The energy Extended Resource Task Network, a general formalism for the modeling of production systems:Application to waste heat valorization

Raphaële Théry Hétreux*, Gilles Hétreux, Pascal Floquet, Alexandre Leclercq

Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France

A R T I C L E I N F O

Keywords:
Energy planning
Waste heat
MNLP optimization
District heating System

A B S T R A C T

While real time control of process plays an important role, it is now increasingly necessary to forecast and plan production systems in order to be energy efficient and to ensure a balance between energy demand and production. In this context, a short term planning approach of energy supply chain is presented in this paper. Because of the presence of enthalpy balance in the optimization model, the core of this system is based on the formulation and the resolution of a Mixed Integer Non Linear Program ming (*MINLP*) model. To facilitate the instantiation of this optimization model and its adaptation to different kinds of value chain, a specific graphical formalism named Energy Extended Resource Task Network (*EERTN*) is exploited. This generic framework makes it possible to model in an unambiguous way the material and energy flows passing through any type of production system. In addition, it takes into account the influence of temperature on the physicochemical phenomena involved in the process.

To illustrate the potentiality of this modeling framework, it is applied to a case study aimed at carrying out the operational planning and performance evaluation of a *waste heat* recovery chain. This system consists, on the one hand of an industrial unit whose heat requirements are provided by a steam utility plant, and on the other hand, of a district heating network (*DHN*). In this study, the problem consists to optimally plan the energy use of the district heating network by recovering the flus gas (the waste heat) from the industrial site's power plant. The planning system leads to a significant reduction in the primary fuel consumption of the overall system and an efficient exploitation of the waste heat generated by the industrial site.

1. Introduction — State of the art

To achieve the European Union climate and energy objectives, a transition towards a future sustainable energy system is needed. The integration of the huge potential of industrial waste heat re covery into the mix of available energies represents a main op portunity to accomplish these goals. According to data available in 2017, heating and cooling account for half of the energy con sumption in the European Union [1]. From which, 45% is used in the residential sector, 36% in industry and 18% in services. Fig. 1 is a chart adapted from a graph proposed by the French Environment & Energy Management Agency ADEME [2]. It displays the future of thermal energy flows encountered at an industrial site in the form of a Sankey diagram and thus highlights the different modes that can contribute to energy optimization of industrial systems. As input to this diagram is represented the total energy consumed by an industrial site, energy often supplied by fossil fuels for example. Some of this energy is considered as heat that is useful to the system: it is the part of the thermal energy directly used for pro duction purposes. The other, not insignificant, part of the energy supplied is considered as waste heat (see Fig. 25).

According to Ref. [2], when a production process is in operation or the thermal energy produced by the energy supplied is not used in its entirety, part of the heat is inevitably rejected. It is because of this inevitability that we are talking about fatal heat, also commonly referred to as *waste heat*. However, this term may be confused because, today, there are various levers that allow recovering part of this *waste heat*. So, it's only if it's not recovered that it's definitely lost. As shown in Fig. 1, there are several ways to

* Corresponding author.
E-mail addresses: raphaele.thery@ensiacet.fr (R. Théry Hétreux), gilles.hetreux@ensiacet.fr (G. Hétreux), pascal.floquet@ensiacet.fr (P. Floquet), alexandre.leclercq@ensiacet.fr (A. Leclercq).

https://doi.org/10.1016/j.energy.2020.118970

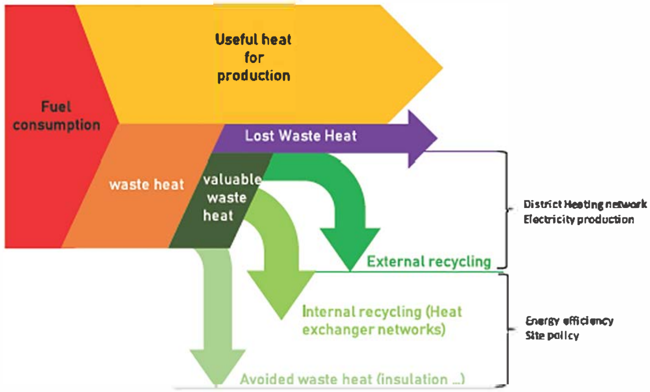


Fig. 1. Various ways to optimize the energy of an industrial system (adapted from Ref. [2]).

reduce the overall consumption and limit the heat flow definitively lost:

- Reduce the useful heat flow for production,
- Avoid unnecessarily generating waste heat,
- Enhance the waste heat produced internally
- Enhance the waste heat produced externally

Mostly available at low temperatures, its valuation remains delicate. The most common way of exploiting this energy is the integration of the process in a more complex system such as an eco park or a district heat network and/or its coupling with the elec tricity network, giving rise to a real supply chain of waste heat. The implementation of this kind of integrated system requires solving two major scientific challenges:

1. On the one hand, the *design of the supply chain* i.e. the definition of the various links from the supplier of the waste heat to its end user (storage, recovery, transport ...),
2. On the other hand, the evaluation and the planning of this system in a dynamic and real context.

This paper deals with this second aspect and proposes a general modeling framework used to instantiate a short-term planning optimization model applied to a waste heat supply chain in an industrial context. The remainder of this paper is organized as follows. A brief state of the art on energy planning are presented in section 2. Section 3 describes the waste heat supply chain used to illustrate the potential of the *Energy Extended Resource Task Network* (EERTN) modeling formalism and the asso ciated optimization model. Section 4 explains extensively the se mantic of EERTN while the constraints of the Mixed Integer Non Linear Programming (MINLP) model are rejected in a supplemen tary materials. The principles of the modeling procedure are set out in section 5. Finally, sections 6 and 7 discuss the results obtained for two waste heat recovery chain topologies (with or without heat storage).

2. State of the art on energy recovery and planning

Our work is relied on 4 recent review papers ([3–6]). In the older one (2014), Prasad et al. [3] define the activity of energy planning as a roadmap for meeting the energy needs of a nation and consider multiple factors such as technology, economy, envi ronment, and society that can impact the energy issues. After a general definition of energy planning, they discussed the terms of energy planning (short, mid and long term). Focused on energy planning models, they split into three families: econometric, simulation and optimization models. The available frameworks and computer aided tools are then listed and a special attention is paid to geographical levels (global, national, regional) of energy plan ning. Huang et al. [4] focused on the Community Energy planning (*CEP*), i.e. the community master plan, the community regulatory plan and the community site Plan. They presented top down and bottom up approaches. After surveying the methods and tools that have contributed to *CEP*, the framework of computer tools for community energy system simulation and design was outlined. The functions (energy demand prediction, renewable energy resource assessment and whole community energy system optimization) and characteristics of these computer tools for community energy system were then listed and compared. Huang et al. [4] finally pointed out the shortage of available tools for determining energy related indictors. The paper of Shankar et al. [5] reviewed the major developments in the area of modeling and simulation of energy systems. They proposed two ways to categorize the diverse con tributions. The first one is according to the modeling approach (computational, mathematical, and physical models) and the sec ond one is according to field namely Process Systems Engineering (*PSE*) and Energy Economics (*EE*). Fig. 3 of this article tries to classify the energy system models according to discipline and level of technological aggregation. There are five levels of technological aggregation (unit operation, plant, supply chain, energy sector and entire economy) and three classical decision making levels (oper ational, tactical and strategic). From this graph, *PSE* works are essentially found in the three first levels of technology aggregates and the two (even three) first levels of decision making (bottom left corner of the chart), whereas *EE* works are found in the two last levels of technology and decision making axes (top right corner of the chart). They claimed they provided a holistic picture of the energy system in a wider economic and policy context. From this article, it is clear that our contribution arises on *PSE* field, namely between plant and supply chain levels and between operational and tactical levels of decision. Finally, the article of Demirhan et al. [6] is in the form of roadmap rather than a classical review paper. It points out 5 key methodologies of energy systems engineering: the design, the operation, the data analysis, the multi objective opti mization and the uncertainty consideration. Some of these meth odologies are developed by the authors elsewhere ([7,8]), but some others aspects (operation, optimization) are involved in this paper.

For the purpose of this work, the literature review can be divided into two parts. First, the relevant literature on the use of waste heat in *DHN*. Secondly, literature that investigates the supply chain energy planning is reviewed. Table 1 summarizes the key points of the literature. The second column is related to the prob lem dealt with, the third with the data necessary for its resolution, the methodology of which is in the fourth column. Finally, the last column groups the case studies handled by the various authors. It can be easily be seen from Table 1 that, for waste heat use relevant literature, the problems treated vary from industrial waste heat estimation with application at a Chinese province scale [9], to waste heat allocation [10], optimal choice of heat recovery technologies [11] or optimal network design ([12,13]). For this kind of problems, the optimization models (in sense of Prasad et al. [3]) are inten sively used and, in these models, Mixed Integer Linear Program ming (*MILP*) approach is praised. For the case of supply chain energy planning references ([14–20]), this kind of models are also favored, and the extensions of State Task Network (*STN*) framework ([15,18]) particularly relevant. For the applications studied, the main strategy consists on designing more or less in detail the coupling of an industrial activity with an urban heating system. There are only very few applications (only [15] in our reference

Table 1
Key points of the recent literature (<5 years).

Reference	Treated Problem	Data Collection	Solution	Case Study
Simeoni et al., 2019 [12]	Waste Heat Recovery Optimal Network Design	Local climate data Characterization of waste heat Characterization of heat sink (DH basin heat demand)	Optimization (Genetic Algorithm) and MultiCriteria Decision Making (MCDM)	City of Udine, Italy
Dou et al., 2018 [13]	Waste Heat Recovery Optimal Network Design	Characterization of waste heat source Characterization of heat demand	Scenario study and GIS utilization	Shinchi Town (Fukushima Prefecture), Japan
Kurle et al., 2016 [10]	Waste heat recovery Waste Heat Allocation (Waste Heat Exchange Design)	Characterization of waste heat source Characterization of heat sink	Optimization (MILP)	Automotive transmission manufacturing
Luo et al., 2017 [9]	Industrial Waste Heat (IWH) estimation	Amount of waste heat Official data statistics (population, density, ...)		Hebei province, China
Wang et al., 2018 [11]	Waste Heat Recovery in distributed energy systems (DES) Optimal Choice of Heat Recovery Technologies	Characterization of waste heat source and heat demand	Optimization (MILP) of annualized costs of used technology	Four cases studied
Bohlayer and Zottl, 2018 [14]	Optimal planning of an energy supply system of a manufacturing company	Characterization of waste heat source and heat demand	Cost Optimization (MILP)	German industrial case (tire manufacturing)
Si et al., *2018* [21]	Optimal energy scheduling	Characterization of energy demand, renewable energy output and energy price information	Resource Task Network (RTN) and MultiCriteria Optimization (MIILP) techniques	Urban area with 100 residential districts and a steel plant.
Silvente et al., 2015 [22]	Short-term scheduling problem of a smart grid	Characterization of energy demand, renewable energy output and energy price information	Cost Optimization (MILP)	Case study includes a PV panel and a micro-wind turbine as renewable energy sources, as well as a bidirectional connection to the power grid to purchase and sell energy.
Parisio et al., 2012 [17]	Scheduling of an energy hub	Characterization of energy demand, renewable energy output and energy price information	Robust optimization of an energy hub operations	Energy hub structure designed in Waterloo, Canada
Zulkafli and M. Kopanos, 2018 [18]	Planning of energy supply chain networks	Characterization of capacity and energy price information	Energy Resource Task Network (E-RTN) framework and bi-criteria (techno-economic and environment) Optimization (MIILP) techniques	Academic case studies
Dotzauer, 2003 [19]	Mid-term planning	Characterization of energy demand and energy price information	Cost Optimization (MILP)	A model of a set of district heating systems in Sweden
Keller and Reinhart, 2016 [20]	Integration of energy supply information to the production planning process		Enterprise Resource Planning Systems (ERP-Systems)	
Prasad et al., 2014 [3]	Review paper			
Huang et al., 2015 [4]	Review paper			
Demirhan et al., 2019 [6]	Review paper			
Shankar et al., 2018 [5]	Review paper			

panel) on planning an industrial waste heat on a district heating system. The aim of our paper is to fill this gap by considering a short term planning approach of a heat supply chain consisting in an industrial site (supplier of the waste heat) and a district heating network (customer of the waste heat). Our approach is based on the formulation and the resolution of a Mixed Integer Non Linear Programming (*MINLP*) model. To facilitate the development of the model and its adaptation to different kinds of value chain, the *Energy Extended Resource Task Network* (*EERTN*) framework is proposed.

3. Presentation of the illustrative case study

The EERTN formalism will be extensively described in section 3. However to make it more understandable, it will be applied to a didactic case study. Then in this section, the case study used in this contribution is briefly introduced. In this way, certain parts of the system will be exploited to illustrate the different aspects of the EERTN formalism in the subsequent section.

The case study represented in Fig. 2 is composed of two main sites:

- an *Industrial Site* (*IS*) consisting of a chemical production plant and an industrial boiler to meet the plant's heat requirements in the form of steam,
- an *Urban Site* (*US*) made up of heat consuming dwellings. An Energy Recovery Unit (ERU) is coupled to a District Heating Network (*DHN*) to produce and distribute hot water to the urban site.

The design of the supply chain, able to exploit the waste heat, is assumed to be done and the problem consists to optimally short term plan the energy use of the district heating network (*DHN*).

3.1. Industrial site

The industrial site consists of two sub systems: a *production unit* whose heat requirements are supplied by a *steam utility plant*.

The *production unit* is a multi product unit composed of several process sections operating in a mixed production mode (continuous/discontinuous). The production unit is available 24 h a day, 7 days a week, but is likely to have periods of inactivity. Steam consumption, which is highly dependenton the current production campaign and the nature of the operations in operation, therefore has a variable profile over time. This steam demand is satisfied by the steam produced by the utility plant.

The *steam utility plant* supplies the industrial unit with steam by means of several boilers. Each boiler consists of a combustion section withinthe combustion chamber anda section that transfers heat from the flue gases to the water through a heat exchanger. Combustion of natural gas with air produces fumes at 800 °C. These fumes feed the heat exchanger that ensures the production of steam necessary for the industrial production unit. However, the fumes leaving the exchanger still contain heat. It is precisely this energy that mustbe recovered. In ourcase, this is done by installing an additional heat exchanger between the flue gases and the dis trict heating network. However, it should be pointed out that the quantity and quality of the energy provided by these flue gases depends very strongly on the steam demand of the industrial unit as well as the operating conditions of the boiler and, in particular, the composition of the fuel and the quantity of excess air. For a steam demand equal to 30 tons per hour, the temperature of the discharged flue gas is equal to 150 °C. This flow of flue gas, currently released directly into the atmosphere, is the source of waste heat for the industrial site.

3.2. *Urban site*

A *district heating network* (*DHN*) is a centrally produced heat distribution system serving several users. It is composed of one or more heat production units, a primary distribution network in which the heat is transported by a heat transfer fluid, and a set of exchange substations, from which the buildings are served by a secondary distribution network. For the case under consideration, one boiler fuelled by wood, which is considered an unlimited resource feeds the primary circuit. Although these temperature set is not typical in a district heating network, in our case study, the distribution network enables the heat from the boiler to be trans ported in the form of water at 60 °C to the points of consumption.

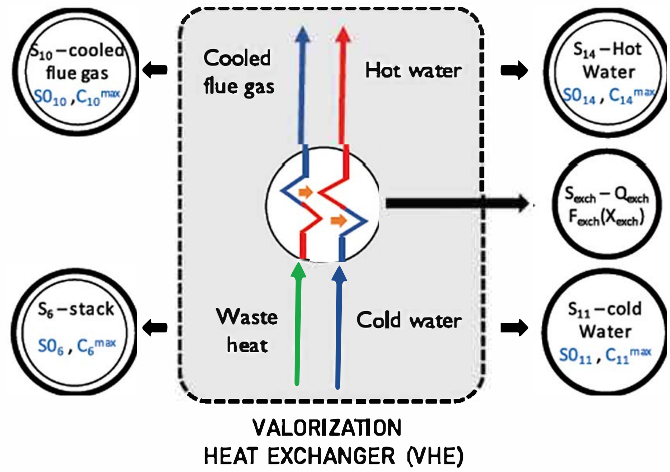


Fig. 3. Ressource nodes: illustration on case study.

The flow rate of the heat transfer fluid depends on the demand from the consumer site. The water returns to 25 °C at the ERU to be heated up again. The primary circuit feeds 150 dwellings meeting the low energy building standard, whose thermal resistance is taken equal to 8 m^2 K/W for the roof and 4 m^2 K/W for the walls and floor. In the case of recovery, the industrial part is therefore also coupled to the district heating network, and is considered as an auxiliary boiler from the point of view of the network.

3.3. *Storage and valorization*

The heat carried by the flue gases leaving the industrial boiler, whose temperature measurements range between 90 °C and 150 °C and flow rate between 10 tons per hour and 100 tons per hour, constitutes the waste heat to be recovered. This heat is recovered by adding an exchanger carried by the industrial flue gases to heat water from the district heating network, as well as adding a storage facility to store part of the heat produced when the district heating

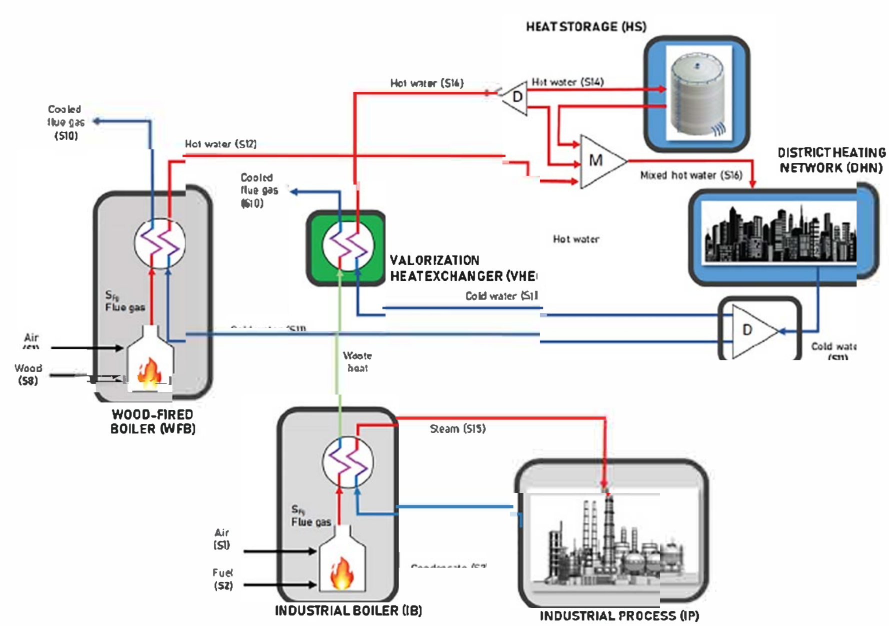


Fig. 2. Case study synopsis.

network does not need it, and to be consumed when demand reappears.

4. The EERTN formalism

One of the major contributions of this work is the development of a generic MINLP planning model whose instantiation is carried out in a systematic way by means of the graphical formalism named EERTN. It constitutes a tool able to plan energy, for a general point of view and particularly in the waste heat context. This framework is an extension of *ERTN* (Extended Resource Task Network) formalism, introduced in a previous work [23,24] and provides a more detailed account of the influence of temperature on the physicochemical phenomena involved in the process. This section describes the semantic elements of the EERTN while all the constraints of the model are explained in the supplementary materials.

4.1. Main features

The underlying *MINLP* model implemented in these work is based on a discrete time formulation with uniform time slots (also called *Global time intervals* formulation in Refs. [25,26]). Since *MINLP* models and EERTN graphs are closely interdependent, an important point is that the constraints constituting these models are written in such a way that they can be directly instantiated with the parameters derived from the EERTN representation. The EERTN is an extension of ERTN formalism. It is an oriented graph whose construction is based on a set of well established rules. These elements make it possible to model the main characteristics encountered in a production system (material and utility flows, manufacturing procedures, resource constraints, etc.). However, the ERTN formalism does not include any temperature and enthalpy variables, nor energy balances. The EERTN formalisms aims at extending the ERTN formalism capacities by integrating the notion of thermal potential on cumulative resources, as well as the associated energy balances. Non linearities of the EERTN model mainly relie on the bilinear enthalpy balances and on some unit operation specific equations such as heat exchanger heat transfer equation: $Q \quad U.A.\,\Delta Tml$.

4.2. Description and illustration of EERTN semantic

In this section, the EERTN semantic is extensively described and illustrated through an emblematic example: the valorization heat exchanger displayed in Fig. 1. As a reminder, the EERTN semantic is an extension of the ERTN semantic already introduced in former publications [24]. To highlight the new semantic elements, the ERTN ones are displayed on shaded rows. Moreover, each semantic element leads to the automatic formulation of a set of descriptive equations of the modeled system: these equations are supplied on the supplementary material.

4.2.1. Resources nodes

The EERTN formalism proposes three kind of resource nodes shown in.

A *cumulative resource* node r ∈ RC represents resources that can be shared by several operations simultaneously. They make it possible to model, for example, a material, a mixture of several components, a finished product, a utility in a given physical state, etc. A distinction is made between:

- Cumulative resources $r \in R^{CSP}$without enthalpic potential (see 1 in Table 2).

Cumulative resources $r \in R^{CSP}$ are characterized only by the three parameters $S0_r$, $C_r^{\max}$ and $Policy_r$. Let $S_{r,t}$, be a state variable representing the quantity of resource $r \in R^C$ available at the end of period *t*. These variables represent only a transient instantaneous state (and not a physical stock) that creates a link between the end of period *t* and the beginning of period *t+1*.

- and cumulative resources $r \in R^{CP}$ with enthalpy potential (see 2 in Table 2). The latter necessitate two supplementary parameters $T0_r$ and Cp_r and induces the definition of additional variables: a temperature variable $T_{r,t}$ and an enthalpy potential variable $h_{r,t}$.

An *enthalpy resource* node (see 3 in Table 2). is used to model an amount of energy produced or consumed by one or more operations simultaneously. By definition, this kind of resource is never stored *(ZW* storage policy*)*. This node is annotated with the name of an equation whose expression is of the type $F_e(X_e) \quad 0$ where X_e is a subset of variables in the model ($X_e \; \boldsymbol{V}$) that must be defined.

For cumulative resources, mass balances constraints are introduced and for cumulative resource with potential enthalpy potential resources and enthalpic resource node enthalpy balances are added.

4.2.1.1. Illustration. Fig. 3 displays cumulative resources with enthalpy balance nodes and an enthalpic resource node that will represent the input/output flows of the valorization heat exchange (VHH).

4.2.2. Task nodes

A *task* node $k \in K$ models any operation carrying out a transformation of matter or energy. To take into account its mode of production and the type of balancing equation to be considered, these nodes are always drawn as a rectangle but declined through different representations:

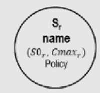
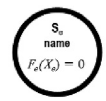
- a *task* node $k \in K^{BE}$ (resp. $k \in K^{SBE}$) with a border represented by a bold line (resp. single line) requires a material balance and an enthalpy balance (resp. a material balance only).
- a *task* node $k \in (K^{dd} \cup K^{dc})$ (resp. $k \in (K^{cd} \cup K^{cc})$) consuming flows discontinuously (resp. continuously) is represented by a vertical bar on the right (resp. horizontal at the top) inside the rectangle. *Discontinuous consumption* means that the device is “instantly” charged with an indivisible batch of product at the start of the task, whereas *continuous consumption* means that the device is charged continuously throughout the duration of the task.
- a *task* node $k \in (K^{dd} \cup K^{cd})$ (resp. $k \in (K^{dc} \cup K^{cc})$) producing flows discontinuously (resp. continuously) is represented by a vertical bar on the left (resp. horizontal at the bottom) inside the rectangle. *Discontinuous production* means that the material treated in the unit is made unavailable for the duration of the task and is released “instantly” at the end of the task, whereas *continuous production* means that the treated material is released continuously throughout the duration of the task.

Any combination of the characteristics described in the previous three points is possible (see 5a to 8 b in Table 3 Table 3: Task nodes).

Any task is characterized by the three parameters $V_k^{\min}$, $V_k^{\max}$ and pf_k and governed by the two decision variables $W_{k,t}$and $B_{k,t}$:

- let $W_{k,t}$ be a binary variable such that $W_{k,t} \quad 1$ if a task $k \in K$ is started at period *t*, $W_{k,t} \quad 0$ otherwise.

Table 2
Resource nodes.

ID	NAME	SYMBOL
1	**Cumulative resource** without enthalpy potential **Node**	
2	**Cumulative resource** with enthalpy potential **Node**	
3	**Enthalpy resource Node**	

- let $B_{k,t}$ be a real variable representing the quantity (in mass) or flow (in mass/period) of matter processed during the duration pf_k by a task $k \in K$ launched in period t (i.e when $W_{k,t}$ 1). $B_{k,t}$ is limited between the minimal bound $V_k^{\min}$ and the maximal bound $V_k^{\max}$.

Note that the duration pf_k of a discontinuous task $k \in (K^{dd} \cup K^{cd})$is fixed and independent of the mass of material treated and must be expressed as an integer number of periods such that $pf_k \geq 1$. On the contrary, the duration pf_k of a continuous task $k \in (K^{cc} \cup K^{dc})$ is always equal to the duration of a period, i.e. pf_k 1. If this operation must be spread over n consecutive periods, then n instances of this task must be launched consecutively. In this way, n mass balances are evaluated to account for *continuous* consumption or production over time.

Finally, the tasks $k \in K^{BE}$requiring an enthalpy balance are also governed with the real variable $hB_{k,t}$, which represents the specific enthalpy of the mass $B_{k,t}$ processed in task k during period t.

4.2.2.1. Illustration. Fig. 4 represent two purely continuous task used to model the heat exchanges tasks: cold stream heating task and hot stream cooling task.

4.2.3. Flow arcs

By definition, any task $k \in K$ can produce or consume one or more cumulative resources $r \in R^C$. The quantities of resources r flowing through a task k are either governed by a conservative mass balance equation between input and output flows or not. In order to distinguish these particular situations, different kind of arcs are introduced into the semantics (Table 1 Table 4).

- *Flow arcs subject to a conservation balance with fixed or free ratio*

Let $C_{r,k,t}$ be the amount of resource $r \in R^C$ consumed by task $k \in K$ during period t and $P_{r,k,t}$, the amount of resource $r \in R^C$ produced by task $k \in K$ during period t. The valuation of flows $C_{r,k,t}$ and $P_{r,k,t}$ depends on the nature of the arcs linking the resource r and the task k.

When a fixed proportion flow arc (see 10 in Table 4 and Fig. 5) links a resource $r \in R^C$ and a task $k \in K$, then the flow $C_{r,k,t}$ (resp. $P_{r,k,t}$) is equal to the proportion $\rho^{cons}_{r,k}$ (resp. $\rho^{prod}_{r,k}$) of flow $B_{k,t}$ through the task k, that is $C_{r,k,t}$ $\rho^{cons}_{r,k}.B_{k,t}$ (resp. $P_{r,k,t}$ $\rho^{prod}_{r,k}.B_{k,t}$).

When a *free proportion flow* arc (see 11 in Table 4 and Fig. 5) links a resource $r \in R^C$ and a task $k \in K$, then the flow $C_{r,k,t}$ (resp. $P_{r,k,t}$) represents an unfixed part of the flow $B_{k,t}$ through the task k, such that $C_{r,k,t} \leq B_{k,t}$ and $P_{r,k,t} \leq B_{k,t}$. In this case, the flows $C_{r,k,t}$ and $P_{r,k,t}$ are calculated when the optimization problem is solved. The *free proportion inlet* (resp. *outlet*) *flow* arcs are characterized by the parameters $\mu^{cons}_{r,k}$ (resp. $\mu^{prod}_{r,k}$) whose value equal to 1 indicates the presence of the arc and a 0, its absence.

When these *flow* arcs specifically link a cumulative resource $r \in R^{CP}$ with enthalpic potential and a task $k \in K^{BE}$ with an enthalpy balance, then enthalpy conservation balances must be added. In this case, two additional variables are considered: $hC_{r,k,t}$, the enthalpy flow of the resource $r \in R^{CP}$consumed by task $k \in K^{BE}$ during period t, and $hP_{r,k,t}$, the enthalpy flow of the resource $r \in R^{CP}$ produced by task $k \in K^{BE}$ during period t.

4.2.3.1. Illustration. In Fig. 6, mass balances concerning hot and cold streams treated in both sides of the heat exchanger are rep resented using fixed ratio arc flows for input flows and free ratio arc flows for.

- ***Flows arcs not subject to a conservation balance***

The *flow* arcs not subject to a conservation balance (see 12 in Table 4 Table 4) make it possible to define a consumption or pro duction of a cumulative resource $r \in R^C$ by a task $k \in K$ indepen dently of the other cumulative resources $r' \in R^C$ consumed or produced by this task k. The flows carried by these arcs are deter mined by exploiting two parameters: $uf^{cons}_{k,r}$ (resp. $uf^{prod}_{k,r}$) for the fixed part, and $uv^{cons}_{k,r}$ (resp. $uv^{prod}_{k,r}$) for the variable part of the consumption (resp. production) of cumulative resource $r \in R^C$ by task $k \in K$. The real variables $UC_{r,k,t}$ represent the amount of cu mulative resource $r \in R^C$ consumed by task $k \in K$ during period t. Similarly, the real variables $UP_{r,k,t}$represent the amount of cumu lative resource $r \in R^C$ produced by task $k \in K$ during period. t.

- ***Enthalpy flows arcs***

Enthalpy resource nodes $e \in R^E$ are linked to task $k \in K^{BE}$ with enthalpic balance via a specific arc called *enthalpy flow* arc (see 13 in Table 4). When an arc (k, e) exists (where $k \in K^{BE}$ and $e \in R^E$), it is

Table 3
Task nodes.

ID	NAME	SYMBOL
5a	Purely discontinuous task without Enthalpy balance	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
5b	Purely continuous task without Enthalpy balance	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
6a	Mixed Task without Enthalpy balance : discontinuous discharging	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
6b	Mixed Task without Enthalpy balance : discontinuous charging	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
7a	Purely discontinuous task with Enthalpy balance	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
7b	Purely continuous task with Enthalpy balance	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
8a	Mixed Task with Enthalpy balance : discontinuous discharging	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$
8b	Mixed Task with Enthalpy balance : continuous discharging	T_k – *Operation* name $(V_k^{min}, V_k^{max}, pf_k)$

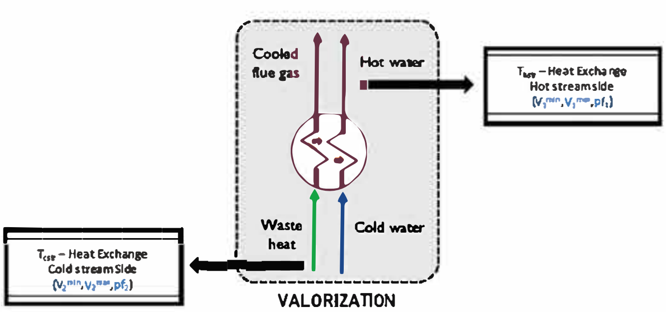
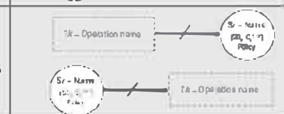
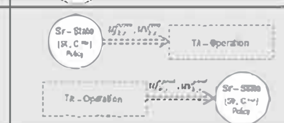
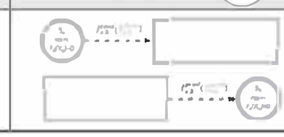


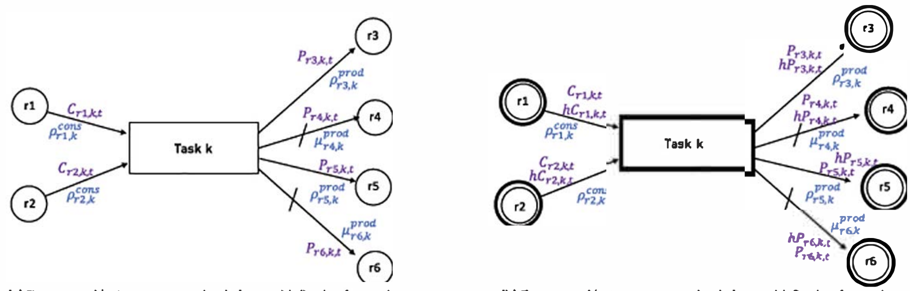
Fig. 4. Task nodes: illustration on case study.

annotated with an expression $f_{e,k}^{prod}(Y_{e,k}^{prod})$ defining a linear or non linear function of a subset $Y_{e,k}^{prod}$ of variables in the model ($Y_{e,k}^{prod} \subseteq V$). Let $QP_{e,k,t}$ be a real variable representing the quantity of enthalpic resource $e \in R^E$ produced by task $k \in K^{BE}$ in period t. Symmetrically, when an arc (e,k) exists (where $k \in K^{BE}$ and $e \in R^E$), it is annotated with an expression $f_{e,k}^{cons}(Y_{e,k}^{cons})$ defining a linear or non linear function of a subset $Y_{e,k}^{cons}$ of variables in the model ($Y_{e,k}^{cons} \subseteq V$). Let $QC_{e,k,t}$ be a real variable representing the quantity of enthalpic resource $e \in R^E$ produced by task $k \in K^{BE}$ in period t. Finally, the enthalpy balance for a task $k \in K^{BE}$ is shown on Fig. 7.

4.2.3.2. Illustration. As illustrated on Fig. 8, the heat flux exchange

Table 4
Flow arc.

ID	NAME	SYMBOL
10	*Fixed ratio flow* arc governed by a conservative mass balance	
11	*Free ratio flow* arc governed by a conservative mass balance	
12	*Flow* arc not governed by a conservative mass balance	
13	*Enthalpic flow* arc governed by a enthalpy balance	



(a) Flow arcs subject to a conservation balance with fixed or free ratio concerning task $k \in K$ and cumulative resource $r \in R^C$

(b) Flow arcs subject to a conservation balance with fixed or free ratio concerning task $k \in K^{ex}$ and cumulative resource $r \in R^{cp}$

Fig. 5. *Flow* arcs without (a) or with (b) enthalpy balance.

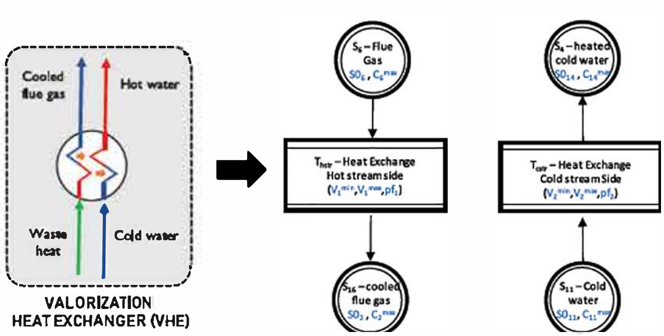


Fig. 6. Flow arc: illustration on case study.

between both parts of heat exchanger (hot stream side and cold stream side) is represented using an enthalpy resource node and two enthalpy flow arcs between hot stream side heat exchange and cold stream side heat exchange.

4.2.4. *Disjunctive resource nodes and disjunctive arcs*

A disjunctive resource node (see 4 in Table 5) represents a resource that, at any given time, can only be used to perform one and only one task, such as a device, a processing equipment, operator, etc. A disjunction arc (see 14 in Table 5) allows to model the mutual exclusion mechanism. Thus, the disjunctive resource at the origin of the arc can execute the operation pointed by the arc and induces an exclusive use of the resource.

Each structure including a *disjunctive resource* arc leads to the formulation of an allocation constraint. At a given time period *t*, a disjunctive resource *m* $(m \in R^D)$ can at most initiate one operation *k* $(k \in K_m)$. Furthermore, this equipment *m* can not execute another task *k'* $(k' \in K_m)$ during the duration of task *k*.

4.2.4.1. Illustration. Both part of heat exchanger are represented as resource nodes as illustrated on Fig. 9.

4.2.5. *Semantic elements linking the system with its environment*

- ***Supply* and *Demand* arcs**

The *supply* and *demand* arcs (see 15 and 16 in Table 6) are known and fixed data of the model allowing to represent respectively flows *coming from* or *going to* the environment. As shown in Table 6, symbols *(a)* and *(c)* represent expected supply of resource $r \in R^C$ in period *t* while symbols *(b)* and *(d)* represent demands of resource $r \in R^C$ to be met in period *t*. The supply of resource $r \in R^C$ can be achieved with a continuous flow $App^C_{r,t}$ (*a.2* and *c.2*) or with a

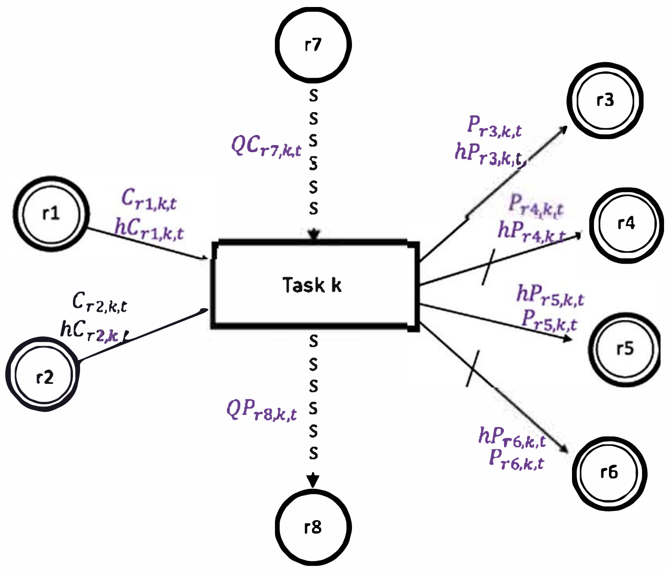


Fig. 7. Enthalpy balance for a task $k \in K^{BE}$

discontinuous flow $App^{d}_{r,t}$ (*a.1* and *c.1*). In addition, it is possible to specify that the supply $App^{c}_{r,t}$ and $App^{d}_{r,t}$ be provided with a specific fixed enthalpy noted respectively $hApp^{c}_{r,t}$ (*c.2*) and $hApp^{d}_{r,t}$ (*c.1*). Likewise, the demand of resource $r \in R^{C}$ to be met can be achieved with a continuous flow $Dem^{c}_{r,t}$ (*b.2* and *d.2*) or with a discontinuous flow $Dem^{d}_{r,t}$ (*b.1* and *d.1*). In addition, it is possible to specify that the demand $Dem^{c}_{r,t}$ and $Dem^{d}_{r,t}$ have to be met with a specific fixed enthalpy noted respectively $hDem^{c}_{r,t}$ (*d.2*) and $hDem^{d}_{r,t}$ (*d.1*).

- Import and Export arcs

The Import and Export arcs (see 17 and 18 in Table 7) are associated with a decision variable of the model allowing to calculate flows of resource $r \in R^{C}$ respectively coming from or going to the environment during a period t.

As for the previous *supply* and *demand* arcs, the *import* (resp. *export*) of resource $r \in R^{C}$ can be achieved with a continuous flow $Imp^{c}_{r,t}$ (resp. $Exp^{c}_{r,t}$) or with a discontinuous flow $Imp^{d}_{r,t}$ (resp. $Exp^{d}_{r,t}$). In addition, it is possible to specify that the import $Imp^{c}_{r,t}$ and $Imp^{d}_{r,t}$ (resp. export $Exp^{c}_{r,t}$ and $Exp^{d}_{r,t}$) are provided with a specific fixed enthalpy noted respectively $hImp^{c}_{r,t}$ and $hImp^{d}_{r,t}$ (resp. export $hExp^{c}_{r,t}$ and $hExp^{d}_{r,t}$). The variables $Imp^{c}_{r,t}$ and $Imp^{d}_{r,t}$ (resp. $Exp^{c}_{r,t}$ and $Exp^{d}_{r,t}$) are limited by the maximum bound Imp^{max}_{r} (resp. Exp^{max}_{r}).

4.2.6. Macro task

Finally, the notion of *macro task* is defined (see 19 in Table 8). Any task is characterized by the three parameters V^{min}_{k}, V^{max}_{k} and pf_{k} and governed by the two decision variables $W_{k,t}$ and $B_{k,t}$:

- let $W_{k,t}$ be a binary variable such that $W_{k,t}$ 1 if a task $k \in K$ is started at period t, $W_{k,t}$ 0 otherwise.
- let $B_{k,t}$ be a real variable representing the quantity (in mass) or flow (in mass/period) of matter processed during the duration pf_{k} by a task $k \in K$ launched in period t (i.e when $W_{k,t}$ 1). $B_{k,t}$ is limited between the minimal bound V^{min}_{k} and the maximal bound V^{max}_{k}.

Note that the duration pf_{k} of a discontinuous task $k \in (K^{dd} \cup K^{cd})$ is fixed and independent of the mass of material treated and must be expressed as an integer number of periods such that $pf_{k} \geq 1$. On

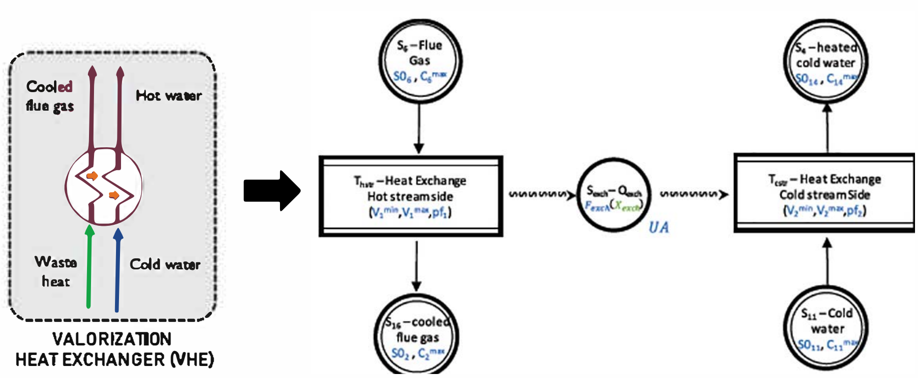


Fig. 8. Enthalpy flow arc: illustration on case study.

Table 5
Disjunctive resources node and disjunctive arc.

ID	NAME	SYMBOL
4	Disjuntive resource node	Resource Name
14	Use Arc	Resource Name - - - -> Tk - Operation

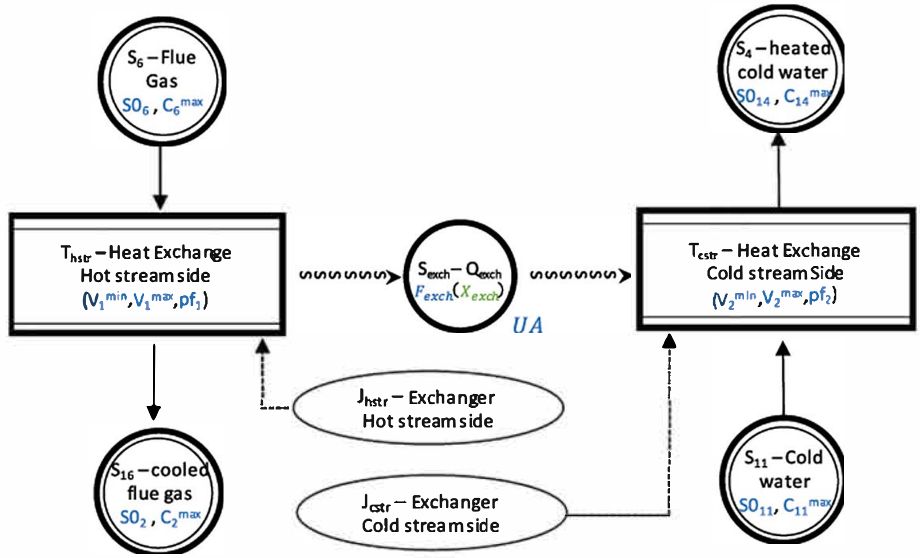


Fig. 9. Disjunctive resource nodes and disjunctive arcs: illustration on case study.

Table 6
Supply and Demand arcs.

ID	NAME	SYMBOL
15	Supply and demand arc without enthalpy potential	
16	Supply and demand arc with enthalpic potential	

Table 7
Import and Export arcs.

ID	NAME	SYMBOL
15	Import and export arc without enthalpy potential	
15	Import and export arc with enthalpy potential	

the contrary, the duration pf_k of a continuous task $k \in (K^{cc} \cup K^{dc})$ is always equal to the duration of a period, i.e. pf_k 1. If this operation must be spread over n consecutive periods, then n instances of this task must be launched consecutively. In this way, n mass balances are evaluated to account for *continuous* consumption or production over time.

Finally, the tasks $k \in K^{BE}$ requiring an enthalpy balance are also governed with the real variable $hB_{k,t}$, which represents the specific enthalpy of the mass $B_{k,t}$ processed in task k during period t. This semantic element aims to simplify the modeling of complex systems by encapsulating a sequence of tasks and resources. In addition, *macro task* can be nested on several level. The inlet/outlet of the *macro task* are identified on the border of the element as *ports*. An *outlet port* is represented by a hexagon with a black background while an *inlet port* is represented by a hexagon with a grey background. Each port is annotated with the nature of the stream to which it has to be connected. Only a *cumulative* or *enthalpy resource* node can be connected to a *port* via a *flow* arc (no *task* node or *disjunctive* resource). The arcs described in section 3.2.5 are also allowed. No additional parameters or variables are added.

Table 8
Macro Task.

ID	NAME	SYMBOL
19	*Macro task* Node	

4.2.6.1. Illustration. In Fig. 10, the detailed view of EERTN is repre sented inside the dotted frame. To make the representation of a global process more concise, an aggregate view of the macro task heat exchange is also available (Fig. 11).

5. EERTN based energy planning methodology

A three steps methodology (illustrated on Fig. 12) has been developed. It consists in the *EERTN model building*, the *model instantiation* and finally, the *EERTN planning*.

- Step 1: *EERTN and MESH model building*

The first step, called *EERTN Model Building*, intends to establish the models necessary to define the generic recipe for the overall system. Two kinds of models must be established: the EERTN model and a steady state M.E.S.H. model ('Material balance Equilibrium Summation Heat balance') required to configure the EERTN model of some of the components of the systems. In our case, the ProSimPlus steady state process simulator [2] was used to develop the M.E.S·H. model.

- Step 2: *EERTN Model instanciation*

The second step called *EERTN Model Instanciation* aims to build the EERTN model corresponding to the site recipe. In this step, the numerical values for the EERTN model are calculated. Whereas some of the parameters can be computed directly, the other ones are deduced from the MESH model established in step 1.

- Step 3: *EERTN planning*

This final step requires the definition of scenarios that represent the interactions of the system with its environment; these are customer requests for finished products or utilities (steam de mand), availability of raw materials (biomass availability) or utili ties .... While some data related to the scenario studied can be provided directly to the model (e.g. industrial site steam demand profiles), others must be deduced from a preprocessing step. Thus, the outdoor temperature profile, combined with the energy per formance of the buildings and the expected indoor temperatures are then converted into a hot water demand profile for the district heating network. Given these scenarios, the MINLP model is solved using the SCIP solver provided by GAMS modeler [12].

6. Energy planning of the decoupled system

6.1. Step 1: EERTN and M.E.S.H. Model building

In the first step, the EERTN graph corresponding to the system under consideration is established.

6.1.1. Boiler macro task

As the boiler operation appears recurrently in industrial sites, a *boiler* macro task dedicated to the formulation of a generic model for this kind of operation has been developed. Fig. 12 presents a detailed view of the EERTN model of the macro task *steam boiling*. Task T_{boil} corresponds to the boiling of a fuel in the combustion chamber (resource J_{boil}). Task T_{boil} consumes natural gas (Material Input Port *fuel*) and air (Material Input Port *Air*) to produce flue gas (state S_{fg}). Their value is calculated to produce flue gas at a given temperature TFT (*Theoretical flame temperature*) The PCI parameter corresponds to the *Lower Calorific Value* of the fuel, i.e. the quantity of heat released by the combustion of 1 kg of fuel.

The heat exchanger is represented by two half exchangers (re sources J_{ss} and J_{fgs}). The *heat exchange* task T_{csh} consists in pro ducing steam from water in the water side (material input port *water*). The heat exchange task T_{fgc} cools down the flue gas in the flue gas side. In this system, the exchanger allows the transfer of heat (S_{exch}) from the flue gas leaving the boiler (state S_{fg}) at 800 °C to water at 90 °C (material input port *water*). At the outlet of the exchanger, steam (material output port *steam*) at 300 °C and cooled flue gas (material output port *stack*) are obtained. The pressure level and steam flow, corresponding to the steam demand, are fixed data of the system. Similarly, it is assumed that the amount of air supplied to the boiler is adjusted to obtain a given value for the boiler flue gas temperature. Therefore, in the resulting model, the flue gas flowrate and the S5 exchange output temperature depends on the required steam flowrate. Fig. 13 displays the aggregate representation of the *boiling* macro task, which will be used in the EERTN representation of the whole system (see Fig. 14).

6.1.2. EERTN model of the industrial site

The EERTN of the industrial site is composed of the EERTN model of the boiler, which is connected to a consumption task corresponding to the industrial site steam demand (see Fig. 15).

6.1.3. EERTN model of the energy recovery plant and district heating network

The wood boiler produces water at 60 °C for the district heating network. The EERTN model of the boiler can also be represented using the steam *boiling* macro task and the urban network is rep resented by a consumption task corresponding to the water de mand of the buildings (Fig. 16) (see Fig. 17).

6.2. Step 2: Instanciation

The model of the industrial site displayed on Fig. 15 lead to the list of parameter given on Table 9 and Table 10. Table 9 concerns the industrial macro task boiling specific parameters. Table 10 concerns the external semantic elements should also be evaluated. The purpose of this step is to instantiate the EERTN graph by defining the values of all these parameters. In this contribution, the

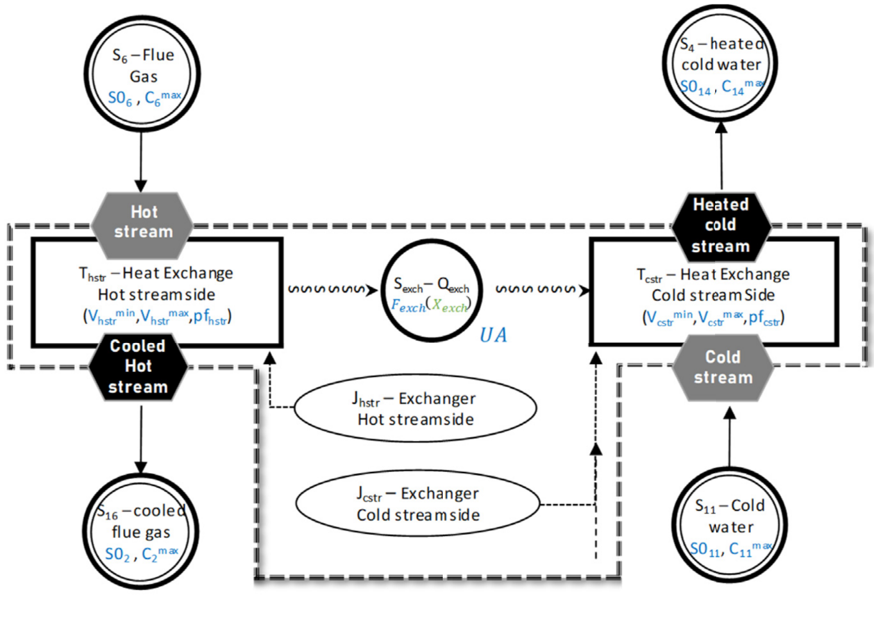


Fig. 10. EERTN model of the heat exchange macro task: detailed view.

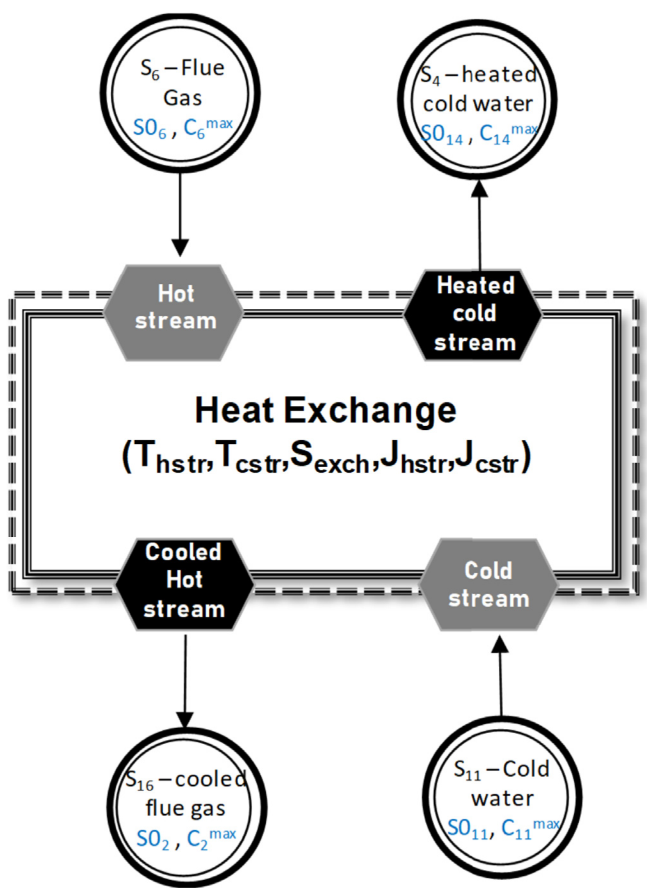


Fig. 11. EERTN model of the heat exchanging macro task: agregate view.

instantiation procedure will be illustrated only for the *industrial boiler* macro task (see Table 11).

6.2.1. Parameters directly deduced from the technical data

The first parameters defined are the limits of the steam site heat exchange task deduced from the technical data. As the boiler pro duces steam between 5 and 30 t/h, we have $V^{min}_{csh\_MT1}$ 5and $V^{max}_{csh\_MT1}$ 30. The second parameters are the initial stocks and the capacities of the stocks, all these values being equal to zero because there is no storage system for any resource in the industrial boiler process. The PCI of natural gas is also deduced from thermody namical data.

6.2.2. Parameters deduced from MESH simulation models

- ***Air/Natural Gas ratio***

The parameters $\rho^{cons}_{Tboil\_MT1,1}$ and $\rho^{cons}_{Tboil\_MT1,2}$ correspond to the air/natural gas proportions entering the combustion chamber. This ratio is determined by means of a MESH simulation set up with entering compositions, and temperatures of air and fuel used in the boiler, fuel PCI and theoretical Flame Temperature. This model performed in ProSimPlus simulation, leads to the following values:

$$\rho^{cons}_{Tboil\_MT1,1} \quad 0,9814 \tag{1}$$

$$\rho^{cons}_{Tboil\_MT1,2} \quad 0,0186 \tag{2}$$

- ***States potential***

For fixed composition, temperature and pressure, the flue gas enthalpy of the fumes is fixed and is deduced from Thermodynamic calculations (see Table 8).

- Characteristics of flue gas/water exchanger

The industrial boiler must be set up with the *UA* value. For an existing heat exchanger, this parameter can be identified applying equation (3) on the nominal operating point.

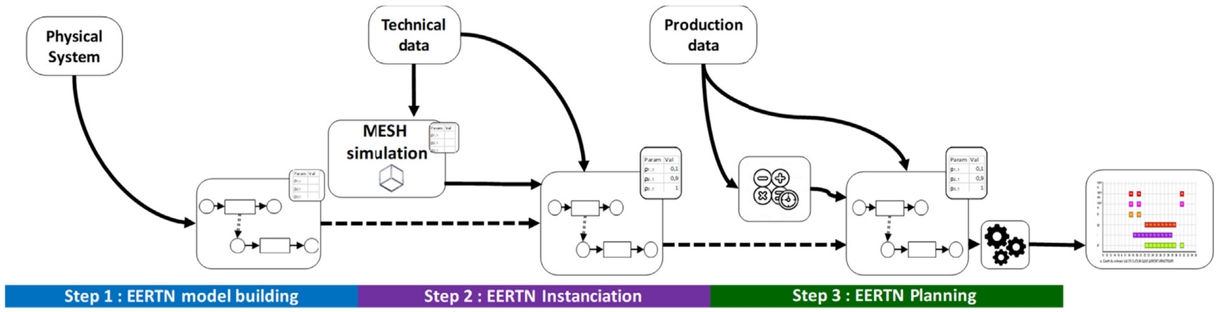


Fig. 12. EERTN based energy planning methodology.

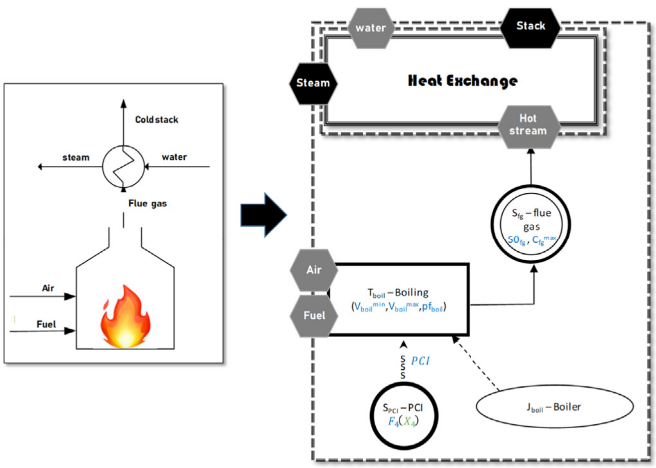


Fig. 13. EERTN model of the *boiling* macro task: detailed view.

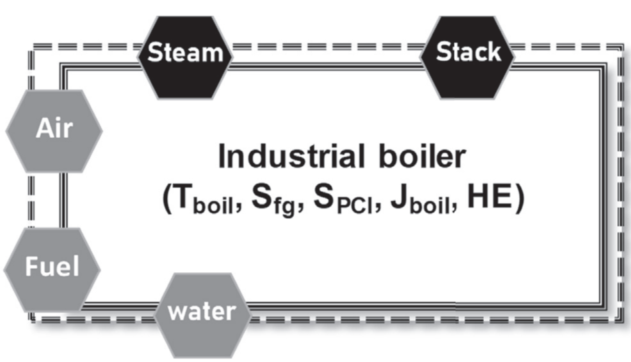


Fig. 14. EERTN model of the *boiling* macro task: aggregate view.

$$Q \quad UA{*}\Delta T_{ml} \tag{3}$$

where

$$\Delta T_{ml} \quad \frac{\left(T_{flueGas}^{in} \quad T_{water}^{out}\right) \quad \left(T_{flueGas}^{out} \quad T_{water}^{in}\right)}{ln\frac{\left(T_{flueGas}^{in}-T_{water}^{out}\right)}{\left(T_{flueGas}^{out}-T_{water}^{in}\right)}}$$

and

$$Q \quad F_{water}{*}\left(h_{water}^{out} \quad h_{water}^{in}\right)$$

then

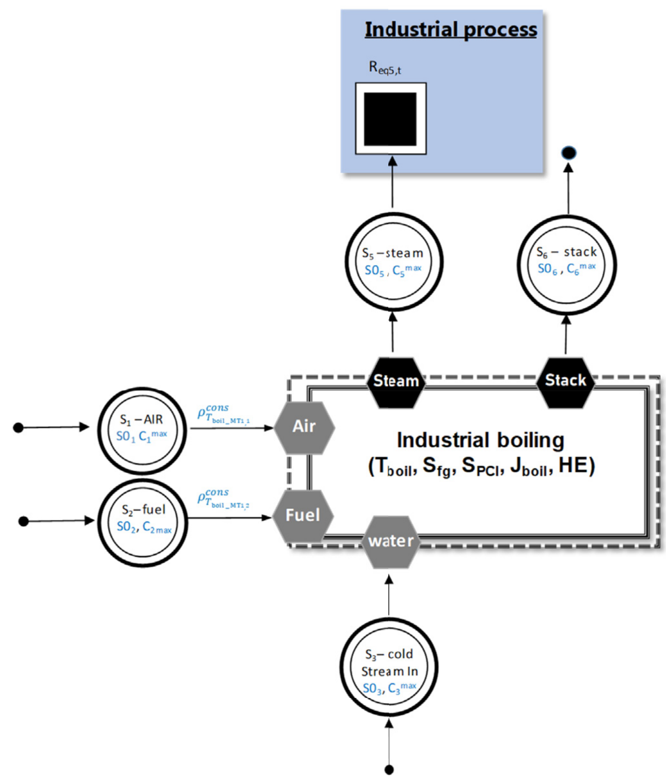


Fig. 15. EERTN model of the *Industrial Site*.

$UA \quad 107662 \ W/K$

The maximum flow V_{fgs}^{max} required to meet the maximum steam demand can be determined by equation (4), where Q_{max} corresponds to the heat required to vaporize 30 t h^{-1} of water.

$$V_{fgs}^{max} \quad \frac{Q_{max}}{h_{steam} \quad h_{water}} \quad 108.3 \ t.hr^{-1} \tag{4}$$

The flue gas maximal flowrate coming out the boiler V_{boil}^{max} and the maximal flue gas export Exp_6^{max} are also equal to 108.3 t h^{-1}. The Imp_7^{max} parameter refers to the maximal import of water. It is equal to the maximal steam flowrate i.e. $Imp_3^{max} \quad 30 \ t.hr^{-1}$. The value of Imp_2^{max}, Imp_1^{max} and respectively corresponding to the maximal import natural gas and air are deduced from the maximal flue gas flowrate and are equal to 2,1 t h^{-1} and 106 t h^{-1}.

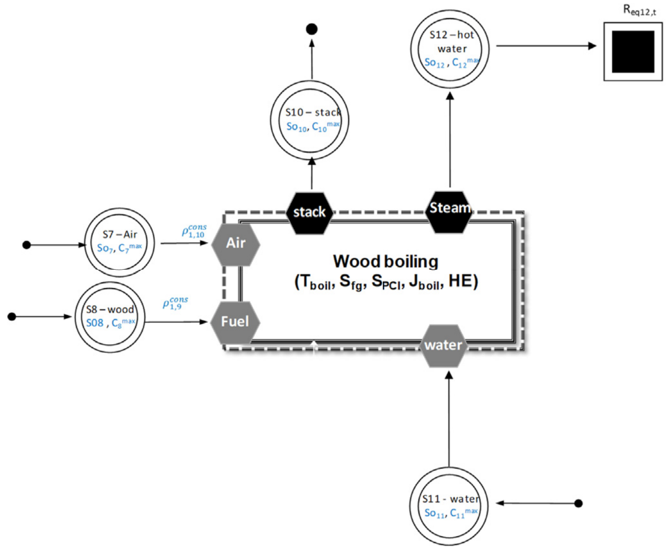


Fig. 16. EERTN model of the energy recovery plant & district-heating network.

6.3. *Step 3: EERTN planning*

6.3.1. *Production data*

In order to complete the planning stage, it is now necessary to define the production data.

○ ***Steam demand of the industrial site***

With regard to the steam demand of the industrial site, the scenario envisaged defines an operation of the production site only during the day, with the plant shut down at night (Fig. 15).

○ ***Urban site demand***

The heat demand in the form of hot water emitted by the district heating network must be deduced. The outdoor temperature profile combined with energy performance of the buildings and the indoor temperature are then converted into a hot water demand profile for the district heating network (Fig. 16).

○ ***Wood availability***

Wood is available in unlimited quantities to satisfy the heating needs of the district heating network.

6.3.2. *Planning results*

For this scenario, which takes place in the spring, the demand for hot water from the district heating network occurs mainly at night. The considered key performance indicators (KPI) are the amount of waste heat carried by the flue gas $Q_{waste\ heat}$ and the amount of wood consumed by the urban site W_{wood}. In this nominal scenario, the value of these KPI are respectively $Q_{waste\ heat}$ 167, 8 *GJ* and W_{wood} 244 *kg*.

Table 9
State potentials.

Nom	Description	Value (MJ/kg)
$h_{NaturalGas}$	Specific enthalpy of natural gas	−0,001066
h_{air}	Specific enthalpy of air	−0,00023381
$h_{FluxGas}$	Specific enthalpy of flue gas	0.92082
h_{steam}	Specific enthalpy of steam	−2.1819
h_{water}	Specific enthalpy of water	0.497620

Nevertheless, as shown on Fig. 19 the simultaneous presence in certain periods of flue gas and demand from the district heating network could allow a reduction in overall energy consumption through the valorization of the waste heat displayed on the third flowchart.

7. Energy planning of the coupled system

7.1. *EERTN model and instantiation*

Fig. 20 represents the EERTN model of the coupled system. The detailed view of the *storage* macro task is represented on Fig. 21 and its parameters are displayed on Table 12 This storage can be disabled by fixing V_{min} and V_{max} values for the Storage, Storage Filling and storage Emptying values to 0.

7.2. *Planning results for direct coupling without heat storage*

For the previous scenario, the planning obtained for the coupled system without storage is shown on Fig. 16. In this strategy, the value of the KPI are respectively $Q_{waste\ heat}$ 166, 1 *GJ*and W_{wood} 155 *kg*. As expected, the recovery exchanger is used for all periods where there is a simultaneous demand from the district heating network and a production of flue gas from the industrial boiler. Compared to the results of the previous nominal strategy, the recovery of 1% of waste heat saves 37% of wood consumption and is used to produce 36.5% of the hot water for the urban heating network.

Nevertheless, Fig. 22 shows that on the one hand, part of the smoke generated is not yet recovered (periods 12 to 22), and on the other hand, wood is still consumed in the following periods (23–30). In order to remedy this temporal mismatch between heat supply and demand, the solution is to introduce a storage unit into the overall system to better coordinate them.

7.3. *Planning results for direct coupling with heat storage*

Always for the same scenario, Fig. 23 focuses on the planning obtained in period 11 to 35. As expected, the introduction of a storage unit in the global system enables a higher level of heat recovery to be achieved. Indeed, during periods 18 and 19 (and period 33 and 34), the flue gas heat initially lost in the previous scenario is recovered by the recovery exchanger and then, sent directly to the storage unit. The evolution of the stock level over the different periods is displayed on Fig. 18, while Fig. 19 shows the temperature decrease due to the thermal losses. In period 23 to 30,

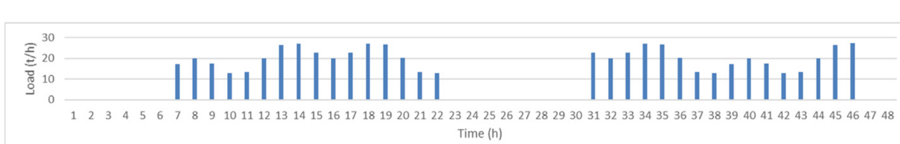


Fig. 17. Steam demand of the industrial site.

Table 10
EERTN Model parameters for the boiling macro task.

TASK k boil: boiler, csh: cold Stream Heating, fgc: flue gas cooling			STATE r		
parameter	Description	Value	parameter	description	value
V_k^{min}	Minimal capacity	k $Tboil$ 0 k $Tcsh$ 5 k $Tfgc$ 0	SO_r	Initial storage	$r_{flueGas}$ 0
V_k^{max}	Maximal Capacity	k $Tboil$ 108.3 k $Tcsh$ 30 k $Tfgc$ 108.3	C_r^{max}	Maximal storage	$r_{flueGas}$ 0
pf_k	Duration	k $Tboil$ 1 k $Tcsh$ 1 k $Tfgc$ 1	hS_r^{spec}	State potential	$r_{flueGas}$ 0
ARC k,r			**ENERGY ARC & SPECIFIC EQUATIONS r,k,t**		
parameter	Description	value	parameter	description	value
$\rho_{k,r}^{cons}$	Weight	r S_{fg} k T_{boil} 0 k T_{fgc} 1	QC_{exch}	Exchanger heat flux	$UA*\Delta T_{lm}$ UA 107662 W/K
$\rho_{k,r}^{prod}$	Weight	r S_{fg} k T_{boil} 1 k T_{fgc} 0			

Table 11
EERTN Model parameters for the global system.

STATE r		
parameter	Description	Value
$S0_r$	Initial storage	$r1$ $r2$ $r3$ $r5$ $r6$ 0 0 0 0 0
$S0_r^{max}$	Maximal storage	$r1$ $r2$ $r3$ $r5$ $r6$ 0 0 0 0 0
h_r	State fixe potential	$r1r2r3r5r6$ – 0.00023381 – 0.0010660.49762 – 2.1819000.92082
ARC k,r		
parameter	**Description**	**value**
$\rho_{k,r}^{cons}$	Weight	$r1$ $r2$ $r3$ $r5$ $r6$ k T_{boil_MT1} 0.9814 0.0186 0 0 0 k T_{csh_MT1} 0 0 1 0 0 k T_{fgc_MT1} 0 0 0 0 0
$\rho_{k,r}^{prod}$	weight	$r1$ $r2$ $r3$ $r5$ $r6$ k T_{boil_MT1} 0 0 0 0 0 k T_{csh_MT1} 0 0 0 1 0 k T_{fgc_MT1} 0 0 0 0 1
ENERGY ARC & SPECIFIC EQUATION r,k,t		
variable	**description**	**Value**
$QC_{4,1,t}$	Boiling enthapic flux	$PCI*C_{4,1,t}$ PCI 49.52
IMPORT r		
parameter	**description**	**value**
Imp_r^{max}	Maximal import	$r1$ $r2$ $r3$ $r5$ $r6$ 106.3 2.1 30 0 0
EXPORT r		
parameter	**description**	**value**
Exp_r^{max}	Maximal export	$r1$ $r2$ $r3$ $r5$ $r6$ 0 0 0 0 108.3

as the industrial boiler is shut down, the whole hot water demand of the district heating network is satisfied by destocking hot water from the heat storage and mixing with others sources. Compared to the previous decoupled system, the recovery saves 82.7% of wood,

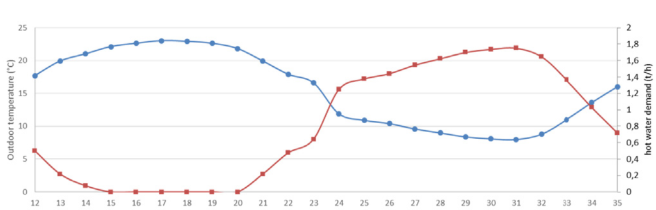


Fig. 18. Outdoor temperature and district heating network demand profile.

since only 21.1 kg of wood is required in this configuration. To cover the demand in hot water, part of the industrial waste heat was consumed, saving 2.22 GJ, i.e. 2.2% of the total available waste heat. Table 13 enables to compare the performances of the three sce narios and highlights the benefits of a coupled configuration introducing storage. Even if only 2% of produced waste heat is valorized, more than 80% of the heat required for district heating network comes from the industrial waste heat (see Fig. 24).

The MILP model corresponding to this scenario with storage and heat losses is composed of 125672 constraints, 91088 variables including 360 binary variables and 390184 non zero elements including 113784 non linear N Z elements. The resolution of this model is carried out with SCIP on an Intel Core™ i7 6500U pro cessor, 2.5 GHz, 16 GB RAM. Its convergence induces a significant resolution time (limited here to 20 h, explaining the reason for the

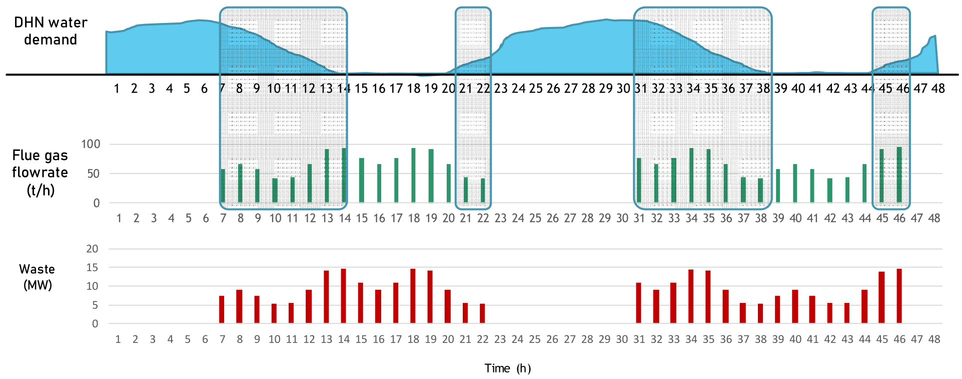


Fig. 19. KPI profiles for the decoupled scenario.

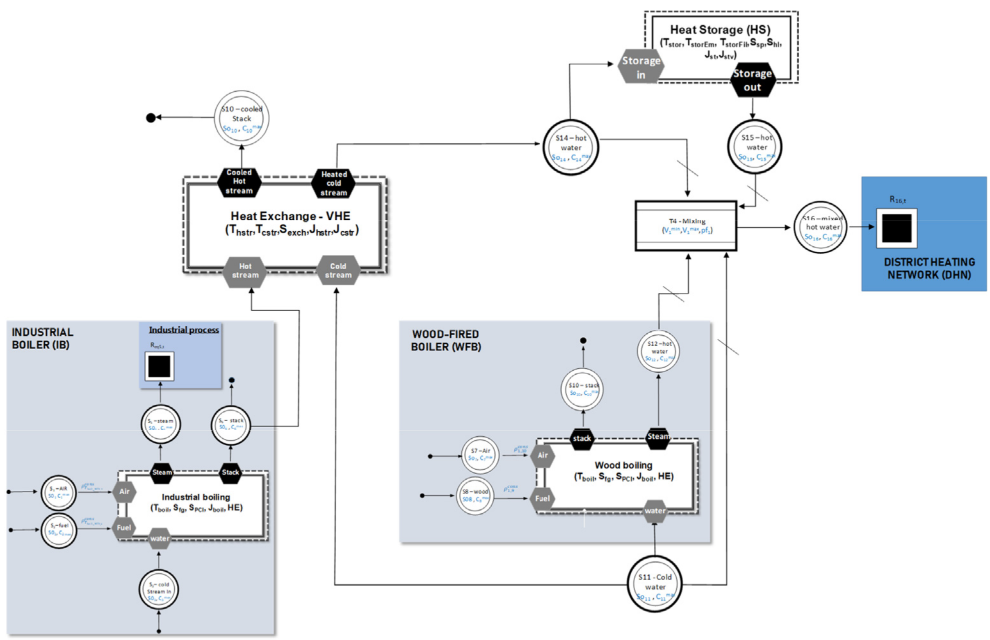


Fig. 20. EERTN model of the coupled system with heat storage.

use of the wood boiler despite the availability of the hot water in stock in periods 25 and 29). To improve the convergence, the alternative solution is to explicitly favour the use of valorization and storage by introducing supplementary constraints rather than leaving the choice to the objective function.

8. Conclusion

External valorization of waste heat constitutes a significant way of improving the energy efficiency of process. Assuming that the technological solutions had been previously defined, this work brings a significant contribution to this waste heat supply chain. More specifically, this document describes a new formalism for energy oriented planning of industrial systems. An original modeling formalism relying on the existing ERTN (Extended Resource Task Network) formalism has been introduced. The EERTN (Extended Energy Resource Task Network) formalism enables the modeling and planning of energy systems by including new semantic elements that lead to the automatic formulation of enthalpy balances. A global modeling approach coupling rigorous M.E.S.H modeling and EERTN planning then allows the instantiation of the EERTN graph and leads to the planning of the energy system. Applied on a reference system coupling an industrial site that generates waste heat (high temperature flue gas) and a district heating network that could consumes this heat, this approach permits to obtain a solution consisting in using the industrial flue gas to produced hot water directly used or stored to significantly reduce the consuming of costly wood. Moreover, this paper clearly demonstrates the benefits of a generic modeling of such systems. Using the EERTN formalism and especially the industrial boiler and heat storage macro tasks makes easier the modeling step and could suggests a great efficiency in the further study of other energy supply chains. However, one has to say that the extension of the ERTN to the EERTN formalism had required a transformation of MILP formulation into a much more complex MINLP one. Numerical issue resulting from this transformation (high computation time especially and global optimum not reached) should be addressed in the future. Definition of other macro task for the

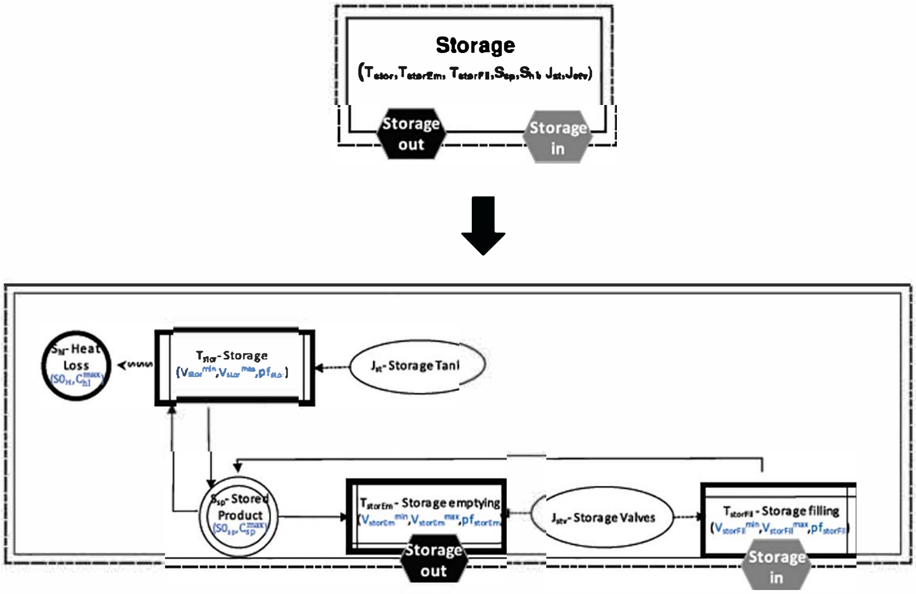


Fig. 21. EERTN model of sensible heat storage macro task.

Table 12
Parameters of the latent heat storage macro task.

TASK k boil: boiler, csh: cold Stream Heating, fgc: flue gas cooling			STATE r		
parameter	description	value	Parameter	description	Value
V_k^{min}	Minimal capacity	k T_{stor} 0 k T_{stor_emp} 0 k T_{stor_fil} 0	SO_r	Initial storage	r_{sp} 0
V_k^{max}	Maximal capacity	k T_{stor} 0/10 k T_{stor_emp} 0/3 k T_{stor_fil} 0/3	C_r^{max}	Maximal storage	r_{sp} 0
pf_k	duration	k T_{stor} 0 k T_{stor_emp} 1 k T_{stor_fil} 1	hs_r^{spec}	State potential	r_{sp} 0
ARC k,r			**ENERGY ARC & SPECIFIC EQUATIONS r,k,t**		
parameter	description	value	Parameter	description	Value
$\rho_{k,r}^{cons}$	weight	r_{sp} k T_{stor} 1 k T_{st_emp} 1 k T_{st_fill} 0	Q_{pertes}	Heat Losses	$F_{flueGas}*\Delta h_{flueGas}$ $\Delta h_{flueGas}$ 100 J/kg
$\rho_{k,r}^{prod}$	weight	r_{sp} k T_{stor} 1 k T_{st_emp} 0 k T_{st_fill} 1			

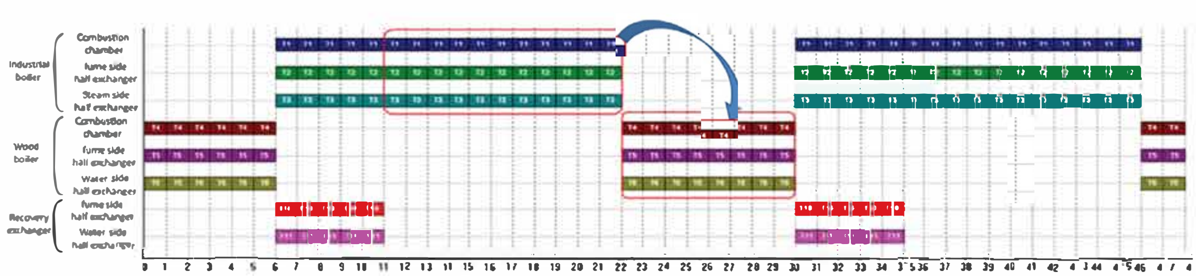


Fig. 22. Planning of the coupled system without storage.

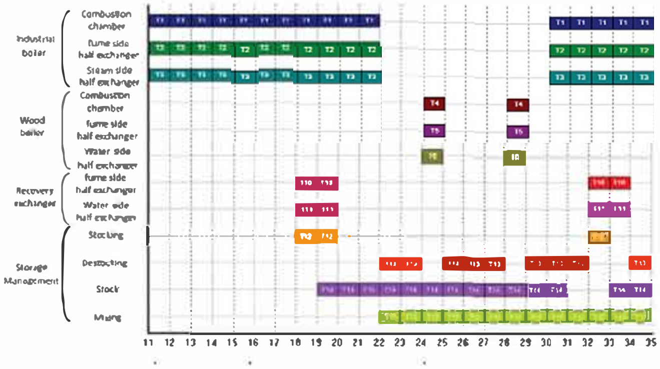


Fig. 23. Planning of the coupled system with heat storage.

Table 13
KPI of the three scenarios.

	No valorization	Direct valorization	Valorization and storage
Available waste heat (GJ)	167,8		
Wood Consumption (kg)	244	155	21
Wood Economy (%)	0	37	83
Lost waste Heat (GJ)	167,8	166,1	97,1
Valorized waste heat (%)	0	1	2
Water fraction produced by waste heat valorization (%)	0	36,5	82,7

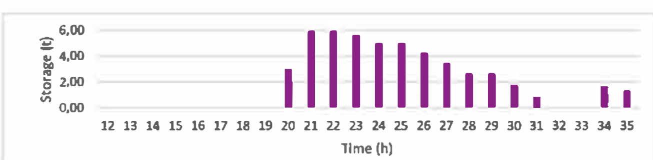


Fig. 24. Storage level during the planning horizon.

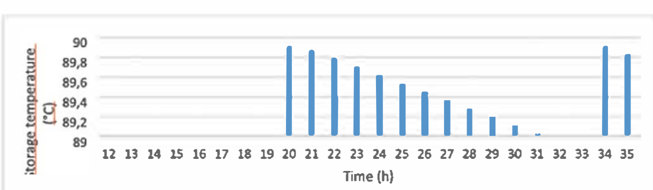


Fig. 25. Temperature of water in storage tank during the planning horizon.

modeling of innovative energy systems (heat pump, organic Rankine Cycle, gas turbine …) will also be performed and tested on new waste heat supply chain.

Credit author statement

Raphaele Hétreux, Methodology, Writing original Draft. Gilles Hétreux, Software, Methodology, Writing original Draft. Pascal Floquet, Reviewing. Alexandre Leclercq, Conceptualization, Investigation.

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.

Acknowledgment

This work was financially supported by the Ministry of Higher Education, Research and Innovation.

Nomenclature

Indexes

- t — period
- k — task
- m — disjunctive resource
- r — cumulative resource
- e — enthalpy resource

Sets

- T — time periods with NP $card(T)$
- K^{dd} — purely discontinuous task k where the consumption and production are discontinuous
- K^{cc} — purely continuous task k where the consumption and production are continuous
- K^{dc} — mixed task k where the consumption is discontinuous and the production is continuous
- K^{cd} — mixed task k where the consumption is continuous and the production is discontinuous
- K^{BE} — tasks with enthalpy balance
- K^{SBE} — tasks without enthalpy balance
- K — all tasks such as K $K^{d} \cup K^{c}$ $K^{BE} \cup K^{SBE}$
- R^{D} — disjunctive resources
- R^{CSP} — cumulative resources without thermal potential
- R^{CP} — cumulative resources with thermal potential
- R^{C} — cumulative resources with R^{C} $R^{CP} \cup R^{CSP}$
- R^{E} — enthalpy resources
- R_k^{cons} — cumulative resources r consumed by the task k
- R_k^{prod} — cumulative resources r produced by the task k
- R_e^{cons} — enthalpy resources e consumed by the task k
- R_e^{prod} — enthalpy resources e produced by the task k
- K_m — tasks k that can be executed on the disjunctive resource m
- K_r^{cons} — tasks k consuming the cumulative resource r
- K_r^{prod} — tasks k producing cumulative resource r
- K_e^{cons} — tasks k consuming enthalpy resource e
- K_e^{prod} — tasks k producing enthalpy resource e
- V — set of decision variable or state of the model

Parameters

- V_k^{min} — minimum flow rate (in mass units/period) through the equipment performing operation k
- V_k^{max} — maximum flow rate (in mass units/period) through the equipment performing operation k
- pf_k — duration of task k in periods
- C_r^{max} — maximum quantity of cumulative resource r that can be stored
- $S0_r$ — quantity of cumulative resource r in stock at t 0
- $T0_r$ — temperature of cumulative resource r at t 0
- $Policy_r$ — storage policy of cumulative resource r. The alternatives are either *UIS (Unlimited Intermediate Storage* $\rightarrow$ C_r^{max} ∞*), FIS (Finite Intermediate Storage* $\rightarrow$ $0 < C_r^{max} < +\infty$) or *ZW (Zero Wait* $\rightarrow$ C_r^{max} 0 and immediat transfert between amont and aval equipment*)*
- Cp_r — calorific capacity of cumulative resource r
- T_{ref} — reference temperature of the system
- $\rho_{r,k}^{cons}$ — mass proportion of cumulative resource r consumed by the task k

$\rho^{prod}_{r,k}$ mass proportion of cumulative resource r produced by the task k

$\mu^{cons}_{r,k}$ $\mu^{cons}_{r,k}$ 1 indicates that the cumulative resource r is consumed by task k, otherwise 0

$\mu^{prod}_{r,k}$ $\mu^{prod}_{r,k}$ 1 indicates that the cumulative resource r is produced by task k, otherwise 0

$uv^{cons}_{k,r}$ coefficient of the variable part of the resource consumption r by task k

$uf^{cons}_{k,r}$ coefficient of the fixed part of the resource consumption r by the task k

$uv^{prod}_{k,r}$ coefficient of the variable part of the production of resource r by the task k

$uf^{prod}_{k,r}$ coefficient of the fixed part of the production of resource r by the task k

Imp^{max}_{r} : maximum quantity or flow rate of resource r to be imported per period

$hImp_{r,t}$ specific enthalpy of resource r imported per period t

Exp^{max}_{r} : maximum quantity or flow rate of resource r to be exported per period

$Dem_{r,t}$ total mass of flow rate of resource r externally requested for period t

$App_{r,t}$ total mass or flow rate of resource r externally supplied for period t

$hApp_{r,t}$ specific enthalpy of resource r externally supplied for period t

Variables

$W_{k,t}$ $W_{k,t}$ 1 if the task $k \in K$ is started in period t, 0 otherwise,

$B_{k,t}$ quantity or flow rate processed by task k during period t

$hB_{k,t}$ specific enthalpy of quantity or flow rate processed by task k during period t

$S_{r,t}$ cumulative resource quantity r in stock at the end of period t

$S'_{r,t}$ quantity of resource r in stock at the end of the time zone ❶ in period t

$h'_{r,t}$ specific enthalpy of the resource r in stock at the end of the time zone ❶ of period t

$S''_{r,t}$ quantity of resource r in stock at the end of the time zone ❷ of period t

$h''_{r,t}$ specific enthalpy of the resource r in stock at the end of the time zone ❷ of period t

$T_{r,t}$ temperature of resource r at the end of period t

$h_{r,t}$ specific enthalpy of the resource r at the end of period t

$UC_{r,k,t}$ quantity or flow rate of resource r consumed by task k during period t

$UP_{r,k,t}$ quantity or flow rate of resource r produced by task k during period t

$C_{r,k,t}$ quantity or flow rate of resource r consumed by task k during period t

$hC_{r,k,t}$ specific enthalpy of resource r consumed by task k during period t

$P_{r,k,t}$ quantity or flow rate of resource r produced by task k during period t

$hP_{r,k,t}$ specific enthalpy of resource r produced by task k during period t

$QP_{e,k,t}$ quantity or flow rate of enthalpy resource e produced by task k during period t

$QC_{e,k,t}$ quantity or flow rate of enthalpy resource e consumed by task k during period t

$Imp_{r,t}$ total mass or flow rate of resource r imported in period t

$Exp_{r,t}$ total mass or flow rate of resource r exported in period t

$hExp_{r,t}$ specific enthalpy of resource r exported in period t

$hDem_{r,t}$ specific enthalpy of resource r externally requested in period t

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2020.118970.

References

[1] Galindo M, Oger-Lacan C, Garset U, Aumaitre V, European Commission. Strategy on heating and cooling - efficient District heating and cooling market in the E.U. : case studies analysis, replicable key success factors and potential policy implications. EU sicence Hub, Publication Office Of The European Commision; 2017. February 2016.
[2] ADEME. La chaleur fatale industrielle. Angers; 2017.
[3] Prasad RD, Bansal RC, Raturi A. Multi-faceted energy planning: a review. Renew Sustain Energy Rev 2014;38:686 99.
[4] Huang Z, Yu H, Peng Z, Zhao M. Methods and tools for community energy planning: a review. Renew Sustain Energy Rev 2015;42:1335 48.
[5] Shankar A, Subramanian R, Gundersen T, Adams II TA. Modeling and simulation of energy systems: a review. Processes 2018;6:238.
[6] Demirhan CD, Tso WW, Ogumerem GS, Pistikopoulos EN. Energy systems engineering - a guided tour. BMC Chemical Engineering 2019:1 11.
[7] Payet L, Thery-Hétreux R, Hétreux G, Bourgeois F, Floquet P. Flexibility assessment of heat exchanger networks: from a thorough data extraction to robustness evaluation. Chemical Engineering Research and Design; 2018. p. 571 83.
[8] Gourmelon S, Thery-Hetreux R, Floquet P, Baudouin O, Baudet P, Campagnolo L. Exergy analysis in ProSimPlus® simulation software: a focus on exergy efficiency evaluation. Comput Chem Eng 2015;79:91 112.
[9] Luo A, Fang H, Xia J, Lin B, Jiang Y. Mapping potentials of low-grade industrial waste heat in Northern China. Resour Conserv Recycl 2017;125:335 48.
[10] Kurle D, Schulze C, Herrmann C, Thiede S. Unlocking waste heat potentials in manufacturing. In: The 23rd CIRP conference on life Cycle engineering, vol. 48; 2016. p. 289 94.
[11] Wang X, Jin M, Feng W, Shu G, Tian H, Liang Y. Cascade energy optimization for waste heat recovery in distributed energy systems. Appl Energy 2018;230: 679 95.
[12] Simeoni P, Ciotti G, Cottes M, Meneghetti A. Integrating industrial waste heat recovery into sustainable smart energy systems. Energy 2019;175:941 51.
[13] Dou Y, Togawa T, Dong L, Fujii M, Ohnishi S, Tanikawa H, Fujita T. Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: a case in Fukushima, Japan, , Resources. Conserv Recycl 2018;128:406 16.
[14] Bohlayer M, Zottl G. Low-grade waste heat integration in distributed energy generation systems - an economic optimization approach. Energy 2018;159: 327 43.
[15] Han Y, Zhao Q, Han P, Li Y. Cost-efficient multi-energy management with flexible complementarity strategy for energy internet, F. Si, J. Wang. Appl Energy 2018;231:803 15.
[16] Silvente J, Aguirre AM, Zamarripa MA, Mendez CA, Graells M, Espuna A. Improved time representation model for the simultaneous energy supply and demand management in microgrids. Energy 2015;87:615 27.
[17] Parisio A, Del Vecchio C, Vaccaro A. A robust optimization approach to energy hub management. Electrical Power and Energy Systems 2012;42:98 104.
[18] Zulkafli NI, Kopanos GM. A general optimization framework for the design and planning of energy supply chain networks:Techno-economic and environmental analysis. Chem Eng Res Des 2018;131:214 33.
[19] Dotzauer E. Experiences in mid-term planning of district heating systems. Energy 2003;28:1545 55.
[20] Keller F, Reinhart G. Energy supply orientation in production planning Systems,13th global conference on sustainable manufacturing. Proceedings CIRP 2016;40:244 9.
[21] Si Fangyuan, Jinkuan Wang, Yinghua Han, Qiang Zhao, Peng Han, Yan Li. Cost-Effective multi-energy management with flexible complementary strategy for energy internet. Applied Energy 2018;23:803 15. https://doi.org/10.1016/j.apenergy.2018.09.152.
[22] Javier Silvente, Adrian M Aguire, Miguel A Zamarippa, Carlos A Mendez, Moises Graells, Antonio Espuna. Improved time representation model for the simultaneous energy supply and demand management in microgrids. Energy 2015;87:615 27. https://doi.org/10.1016/j.energy.2015.05.028.
[23] Théry R, Hétreux G, Agha M. The extended resource task network : a framework for the combined scheduling of batch processes and CHP Plants. Int J Prod Res 2012;50(3):623 46.
[24] Agha M, Théry M, Hétreux G, Hait A, Le Lann JM. Integrated production and utility system approach for optimizing industrial unit operations. Energy 2010;35:611 27.
[25] Kondili E, Pantelides CC, et Sargent RWH. A general algorithm for short-term scheduling of batch operations I MILP formulation. Comput Chem Eng 1993;17(2):211 27.
[26] Maravelias CT, Grossmann IE. Minimization of the makespan with a discrete-time State-Task network formulation. Ind Eng Chem Res 2003;42:6252 7.