batteries multiplied by potential energy loss if it has to be converted or discharged. Any loss corresponds to charging efficiency (90%) and converter efficiency (95%).

Energy balance for the storage system is also considered, i.e. the total amount of energy stored at the end of a time slice is the sum of the initial amount of energy stored and the net difference of charging and discharging. Additional constraints are added in order to limit converter and batteries capacities to maximal values observed throughout the duration time of the simulation. Furthermore, the geographical influence is considered through input model parameters. These parameters are outsourced electricity (OE) price, wind and solar power, and environmental impact of each renewable energy sources. The parameters related to geographical position are external electricity price, impact of sources, wind speed and solar irradiation.

The variables are the power rate of each renewable energy source, power capacity of converter (inverter and rectifier), the storage capacity and the amount of OE purchased.

A multi-objective optimization model is solved with an economic and an environmental criteria. The economic criteria to minimize is defined as the total Net Present Value of HPS over its lifetime, including capital investment, maintenance cost, operational expenditure for designed decision variable which are renewable energy sources, lead-acid batteries, and converters. Finally cost of purchased OE from external network is taken into account. The environmental objective is based on a LCA approach (cradle-to-grave), for each source (renewable energy and outsourced electricity) producing 1 kWh, the impact is quantified through SIMAPRO® software. This value depends on the country where energy is produced. The function to minimize is calculated by adding total impact produced by each source.

The resulting optimization model is an LP model able to find a global optimal solution and it has been solved with IBM ILOG CPLEX Optimizer.

3. Case study

In this case study, Malaysian data are taken from a previous work so that the model can be validated (Theo et al., 2016). The second location, i.e. Germany, is chosen to be very different from the first one because they have adopted a policy to promote renewable energy sources, favourable to renewable energy HPS implantation. Germany is a windy country with an important potential for wind turbines and low solar potential while

Malaysia is sunnier. Furthermore, in Germany, impact of RE sources is globally really lower than in Malaysia (Figure 2).

To get reliable data, horizon time of this simulation is set at 4 days, one per season, which allows to consider annual climate changing. Indeed, while Malaysia is near from equator with low seasonal impact, in Germany huge variations can be noted between seasons.

Solar information, are obtained with PVGIS® tool from the European commission. On the other hand wind speed for Malaysia comes from Theo et al. (2016) and for Germany from Fraunhofer ISE European research institute (2014). Outsourced electricity price used in this model is the average for industries in Malaysia: 0.078 USD/kWh (Theo et al., 2016) and in Germany: 0.103 USD/kWh according to Clean Energy Wire (2015).

The different sources taken into account in this model and their impact are shown in figure 2, for Malaysia and Germany. Values come from SIMAPRO® software, using Ecoinvent® database and Impact 2002+ method. It allows to propose an aggregated indicator, gathering 4 damage categories: Human health, Ecosystem quality, Climate change and Resources. The unity of this unique indicator is the mean environmental impact of a European during a year.

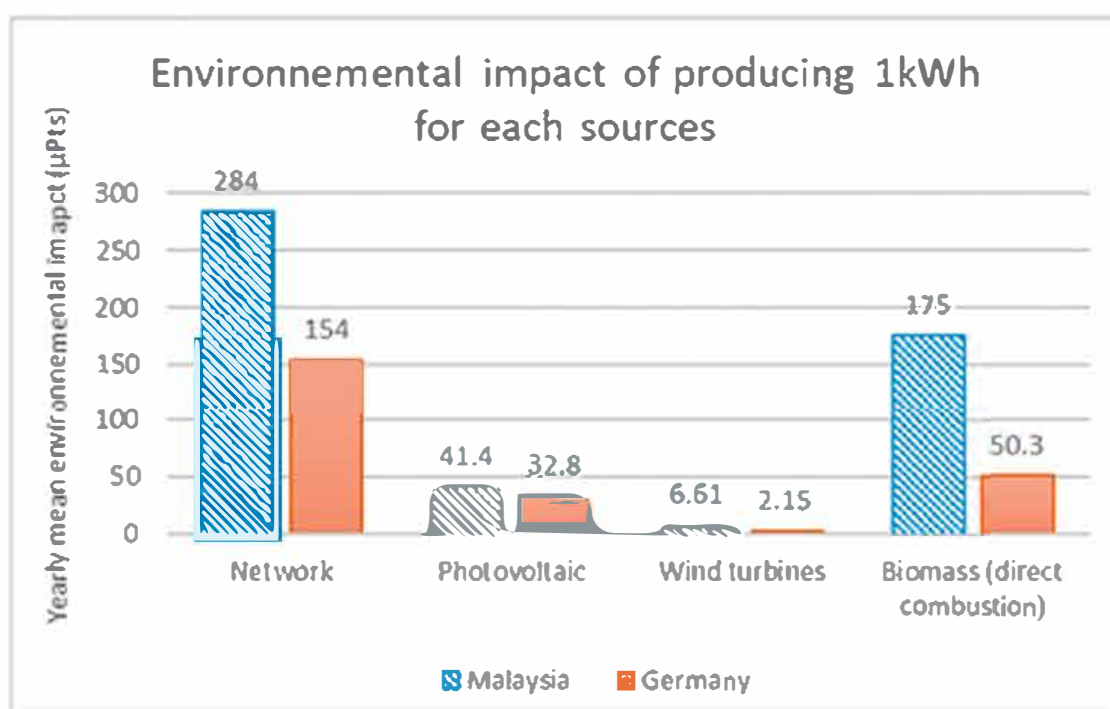


Figure 2 Environmental impact data collected for each country

4. Results and discussion

This section highlights the differences between mono and multi-objective optimization and also investigates the influence of geographical position. Figure 3 shows the Pareto front solutions obtained for Malaysia (MY) and Germany (GE). In addition, detailed results for designed HPS are presented in Table 1 where the geographic influence between Malaysia and Germany can be clearly highlighted.

According to these results, it can be noticed that these criteria are antagonist (when cost increases, environmental impact (ENV) decreases) what justifies the choice to use a MO

analysis. As a result, the MO approach epsilon-constraint is retained to obtain the Pareto front illustrated in figure 3. Multi-criteria decision analysis (MCDA) tool TOPSIS gives a solution among optimal ones, this solution is the nearest from the best value for each criteria and the farthest from worst ones.

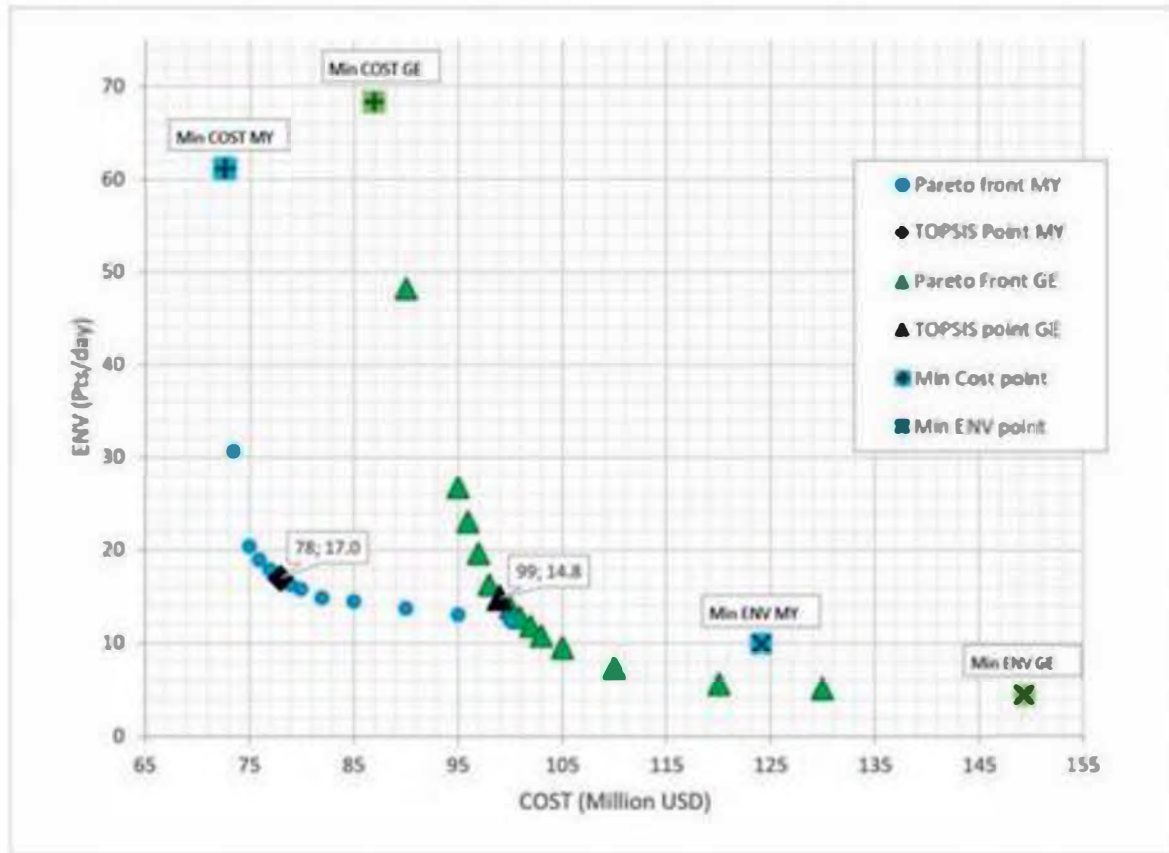


Figure 3 Pareto fronts and optimal points for Malaysian and German HPS implantation

Compared to the minimal cost point (Min COST), the TOPSIS multi-criteria solution observes a project cost 7% higher but a decrease of 72% on environmental impact for Malaysia. In Germany, it is also significant with a cost 14% higher and an ecological effect 78% lower. These results emphasize the importance of using a MO optimization because it shows that a little invest can have a big effect on environmental impact. One can also observe that when cost is minimized (min COST), compared to Malaysia, the German project is more expensive (+20%) and environmental impact also (+12%). This is mostly due to the higher price of OE which favours biomass. The latter gets a bigger impact than wind turbines used in Malaysian case.

Then, when environmental impact is minimized (min ENV), the German case observes a lower impact than Malaysia (-56%) that can be attributed to lower LCA impact of German RE sources (Figure 3). Lastly, with comparison of TOPSIS, the values obtained show a higher cost and a lower environmental impact. In both cases, wind turbines are essentially used. To conclude about geographic influence, this comparison between countries implantation shows some important differences on the respective solutions. This can be explained by (i) price for OE, (ii) impact for renewable energy sources, and (iii) by weather conditions, like seasonal influence (Germany is far from equator while Malaysia has a more regular climate). Regarding the types of renewable energy sources used, no solution proposes the solar one, it can be explained by an important investment cost and its high environmental impact (mainly due to the step of production of

photovoltaic panels) (cf. figure 2). Simulating in a more sunny country and including government helps should promote this technology. Biomass can be chosen, depending on countries, indeed, in Germany its impact is really low. At last, due to its low impact on environment, wind turbines appear to be the most used solution in this design.

		Cost (M USD)	ENV (Pts/day)	Cost storage (M USD)	Cost OE (M USD)	Wind Power rated (kW)	Biomass Power rated (kW)	Solar Power rated (kW)
Min COST	Malaysia (MY)	72.6	61.2	2.7	18.4	8764	2262	0
	Germany (GE)	86.9	68.4	6.6	8.6	0	13497	0
Comparison	GE/MY (%)	20%	12%	142%	53%	100%	497%	-
Min ENV	Malaysia (MY)	124.1	9.9	35.1	0	14717	0	0
	Germany (GE)	149.4	4.3	42.8	0	16578	0	0
Comparison	GE/MY (%)	20%	-56%	22%	-	13%	-	-
TOPSIS	Malaysia (MY)	78	17.0	8.0	9.1	12545	0	0
	Germany (GE)	99	14.8	10.4	33.3	9027	0	0
Comparison	GE/MY (%)	27%	-13%	30%	267%	28%	-	-

Table 1 Detailed results for each designed solution

5. Conclusion

In support of a framework for energy supply of an eco-industrial park, we have presented a generic methodology to optimize the renewable energy sources with a MO optimization approach. Using this methodology, we can determine, economic cost and environmental impact of such a solution but also the corresponding size for storage batteries. It also allows to determine the most profitable RE sources for a given geographic position. An interesting perspective, after this design of the EIP depending on its geographic implantation is to achieve a sensibility analysis. To go further future improvements for this model can be to allow it to select between several technological alternatives for RE sources or storage, due to its genericity it can be done easily by transforming it into an MILP. Finally because an EIP is constantly evolving, by using a multi-period approach, future research may make possible to modify network over time to adapt it to its moving context.

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