A tactical maintenance optimization model for multiple interconnected energy production systems

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Abstract

Multiple interconnected energy production systems are a common solution to satisfy the energy demand of industrial processes. Such energy demand is usually the combination of various energy types such as heat and electricity. This implies the installation of different technologies able to produce one or multiple energy types, to satisfy all energy needs. However, multiple interconnected energy production systems may be extremely challenging from a management point of view.

In this paper we investigate fundamental issues related to the management of multiple interconnected energy systems. We develop a tactical optimization model for the maintenance operations' scheduling phase of Combined Heat and Power (CHP) plant. Specifically, we consider two types of cleanings operations, i.e., online cleaning and offline cleaning. Furthermore, we include a piecewise linear representation of the electric efficiency variation curve, accurately describing the impact of load and inlet air temperature inside the compressor on the electric efficiency of the CHP plant.

Given the challenge in solving the tactical management model, we propose a heuristic algorithm. The heuristic works by solving the daily operational production scheduling problem, based on the final consumer's demand and on the electricity market price. The aggregate information from the operational problem is used to derive maintenance decisions at a tactical level.

Keywords: *multiple interconnected energy production systems, CHP plants, operational model, tactical model, electric efficiency variation curve, maintenance operations' scheduling*

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1. Introduction

During the last decades, there has been an increasing trend in developing more economically and environmentally efficient energy production technologies. Undoubtedly, the needs for coping with the climate change threat and for keeping the commitments taken up by several countries by signing the Kyoto-Protocol, represent further key drivers towards pushing the changes the energy sector is undergoing. Considering the Italian context, *distributed energy generation* has been incetivized, resulting in an increasingly decentralization of energy production plants, see Chicco et al.[3] for further details.

In the distributed energy production context, an important role has been played by *self-consumption*, meaning that a portion of the distributed energy generation is consumed in place. This option has widespread lately as a consequence of its potential in improving the security of energy supply. Therefore, self-consumption has been undertaken not just in the domestic field, but also in the industrial one, where this concept is even more important considering the massive consumption that most of industrial processes need to handle.

The energy demand of industrial processes is usually the combination of various energy types such as heat and electricity. The most commonly adopted self-consumption framework, as for now, is coupling multiple interconnected energy production systems, see Illerhaus et al.[7]. This implies the installation of different technologies able to produce one or multiple energy types, to satisfy all energy needs.

It must be said that multiple interconnected energy production systems, even though very convenient, may be extremely challenging from a management point of view. The challenge comes principally from a need to achieve a perfect synchronization between the different energy production facilities, when operating the whole system. All the difficulties related to running an energy production plant, are extended to a group of plants. To achieve an optimal management of multiple interconnected energy production systems, a proper modelling of the system needs to be performed.

Zooming inside the multiple interconnected energy production system, a further analysis needs to be done over one specific technology, which is the cogeneration of Combined Heat and Power (CHP). This technology can be frequently found in industrial power systems, because of its capacity of simultaneously providing different kinds of energy, and because it has shown itself as crucial in terms of efficiency in energy savings, see Illerhaus et al.[7]. Even though these facilities may be interesting especially when applied in multiple interconnected energy production systems configurations, scheduling their production and maintenance is challenging. Optimal management in this case is of extreme importance, to run CHP plants at best, and subsequently to meet the target profit expected during the investment's phase.

Several studies centered on optimizing CHP plants' management have been conducted in the past. For example Gardner et al.[6] and Chicco et al.[4] treated this electrical efficiency as a constant. As observed by Lozza[10], electric efficiency is non linear with respect to the load at which the plant is operated, and according to the external environment's conditions of the site where the plant is located, in particular to the environment's air temperature. Therefore its simplification could lead to an overestimation of what is the real functioning of the CHP plant. Another aspect of managing a CHP plant that has been neglected in past optimization models, is the scheduling of maintenance operations. There are several kinds of maintenance operations, often requiring a partial periodic shutdown of the production operations. Therefore, optimizing the scheduling of such maintenance operations is fundamental. The maintenance activities are typically of a tactical nature, i.e., they need to be planned in during the upcoming year. Thus embedding maintenance planning in the energy production schedules of multiple interconnected energy systems requires considering a tactical planing horizon, which is substantially longer than the typical daily planning horizon considered for operational energy production optimization problem.

The scientific aim of the this paper is model and solve the tactical maintenance optimization problem encountered in multiple interconnected energy production systems. We based our models on a specific case study, with three energy production facilities (one CHP plant and two Dual Fuel boilers). We propose optimization models for both operational and tactical production planning. We implement a tactical management model for the maintenance operations' scheduling phase of the CHP plant, which is essential to reach a correct and complete understanding of the system. We specifically considered two cleaning options, i.e., online and offline. Furthermore include a piecewise linearization procedure of the efficiency variation curve as a function of load and inlet air temperature inside the compressor. Given the challenge in solving the tactical management model, we propose a computationally efficient heuristic algorithm. To do so, we develop a basic operational model for production scheduling based on the final consumer's demand, and on the electricity market price. The aggregate information from the operational problem is used to derive maintenance decisions at a tactical level. The remainder of this paper is organized as follows. Section 2 presents a literature review of the topics discussed in this paper. Section 3 formally presents the tactical management of maintenance operations of multiple energy systems problem and the proposed solution method. Section 5 shows the computational results. Finally, Section 6 concludes and outlines research perspectives.

2. Literature review

As previously discussed, the use of multiple energy systems has recently become a commonly adopted solution in the energy production field. At the same time, it also raises a need to find proper tools to model its complex management, creating new interesting topics for the scientific community.

Mancarella and Chicco[11] use the *black-box-approach* to capture the relevant energy efficiency relationships (including off design performance models), while reducing the level of complexity. According to this approach, the system is reduced to its energy production part, that becomes the core of the problem, and it is set up to supply the time-varying demand.

Lahdelma and Hakonen[9] focus on the optimization of the single CHP plant's production scheduling problem. They model the hourly CHP operation as an LP problem, where the hourly electric power production and heat production of the CHP plant must be contained within a characteristic region of operation, assumed to be convex. Consequently the production of the CHP plant for each time interval is found as a convex combination of the extreme characteristic points of this region of operation.

Ladhelma and Hakonen[9] has triggered further research in several directions. Kumbartzky et al.[8] start from Lahdelma and Hakonen's model to demonstrate how participating into the electricity market may be profitable for CHP plants, which are usually used for self-consumption. Wang et al.[16] extend the problem to a multiple energy system. The cost is allocated directly to the product, meaning heat and power, without differentiating between all of its components, such as fuel or maintenance costs. A similar assumption has been adopted in the work of Rong et al.[14] . This seems correct according to the time interval of at most one month at which the algorithm works. However, in reality decisions such as maintenance operations are usually taken given a larger time interval, such as one year.

Milan et al.[13] focus mainly on the efficiency curves of the CHP plant. The authors seek to solve a non-linear model representing these curves, showing that the system's performance was affected considerably, when considering the effects of a variable efficiency. However, the solution found by Milan et al.[13] creates a non-linear problem, which is significantly more complex than linear problems.

Bischi et al.[2] present a data-driven MILP model for planning the short-term operation of combined cooling, heat and power (CCHP) energy systems. This work adds to previous studies a penalization of start-up operations of production facilities, and an effective handling of production units with non-linear performance curves. Bischi et al.[2] apply a piecewise linear approximation of performance curves considering a different number of intervals, that can vary with temperature during the planning horizon.

The previously presented approaches concentrated on short time intervals, neglecting the effect that the scheduling of maintenance operations may have on operating the system, especially on the CHP plant. In this sense, many studies and insights have led to a deep understanding of the real effects of maintenance operations on the CHP plant. Aretakis et al.[1] present a method to predict the impact of the compressor's cleaning process on the power plant's overall profit, focusing on an offline type of cleaning of the compressor. This way other types of cleanings are neglected, which has been proven to be sub-optimal from other studies, e.g. Meher-Homji[12]. Ogbonnaya[15] concentrated mainly on the consequences that an online cleaning has when conducted on a compressor, but proceeds further by considering a combination with offline cleaning. Even though this article does not develop an optimization model, it highlights the importance that a combination of compressor online and offline washing may have on the performance of the plant.

To the best of our knowledge, the tactical problem we introduce in this paper is the first to simultaneously take into account the management of multiple interconnected energy systems, the impact of load and inlet air temperature inside the compressor on the electric efficiency of the CHP plant, and the maintenance operations' scheduling phase of the CHP plant.

3. Problem description and formulation

In this section we present optimization models for multiple interconnected energy production systems. We present in section 3.3 a tactical management (TM) model which accounts for scheduling maintenance activities along with production operations. We include a piecewise linearization of the efficiency variation curve with load and inlet air temperature inside the compressor in section 3.1.

A simplified scheme of the system considered is depicted in Figure 1.

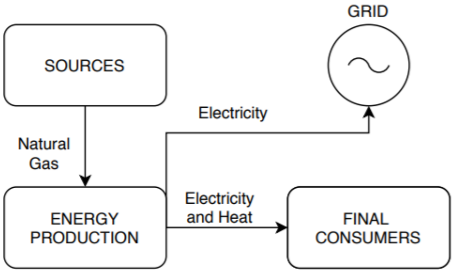

Figure 1: System studied

The system considered can be divided in three main parts: sources, utilities that produce electrical and thermal energy and final consumers. The main input, that has to be provided to the whole system in order to satisfy the final demand, is *natural gas*. The natural gas coming from the sources is processed inside the utilities in order to produce *electric energy* and *thermal energy* to satisfy the demand of the final consumers. In order to do so, three main components are currently used: a CHP plant, based on a Gas Cycle in combination with a Heat Recovery Steam Generator (HRSG), and two Dual Fuel Boilers. A further consideration needs to be done for electric energy. In fact this final product represents a further income, since it can be sold on the electricity market and subsequently injected into the grid. This depends mainly on whether the production exceeds the self-consumption or not, coupled with the electricity market price. Similarly the grid can be considered as a source of electric energy, whenever the production of the utilities does not meet the expected values.

The planning horizon is divided into $t \in \{0, ..., T\}$ hourly intervals. Note that this can be adjusted to meet the needs of the application of the model. We denote as K the set of final consumers and U the set of utilities that need to fulfill the demand. Moreover, $B \subseteq U$ represent those utilities that produce only thermal power.
For each time interval the demand of user $k \in K$ is given in terms of electric energy P_k^t and thermal energy Q_k^t, measured as $[kWh]$. Several parameters are related to the thermodynamic characteristics of the system. The efficiency of utility $b \in B$, is denoted by η_b. The maximum and minimum daily energy production limits for utility $u \in U$ are $P_{u,max}$ and $P_{u,min}$, whereas the maximum and minimum daily energy production limits for utility $u \in U$ are $Q_{u,max}$ and $Q_{u,min}$.
The decision variable P_u^t quantifies the electric energy produced by the utility $u \in U$ in time t. The decision variable Q_u^t quantifies the thermal energy produced by the utility $u \in U$ in time t. Furthermore binary variable y_u^t takes the value of one if utility $u \in U$ is operating in t, and zero otherwise.
Based on Ladhelma et al. [9], considering the CHP plant, a set J_{CHP} of characteristic points is given. Each point $j \in J_{CHP}$ has coordinates in terms of electric energy p_j and thermal energy q_j, these four points determine the operational limits of the CHP plant. Namely, the operating values of thermal and electric energy of the CHP plant, Q_{CHP}^t and P_{CHP}^t, hence will be calculated as a convex combination of the points in J_{CHP}. In order to do this, it is necessary to introduce a continuous variable $x_j^t \in \{0, 1\}$, associated to each characteristic point of the feasible region at time $t \in \{0, ..., T\}$.
Let $V_{NG,u}^t$ be the continuous variable that represents the volumetric flow rate of natural gas consumed by each energy production utility $u \in U$ in time t, measured as $[Sm^3/h]$. Natural gas is the main fuel needed to supply each production plant, and is usually expressed in terms of primary thermal energy thanks to a parameter, the Lower Heating Value (LHV). The LHV represents the amount of energy obtainable by the use of that specific fuel and is expressed as $[MJ/Sm^3]$. We can then define the cost of natural gas according to the natural gas market as C_{NG} $[€/Sm^3]$. This cost is the result of an agreement between the plant operator and the natural gas market operator, and stays constant throughout the whole time period considered. The system can either withdraw electric energy from the grid to compensate for a lack in electric

energy production by the CHP plant, or it can sell surplus of electric energy production to the grid. We denote as $P^t_{grid,in}$ the amount of electricity that is being withdrawn from the grid and is entering the system at time t. While $P^t_{grid,out}$ represents the amount of electricity that is being injected into the grid and exiting the system at time t. Both these variables are each linked to a binary variable, respectively $w^t_{grid,in}$ and $w^t_{grid,out}$, that express whether or not the electricity is being withdrawn or injected in time t.

The price of electricity established by the electricity market at t is given by PUN^t. We recall that in the italian context the hourly electricity prices are essentially known one day in advance of the actual production day. Therefore, we assume them to be known parameters. Furthermore, since we aim at constructing a tactical management model, we assume that any surplus production can be sold to the grid.

Other economic aspects that have been considered to evaluate the model are related to incentives. The incentives are calculated for every $t \in \{0, ..., T\}$ with respect to the energy savings, that the cogeneration of heat and power simultaneously creates. We denote the energy savings in period t by TEE^t. The revenue connected to each incentive produced at t, is given by R_{TEE} [€/TEE].

3.1. Electric efficiency variation according to load and temperature

The electric efficiency of a CHP plant can substantially change according to the inlet air temperature inside the compressor, and according to the load at which the plant is operated. Such changes are usually of a non-linear nature and can be expressed through various curves. Starting from the relationship between temperature and electric efficiency, Figure 2 shows exactly this concept extended for each load level at which the plant can be operated.

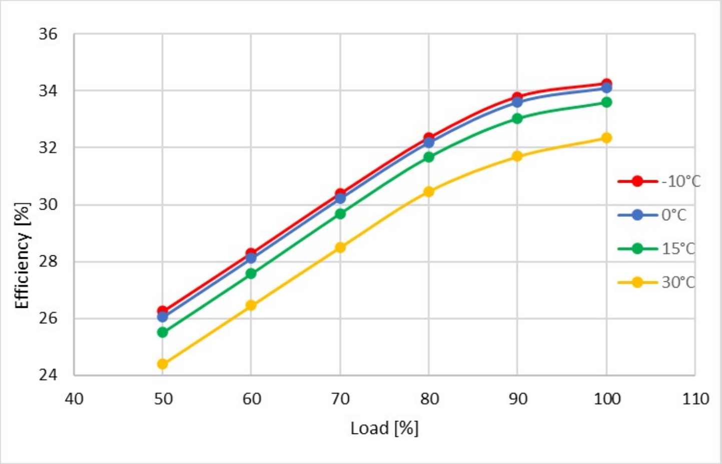

Figure 2: Efficiency correlation with inlet air temperature for each load level of the CHP plant

The data-points corresponding to the curves in Figure 2 are given to the plant's operator as tabled values, where load levels and temperature values are the ones indicated on the plot. One must consider that the inlet air temperature inside the compressor is dependent on external weather conditions of the site where the plant is located. This of course if an air treatment unit, such as a cooler, has not been installed before the compressor. Hence the inlet air temperature is usually a value known a priori, and is not affected by the decision making process inside the optimization model.

It seemed correct not to include the temperature-efficiency correlation inside the optimization model, as a constraint. Instead it has been implemented as a function, that we define as efficiency variations function (EVF). Given as input the inlet air temperature inside the compressor, the EVF calculates the relative electric efficiency-load curve. This curve is then introduced inside the optimization model as an input parameter. Figure 3 explains how the EVF actually works.

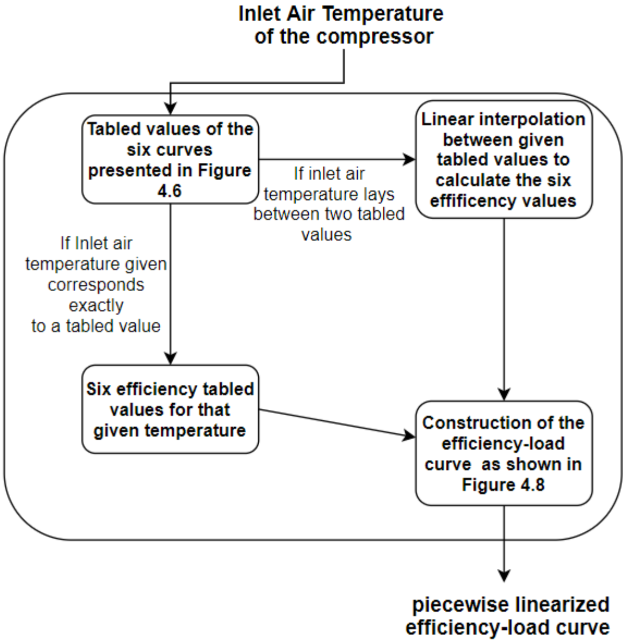

Figure 3: Process of the EVF

A last consideration needs to be made before proceeding further. Considering the electric efficiency of the CHP plant as a variable may result in non-linear constraints. In order to avoid this, the efficiency-load curves were actually transformed to correlate directly natural gas consumption $V^t_{NG,CHP}$ to load. What is obtained is a curve that relates a non-dimensional natural gas consumption $\frac{(V^t_{NG,CHP}\ LHV)}{P_{CHP,max}}$ to load. To model the piecewise linear efficiency variations we introduce the set of intervals of the EVF $d \in \{1, .., D+1\}$, where D is the number of break-points, and the parameters m_d, that represents the inclination of the piecewise linearization of the curve between $d-1$ and d for $d \in \{1,..,D+1\}$, and q_d that represents the intercept of the piecewise linearization of the curve between $d-1$ and d.

Moreover, we introduce L_d^t, that represents the decisional variable associated to the piecewise linearization of the curve between $d-1$ and d in $t \in \{1,...,T\}$, and z_d^t, that represent the binary variable connected to the piecewise linearization of the curve between $d-1$ and d in $t \in \{1,...,T\}$.

3.2. Maintenance operations

This subsection will focus on maintenance operations on the compressor, in order to reduce the degradation of this component due to fouling. Maintenance operations are essential, in order to better model the real functioning of the CHP plant. We focus on two possible cleaning options on the compressor. The two options are online cleaning and offline cleaning, and are quite different in the way they must be executed, in their duration and in their impact on the CHP plant's performance.

We now discuss how the fouling phenomenon was included in the optimization model. According to Lozza [10], a constant degrading rate of performance of the CHP plant can be observed, with respect to its cumulative operating hours. The consumption calculated through the EVF, does not consider the degrading phenomena of performance connected to fouling. In fact, one can say it represents a theoretical consumption for each period $t \in \{1,...,T\}$. Therefore, from now on we will refer to it as $V_{NG,th}^t$. Based on real historical data of the considered system, the fouling phenomenon directly impacts on the non-dimensional consumption curve. This results in an increase in non-dimensional consumption for every period $t \in \{1,...,T\}$, $\frac{(V_{NG,CHP}^t\ LHV)}{P_{CHP,max}}$, of a constant rate denominated as ΔFl.

The considered online cleaning can be performed without turning off the CHP plant, but it still hinders its maximum electric energy production $P_{CHP,max}$ to $P_{reduced}$. An online cleaning activity takes two hours, once performed the CHP plant does not have to undergo other cleaning activities for a maximum period L_{on}, which in our case is of fifteen days.

The considered offline cleaning, once performed, involves the complete shut down of the CHP plant for at least four hours. The time interval that has to pass between an offline cleaning and another maintenance operation (i.e., online cleaning or offline cleaning), is at most L_{off}, in our case sixty days. The added value of offline cleaning ΔOff, is greater than that of online cleaning ΔOn, measured on non-dimensional natural gas, $\frac{(V_{NG,CHP}^t\ LHV)}{P_{CHP,max}}$. Therefore, there exists a trade-off between the number of cleanings and the degrading rate of fouling.

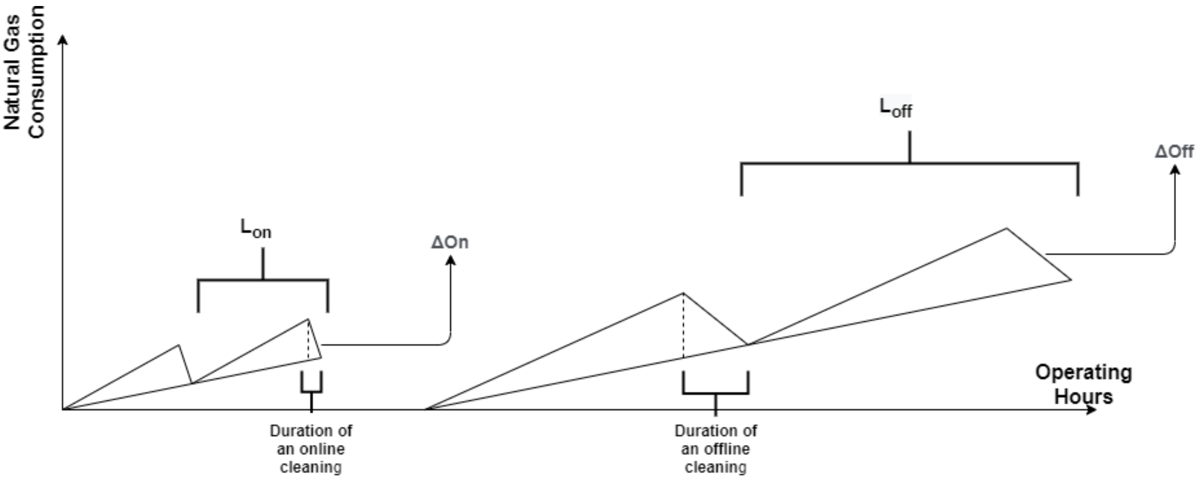

Figure 4: Effects of maintenance operations on non-dimensional consumption worsening due to fouling

The additional decision variables used in the mathematical formulation of the model are all binary variables, and are defined as follows. Variable s^t refers to whether or not a maintenance operation is performed on the CHP plant in periood t. Variable r^t indicates whether or not an online cleaning is performed on the CHP plant in t, while variable o^t indicates whether or not an offline cleaning is performed on the CHP plant in t. Finally variable q^t takes the value of one if a maintenance activity occurs in t or if the most recent maintenance activity wasn't an online cleaning, while variable u^t indicates if a maintenance activity occurs in t, or if the most recent maintenance activity wasn't an offline cleaning.

3.3. Tactical management model

Table 1 summarizes all sets, parameters and variables definitions discussed in this section. The TM model is thus stated as follows:

$$[\text{TM}] \text{ maximize} \sum_{t \in T} \sum_{u \in U} C_{NG} V_{NG,u}^t + PUN^t (P_{grid,out}^t - P_{grid,in}^t) + R_{TEE} TEE^t \tag{1}$$

s.t.

$$P_{u,min}\ y_u^t \leqslant P_u^t \leqslant P_{u,max}\ y_u^t\ \forall t \in \{0, ..., T\},\ u \in U \tag{2}$$

$$Q_{u,min}\ y_u^t \leqslant Q_u^t \leqslant Q_{u,max}\ y_u^t\ \forall t \in \{0, ..., T\},\ u \in U \tag{3}$$

$$Q_b^t = \eta_b\ LHV\ V_{NG,b}^t\ \forall t \in \{0, ..., T\},\ b \in B \tag{4}$$

$$P_{CHP}^{t} = \sum_{j \in J_{CHP}} p_j^t \ x_j^t \ \forall t \in \{0, ..., T\} \tag{5}$$

$$Q_{CHP}^{t} = \sum_{j \in J_{CHP}} q_j^t \ x_j^t \ \forall t \in \{0, ..., T\} \tag{6}$$

$$\sum_{j \in J_{CHP}} x_j^t \leqslant y_{CHP}^t \ \forall t \in \{0, ..., T\} \tag{7}$$

$$P_{grid,in}^{t} \geqslant \sum_{k \in K} P_k^t \ w_{grid,in}^t - \sum_{u \in U} P_u^t \ \forall t \in \{0, ..., T\} \tag{8}$$

$$P_{grid,in}^{t} \leqslant M \ w_{grid,in}^t \forall t \in \{0, ..., T\} \tag{9}$$

$$P_{grid,out}^{t} \leqslant \sum_{u \in U} P_u^t - \sum_{k \in K} P_k^t \ w_{grid,out}^t \ \forall t \in \{0, ..., T\} \tag{10}$$

$$P_{grid,out}^{t} \leqslant M \ w_{grid,out}^t \forall t \in \{0, ..., T\} \tag{11}$$

$$w_{grid,in}^t + w_{grid,out}^t \leqslant 1 \ \forall t \in \{0, ..., T\} \tag{12}$$

$$\sum_{u \in U} Q_u^t = \sum_{k \in K} Q_k^t \ \forall t \in \{0, ..., T\} \tag{13}$$

$$\sum_{u \in U} P_u^t + P_{grid,in}^t = \sum_{k \in K} P_k^t + P_{grid,out}^t \ \forall t \in \{0, ..., T\} \tag{14}$$

$$TEE^t = 0,0086 K_{TEE} \ (\frac{P_{CHP}^t}{\eta_{e,r}} + \frac{Q_{CHP}^t}{\eta_{th,r}} - LHV \ V_{NG,CHP}^t) \ \forall t \in \{0, ..., T\} \tag{15}$$

$$\frac{LHV \ V_{NG,CHP}^t}{P_{CHP,max}} \leqslant \sum_{d \in \{1,..,D+1\}} m_d \ L_d^t + q_d \ z_d^t \ t \in \{0, ..., T\} \tag{16}$$

$$z^t_{CHP,d}\ d^t_{d-1} \leqslant L^t_d \leqslant z^t_{CHP,d}\ d^t_d\ \forall t \in \{0,...,T\},\ d \in \{1,..,D+1\} \tag{17}$$

$$\sum_{d \epsilon \{1,..,D+1\}} z^t_d = y^t_{CHP}\ \forall t \in \{0,...,T\} \tag{18}$$

$$\frac{P^t_{CHP}}{P_{CHP,max}} = \sum_{d \in \{1,..,D+1\}} L^t_d\ \forall t \in \{0,...,T\} \tag{19}$$

$$\sum_{\tau \in (0,1,..L_{online}-1)} (1 - s^{t+\tau}) \leqslant L_{on} q^t + L_{off} u^t + (1 - q^t - u^t) M\ \forall t \in \{0,\ldots,T - L_{on} + 1\} \tag{20}$$

$$\sum_{\tau \in (0,1,..L_{off}-1)} (1 - s^{t+\tau}) \leqslant L_{off} u^t + (1 - u^t) M\ \forall t \in \{0,\ldots,T - L_{off} + 1\} \tag{21}$$

$$1 - s^t = q^t + u^t\ \forall t \in \{0,...,T\} \tag{22}$$

$$s^t = o^t + r^t\ \forall t \in \{0,...,T\} \tag{23}$$

$$r^t + q^t \leqslant 1\ \forall t \in \{0,...,T\} \tag{24}$$

$$o^t + u^t \leqslant 1\ \forall t \in \{0,...,T\} \tag{25}$$

$$P^t_{CHP} \leqslant P_{reduced} r^t + P_{max,CHP}(1 - r^t)\ \forall t \in \{0,...,T\} \tag{26}$$

$$P^t_{CHP} \leqslant P_{max,CHP}(1 - o^t)\ \forall t \in \{0,...,T\} \tag{27}$$

$$\begin{aligned} \frac{LHV\ V^t_{NG,CHP}}{P_{CHPmax}} &= \frac{LHV\ V^t_{NG,th}}{P_{CHPmax}} + \left(\frac{LHV V^{t-1}_{NG,CHP}}{P_{CHPmax}} - \frac{LHV\ V^{t-1}_{NG,th}}{P_{CHPmax}} \right) + \\ &- \Delta Off\ o^t - \Delta On\ r^t + \Delta Fl\ \forall t \in \{0,...,T\} \end{aligned} \tag{28}$$

$$u^t \geqslant o^{t-1} - o^t \ \forall t \in \{0, ..., T\} \tag{29}$$

$$w^t \geqslant r^{t-1} - r^t \ \forall t \in \{0, ..., T\} \tag{30}$$

$$Temp^t \geqslant 8r^t - (1 - r^t)M \ \forall t \in \{0, ..., T\} \tag{31}$$

$$\sum_{\tau \in (0,1)} r^{t+\tau} \geqslant 2(r^t - r^{t-1}) \forall t \in \{0, ..., T\} \tag{32}$$

$$\sum_{\tau \in (0,..,3)} o^{t+\tau} \geqslant 4(r^t - r^{t-1}) \forall t \in \{0, ..., T\} \tag{33}$$

The objective function (1) is the maximization of the plant's overall profit of the whole time period considered. The main costs that the plant has to face are connected to the cost of natural gas and to the cost of electricity, that has to be withdrawn from the grid whenever consumption exceeds production of the energy production utilities. The profit is a result of two main incomes, incentives and electricity sold to the grid.

Constraints (2) impose a lower and an upper bound to the electric energy production. While constraints (3) set a limit on the maximum and minimum thermal energy that can be produced by each facility when operated. Constraints (4) express the energy balance of the subset B, considering in this case a thermal efficiency that connects the outputs (Q_b^t) to the inputs (primary energy) of plant b.

Constraints (5) and (6) are used to calculate the production of the CHP plant as a convex combination of the points present inside the feasible operating region. While constraints (7) limit the variables representing the points of the region to whether the plant is operated in $t \in \{1, ..., T\}$ or not.

Constraints (8) and (9) define and regulate the amount of electricity withdrawn from the grid that enters the system in each period. While constraints (10) and (11) define and regulate the amount of electricity produced from the CHP plant that can be sold to the grid, because it is not needed by the final consumers. Constraints (12) regulate the fact that grid cannot be simultaneously withdrawn and injected to the grid. The following constraints represent the overall energy balances that regulate the system. The main limit here is given by the demand of the final consumers, that must be satisfied in every $t \in \{1, ..., T\}$. This balance is divided in two different sets of constraints, one for thermal energy, as one can see in constraints (13), and the other for electric energy, as one can see in constraints (14). Constraints (15) define the value of incentives for each t when the CHP plant is working.

Similar to Froger et al. [5], constraints (16)-(19) impose the piecewise linear curves in the model.

Constraints (20) and (21) determine the maximum time interval that can pass between two cleanings, with respect to which type of maintenance operation has been performed as last.

Constraints (22)-(25), determine all the consistency constraints between the binary variables.

Constraints (26) and (27) are constraints related to maximum capacities of electric energy, at which the CHP plant needs to be limited when a certain kind of cleaning is operated.

The real consumption of natural gas is determined through constraints (28). While constraints (29) and (30) determine the correlation between the binary variables of each cleaning. The last constraint (31) limits the minimum inlet air temperature inside the compressor $Temp^t$ at which an online cleaning can be performed, which is of 8°C in our case. Under this value there might be problems of water freezing on blades. Constraints (32) and (33) impose the minimum duration of each cleaning.

Table 1: Set, parameter and variable definitions of TM model

Sets	
$t \in \{1, ..., T\}$	Set of time intervals in which the planning horizon is divided into
$u \in U$	Set of utilities that produce electrical energy or thermal energy or both
$k \in K$	Set of final consumers
$j \in JCHP$	Set of characteristic points of the feasible region associated to CHP plant
$b \in B \subseteq U$	Set of utilities that produce just thermal energy
$d \in \{1, ..D + 1\}$	Set of intervals of the piecewise linearization of the efficiency curve, where D is the set of breakpoints
Parameters	
c_{NG}	Cost of natural gas expressed as €$/Sm^3$
PUN^t	Cost of electricity expressed as €/kWh for every t
R_{TEE}	Revenues associated to incentives expressed as €/TEE
LHV	Lower Heating Value of Natural Gas expressed as kJ$/Sm^3$
η_b	Efficiency of utility $b \in B$
$\eta_{e,r}$	Reference electric efficiency given by the electricity market
$\eta_{th,r}$	Reference thermal efficiency given by the electricity market
K_{TEE}	Coefficient given by electricity market
$P_{CHP,min}$	Minimum power boundary of the CHP plant, expressed as kWh
$P_{CHP,max}$	Maximum power boundary of the CHP plant, expressed as kWh
$Q_{b,min}$	Minimum power boundary of utility $b \in B$, expressed as kWh
$Q_{b,max}$	Maximum power boundary of utility $b \in B$, expressed as kWh
P_k^t	Electric energy flux needed each $t \in \{1, ..., T\}$ by $k \in K$,expressed as kWh
Q_k^t	Thermal energy flux needed each $t \in \{1, ..., T\}$ by $k \in K$,expressed as kWh
p_j, q_j	Coordinates of the characteristic points of the feasible operating region of the CHP plant
m_d	Inclination of linearization of the curve between $d - 1$ and d for $d \in \{1, ..D + 1\}$
q_d	Intercept of linearization of the curve between $d - 1$ and d for $d \in \{1, ..D + 1\}$
$P_{reduced}$	Maximum electric energy value of the CHP plant when an online cleaning is performed
L_{on}	Maximum period between an online cleaning and the next maintenance operation
L_{ff}	Maximum period between an offline cleaning and the next maintenance operation
ΔOn	Added value in terms of non-dimensional fuel consumption when an online cleaning is operated
ΔOff	Added value in terms of non-dimensional fuel consumption when an offline cleaning is operated
Variables	
x_j^t	Continuous variable associated to each characteristic point of set J_{CHP} in $t \in \{1, ..., T\}$
y_u^t	Binary variable that indicate whether $u \in U$ is producing in t
P_u^t	Electric energy flux produced in t by the utility $u \in U$
Q_u^t	Thermal energy flux produced in t by the utility $u \in U$
$P_{grid,out}^t$	Electricity flux injected to the grid in t
$P_{grid,in}^t$	Electricity flux withdrawn from the grid in t
$w_{grid,out}^t$	Whether on not electric energy is injected to the grid in t
$w_{grid,in}^t$	Whether or not electric energy is withdrawn from the grid in t
$V_{NG,u}^t$	Volumetric flow rate of natural gas consumed by each utility u in t
TEE^t	Incentives produced in t
$V_{NG,th}^t$	Theoretical volumetric flow rate of natural gas consumed by each utility u in t
L_d^t	Decisional variable associated to the piecewise linearization of the electric efficiency curve between $d - 1$ and d in t
z_d^t	Binary variable connected to the piecewise linearization of the electric efficiency curve between $d - 1$ and d in t
s^t	Whether or not a maintenance operation is performed on the CHP plant in t
r^t	Whether or not an online cleaning is performed on the CHP plant in t
o^t	Whether or not an offline cleaning is performed on the CHP plant in t
q^t	Whether or not a maintenance activity occurs in$t$ or if the most recent maintenance activity wasn't an online cleaning
u^t	Whether or not a maintenance activity occurs in t or if the most recent maintenance activity wasn't an offline cleaning

4. Heuristic for the tactical management model

As will be shown in Section 5.2, the TM model requires a substantial amount of computational time (e.g., more than 10 hours in our case study). Therefore, we now present a heuristic algorithm for the problem. The objective of the heuristic is to produce a high quality solution in a relatively short time. The tactical model works with a planning horizon of one year divided into hourly intervals, thus leading to T=56760. Therefore, applying the TM model results in a rather large MILP. We observe that ignoring the maintenance decisions leads to a much simpler model to solve. This is due to the fact that the linkage between the periods in the TM model is primarily due to the maintenance decisions. Therefore, we propose a heuristic for the TM model based on aggregation principles. We denote this heuristic by HTM. We define the Operational model with Efficiency Variations OEV, as the TM model without maintenance decisions. Therefore, the OEV model is the TM model excluding constrains (20)-(33).

The basic idea of the HTM is to solve the OEV model on hourly basis. The results are then aggregated on a daily basis. Once this step has been completed, the results obtained for each day are aggregated and used as parameters to solve the TM model for time set F, which is a set divided into daily intervals. An aggregate version of the TM model is then run on a daily planning horizon, the results from which indicate the days in which maintenance operations are to be performed. The TM model is then run on an hourly basis for those particular days, in order to schedule the maintenance activities. The heuristic algorithm is outlined in Figure 5. The algorithm starts by solving OEV (T), with i.e., T=56760. The results are then aggregated on a daily basis according to the procedure detailed in Figure 6. The TM model is then solved with the aggregated data, this is denoted by TM(F). We note that the planning horizon of TM(F) consists of 365 time steps. The solution of TM(F) will have days in which online cleaning is performed and days in which offline cleaning is performed. We denote the former by F' and the latter by F". Then an hourly version of TM is run for each day in F' and each day in F". The cost from these days are added to the cost of OEV based on T set, but without considering the days included in sets F' and F" days, to yield a complete solution. In conclusion the total profit will be calculated as the sum of the OEV T-based model's profit, plus the TM model's profit of days F' and F".

Fig. 5 shows the time sequence at which the aggregated algorithm works.

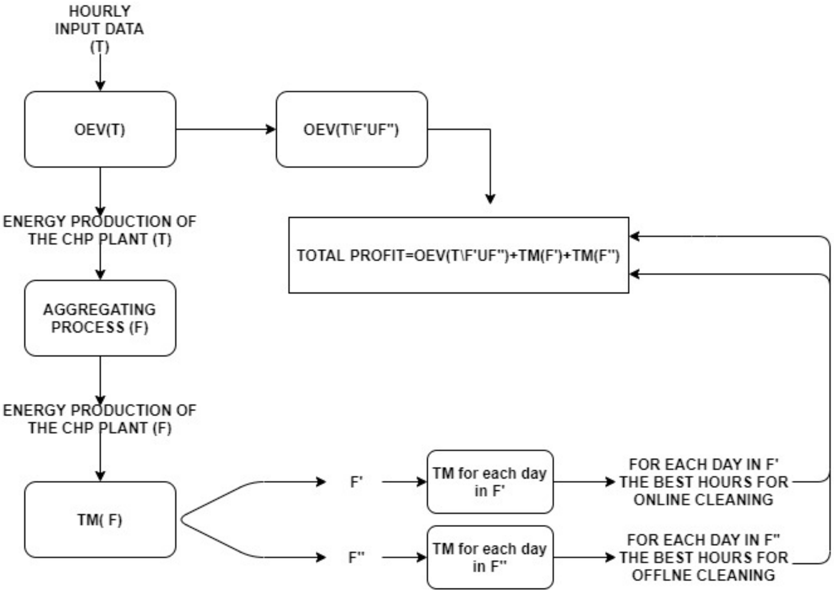

Figure 5: Heuristic algorithm outline

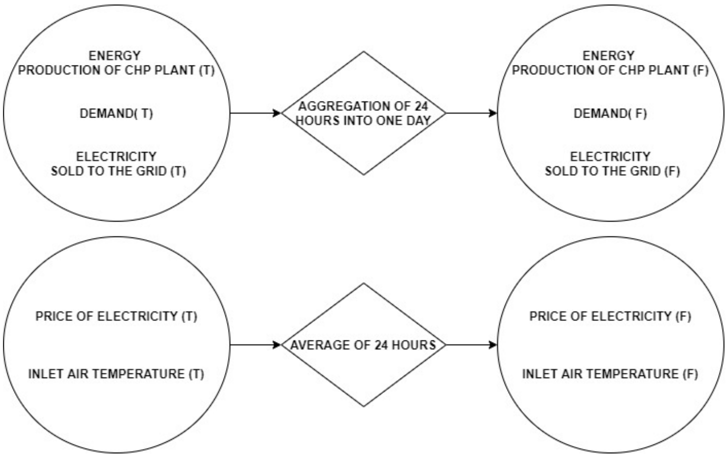

Figure 6: Aggregating procedure

5. Computational tests

To test our model we used CPLEX 12.9.0 to solve the MILP models through its Python API. All experiments were performed, using a single thread with 8 GB, on one computer having 4 cores and Intel(R) Core(TM) i5-7200U @2.50 GHz 2.71 GHz processor. The data used come from the case study described in section 3, which is an example of self-consumption setting where the final consumer is represented by an industrial process. However for confidentiality reasons the results are distorted to be presented publicly.

In what follows we discuss the historical data of the case study in section 5.1. In section 5.2 we present the results of the TM model and compare them to the case study. Finally, in section 5.3 we present the results of the heuristic algorithm.

5.1. An overview of historical data

In this section an overview of how the considered system has been operated in the past will be presented.

The historical data regarding how the system has been operated in the past, takes into account also the real functioning of the electricity market, in terms of price and capacities. This means that not all the electric energy, which was bid on the electricity market has been accepted. This influences how, the CHP plant and the whole system have been operated in the past.

The production levels established by the company are presented in Figure 7-8. We note that the CHP plant's production is not as stable and tends to adapt not just to demand but also to the electricity market's needs. This is evident especially in Figure 9. At the same time one can see that as in the model, the flux of electric energy exiting the system to be injected inside the grid (Grid Out) tends to compensate the fluctuations in demand to keep the CHP plant's production as stable as possible. The role undertaken by the flux of electric energy withdrawn from the grid entering the system is always the one to fulfill demand, whenever the CHP plant does not produce enough because of maintenance or other events that may hinder its production.

For what concerns the thermal energy production, as before the primary production is represented by the CHP plant, while the two boilers are used as a back-up to fulfill demand's needs.

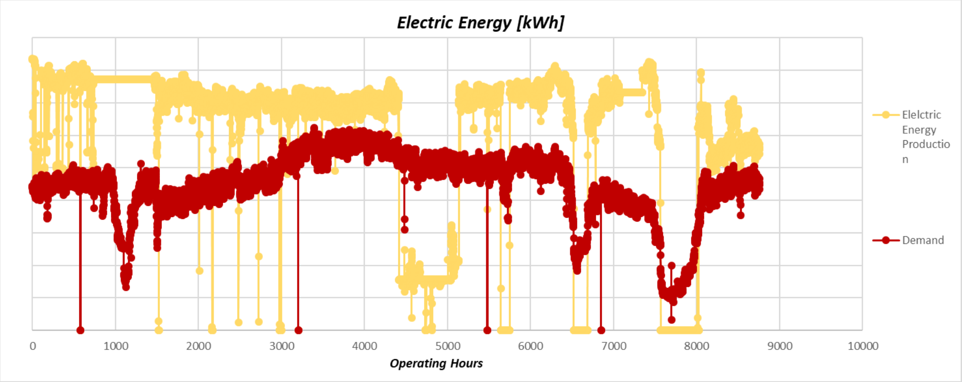

Figure 7: Real electric energy of historical data

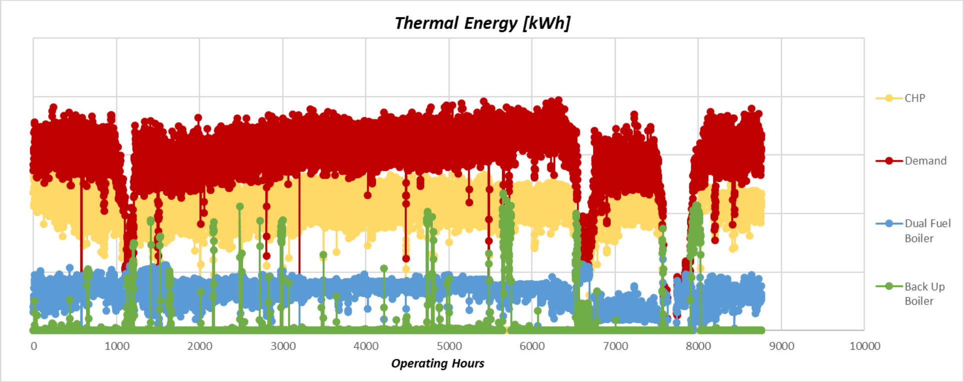

Figure 8: Real thermal energy of historical data

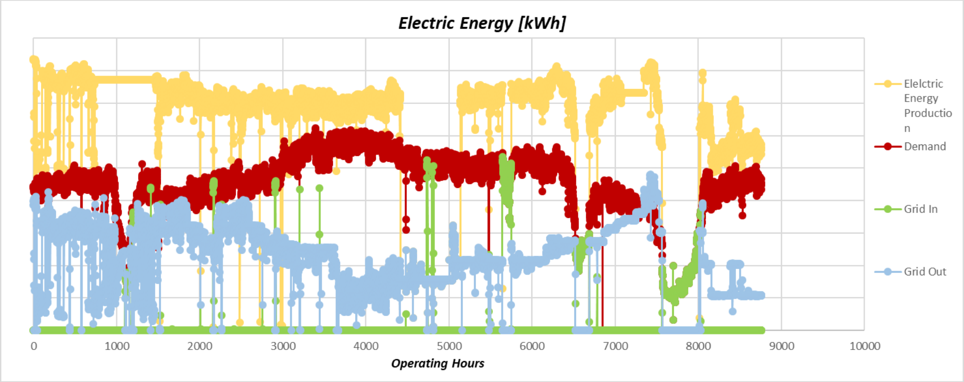

Figure 9: Real electric energy fluxes of historical data

5.2. Results from the tactical model

We run the TM model over a planning horizon of one year with an hourly planning interval (i.e., T=56760). The results are presented in Figures 10-13, and are summarised in Table 2. As can be observed in Figure 11, the TM model tries to set the level of electric energy produced at its maximum capacity. This is due to the attractive electricity prices on the market. In fact, as long as this value is favourable to sell, the electricity production stays at the maximum capacity level. Where the production is set to zero an offline cleaning is performed on the CHP plant, while where an online cleaning is performed the value of production is set at the value of its maximum reduced capacity. Figure 13 shows how the amount of electric energy exiting the system to be sold to the grid, compensates the variations in demand in order to keep the production as constant as possible. While the amount of electric energy entering the system is used by the model to compensate for the lack of production during the maintenance operations, or is kept at minimum to minimize costs in the objective function.

Concerning the thermal energy production, the CHP plant is considered as the first source of thermal energy. While the two boilers are used as back-ups, to fulfill the amount of thermal energy not produced by the CHP plant, as shown in Figure 12.

We now focus on the results concerning the electric efficiency variations. The consumption adapts to the fluctuations of electric efficiency with respect to inlet air temperature inside the compressor and load. We tested also the TM model considering the electric efficiency as a constant, thus neglecting constraints (16)-(19). The results are compared in Figure 10.
The results connected to the TM model, were obtained by setting the computational time to 10 hours, at which time the MILP gap was 0.22%.

TM model	
Computational time (h)	10
MILP gap (%)	0.22
Objective Function value (€)	2051446
Number of offline cleanings	6
Number of online cleanings	4
Difference in profit compared to an operational model (%)	10.66
Effects of considering the electric efficiency as a variable	
Average difference in terms of natural gas consumption (%)	16.5
Difference in profit (%)	7.82

Table 2: Main results obtained from the TM model

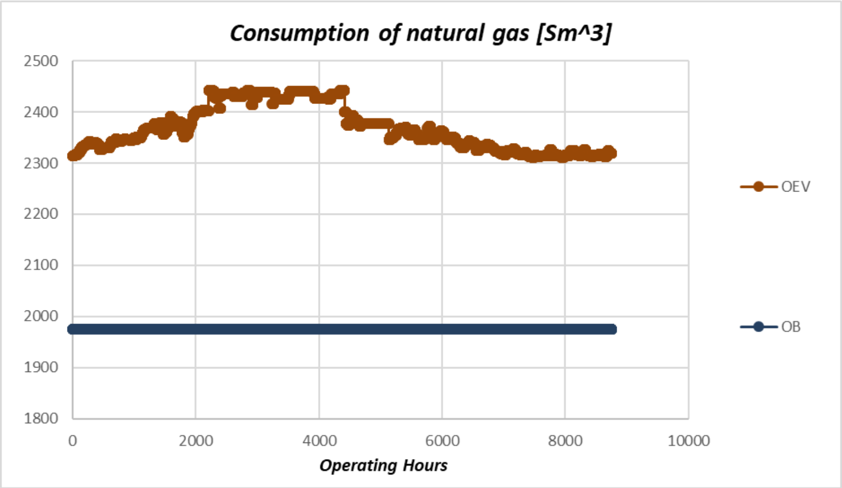

Figure 10: Comparison of the yearly Natural Gas Consumption considering the electric efficiency of the CHP plant as a constant or as a variable

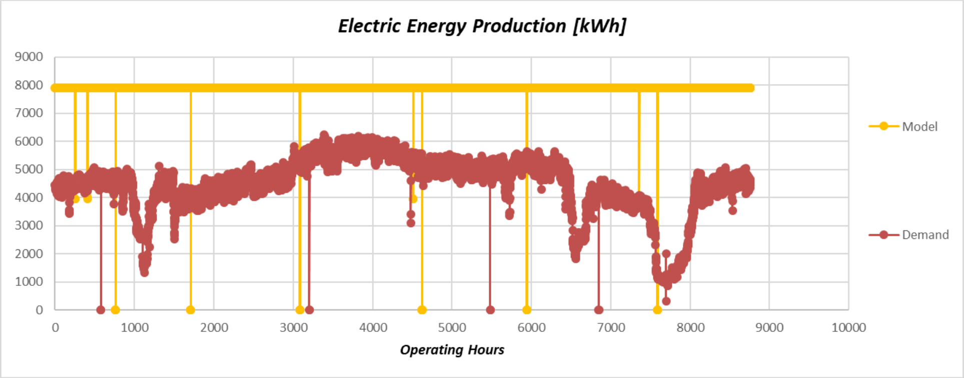

Figure 11: Electric energy production by the TM

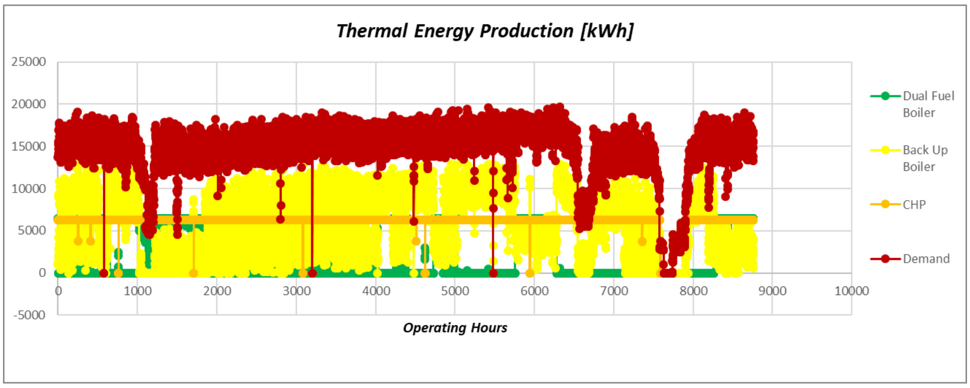

Figure 12: Thermal energy production by the TM model

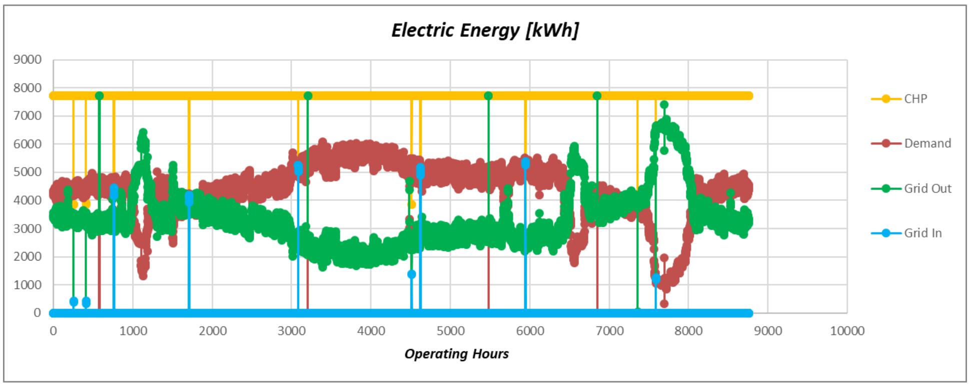

Figure 13: Electric energy fluxes by the TM model

We now focus on economic factors. Table 3 compares the monthly profits of the model's results and of real functioning of the system. For confidentiality reasons the data has been distorted. As one can see the difference between the two values is evident for each month.
The main difference in profit between the real functioning of the system considered and the model's results, is given by the amount of electric energy sold on the electricity market, but also by implementing the maintenance operations' scheduling inside the optimization model. In fact, the scheduling of cleanings is strictly interconnected to the demand variations of the final

consumers, and to the price of electricity. Therefore, if optimized it can improve the overall profit during the tactical time range.

	Model	Real Data
Number of offline cleanings	6	2
Number of online cleanings	4	10
	Difference in profit (%)	
Average	49	
March	24.6	
April	50.4	
May	40.4	
June	30.5	
July	5	
August	3.2	
September	28.6	
October	43.8	
November	38.2	
December	52.3	
January	75	
February	25.8	

Table 3: Comparison between TM model and real data

5.3. Results from the heuristic algorithml

To evaluate the quality of the solution obtained by the heuristic, we compared its performance with that of the TM model. These results are presented in Figure 14. We observed that the ATM model is coherent with the hourly TM model, proposing a combined solution of offline and online cleanings. Even though the two solutions are not exactly the same, they result in similar profits, where the difference is 3.61%.

Table 4: Comparison between maintenance operations' scheduling in Tm model and heuristic

	TM model	Heuristic
Number of offline cleanings	6	4
Number of online cleanings	4	6
Computational time	10 h with 0.22% gap	367 sec.

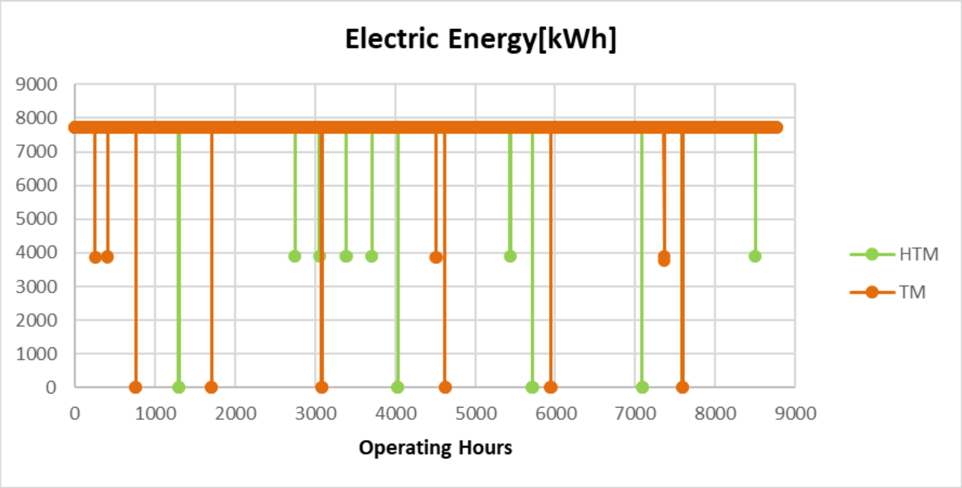

Figure 14: Comparison between maintenance operations' scheduling in TM model and heuristic

6. Conclusion

We proposed an optimization model and a heuristic algorithm for the management of multiple interconnected energy systems. We proposed a model for the tactical setting, i.e., the TM model. The TM model is able to schedule maintenance operations of multiple interconnected energy systems for a planning horizon of one year. Including the electric efficiency variations in the tactical model, led to results that are more in line with the company's decisions. This improvement is evident when observing the natural gas consumption, that is more realistic.
Furthermore, given the challenge in solving the tactical management model, we proposed a heuristic algorithm to decrease the computation time of the tactical management model, reaching a difference in terms of profit of 3.61%. This result opens the possibility to extend the time range of the tactical management model from one year to several years, giving the chance to increase the planning horizon for the plant's operator.
At the same time it must be said that even though the production of the system has been calculated with respect to the hourly electricity price, this price has been considered as an input parameter. This is a valid approximation for tactical planning purposes, but does not fully represent reality. Specifically, in the TM model we explicitly assumed the a priori knowledge of the electricity prices one year in advance. To relax this assumption we conducted an additional experiment, assuming a naive forecasting method for the electricity prices. Essentially we assumed that the price of electricity at a given period, is precisely the price observed in the same period of the previous year. Running the TM model with this configuration led to a difference in terms of profit of 4.56%. Hence the TM model can be considered reliable also with a naive forecast based on historical data of the electricity prices of previous years.

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