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Abstract

Eco-Industrial Parks (EIP) aim to preserve environment while increasing competitiveness of companies. This paper presents a mathematical Mixed Integer Linear Programming (MILP) model to optimally grassroots design an EIP energy network comprising heat and electricity. In the utility system, heated steam is produced, network is designed by selecting boilers and turbines technologies and interconnection pipes between companies. Simultaneously in the on-grid Hybrid Power System (HPS) composed of wind turbines, solar Photovoltaic (PV) panels, steam turbines and external grid, the model can select which source to use to meet the power demand. A case study of 10 industries from Yeosu real industrial park with seasonal data is provided to assess the model, first on economic comparison between stand-alone and EIP situation of companies, and secondly to determine which power source is profitable for HPS based on the sale price of electricity on the external power grid. In conclusion, this model allows the optimal design of the energy network of an EIP with dynamic data and with the objective of minimizing the net present cost.

Keywords: Industrial Ecology, Eco-Industrial Parks, Utility Network, Hybrid Power System, Mathematical Optimization, Renewable Energies.

1. Introduction

Nowadays the risks of human-induced climate change are increasingly pointed out by scientific reports. These reports conclude that limiting global warming would require ambitious mitigation actions while achieving sustainable development which means a development leading to economic, environmental and social benefits (Brundtland et al., 1987). To these objectives, industry has an important role to play because classical linear model (extract, produce, consume, throw) is responsible for overwhelming extraction of natural resources and waste rejection.

Facing these environmental issues, Industrial Ecology (IE) provides an innovative way to produce goods and services based on a circular model (share, reuse, mutualize). Indeed, in these industrial ecosystems, energy and resources consumption are optimized, waste generation is minimized and effluents from one production process are used as raw materials for another (Frosch & Gallopoulos, 1989). An application to this concept are EIP, in which industries gather on a same site and thanks to their vicinity they share and exchange efficiently different flows (material, energy, utilities). Furthermore, while reducing their environmental impacts they can also achieve greater economic competitiveness. To implement EIP in a sustainable way, companies need methods and optimization tools to design appropriate inter-enterprises exchanges. While an increased number of research projects have been carried out in recent years, Boix et al. (2015) pointed out that only a few deal with energy flow management neither with coupled networks. However, a systemic approach studying interactions between the different flows and optimizing them simultaneously would allow a better synergy between companies.

In the great majority of industrial parks, the facilities to meet energy demand are utility systems producing utilities for processes (i.e. mainly heat, cold streams and compressed air) and HPS that produce electricity using several power sources.
In utility systems, main energy consumption concerns heat, due to its high calorific value and its ability to generate power by rotating turbine. Moreover, in these utility systems, Combined Heat and Power (CHP) is an energy-efficient way to produce simultaneously electricity and thermal energy. Indeed, compared to the separate generation of heat and power, cogeneration can improve energy efficiency between 10 and 40% (Madlener & Schmid, 2003) and thereby reduces CO2 emissions. Through combined production raises other constraints such as operational planning of production. Yet a large number of publications are dedicated to optimizing the operational management of existing CHP, (Aguilar, 2007; Mitra, 2013) but only a few to design such facilities even less so adapted to EIP context with heat utility exchanges between companies. Afterwards, HPS, as a coupled system, is an efficient way to harness RE sources, relying on complementarity between sources. When it is connected to the external grid it is possible to compensate for the lack of production from other sources purchasing power, it is then called on-grid HPS. In addition, a decentralized production means to reduce reliance on external grid and reinforces the robustness of the power system.
In a previous publication, a study on on-grid HPS to supply electricity in an EIP was carried out using a mathematical LP model for the optimal design of this HPS with dynamic demand, on an hourly basis (Mousqué et al., 2018). This model has the possibility to select power sources to install between wind turbines, solar PV panels, biomass by combustion or also buy electricity from the grid.

To go further, this work extends the previous HPS model by presenting a generic optimization model to the grassroots design of both the utility network and the HPS of an EIP. The first purpose of this article is to assess economic interest that companies can encounter by sharing their heat and power facilities in comparison to their stand-alone situation. Another objective is to discuss which RE or energy-efficient electricity source can be profitable to supply EIP demand. Two optimal solutions are finally discussed depending on the sale price of electricity fixed by politic regulation. These results are obtained on a complex real problem using the proposed approach involving 10 companies in an EIP with real demands taken from Yeosu industrial park (Kim et al., 2010).

2. Problem statement

The aim is to design the exchanges of water, steam and electricity between processes inside a single company as well as exchanges between different companies, during several time steps. A generic superstructure (Figure 1) has been developed in order to show the different components taken into account in the model.

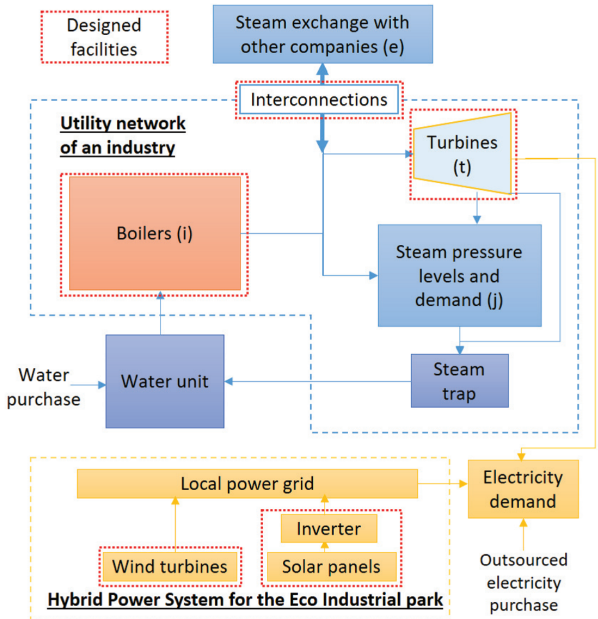

Fig 1. Superstructure of the utility system of an industry and HPS of the EIP.

In a company, steam flows through steam headers, different levels of steam pressure are taken into consideration. Pressure release valves are used to convert higher pressure steam into lower pressure steam by dropping its pressure. Steam is produced by boilers installed in companies. In the case studied in this publication, they are natural gas boilers. Different types of boilers can be installed depending on the maximum production capacity and the level of steam pressure produced. Boiler capacity range is between 50 and 100 % of its maximum power, because in this range boiler has a relatively constant efficiency (Aguilar et al., 2007) and also in seasonal operation it would be a big loss to operate the boiler at a low capacity, which means at a low efficiency level.

These power sources are selected to be RE technologies, i.e. wind turbines and photovoltaic panels, or energy-efficient such as cogeneration by mean of turbines. Data are dynamic with a seasonal variation (one-step for each season). In an EIP configuration, the power production is shared between companies and used to supply their demand. By connecting to external power grid, power can be bought and excess production can be sold. Finally, multi-stage extraction turbines can be selected between three technologies (i.e. 500 kW, 3 MW, and 15 MW). These turbines convert energy contained in high-pressure steam to a lower level of pressure or to condensed water. Higher is the pressure difference, higher the power production.
In this case, the production of renewable energy is considered as an average over a season. This estimate is only possible thanks to the external grid connection. Indeed, periods when production is higher or lower than the average production are supposed to be offset by the purchase or sale of electricity.
Water flow is a closed loop, after consumption from the process, water returns to the water unit, reducing water consumption. Each company has the possibility to buy water at every time step if necessary. Indeed, water losses by evaporating in water unit and steam losses by condensing trap or vent to evacuate overload are included.

3. Generic optimization model

Regarding the superstructure previously shown and the complexity of this model, due to the important numbers of continuous and binary design variables, a large-scale MILP model is developed. Due to its genericity, it is intended to be adaptable to the initial design of new EIP or to the retrofit of existing industrial parks, this last case by setting the initial structure.
The selected objective function is to minimize NPV of the designed utility network and HPS for a project duration considered of 20 years, with a discount factor of 7%. Constraints to model units are based on thermodynamic principles, mass and energy balances. Decisions variables are the different possible connexions between units and enterprises characterized by their type (VHS, HS, MS, LS, water…) and their flow and the decision to install or not a boiler and if it is installed which one is chosen? Capital and operational cost for installed boilers, turbines, pipes and the consumption of raw material are thus determined by the decision variables. Raw materials are fuel i.e. natural gas, treated water and electricity, which can be purchased or sold. Binary variables are used to select installed pipes between companies, installed technologies for boilers and turbines and operational state of boilers (i.e. switched on or off).

Given the high capacity of the superheated steam to be transported, losses in the interconnection pipes between the companies are considered negligible. Implemented data for boiler cost and steam pipes comes from economic evaluation manual (Chauvel et al., 2001) and are actualized using OECD Industrial Production Index. Renewable production is supposed to take place in France, with RTE report seasonal production (RTE, 2018) for these sources complete cost are those from ADEME (2016). Price for natural gas is set at 280 €/ton.
This model has 4101 constraints, 5103 variables including 540 binaries and it was solved with IBM ILOG CPLEX Optimizer.

4. Results and discussion

Two studies are conducted: an economic analysis of the case study to determine the interest of a company to take part of an EIP while the second one deals with the design of HPS power sources considering a different price for sale electricity.
This first study will compare Stand-alone and EIP solutions, both with a sale price of 0.05€/kWh which reflects the average price for electricity producer in France. While the second analyse will be a comparison between EIP (0.05) and EIP (0.10), latter case with a price of 0.10 €/kWh, considering politic aids to enhance creation of a local power grid. Detailed costs for these discussed optimal solutions are presented in Table 1.

Table 1
Overall economic comparison between Stand-alone and EIP situation.

Overall cost	Net Present Cost	Boilers cost	Power sources cost			Raw Materials cost				Pipes cost
			Turbines	Solar PV panels	Wind Turbines	Fuel	Water	Electricity purchased	Electricity sold	
Stand-alone	1,097,762 k€	56,294 k€	4,181 k€	- €	- €	1,040,671 k€	3,781 k€	4,311 k€	-11,478 k€	- €
EIP (0.05)	1,048,715 k€	36,186 k€	- €	- €	- €	1,001,113 k€	3,416 k€	4,430 k€	- €	3,569 k€
EIP (0.10)	982,324 k€	55,638 k€	56,647 k€	- €	38,594 k€	1,184,730 k€	3,923 k€	4,431 k€	-366,036 k€	4,396 k€

4.1. Stand alone and EIP (0.05) comparison

Observations show that while cost is slightly different for NPV of the EIP (0.05) (i.e. -4.7 %), for water (i.e. -10.7 %) and for fuel (i.e. -4.0 %), main reduction observed is for the cost of installed boilers (i.e. a reduction of 55.6 %). Additionally in stand-alone situation, the model proposes to invest in turbines, produce electricity and sale it.
This is because single companies have oversized boilers during seasons with lower demand, and this overproduction cannot be valorised. To avoid dumping it, it is profitable to install turbines to value this overproduction. In EIP configuration, cost for installed boilers is significantly reduced. In fact, pipe cost being less expensive than gain resulting from creating interconnections, companies share their production and their demand. This share allows a better size and management of installed boilers. This is observable by an average production ratio of installed boiler at 77% of their maximal production in EIP against 60% in stand-alone. However, on project life span, fuel is the most important cost, and in comparison between cases, only a few difference is observed. More accurate fuel consumption results should be obtained by including boiler inertia on a daily basis.

4.2. Impact of the electricity sale price on the design

Figure 2 shows the optimal solution of the utility network for EIP (0.05) case, with boiler for each company and different pressure level exchanges, highlighting results that this model achieves and its complexity.

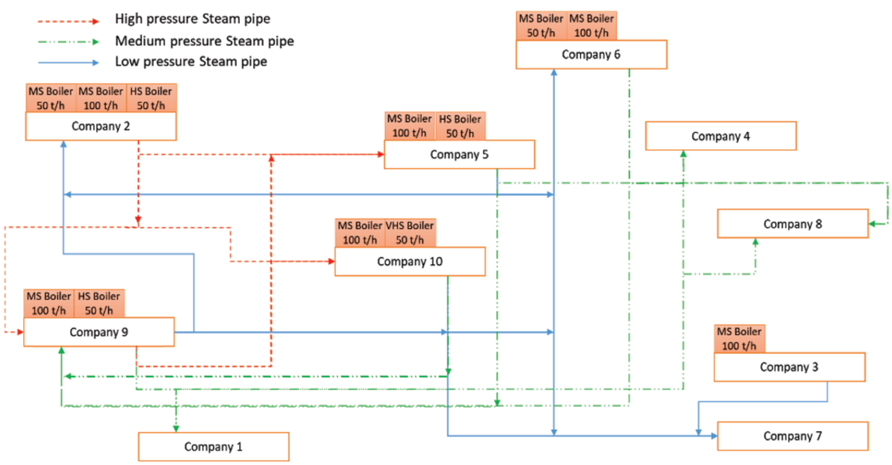

Fig 2. Designed boilers and utility steam exchange network for EIP (0.05).

With a sale price of 0.05 €/kWh neither turbines nor RE are selected, whereas when the sale price increases at 0.10 €/kWh both wind turbines and turbines are selected with three turbines of 15 MW. These choices can be justified with wind turbines and PV panels break-even point, which is calculated as respectively 0.094 €/kWh and 0.125 €/kWh, depending on discount factor and overall production and complete cost of each technology. For turbines, it is also dependent on utility system criteria, such as turbines and boilers technology (i.e. investment cost and efficiency), output pressure steam and if extra steam production is available to value it. However, over the lifespan of the project, the complete discounted cost for the installation of the turbines represents only a relatively small part. For example, for a 500 kW system operating at nominal power, the cost of the installation is calculated at 0.019 €/kWh. Only based on an economic criterion, external electricity price has been identified as a main parameter to decide which technology to use. Turbines can be considered as an efficient way to value overproduction or overheated steam. Currently, wind turbines are cheaper than PV panels, although the difference is small, the design will depend mainly on the renewable resource available on the site.

5. Conclusion

A model of grass-root design of an EIP utility system and HPS with an economic criterion has been developed to determine the facility to invest in and the exchanges between companies. In this model, the implementation of this EIP represents a slight NPV gain, but a significant reduction in the investment cost of boilers. For HPS, a too low price of outsourced electricity does not foster to create a local grid with cogeneration, wind turbines or PV panels. However, other criteria could be taken into account, such as public subsidies on investment or on sale price to incite such technologies. This mathematical model has validated a first frame to assess capability of MILP to be solved on a real case of 10 companies taken from Yeosu industrial park with dynamic seasonal data. Further improves could be achieved, using this model on a case study with dynamic data on a daily basis (day and night) allowing more accurate results for boiler management, more detailed analyse on RE sources variation production depending on weather conditions. Another interesting point is that due to fuel cost importance, other fuels and boilers technology could be added. Finally using a multi-objective optimization, including environmental objective is another way to explore.

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