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Optimal Design of Eco-Industrial Parks with coupled energy networks addressing Complexity bottleneck through an Interdependence analysis

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ABSTRACT

By gathering in Eco-Industrial Parks (EIPs), companies obtain benefits from synergistic cooperation but it also creates a risk by increasing interdependencies. The aim of this paper is to provide a method for optimally design exchanges that takes into consideration real stakes of companies. This resolution method is assessed on a multi-period MILP model of coupled energy networks integrating a utility system producing steam at different pressure levels and a mutualized on-grid Hybrid Power System (HPS) providing electricity using Renewable Energy (RE) sources. Design concerns interconnections between companies such as boilers, turbines and power of RE sources. A multi-stage approach is developed to minimize network complexity and Net Present Value (NPV) of the overall network. Lastly, an interdependency analysis is proposed to choose the optimal solution. Tested on a case study involving 15 companies, the optimal exchanges have been raised to satisfy demands over four time periods.

1. Introduction

According to recent reports (IPCC 2018), facing global warming and the ensuing environmental challenges is a priority to design new ways of goods production. Finding ecological ways to produce goods and services while ensuring economic benefits constitutes a major research challenge. As a solution, industrial ecology aims to reconcile industrial and environmental constraints by drawing inspiration from natural ecosystems to design industrial systems (Frosch and Gallopoulos, 1989). Indeed, in such ecosystems, the use of resources (raw materials or energy) is optimized through transformations that minimize losses and therefore wastes. The fulfilment of this concept is the implementation of Eco-Industrial Park (EIP), in which industries gather on the same site in order to benefit of synergetic advantages of cooperation, with two main goals, increasing their competitiveness while reducing their environmental impact (PCSD, 1996). To date, most of these parks have been implemented in industrialized countries such as North America, Europe or Australia, but nowadays many of them are also be-

ing created in developing countries; e.g. China, Brazil and Korea (Montastruc et al., 2013).

In order to design exchanges in EIPs, it is necessary to use and develop optimization approaches. Reviews on the optimization of EIP (Boix et al., 2015) and on the tools used for EIP development (Kastner et al., 2015; Afshari et al., 2016) classify the existing approaches depending on the network considered: water network, material, energy or coupled networks. These reviews have reported that in contrast to EIP material or water flow management where there is a relatively large number of researches, only a small amount of publications are dealing with interplant energy flow management. The following part provides details on previous optimization methods dedicated to EIP energy network.

Lowe (2001) defines two main axes for designing sustainable energy networks, the first one consists of maximizing the efficiency of energy production and transportation systems, the second one is to harness renewable power sources. For the former, the recommendations include the use of large-scale inter-plant utility system or cogeneration sources such as Combined Heat and Power (CHP) plant. The latter axis focuses on substituting conventional fossil power production by renewable energy (RE) sources such as solar, wind turbines, biomass, geothermal energy, etc., depending on the potential of the local area. To this extent, in most eco-industrial parks, facilities designed to meet energy demand

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Nomenclature

Sets

b:	boiler
f:	fuel
tu:	turbine
so:	photovoltaic (PV) solar panel
wi:	wind turbine
sr:	electrical sources (so; wi \in sr)
sr _{AC} :	Alternative Current (AC) electrical power sources (wi \in sr _{AC})
sr _{DC} :	Direct Current (DC) electrical power sources (so \in sr _{DC})
C:	company (c \in C, c' \in C, c \neq c')
H:	steam header (h \in H, h' \in H, h < h')
T:	time period (t \in T, tm \in T, \forall tm \leq t)

Parameters

M:	large positive value
Nbtime:	number of step time
i:	discount rate
n:	project lifespan (years)
SL ^h :	percentage of steam losses by trap at steam header
WL ^{wu} :	percentage of water losses at water unit
Cal _f :	fuel calorific power (kWh/t)
Eff _{b, f} :	boiler efficiency for each fuel
Eff _{tu} :	turbine efficiency
ConP:	condensate parameter for turbine
h _h :	steam enthalpy depending on pressure level (kWh/t)
h _w :	water enthalpie before boiler heating (kWh/t)
D ^s _{h, t, c} :	steam demand (ton/h)
D ^e _{t, c} :	electricity demand (kWh)
ECon _b ^{fix} :	fixed electricity consumption for boiler (kWh)
ECon _b ^{var} :	variable electricity consumption for boiler (kWh)
p ^{Max} _{b, h} :	maximum steam production at boiler b (ton/h)
p ^{min} _{b, h} :	minimum steam production (ton/h)
S ^{Max} _{h' // tu} :	maximum steam in turbine tu (ton/h)
S ^{min} _{h' // tu} :	maximum steam in turbine tu (ton/h)
LoadFactor _{so, t} :	load factor for the solar PV production
LoadFactor _{wi, t} :	load factor for the wind turbines production
V _{wi, t} :	wind speed in the time interval t (m/s)
v ^{rated} _{wi} :	rated wind speed (m/s)
DFA:	Discount factor for allocation of annual operational expenditure and resources over the life of the project.
Pri ^{fuel} _f :	fuel purchase price (USD/ton)
Pri ^{water} _f :	water purchase price (USD/ton)
PriElec ^{purchase} _f :	electricity purchase price (USD/kWh)
PriElec ^{sales} _f :	electricity sales price (USD/kWh)
F ^{stock_safety} _{b, f, t, c} :	fuel safety stock (ton)
CAPEX _b :	capital expenditure for boiler (USD)
OPEX _b :	operational expenditure for boiler (USD per year)
DFI _b :	discount factor for investment and replacement cost of boiler
CAPEX _{tu} :	capital expenditure for boiler (USD)

OPEX _{tu} :	operational expenditure for turbine (USD per year)
DFI _{tu} :	discount factor for investment and replacement cost for turbine
CAPEX ^{fix} _{pipe} :	fixed capital expenditure for pipeline (USD)
CAPEX ^{var} _{pipe} :	variable capital expenditure for pipeline (USD/ton/h)
OPEX _{pipe} :	operational expenditure for pipeline (USD/ton/h)
DFI _{pipe} :	discount factor for investment and replacement cost of boiler
minInterc ^{Diameter Threshold} :	minimum diameter of interconnection pipes (ton/h)
MaxInterc ^{Diameter Threshold} :	Maximum diameter of interconnection pipes (ton/h)
CAPEX _{sr} :	capital expenditure for electric power sources (USD/kW)
OPEX _{sr} :	operational expenditure for electric power sources (USD/kW per year)
DFI _{sr} :	discount factor for investment and replacement cost of electric power sources
Effinv:	inverter efficiency for DC sources
MaxEprodTur:	maximum production for turbines (kWh)
MaxInstall _{sr} :	maximum power installed for electrical source (kW)

Variables

NPV:	Net Present Value of the overall project
Cost ^{Raw} :	raw material cost for the project lifespan (USD)
Cost ^{Boilers} :	boilers cost for the project lifespan (USD)
Cost ^{Pipes} :	pipes cost for the project lifespan (USD)
Cost ^{Turbines} :	turbines cost for the project lifespan (USD)
Cost ^{Elec_sources} :	electrical sources cost for the project lifespan (USD)
Cost ^{Elec} :	electricity cost for the project lifespan (USD)
Cost ^{Fuel} :	fuel cost for the project lifespan (USD)
Cost ^{Water} :	water cost for the project lifespan (USD)
Nb _{interc} :	number of interconnection in the utility system
Av ^{Interc} _{Diameter} :	average of interconnection diameters
Max ^{Interc} _{Diameter} :	maximum of interconnection diameters
ΔQ1Q3 ^{Interc} _{Diameter} :	difference between quartile 1 and quartile 3 of the interconnection diameters
T ^s _{h, t, c, c'} :	steam transfer from company c to company c' (ton/h)
T ^w _{t, c, c'} :	water transfer from company c to company c' (ton/h)
y ^{sel} _{b, c'} :	binary variable to select boiler technologies
y ^{prod} _{b, t, c'} :	binary variable to regulate boiler steam production
y ^{sel} _{tu, c} :	binary variable to select turbine technologies
y ^{pipe} _{h, c, c'} :	binary variable to select interconnection pipes from company c to company c'
p ^{rated} _{sr} :	rated installed power of electrical power source (kW) (so; wi \in sr)
Interc ^{Diameter} _{h, c, c'} :	diameter of an interconnection pipe (ton/h)
F _{b, f, t, c} :	fuel consumed by boiler (ton)
F ^{purchase} _{b, f, t, c} :	fuel purchase by boiler (ton)
F ^{stock} _{b, f, t, c} :	fuel stock by boiler (ton)

$S_{b,h,t,c}^{prod}$	steam production from boiler to steam header (ton/h)
$S_{h',h,t,c}$	steam flow from header h' to steam header h (ton/h)
$S_{h,tu,t,c}^{In}$	steam flow from steam header to turbine (ton/h)
$S_{h,tu,t,c}^{Out}$	steam flow from turbine to steam header (ton/h)
$S_{h,t,c}^{trap}$	steam losses by condensate trap at steam header (ton/h)
$S_{h,t,c}^{vent}$	steam vented at steam header (ton/h)
$W_{h,t,c}$	water flow from process use to water unit (ton/h)
$W_{b,t,c}$	water flow from water unit to boiler (ton/h)
$W_{tu,t,c}^{Out}$	water flow from turbine to water unit (ton/h)
$W_{t,c}^{stock}$	quantity of water in the utility network during time interval t (ton)
$W_{t,c}^{purchase}$	water purchase for water unit feeding (ton)
$W_{t,c}^{feeding}$	water purchase for water unit feeding (ton)
$W_{t,c}^{losses}$	Water losses in water feed boiler (ton)
$W_{t,c}^{dump}$	water dumped from the utility network (ton)
$E_t^{prodSources}$	produced electric power in the HPS (kWh)
$E_{sr,t}^{prod}$	produced electric power depending on the electrical source (kWh) (so; $w_i \in sr$)
$E_t^{prodCons}$	produced electric power consumed (kWh)
$E_t^{prodSell}$	electric power sold per step time (USD)
$E_{t,c}^{purchase}$	electric power purchased per step time by a company (USD)
$E_{b,t,c}$	consumed electric power by boiler (kWh)
$E_{tu,t,c}$	electric power produced by turbine (kWh)
$E_{sr,t}$	electric power produced by sources in the HPS (kWh)

are utility systems, they produce utility for processes (i.e. mainly heat, cold and compressed air) (Hipólito-Valencia et al., 2014), although Hybrid Power Systems (HPS) generate electricity using multiple power sources (Xu et al., 2013). Several techniques have been introduced to assess the economic feasibility of utility system and HPS. In most methods, the final objective is to search for the energy network design with the lowest investment cost (Kastner et al., 2015).

1.1. Energy networks for EIP

During the last decades, a great majority of studies deals with utility systems design and planning by the mean of economic and thermodynamic optimization. Among them, Papoulia and Grossmann (1983) developed a Mixed-Integer Linear Programming (MILP) model to design the utility system at the industrial park scale. In this model, different configurations and technologies (e.g. boilers, steam turbines, and gas turbines) are available in order to provide fixed demands of electricity and of steam at different levels of pressure. Later on, including demand variations, a multi-period enhancement of this model has been proposed. Afterwards, Aguilar et al. (2007) developed a multi-period MILP model to optimize the design and operation of industrial utility systems. Thereafter, Kim et al. (2010) developed a multi-period MILP model to optimize steam, water and electricity networks planning and to design the interconnections to implement regarding economic and environmental criteria. Most recently, Combined Heat and Power

(CHP) has been also included as a technology to design industrial parks. Indeed, CHP allows generating electricity while producing thermal energy (mainly steam and hot water) with heat that would have been wasted (Chicco and Mancarella 2009). Compared to the separate generation of heat and power, cogeneration can improve energy efficiency between 10 and 40% (Madlener and Schmid, 2003) and thereby reduce CO2 emissions. Among these scheduling works, Agha et al. (2010) introduced an integrated optimization approach that simultaneously optimizes the production system and the utility system. In addition, Mitra et al. (2013) took into account the variation of the selling price of the electricity with a time-sensitive model. Later, Li et al. (2016) have developed a model that considers storage for CHP coupled with wind turbines to sell it on the electricity market. Finally, designing an EIP utility system, Ramos et al. (2018) developed a model based on game theory concepts in order to take into account the behaviour of participants. Their optimization method consists into a multi-leader-follower game model that is transformed as a MO problem with equilibrium constraints and solved as a Non Linear Programming (NLP).

Hybrid power systems (HPS) are considered as a decentralised electric power generation system directly connected to the local distribution network or close to the power demand (Paliwal et al., 2014). The advantages of these types of systems are the reduction of the reliance on the external grid, the stability of power prices (Gao et al., 2014), the security and power quality (Dondi et al., 2002) and the possibility to provide power in remotes region. Considering environmental aspects, the main benefits is the reduction of carbon emissions by contributing to the development of renewable sources (Abou El-Elai et al., 2010; Bellamy et al., 2014). One of the most used methods for HPS design and planning is the Power Pinch Analysis (PoPA). This method introduced by Bandyopadhyay (2011), is based on the concepts of mass and energy balances and integrates time dimension, allowing energy storage. Bandyopadhyay developed a model to optimally design sources and storage capacity for off-grids HPS. A set of possible optimal solutions is provided using graphic visualization where the battery capacity is a function of the size of the energy sources. From this method, Wan Alwi et al. (2012) developed a model to design an HPS system with the minimum outsourced electricity supply and the minimum storage capacity in on-grid cases. Addressing this issue, mathematical optimization is an efficient solution for HPS design, as presented in HPS optimization review papers (Zhou et al., 2010; Sinha and Chandel, 2015) developed a generic LP model to minimize the minimum outsourced electricity supply and the storage capacity of HPS while taking into account the energy losses in the allocation of power generated from renewables. This model has been tested on a typical household case study in the UK. Whereas Ho et al. (2014) propose a MILP biomass-based HPS connected to the residential demand of Iskandar Island in Malaysia. Thereafter Theo et al. (2016) presented a MILP model to optimize cost and storage capacity of an on-grid HPS for an EIP, comprising Alternative Current (AC) and Direct Current (DC) power. In this paper, several storage technologies are assessed.

To our knowledge, no other study has presented the coupling of utility systems and HPS in an EIP. Thus, the following section focuses on the specific issues related to the design of a coupled energy network. In this regard, increasing the size of the exchange network by coupling networks (e.g. heat, power, water, material, wastes, etc.) is a major issue that can be overcome by the development of generic optimization methods able to solve large problems. Indeed, it is particularly true for EIP networks design and planning, that can involve many interconnected plants and processes and therefore many constraints and variables including binaries.

1.2. Network complexity of an EIP

Another major issue underlined by [Kastner et al. \(2015\)](#), is to deal with the network complexity of the designed solutions. Indeed, the network complexity is represented by the number of connections between the several companies involved in the EIP, named interconnections ([Nobel and Allen, 2000](#); [Aviso et al., 2011](#)), and it is directly linked to the feasibility of the network ([Rubio-Castro et al., 2011](#)). In addition, ([Boix et al., 2012](#)) have demonstrated that cost and network complexity are antagonists, so they can be considered as objective functions in a MO optimization. Finally, [Tian et al. \(2014\)](#) highlighted that infrastructure sharing (e.g. boilers, wastewater treatment, etc.) allowed by the interconnection network is also another major issue to cope with EIP development. Therefore, interconnections are more relevant for an EIP development than connections between processes inside the same company, because they involve other concepts such as confidence and interdependence between companies. While network complexity has been widely analysed in the sense of technical feasibility, a lack of studies is found regarding the reliance between companies and therefore the interdependence that interconnection between companies implies. Indeed, dependencies allow to benefit of the advantages of synergetic exchanges, but it is also a way to propagate failures within the network ([Valenzuela-venegas et al., 2019](#)). These organisational aspects are addressed in this paper through the interdependence indicator developed hereafter.

The contributions of this paper are: i/ the development of a generic approach for the optimal design of an energy network coupling the utility system and the HPS in an EIP and also ii/ addressing the complexity challenge through the development of a new procedure and indicators. In the first part, this article details the problem statement as well as the developed superstructure, after which the mathematical formulation is presented. The resolution methodology is then given. This method is discussed in an application case study of a complex real problem involving 15 companies in an EIP with energy demands taken from Yeosu industrial park ([Kim et al., 2010](#)). The final section aims at applying a multicriteria decision making tool to choose an optimal network based on an interdependence analysis.

2. Problem formulation

2.1. Problem statement

Given is a set of input parameter including: energy demands (i.e. steam at different levels of pressure and electric power), efficiency and nominal power for the utility system energy sources (i.e. boilers, turbines), fuel type for the boilers, efficiency and maximum installable power for the HPS energy sources. The optimization problem has to find the design of:

- i. The energy network of the EIP: the flowrates exchanged for a given time period, the power of the energy sources installed, and the steam exchanged between companies.
- ii. The power generation and exchanges planning over time periods represent the dynamics of production and demand.

Design variables are binaries for the boilers, turbines, interconnections selection and position (i.e. in which company) and for the operation of boilers (i.e. turned on or off). Continuous variables are used to allocate the amount of resources (i.e. fuels, water, and outsourced electric power), the power installation of wind turbines and solar PV and the diameter of interconnections. Due to its genericity, this model is applicable to both the grassroots design of EIPs and the retrofit design of existing industrial parks. The MO optimization model consists in minimizing the overall cost of the whole energy system (i.e. utility system and HPS) and minimizing

the interconnections. This optimization model is solved over several time periods.

2.2. Superstructure based model

An overview of the general model description is provided in [Fig. 1](#). It presents the developed energy exchange network model coupling the utility system to supply the steam demand and the on-grid HPS to supply the electric power. Companies can exchange steam using interconnection pipes. Coupling the utility system and the HPS, and optimizing them simultaneously, enables a more realistic design to be achieved, by considering the whole system and interaction between heat and power.

For both steam and electric power demands, the dynamic is taken into account. Indeed, as shown in the energy profile section, energy demand varies over time for companies depending on their production mode (i.e. batch or continuous) but also depending on seasonality. To go further, on the left side of the figure the energy sources are represented and the dynamic of their production is highlighted with shorter variation steps for the intermittent renewable sources than for the steam production with boilers. From period to period, continuity constraints are imposed, they involve the stock levels (water and fuel). The superstructure of the whole network is represented on [Fig. 2](#). It describes the operation of the internal utility system of a company, the possible exchanges to other industries and finally the HPS for the whole EIP. Considering the utility system, different level of pressure and temperature, between boilers and processes inside a single company as well as exchanges with the other companies over several time periods are considered. Boilers are producing the steam, to supply the heat demand of the processes. Moreover, the transfer from a higher-pressure steam header to a lower one is done by Pressure Relief Valves (PRV) or using turbines. Indeed, a cogeneration system is integrated through the use of turbines that convert high-pressure steam to a lower level of pressure or to condensed water into electric power by driving generators.

The steam network of this model is a loop system. After the processes use, the water returns to the water unit. The water stock in the water unit is considered as one hour of consumption. This model includes water losses due to evaporation in the water unit and steam losses in the network, through condensate traps or vents. The latter is used as an excess purge and it gives to the system a degree of freedom by enabling it to evacuate overloads. To compensate these water losses, industries can purchase feed-water.

While designing the utility system, to supply the energy demand, the model selects the boilers and turbines to be installed among different technologies. The sizing specifications for boilers are their maximum production capacity, their level of steam pressure produced, the fuel consumed and the cost of the boiler.

In this model, the turbines can be single-stage or multi-stage. In single-stage turbines, only the inlet flow rate can be controlled, in multi-stage, the distribution between the outlets is also manageable ([Agha et al., 2010](#)).

Boilers and turbines of this model are installed in companies. In this way, stand-alone mode (i.e. companies without interconnections to the sharing network, with its own production) or in EIP mode, interconnected with other companies can be reachable. To exchange the heated steam, the network composed of interconnections between companies is also designed. An interconnection is directional, i.e. steam can only flow in one direction.

Regarding RE sources, the model determines the power to be installed. The production of intermittent RE sources depends on their estimated load factor, which is an average of previous measures related to the geographic position of the EIP and to time period. Because the HPS is on-grid, at each time step, the model can

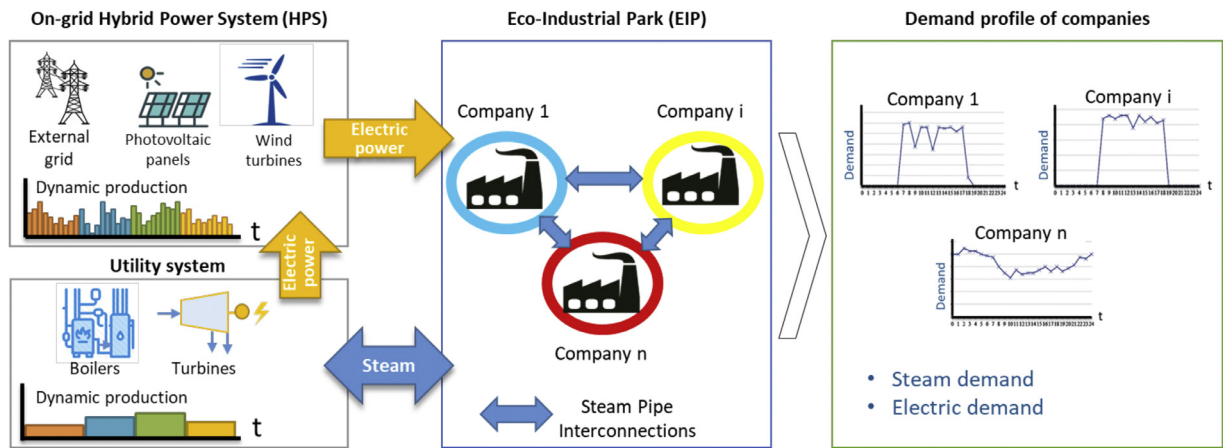


Fig. 1. Schematic representation of the utility system coupled to the HPS to supply the EIP demand.

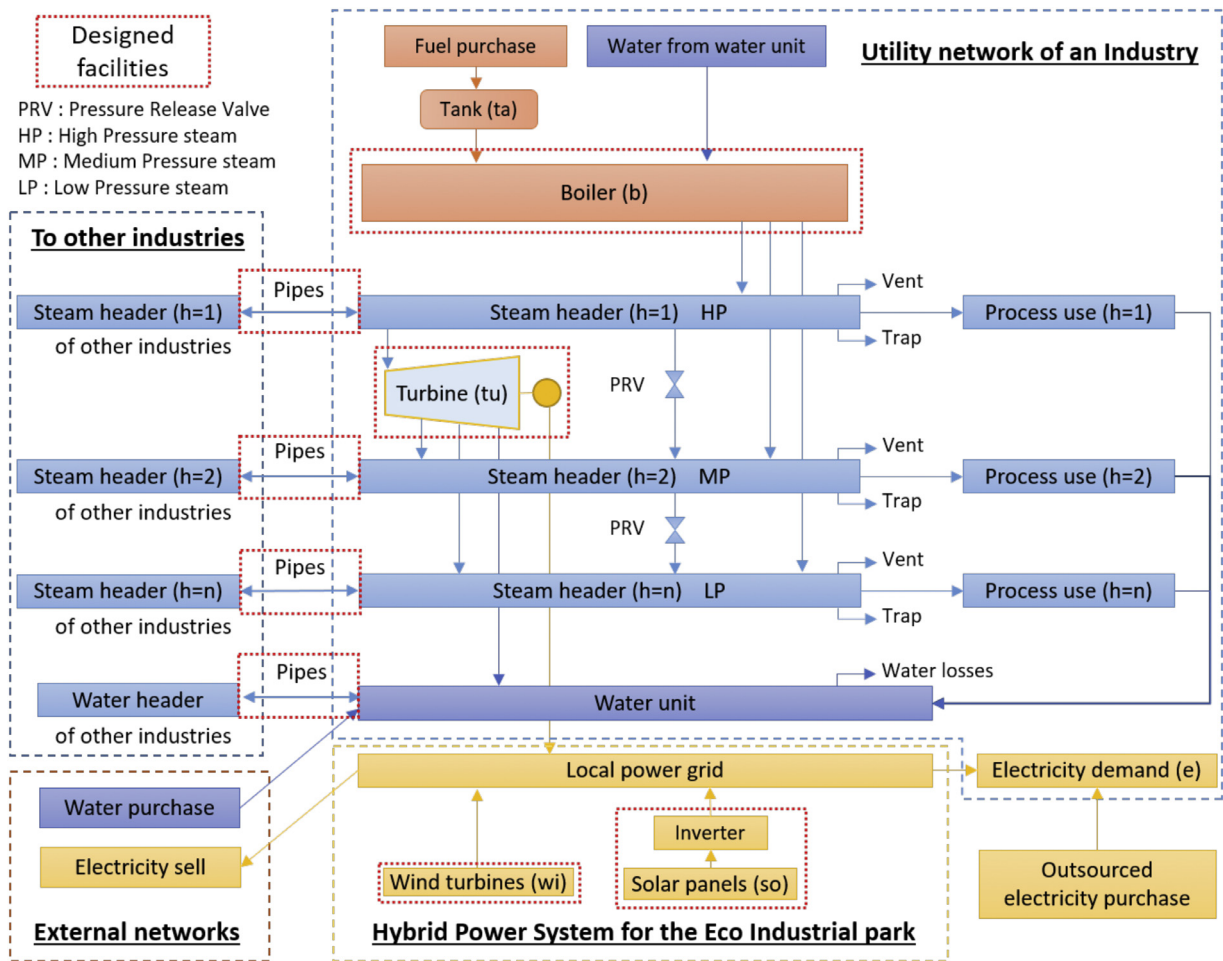


Fig. 2. Superstructure of the utility system an industry and HPS for the EIP.

decide to purchase electricity. It may also choose to sell the electricity produced on-site to the external grid.

Conversely to boilers and turbines, the location of wind turbines and solar PV sources is not considered as a parameter in this model, which means that HPS sources can be located at any place: within the site of a company or on a dedicated site. Indeed, it is considered that the electricity grid already exists, its installation costs are therefore negligible.

The assumptions for this model are:

- When designing interconnections, their length is not taken into account. This is possible because all companies are expected to be located on the same EIP site, close enough that the distances between them are relatively short.
- Power and heat losses are not taken into account, indeed it is considered as an insignificant amount in comparison to energy exchanges flows (Kim, et al., 2010; Theo et al., 2016).

- The transitory behaviour of elements such as warm and cold start-ups, shutdowns for boilers are not taken into account because this model is dedicated to long term design and not to short term scheduling.
- The HPS does not include energy storage, as current technologies are considered uneconomic, particularly when connected to the external network as proven by (Mousqué et al., 2018).

3. Mathematical formulation

This section details the mathematical formulation resulting from the superstructure presented above.

3.1. Objective functions

Economic objective:

The economic objective used is the minimization of NPV, which is the discounted value of the designed energy network over its lifetime. It comprises the costs of raw materials, boilers, interconnections, turbines and power generation sources (1).

$$\min \text{NPV} = \text{Cost}^{\text{Raw}} + \text{Cost}^{\text{Boilers}} + \text{Cost}^{\text{Pipes}} + \text{Cost}^{\text{Turbines}} + \text{Cost}^{\text{Elec_sources}} \quad (1)$$

The cost of raw materials includes fuel, electricity and water (2).

$$\text{Cost}^{\text{Raw}} = (\text{Cost}^{\text{Fuel}} + \text{Cost}^{\text{Elec}} + \text{Cost}^{\text{Water}}) \quad (2)$$

As with other raw materials and operational costs, the fuel cost is calculated over the duration of the project. Thus, to obtain the fuel cost, the total quantity of fuel purchased over all time steps is multiplied by the purchase price of the fuel (3). Depending on their specifications, boilers can operate as multi-fuel boilers.

$$\text{Cost}^{\text{Fuel}} = \sum_{b,f,t,c} (F_{b,f,t,c}^{\text{purchase}} \times \text{Pri}_f^{\text{fuel}}) \times \text{DFA} \quad (3)$$

The cost of electricity is determined from the electricity purchased from the grid minus the electricity sold (4).

$$\text{Cost}^{\text{Elec}} = \left(\sum_{t,c} E_{t,c}^{\text{purchase}} \times \text{PriElec}^{\text{purchase}} - \sum_t E_t^{\text{prodSell}} \times \text{PriElec}^{\text{sales}} \right) \times \text{DFA} \quad (4)$$

Purchased water is the amount of water required to operate the steam system plus the water to compensate losses and leaks (5). $W_{t,c}^{\text{purchase}}$ represents purchases for the water stock, while $W_{t,c}^{\text{feeding}}$ stands for the replacement of water losses throughout the duration of the project. Moreover, the price of the purchased water encompasses the treatment cost.

$$\text{Cost}^{\text{Water}} = \left(\sum_{t,c} W_{t,c}^{\text{purchase}} + \sum_{t,c} W_{t,c}^{\text{feeding}} \right) \times \text{Pri}^{\text{water}} \times \text{DFA} \quad (5)$$

The cost of the boilers (6) covers both the investment (i.e. CAPEX) and the operational cost (i.e. OPEX). The binaries $y_{b,c}^{\text{sel}}$ and $y_{b,t,c}^{\text{prod}}$ represent respectively if a boiler is selected and if it is in operation at the given time step. DFI allows the replacement of a boiler to be taken into account if its average lifetime is less than the duration of the project.

$$\text{Cost}^{\text{Boilers}} = \sum_{b,c} y_{b,c}^{\text{sel}} \times \text{CAPEX}_b \times \text{DFI}_b + \sum_{b,t,c} y_{b,t,c}^{\text{prod}} \times \text{OPEX}_b \times \text{DFA} \quad (6)$$

Similarly, if a turbine is purchased ($y_{tu}^{\text{sel}} = 1$), its cost consists of the investment and the operational cost (7).

$$\text{Cost}^{\text{Turbines}} = \sum_{tu,c} y_{tu,c}^{\text{sel}} \times (\text{CAPEX}_{tu} \times \text{DFI}_{tu} + \text{OPEX}_{tu} \times \text{DFA}) \quad (7)$$

The interconnection cost includes the fixed investment cost and the variable cost proportional to the pipe diameter. This diameter corresponds to the maximum flow-rate flowing through the interconnection. Moreover, the operating cost depends on the pipe section (8). $y_{h,c,c'}^{\text{pipe}}$ is a binary variable to select an interconnection from company c to company c' (c and c' are subsets of C, and c is different from c').

$$\begin{aligned} \text{Cost}^{\text{Pipes}} = & \sum_{h,c,c'} y_{h,c,c'}^{\text{pipe}} \times \text{CAPEX}_{\text{pipe}}^{\text{fix}} + \sum_{h,c,c'} \text{Interc}_{h,c,c'}^{\text{Diameter}} \\ & \times \text{CAPEX}_{\text{pipe}}^{\text{var}} \times \text{DFI}_{\text{pipe}} + \sum_{h,c,c'} \text{Interc}_{h,c,c'}^{\text{Diameter}} \\ & \times \text{OPEX}_{\text{pipe}} \times \text{DFA} \quad (\forall c' \neq c) \end{aligned} \quad (8)$$

For the cost of electricity production, investment and operational costs depend on the nominal installed capacity $\text{Prated}_{\text{sr}}$ (9).

$$\text{Cost}^{\text{Elec_sources}} = \sum_{\text{sr}} (\text{Prated}_{\text{sr}} \times (\text{CAPEX}_{\text{sr}} \times \text{DFI}_{\text{sr}} + \text{OPEX}_{\text{sr}} \times \text{DFA})) \quad (9)$$

The Discount Factor for Allocation of annual expenditures (DFA) (10) is used to calculate the NPV of an operating or resource cost that lasts for the duration of the project. Here n represents the number of years of the project and i is the discount rate.

$$\text{DFA} = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (10)$$

Connections in the network

The interdependence indicator is assessed in a first step, thanks to the number of interconnections (11):

$$\text{Nb}_{\text{interc}} = \sum_{h,c,c'} y_{h,c,c'}^{\text{pipe}} \quad (\forall c' \neq c) \quad (11)$$

Three other sub-criteria, detailed in section 4.2 will be studied in the multi-criteria decision making step further in this study. They are representative of the distribution of the diameter of interconnections in the network.

3.2. Constraints

The constraints of the optimization problem are the physical and thermodynamic constraints of the energy network as well as the mass and energy balances. The constraints are formulated for each element of the superstructure: steam headers, processes, water unit, fuel stocks, turbines, boilers and finally the HPS divided into electricity grid, demand and sources of electric power production and finally the interconnections.

Steam headers:

The inlet of a steam header comes from the steam produced by the boilers, from turbines outlet or from the Pressure Release Valve (PRV). The outlet streams of the steam header feed the turbines and the demand of the processes. It can also flow through the PRV to go from one header h' to another header h with a lower pressure (with h and h' subsets of steam headers H, h' having a higher-pressure level than h). In addition, a part of the steam is lost in the trap or can exit freely through the vent. Finally, steam transfers are possible from one company to another (12).

$$\sum_b S_{b,h,t,c}^{\text{prod}} + \sum_{h'} S_{h',h,t,c} + \sum_{tu} S_{h,tu,t,c}^{\text{out}} + \sum_{c'} T_{h,t,c',c}^s$$

$$= D_{h,t,c}^s + \sum_{h'} S_{h,h',t,c} + S_{h,t,c}^{trap} + S_{h,t,c}^{vent} + \sum_{tu} S_{h,tu,t,c}^{in} + \sum_{c'} T_{h,t,c,c'}^s \quad (\forall c' \neq c, \quad h < h') \quad (12)$$

Condensate losses through the traps are a percentage of the total steam flowing in the steam utility system. These steam losses include trap losses in pipes and headers as well as process trap losses (13).

$$S_{h,t,c}^{trap} = SL^h \times \left(\sum_b S_{b,h,t,c}^{prod} + \sum_{h'} S_{h',h,t,c} + \sum_{tu} S_{h,tu,t,c}^{Out} + \sum_{c'} T_{h,t,c,c'}^s \right) \times (\forall c' \neq c, \quad h < h') \quad (13)$$

Process steam demands:

The water that is released after processes use is equal to the steam demand (14).

$$D_{h,t,c}^s = W_{h,t,c} \quad (14)$$

Water unit:

The water flowing into the water unit comes from other companies, from turbines, from processes, and from water feeding to compensate water losses. The water that exits, corresponds to the water that flows to boilers, other companies and water losses (15).

$$\begin{aligned} & \sum_{c'} T_{t,c,c'}^w + \sum_{tu} W_{tu,t,c}^{Out} + \sum_h W_{h,t,c} + W_{t,c}^{feeding} \\ &= \sum_b W_{b,t,c} + W_{t,c}^{losses} + \sum_c T_{t,c,c'}^w \quad (\forall c' \neq c, \quad h < h') \end{aligned} \quad (15)$$

Water losses are a part of the water flowing into the water unit (16).

$$W_{t,c}^{losses} = WL^{wu} \times \left(\sum_{tu} W_{tu,t,c}^{Out} + \sum_h W_{h,t,c} \right) \quad (16)$$

The water feeding the losses is the sum of all the losses, at the traps but also at the vents that evacuate the excess (17).

$$W_{t,c}^{feeding} = W_{t,c}^{losses} + \sum_h (S_{h,t,c}^{trap} + S_{h,t,c}^{vent}) \quad (17)$$

The quantity of water in the system $W_{t,c}^{stock}$ corresponds to the quantity consumed by the boilers during a time step t (18).

$$W_{t,c}^{stock} = \sum_b W_{b,t,c} \quad (18)$$

Multi-period constraints:

Water stock:

The quantity of water in the network at time step t depends on the quantity of water purchased and dumped during current and previous time steps tm (t and tm are subsets of T , and tm is less than or equal to t) (19).

$$W_{t,c}^{stock} = \sum_{tm=0}^{tm} (W_{t,c}^{purchase} - W_{t,c}^{dump}) \quad (\forall tm \leq t) \quad (19)$$

Fuel stock:

The fuel stock is equal to the stock initially present plus the fuel purchased, minus the fuel consumed by the boiler. Each boiler has its own fuel stock for each fuel to which it is adapted. (20).

$$F_{b,f,t,c}^{stock} = F_{b,f,t-1,c}^{stock} + F_{b,f,t,c}^{purchase} - F_{b,f,t,c} \quad (\forall t > 0) \quad (20)$$

The fuel stock must be greater than the minimum safety stock (21).

$$F_{b,f,t,c}^{stock} \geq F_{b,f,t,c}^{stock_safety} \quad (21)$$

For its initialization, the fuel stock at the first time step is equal to the stock at the end of the previous cycle (22).

$$F_{b,f,t=0,c}^{stock} = F_{b,f,t=Nbtime,c}^{stock} \quad (22)$$

Turbines:

The amount of steam entering in the turbines, $S_{h',tu,t,c}^{in}$, has an upper and lower limit threshold (23).

$$S_{h',tu}^{min} \times y_{tu,c}^{sel} \leq S_{h',tu,t,c}^{in} \leq S_{h',tu}^{Max} \times y_{tu,c}^{sel} \quad (23)$$

An upper limit threshold is also applied to the amount of steam leaving the turbines $S_{h,tu,t,c}^{Out}$ (24). In the case that an outlet is not connected to a steam header, this threshold is fixed at zero. Thus, for a single-stage turbine, all but one of the outputs are connected to a steam header.

$$S_{h',tu}^{min} \times y_{tu,c}^{sel} \leq S_{h',tu,t,c}^{Out} \leq S_{h',tu}^{Max} \times y_{tu,c}^{sel} \quad (24)$$

In the turbines, the steam entering through higher pressure inlet h' is distributed at the outlets between the different lower pressure levels h and the condensed water (25).

$$S_{h',tu,t,c}^{in} = \sum_h S_{h,tu,t,c}^{Out} + W_{tu,t,c}^{Out} \quad (h < h') \quad (25)$$

The electricity produced depends on the efficiency of the turbines but also on the pressure of the steam at the inlet and its pressure at the outlets (26) (Agha et al., 2010).

$$E_{tu,t,c}^{turbine} = \text{Eff}_{tu} \times \left(S_{h',tu,t,c}^{in} \times h_{h'} - \sum_h S_{h,tu,t,c}^{Out} \times h_h - W_{tu,t,c}^{Out} \times h_w \right) \quad (h < h') \quad (26)$$

A proportion corresponding to ConP of the steam entering the turbine is condensed (27).

$$W_{tu,t,c}^{Out} = \text{ConP} \times S_{h',tu,t,c}^{in} \quad (27)$$

Boilers:

The steam production of the boilers is between its minimum power production $P_{b,h}^{min}$ and its maximum capacity $P_{b,h}^{Max}$ (28).

$$P_{b,h}^{min} \times y_{b,t,c}^{prod} \leq S_{b,h,t,c}^{prod} \leq P_{b,h}^{Max} \times y_{b,t,c}^{prod} \quad (28)$$

Boilers can be multi-fuel boiler (Aguilar et al., 2007), steam production depends on the enthalpy difference between the water at the inlet and the steam at the outlet, on the quantity of fuel consumed, on the calorific value of the fuel, and also on the efficiency of the boiler (29).

$$S_{b,h,t,c}^{prod} = \frac{\sum_f \text{Cal}_f \times F_{b,f,t,c} \times \text{Eff}_{b,f}}{(h_h - h_w)} \quad (29)$$

The amount of water entering the boilers corresponds to the amount of steam produced (30).

$$S_{b,h,t,c}^{prod} = W_{b,t,c} \quad (30)$$

The electricity consumed by the boilers is described by equation (31).

$$E_{b,t,c}^{boiler} = E\text{Cons}_b^{fix} \times y_{b,c}^{sel} + E\text{Cons}_b^{var} \times S_{b,t,c}^{prod} \quad (31)$$

If a boiler is started at least once then it is selected, that means purchased (32).

$$y_{b,c}^{sel} \geq y_{b,t,c}^{prod} \quad (32)$$

Hybrid Power System:

The electricity produced by the energy sources in the HPS is equal to the electricity produced by the turbines, by the AC (i.e. wind turbines) and DC (i.e. solar PV panels) sources multiplied by the efficiency of the converter (33).

$$E_t^{prodSources} = \sum_{sr \in sr_{AC}} E_{sr,t}^{prod} + \sum_{tu, c} E_{tu,t,c}^{turbine} + \sum_{sr \in sr_{DC}} E_{sr,t}^{prod} \times \text{Eff}_{inv} \quad (33)$$

The electricity produced on-site is distributed between the local consumption of the industrial site and the potential sale to the external grid (34).

$$E_t^{\text{prodSources}} = E_t^{\text{prodCons}} + E_t^{\text{prodSell}} \quad (34)$$

The electricity consumed by the different industries is produced by the installed sources or purchased from the grid (35).

$$\sum_c D_{t,c}^e = E_t^{\text{prodCons}} + E_t^{\text{purchase}} \quad (35)$$

The production of solar PV panels and wind turbines depends on the installed capacity and the load factor during the time period (36)(37).

$$E_{\text{so},t}^{\text{prod}} = P_{\text{so}}^{\text{rated}} \times \text{LoadFactor}_{\text{so},t} \quad (36)$$

$$E_{\text{wi},t}^{\text{prod}} = P_{\text{wi}}^{\text{rated}} \times \text{LoadFactor}_{\text{wi},t} \quad (37)$$

The maximum power that can be installed for an electrical source is limited, this constraint depends on the resource available on the site (38).

$$P_{\text{sr}}^{\text{rated}} \leq \text{MaxInstall}_{\text{sr}} \quad (38)$$

The electric power production of the turbines is also limited depending on the possibility of installation on site (39).

$$E_{\text{tu},n,t,c}^{\text{turbine}} \leq \text{MaxEproTur} \quad (39)$$

Interconnection pipes:

An exchange of steam, $T_{h,t,c,c'}$, between industries is only possible if the interconnection exists ($y_{h,c,c'}^{\text{pipe}} = 1$) (40). M is a big positive value used to satisfy the existence constraint of a pipe.

$$y_{h,c,c'}^{\text{pipe}} / M \leq T_{h,t,c,c'}^s \leq y_{h,c,c'}^{\text{pipe}} \times M (\forall c' \neq c) \quad (40)$$

If an interconnection exists, its diameter must be larger than the threshold, $\text{minInter}_{\text{Threshold}}^{\text{Diameter}}$, that represents the minimum technically feasible section of pipes (41).

$$\text{Inter}_{h,c,c'}^{\text{Diameter}} \geq y_{h,c,c'}^{\text{pipe}} \times \text{minInter}_{\text{Threshold}}^{\text{Diameter}} (\forall c' \neq c) \quad (41)$$

From the linear behaviour of the systems of the energy network and the use of binaries to select the designed facilities, this model is a MILP solved with CPLEX®.

4. Resolution procedure

4.1. Optimization procedure

While taking into account an economic criterion and the interdependence of companies through the number of interconnections, the optimization model can be hard to solve, especially when the industrial park considered is large.

In this part of the study, a classic MO optimization method (i.e. epsilon-constraint) has been tested in order to justify the development of the optimization procedure detailed further. Epsilon-constraint (Marglin, 1967) method is a lexicographic approach that consists in minimizing one criterion, while slicing the research space of the other criteria using constraints and finally finding a solution for each slice. In this case, the number of interconnections is settled as a constraint and NPV is minimized.

Applied on the case study detailed hereafter (15 companies, specificities described in section 5), this method could not achieve an optimal solution due to an important combinatory of the MILP problem. Indeed, during the optimization stage of CPLEX® solver, branch-and-cut tree of possibilities size is exceeding the available computing memory. With this formulation, the constraint on the super-variables used by the epsilon-constraint method to set the number of selected interconnections is important. This remark is

particularly relevant for super-variables, that is to say, bottleneck variables for the calculation time which has been identified as the binary variable to select interconnections. Indeed, when super-variables are binaries, it can be difficult for the solver to handle them appropriately and to reach convergence. The number of these variables is increasing exponentially with the number of companies in the network. Hence, the principle of the procedure is to reduce the number of super-variables by designing the network step by step with a limited number of interconnections. This approach is then intended to provide results close to the global optimum while ensuring shorter calculation time. Consequently, because this problem cannot be solved by classical MO methods (i.e. epsilon-constraint) an optimization procedure has been developed to overcome these difficulties and its schematic representation is presented in Fig. 3. The different steps achieved and their motivations are detailed hereafter.

The proposed method consists then in an iterative procedure, starting from the economic minimum solution and obtaining a solution for each number of interconnections until there is no more interconnection, the minimum for interdependence indicator being reached. Several steps are carried out: the first consists in a mono-objective optimization by minimizing NPV. Then, a multiobjective optimization considering NPV and interconnection number is achieved. This step leads to build the Pareto front which is obtained by using an epsilon-constraint approach for two objective functions. After obtaining all the optimal solutions, the multicriteria analysis is conducted through AHP method to evaluate the interdependence of the different companies in the EIP by using 4 different criteria:

- 1st step of the procedure

During the procedure, the first step consists in a mono-objective optimization to obtain the optimal design by minimizing the economic criterion (1). The result of this step is the design of the network that minimizes the cost so it involves usually a lot of interdependencies.

- 2nd step of the procedure

From the solution obtained during the first step, a limited list of interconnections available for the next step of the procedure is determined. This is done by setting the selection binary of the unused interconnection (the corresponding flow is equal to 0) as a parameter equal to 0 (i.e. the interconnection is not selected). The number of the selected interconnections is now equal to n .

Another important parameter is also constrained during this step: the diameter of an interconnection (directly dependant of the exchanged flow). It is considered as an indicator of the interdependence between companies. In this way, a large flow between companies corresponds to a high degree of interdependence. The maximum threshold for the diameter of interconnections ($\text{MaxInter}_{\text{Threshold}}^{\text{Diameter}}$) is constrained to be inferior or equal to the value of the maximum diameter of interconnections present in the result of the first step (42).

$$\text{Inter}_{h,c,c'}^{\text{Diameter}} \leq y_{h,c,c'}^{\text{pipe}} \times \text{MaxInter}_{\text{Threshold}}^{\text{Diameter}} (\forall c' \neq c) \quad (42)$$

Afterwards, the procedure is iterative. At each iteration, the principle is to reduce by one ($n=n-1$) the number of interconnections in the designed network and to select n interconnections among the initial limited list. Then the problem is economically optimized. As shown in Fig. 4, throughout the resolution procedure, while removing interconnections, this constraint allows to limit the maximum diameter of interconnections and therefore the average diameter. Whereas without this constraint, interconnection diameter tends to increase because production flows are distributed in fewer connections.

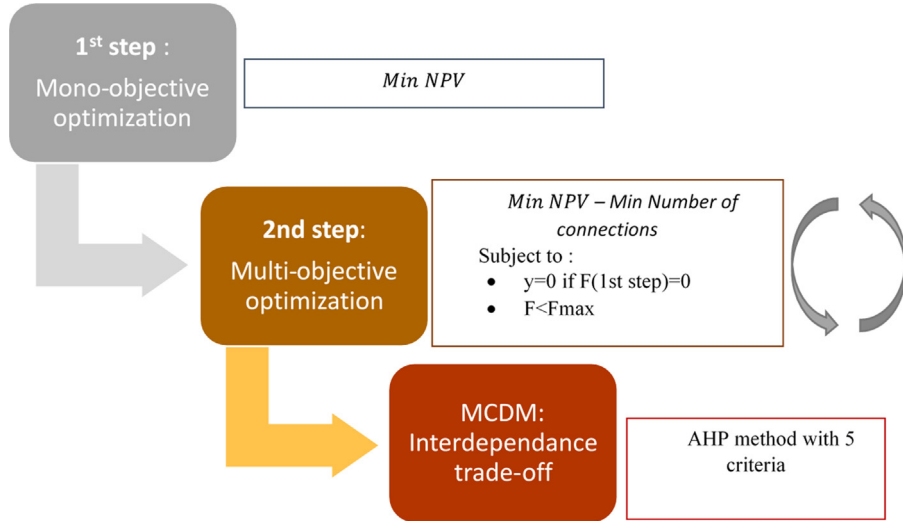


Fig. 3. Schematic representation of the procedure.

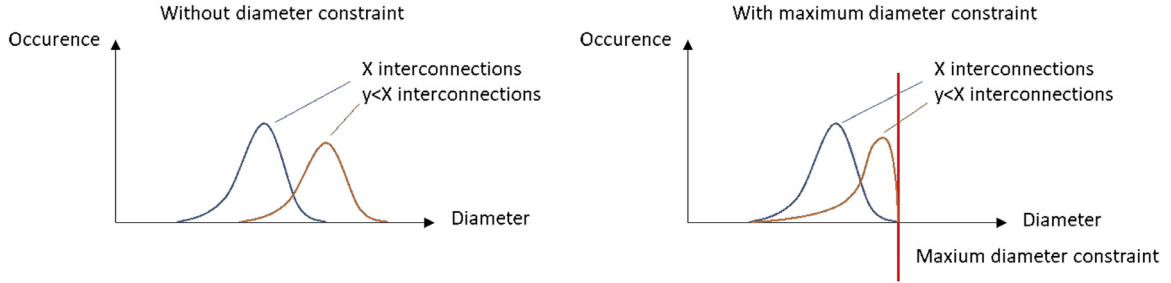


Fig. 4. Influence of the maximum diameter constraint throughout the resolution procedure.

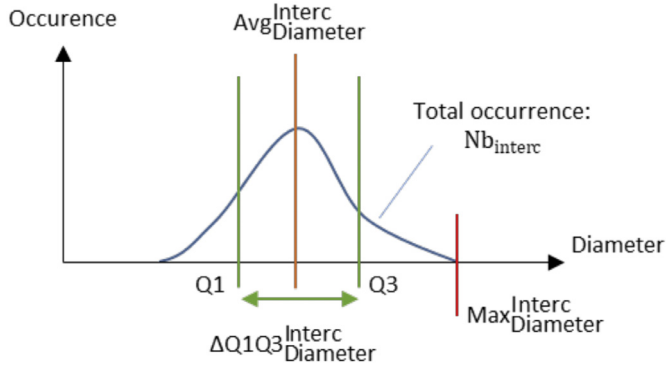


Fig. 5. Figurative case study representing the distribution of interconnections and interdependence sub-criteria.

4.2. Multi-Criteria Decision Making (MCDM): Interdependence trade-off

From the MO optimization previously proposed, a set of optimal solutions is built, near the Pareto front. Among these solutions, an innovative evaluation of interdependence is developed for choosing a solution.

To evaluate flow exchanges over the entire network, the distribution of the diameter of the interconnections is taken into account. As an illustration, Fig. 5 presents the defined interdependence trade-off subdivided into four sub-indicators:

- The number of interconnections (Nb_{interc}): even if an EIP seeks to enhance collaboration, inter-companies exchanges will be used because they allow to minimize the costs. This indicator has to be minimized in order to limit the interdependencies which are a bottleneck to participate into an EIP. In addition, the more interconnections there are in the network, the more management constraints it implies for companies. The number of interconnections is also linked to topological constraints and therefore to the feasibility of the exchange network (Rubio-Castro et al., 2011).
- The average diameter of interconnections ($Avg_{Diameter}^{Interc}$): is considered to minimize flows over the whole network (low flow interconnections being considered as connections with fewer interdependencies). Thus, while interconnection allows economic synergetic advantage, the final goal of this approach is to give priority to interconnections with low flows by minimizing their average flows but with high economic gain by minimizing global cost.
- The maximum diameter of interconnections ($Max_{Diameter}^{Interc}$), is minimized to avoid an interconnection with a large flow-rate relatively to others. That is to say, an interconnection with a strong dependence, because if this interconnection is removed it has a strong impact on the network.
- The difference between the first and third quartile of interconnection diameters ($\Delta Q1Q3_{Diameter}^{Interc}$), to be minimized, with the aim of grouping interconnection diameters. This allows a fair distribution of the risks incurred by companies by avoiding that some companies are left with small interconnection flows and others with large ones.

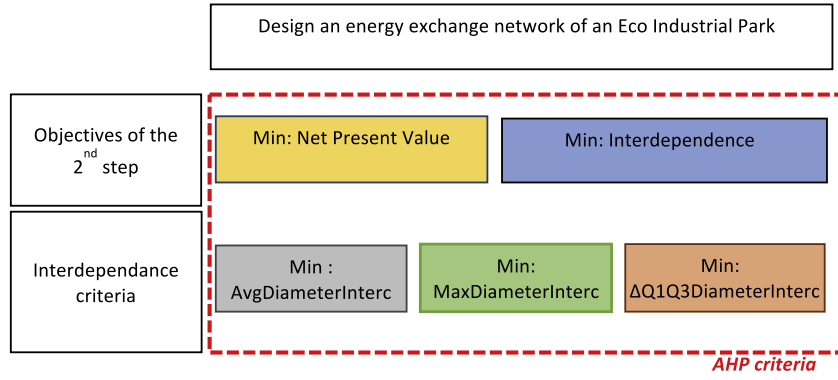


Fig. 6. Developed AHP structure for the design of the energy exchange network of an EIP.

In order to evaluate all the solutions obtained at the end of the resolution procedure, MCDM tools can be used. Among the earliest and the most basic MCDM tools is the weighted sum method, also called the decision matrix approach (Bhushan and Rai, 2007). One of the main biases of this method is the use of criteria for which units cannot be added in a balanced way. One of the criteria may take precedence over the others. To overcome this, the weighted-product method is a dimensionless method using the same principle, except that each term is normalized. Another bias of these methods is the subjectivity and the prejudice in assigning the weights that cannot be eliminated or assessed using this method. Addressing this issue, the Analytical Hierarchy Process (AHP) developed by (Saaty, 2002) is using the weighted-product method but it allows to organise and prioritize the criteria in a structured way by giving a weight between each pair of criteria. For this reason, it can help assign weights with several decision-makers. In the meantime, the consistency of these weights is checked, validating their choice in order to assess each solution and select the optimal one (Forman and Gass, 2001). Nevertheless, AHP is the method chosen because in this MO study, prioritizing the criteria between complexity and cost but also select and verify the relevance of weights are the major issues.

AHP detailed procedure is described hereafter:

- Step 1: as presented in Fig. 6, the problem is decomposed into goal, criteria and sub-criteria;
- Step 2: decision-makers or experts set a weight for each pair of criteria or sub-criteria;
- Step 3: these weights are plotted into a comparison pairwise square matrix where each criterion is represented by a line and a column. The (i,j) value representing the pairwise weight between the criteria in the i^{th} row and the one in the j^{th} column;
- Step 4: previous weights are normalized in the standardized matrix and a global weight for each criterion is calculated from the sum of previous pairwise normalized weight divided by the number of criteria;
- Step 5: the consistency of the matrix is assessed using the developed consistency index (Saaty, 2002). This indicator assesses whether there is no inconsistent weight assignment due to transitivity. For example, if criterion weight A is higher than B and B is higher than C, then A should be higher than C. Saaty suggests a value higher than 0.1 for this index. If it is lower it is recommended to reconsider pairwise comparison;
- Step 6: a weighted sum is realized for each solution based on the normalized value of criterion multiplied by the weight obtained with AHP method. A ranking between the solutions is then obtained, with the solutions with the highest scores being the best.

Table 1

Steam properties in the Yeosu EIP of the case study (Kim et al., 2010)

Properties	VHP	HP	MP	LP
Temperature (°C)	525	370	270	195
Pressure (atm)	121.5	40.0	15.0	3.5
Enthalpy (kJ/kg)	3422	3156	2982	2858

Thus, Fig. 6 shows the AHP structure developed to design the energy exchange network of an EIP. The two objective functions of the optimization step are NPV and interdependence. Finally, the solutions are compared and analyzed using a normalized weighted sum with the different indicators previously developed, the solution with the highest score is the selected one for the designed energy network.

5. Case study: results and discussion

5.1. Case study description

The procedure previously developed is applied on a case study composed of 15 industries and four operating periods are taken into account, one per season. The data are taken from Yeosu industrial park in China (Kim et al. (2010)).

Steam and power demands are provided in Appendix A1. Four pressure levels are taken into account for steam: Very High Pressure (VHP), High Pressure (HP), Medium Pressure (MP) and Low Pressure (LP), the pressure levels are detailed in Table 1.

Steam is produced by natural gas boilers installed in companies. Nine different technologies are available: VHP, HP or MP and for each one, maximum capacity can be settled at 50 t/h, 100 t/h or 500 t/h. Boiler capacity range is between 50 and 100 % of its maximum power because within its range boiler has a relatively constant efficiency (Aguilar et al., 2007) and in seasonal operation, it would be a significant loss to operate the boiler at a low capacity, which means at a lower efficiency level.

The VHP cannot be exchanged using interconnections due to the high steam pressure and to the technical constraints involved (43). For this reason, the interconnections only concern HP, MP and LP steam.

$$y_{h=vhp'',c,c'}^{\text{pipe}} = 0 \quad (43)$$

The electric power sources are wind turbines and solar PV panels, corresponding load factor per season are given in Table 2. These load factors are estimated for a potential location in France, from average climate conditions of previous years (RTE - Réseau de transport d'électricité, 2018). By connecting to the external power grid, power can be bought and excess production can be sold. Turbines are multi-stage and three technologies can be selected (i.e.

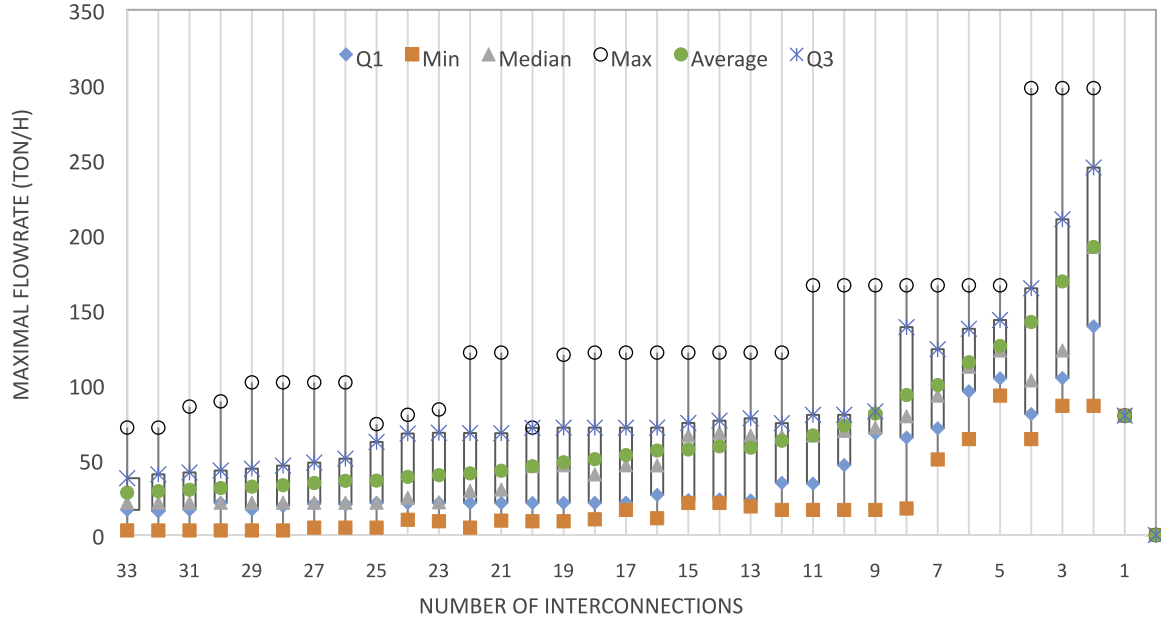


Fig. 7. Repartition of the flowrates in the network with the method without constraint.

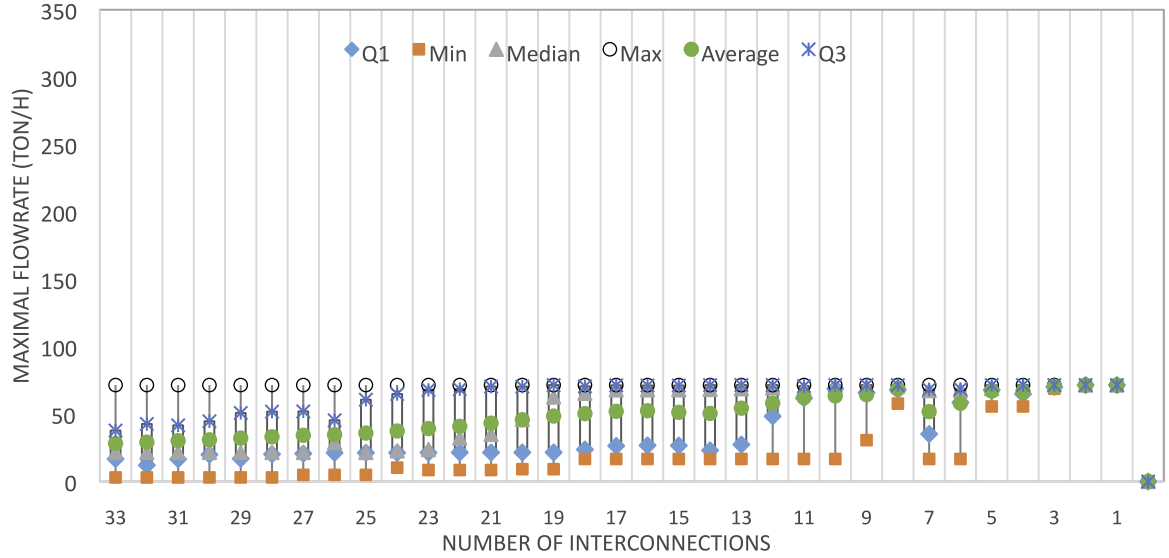


Fig. 8. Results for the method developed with constraint.

Table 2
Load factors per season for solar PV and wind turbines

	Winter	Spring	Summer	Autumn
Wind Load Factor ($\text{LoadFactor}_{wi,t}$)	0.317	0.171	0.145	0.247
Solar PV Load Factor ($\text{LoadFactor}_{so,t}$)	0.1	0.2	0.195	0.093

500 kW, 3 MW, and 15 MW). Price for natural gas is set at 280 €/ton and electricity purchased price is fixed at 0.07€/kWh while its sale price is 0.1€/kWh.

The mathematical model formulated includes 7864 constraints, 7281 variables including 1328 binary variables.

5.2. Analysis of the influence of maximum diameter constraint

This study aims at discussing the influence of maximum diameter constraint introduced in the optimization procedure (second

step of the procedure). The procedure developed is compared to a second method without the constraint on the maximum diameter of the interconnections. Procedures are referred to “method with constraint” (i.e. developed procedure) and “method without constraint” in the following.

The distribution of all the exchanges in the network obtained for each solution is shown in Figs. 7 and 8 for both methods (without and with constraint, respectively). Results are presented as box plots for each solution including values of the minimum, maximum and the average flow.

Obtained solutions are presented from the point of the first step, the mono-objective economic minimum (i.e. 33 interconnections). Then, according to the procedure previously introduced, from the initial list of selected interconnections, at each iteration, a solution is obtained by reducing the number of interconnections in the designed network until there are no more interconnections (i.e. stand-alone mode) (Fig. 9).

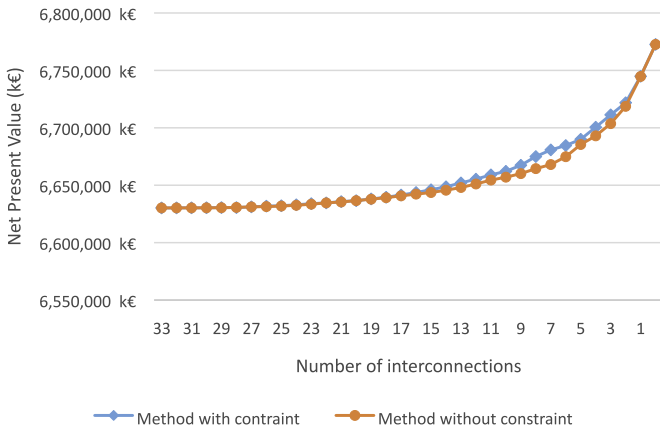


Fig. 9. Pareto front obtained with both methods (with and without constraint).

One can observe that flow rates increases while the number of interconnections decreases with the method without constraint. Regarding the maximum diameter, it goes from the initial point with 71.6 ton/h to 297.8 ton/h (i.e. with 4 interconnections). The average exchanged flow-rate also increases from 28.2 ton/h to 192 ton/h (i.e. with 2 interconnections). Finally, the difference between Q1 and Q3 is increasing in an irregularly way, from the initial point with a difference of 26.7 ton/h to the point with 3 interconnections, with a difference of 105.9 ton/h. At some points, this difference is smaller than the initial point (12.9 ton/h with 20 and 19 interconnections and 14.7 ton/h with 9 interconnections). It should be noted that the point with one interconnection is different from these observations, indeed, the flows decrease at this point.

With respect to the method with constraint, the maximum flow-rate limited to the value of the initial point, i.e. 71.6 ton/h remains constant throughout the resolution procedure. The average value increases while removing interconnections from 28.2 ton/h to the maximum flow-rate of 71.6 ton/h (with 3 interconnections) and the difference between Q1 and Q3 decreases.

The increase of diameters of interconnections while reducing the number of interconnections is explained because the same amount produced by wide cost-effective boilers or turbines needs to be shared with fewer interconnections having, therefore, a bigger flow. In regards to these results, main evidence is that exchanged flows are widely reduced with the method with constraint in comparison to the method without constraint. Therefore, the interdependence of designed solutions is also reduced with the constrained method. Nevertheless, the economic criterion of solutions for both method needs to be analysed to conclude. Comparison of NPV according to the number of interconnections for both methods is given in Figure .

The evolution profiles of the NPV curves for both methods are similar, i.e. the cost increases with the decrease in the number of interconnections. However, from 15 to 2 interconnections, the method with constraint achieve a slight decline in economic performance with 0.2% more expensive solutions. A main postulate of this developed procedure is that the counterpart of the constraint limiting the diameter is that best economic solutions cannot be achieved with few interconnections possibilities, nevertheless, interdependence is highly improved.

In conclusion of this section, the developed resolution procedure has proven to be able to solve large MILP network design problems. Furthermore, using this approach, the constraint limiting the interconnection diameter allows producing solutions with better value for interdependence criterion while slightly increasing the cost. This means that this procedure provides exchange networks with the most interesting interconnections according to industrials, i.e. interconnections with low interdependencies and high economic gain. The continuation of this study analyses the obtained results on this case study.

5.3. Design of energy exchange network

This section gives an analysis of the evolution of the exchange network designed throughout the procedure, from the EIP with maximum interdependence (i.e. maximum interconnections) to the stand-alone situation. The selected optimal solution is then described.

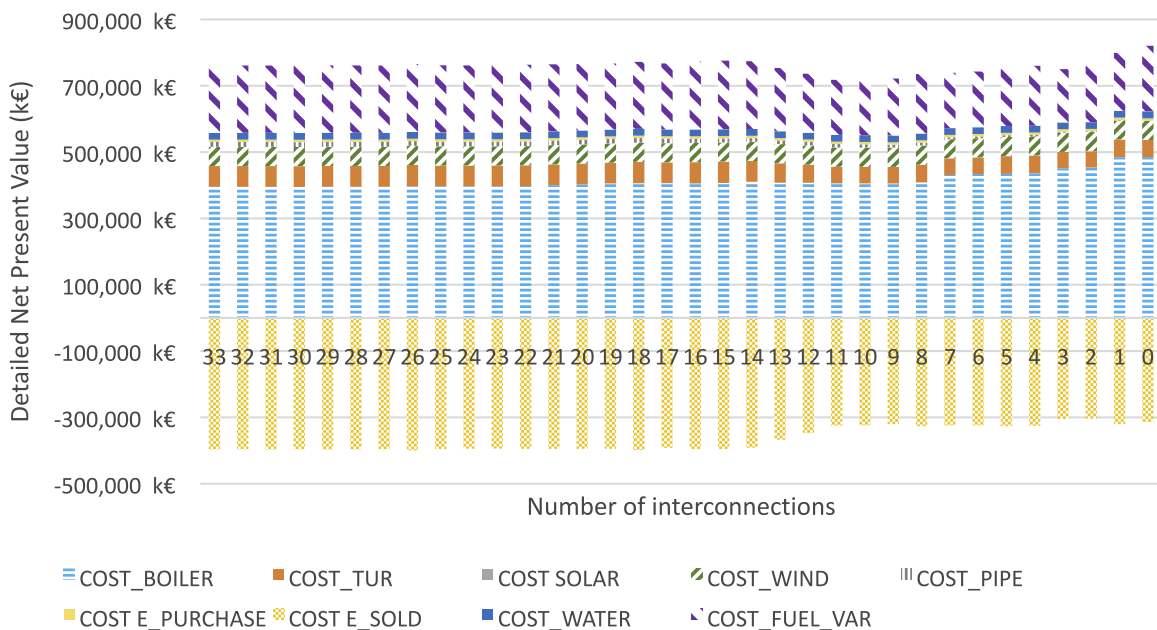


Fig. 10. Detailed cost according to the number of interconnections for the set of obtained solutions.

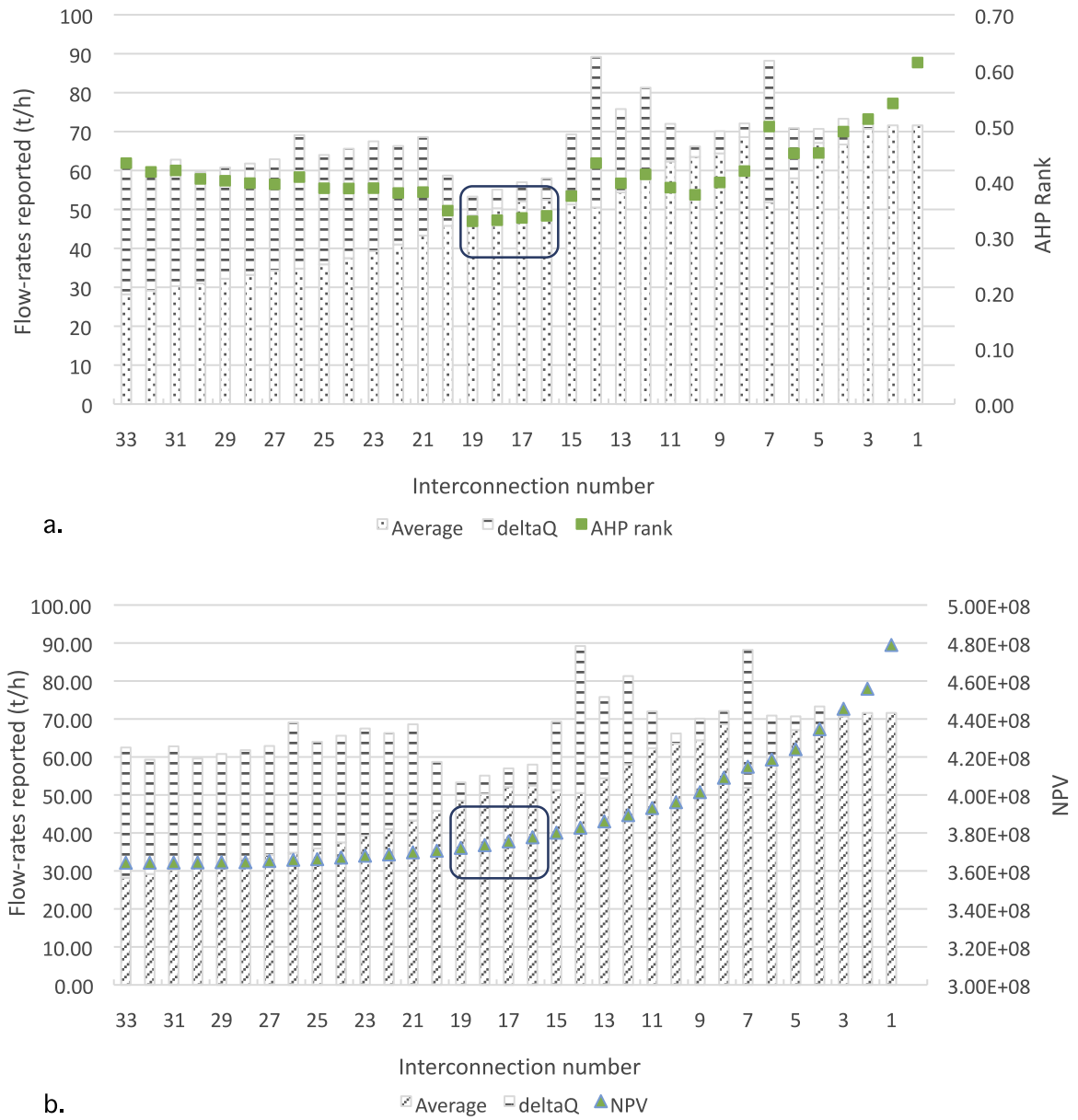


Fig. 11. Values of criteria and AHP rank (a) or NPV (b) for each solution of the developed procedure.

5.3.1. Technology selection analysis

The evolution of the design of the network according to the number of interconnections is given in Fig. 10. For each solution, the stacked bar chart represents the costs for boilers, pipes, steam turbines, wind turbines and the cost for resources, i.e. fuel, water, electricity purchased and sold. For more clarity in the graph, only the variable part of the fuel cost is shown. Indeed, a part of the fuel costs does not depend on the design choice. This part corresponds to the fuel used to produce steam to meet demand if it is produced with the most energy-efficient technology. In addition, over a 20-years project, operating costs, and more particularly fuel costs, represent the bulk of the cost. Thus, the sum of these detailed costs is represented as the Global Cost curve.

NPV for wind turbines is then of 57 891K€ with 30 MW installed, it is the maximum limit for this technology. The installed power reached the upper limit because it is profitable. Besides, the installed power for solar panels is null, this technology has not been selected. Indeed, it is not profitable with this case study that is not included subsidies. Water and electricity purchased are also

relatively constant. Moreover, naturally, the cost of the pipes reduces with the number of pipes. The main variations as the number of interconnections decreases are observed for the cost of boilers which increases while the cost of steam turbines decreases.

This last observation led to the following explanation of the operation of the exchange network. First of all, thanks to pipes, boilers are shared, and large boilers are selected (i.e. 500 t/h of production capacity). Whereas, without these pipes, large boilers are not profitable to supply a single company because they do not have enough steam demand to supply. According to the turbines, the logic is similar, producing power thanks to turbines is particularly profitable to expand steam from a higher level of pressure to a lower one, and therefore to consume the outlet steam in processes. In the absence of interconnections, this is not enough steam demand in stand-alone companies to be supplied by a turbine.

To go further on the understanding of the coupling of heat and power networks, these interpretations show that the energy production of turbines is strongly linked to steam demand and boiler production capacity. In addition to that, pilotable turbine produc-

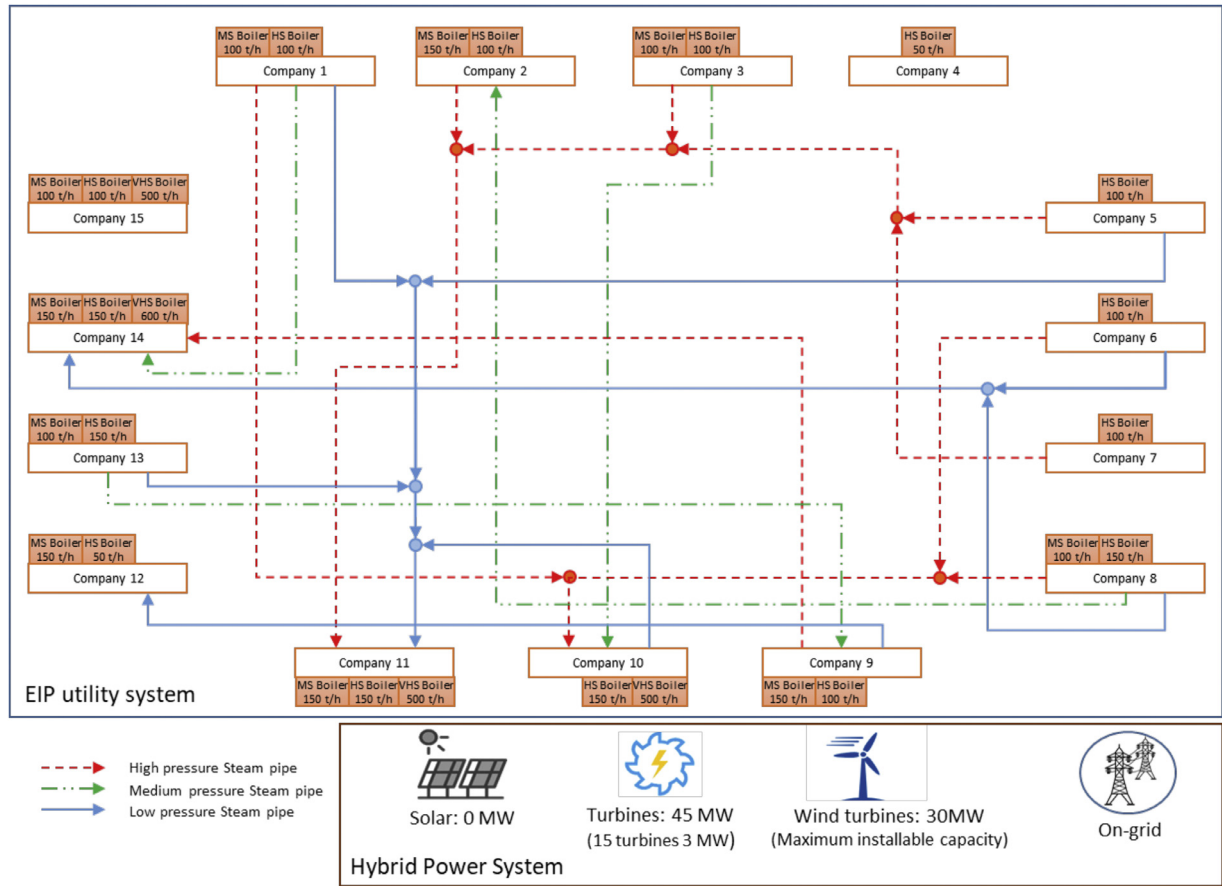


Fig. 12. Utility system and HPS of the final designed solution

tion could complete the intermittent RE production to supply the demand. Finally, with regard to the HPS, this model is based on an off-grid model, in which case the production of RE is linked to the prices of the electricity grid, as the lack and surplus of production can be bought and sold respectively.

5.3.2. Exchange network design: using MCDM tool

Henceforth, once the different solutions of the developed MO optimization method have been obtained, the continuation of the method consists in using the MCDM tool AHP to determine the optimal final solution. This process consists of selecting a weight for each pair of criteria. In this case, the weights were chosen to be equally balanced between the NPV and the interdependence. Considering the NPV, the criterion applied in this case study is the percentage of loss of solutions in relation to the economic minimum (i.e. the initial point of the procedure). This choice is made in order to accentuate the NPV criteria difference that is originally thin between EIP and standalone mode. Indeed, a particularity of utility systems is that on a 20 years duration project, the operational cost tends to take over the investment costs. Whereas in this case study, the different technologies for natural gas boilers implanted have a thin operational cost difference. To continue, the criteria are normalized using linear max technic, which has been demonstrated to be the most appropriate for AHP (Vafaei et al., 2017).

The AHP method led to a weight of 18.9% for the number of interconnections, 49% for NPV criteria and finally 10.7% for the maximum and the average diameter of interconnections and for the difference between Q1 and Q3. The aim was to attribute equivalent weights for each level of Fig. 6: NPV and the package of interdependence indicators. At the lower level, for interdependence

indicators, all the criteria have the same weight. The results of the AHP method for pairwise comparison are summed up in table 3.

This approach remains available for different strategies as weights could be changed accordingly to the preferences of the decision maker. Indeed, in this case study, equivalent weights have been attributed to the different classes of criteria but it could be adjusted as a function of the preferred criterion, if this criterion is identified. In this case, the consistency ratio which evaluates the absence of contradictions in the pairwise comparison is 1.3%. According to the indications of (Saaty 2002), it is validating the consistency of weight allocation, because it is lower than 10%. Then, these weights were applied to the set of solutions obtained using the developed procedure. Thus, Fig. 11 presents the value of criteria for each solution obtained and the raking attributed to each one with AHP.

Therefore, the optimal solution selected using AHP is the one with 19 interconnections, its NPV is 0.12% higher than the minimum economic solution, while the average flowrate is 48.5 ton/h compared to 28.2 ton/h. As described earlier, the maximum flowrate is equivalent to the limited constraint (i.e. 71.6 ton/h). Lastly, the difference between Q1 and Q3 is significantly reduced to the value of 4.8 ton/h from 34.3 ton/h for the initial point. This means that most interconnections are close in diameter in the selected solution and therefore that the interdependence implied by most of the interconnections is relatively balanced.

The corresponding designed network is provided below in Fig. 12. For the sake of clarity, some interconnections to the same company have been linked, but they are indeed different interconnections. It is to note that with this model companies can operate in stand-alone mode, as company 4 does. With regard to the HPS,

Table 3
Standardized matrix for AHP method.

	NPV	Nb Interc	Avg Interc Diam.	Max Interc Diam.	$\Delta Q1Q3$ Interc Diam.	Weight
NPV	0,50	0,62	0,44	0,44	0,44	49,0%
Nb Interc	0,13	0,15	0,22	0,22	0,22	18,9%
Avg Interc Diam.	0,13	0,08	0,11	0,11	0,11	10,7%
Max Interc Diam.	0,13	0,08	0,11	0,11	0,11	10,7%
$\Delta Q1Q3$ Interc Diam.	0,13	0,08	0,11	0,11	0,11	10,7%

the solar PV has not been selected, while steam turbines and wind turbines are set at their maximum capacity. In this case of an on-grid HPS, the selection of electrical sources is due to their profitability, which depends on the purchase and sale price of external electricity (Mousqué et al., 2019).

In conclusion to this section on the results, these analyses show the importance of using a MO method with complex systems such as EIP exchange networks. Indeed, including interdependence indicator, the designed solution is significantly different from the mono-objective solution on cost.

6. Conclusion

A model to optimally design an energy exchange network of an EIP, coupling a utility system carrying steam and an HPS providing electric power has been presented. It allows to size energy sources for the utility system (i.e. boilers and turbines) and to size renewable energy sources such as solar PV panels and wind turbines. It optimizes the planning to supply the energy demand as well as the resources purchase to operate the energy network (i.e. fuels, water to produce the steam and outsourced electric power) with data varying over periods. The optimization is done through an economic criterion (i.e. NPV) and an innovative interdependence indicator.

This interdependence indicator is representative to company stakes when engaging into EIP, i.e. they want to keep their independence to maintain control over their own industrial site.

The objectives of this MO optimization procedure are then to provide exchange networks with maximum economic gain and minimum dependence between companies and therefore risks to engage. This indicator is taking into account the number of interconnections and the whole exchange flows in the network by measuring their distribution.

Finally, an iterative procedure for the optimization of the interdependence of companies and for solving large MILP problems has been provided. This procedure consists of obtaining a set of solutions by removing one interconnection from the minimum economic solution to the minimum of interdependence (i.e. stand-alone mode). In order to contain the interdependence sub-criteria of flow distribution in the whole network, the principle is to fix a maximum diameter of interconnection constraint. The final solution is then selected using the AHP tool.

As a result, this developed resolution procedure has solved a large case study of 15 companies taken from Yeosu EIP while classical optimization method could not solve it (i.e. lexicographic method). Results show that this method provides significantly improved results in terms of interdependence with a slightly higher cost.

Perspectives for this research work that addresses the interdependence of companies were identified as the integration of a flexibility indicator (i.e. the ability to withstand flow variations) as well as a resilient indicator (i.e. the capacity to support the departure of a company from the network with minimal impact). Furthermore, this study focuses on the whole EIP optimization, next

studies could consider individual plant objectives, for this purpose, among methods, game theory is particularly suitable.

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.

CRediT authorship contribution statement

Florent Mousqué: Methodology, Formal analysis, Writing - original draft, Methodology. **Marianne Boix:** Investigation, Writing - review & editing. **Ludovic Montastruc:** Formal analysis, Validation, Formal analysis. **Serge Domenech:** Supervision, Supervision. **Stéphane Négny:** Supervision, Data curation, Writing - review & editing, Supervision.

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