A lazy control strategy layer in validating daily-plan of multi-energy systems*

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***Abstract*—. This paper presents a simulation tool to validate daily operational plans against the dynamic behaviour of devices in a multi-energy system (MES). The tool models system components using timed automata (TA), which represent the behaviour of conversion devices in a natural and detailed way, enabling an accurate description of their dynamics. Moreover, the TA framework is easily configurable, facilitating future extensions and adaptations. The need to verify daily short-term plans arises because optimization tools, commonly used to compute operational schedules and multi-market bids, often neglect detailed technical constraints governing device behaviour. As a result, plans that appear feasible at a coarse time resolution may expose operational limitations during real-time operation, potentially requiring costly corrective actions. The proposed tool addresses this issue by validating the operational plan before market clearing. It simulates command execution while accounting for device delays and the dynamic evolution of energy carrier variables. The simulation environment combines the TA-based representation with several control strategies that lazily adjust the setpoints of the original plan to meet operational commitments. Each coordination strategy is formulated as a mixed-integer linear programming problem.**

Keywords*— *Multi-Energy Systems, Timed Automata, Flexibility, Optimization, Sector Coupling

I. INTRODUCTION

Sector coupling is a key approach to addressing the increasing variability of power generation in modern energy systems [1]. This ability is inherently owned and naturally leveraged by multi-energy systems (MESs) [2], which simultaneously process multiple energy carriers at local, national, and regional scales. In particular, the integration of power, gas, and heating/cooling sectors represents the main form of energy carrier coupling. Operationally, sector integration relies on the availability of flexibility, defined as the capability to reliably shift from one operating point to another [3]. From a bottom-up perspective, flexibility is provided by technological units and is limited by the need to maintain energy carrier balances, as well as by regulatory and market constraints. As a result, flexibility represents a valuable resource at local, national, and regional scales [4].

This paper presents a simulation tool devoted to the validation of commitments of multi-energy system (MES), that is the multi-energy demand and multi-market bids. The tool is based on the Timed Automata (TA) paradigm [5], where each device is modelled by an automaton describing its state, internal variables, and outputs. TA uses clock variables to model real-time operations and supports both discrete and continuous processes, enabling hybrid simulations. About the market bids, the analysis focuses on day-ahead and intraday of the Italian electricity and gas markets ([6]). Bid validation verifies whether the simulated operation of the MES, performed on the seconds time scale, complies with bid activation and delivers the committed energy within the corresponding hour. The present version of the simulation tool follows a very earlier versions: [7], coded in Matlab®, and [8], coded in Python with a limited treatment of multiple energy carriers with a unique control strategy. The present version of the simulation tool distinguishes several control strategies, to keep feasible the error recovery actions, and a detailed model of the devices to support the model predictive control scheme implemented. Even if distinguish several strategies helps in facing the different commitments in some cases brings to conflicting decisions. A lazy mechanism is introduced to collect the recovery actions decided which are feasible, following a priority relationship among commitments. A 3rd generation district heating, really operating in the Milan area (Italy), was adopted for the validation of the tool. A quantitative assessment step of the daily simulation completes the scheme according to the manager of a MES can validate a daily plan and in case operate suitable amendments. Several advanced simulation environments, such as Dymola, OpenModelica [9], APMonitor [10], PyTorch [11], and PowerFactory [12], can model heating, gas, and electricity systems with high accuracy. However, their modelling effort and computational complexity may be excessive when detailed physical representation is not required. Pure optimization-based frameworks ([13]) often struggle with nonlinearity and non-convexity, requiring computationally expensive solution methods and typically operating at time scales no finer than minutes. Agent-based and hybrid approaches (e.g., [14] and [15]), reduce complexity and support system-level simulation, but may neglect dynamic details that significantly influence results.

The paper is organized as follows, in chapter II the modelling of MES behaviour is proposed, in chapter III the details of the simulation of a real MES are shown and conclusions recap the work and give an overview about next steps.

II. THE SIMULATION MODEL

A. *The model of MES behaviour*

1) *Generality of the simulation framework*

The behaviour of a MES is simulated by modelling each device through a Timed Automaton (TA) ([5]) and running the set of automata cyclically. This tool was originally defined in [7]. A set of automata are cyclically evaluated with respect to a discrete time representation. At each evaluation step, the automata receive inputs from the command input-stream (i.e., the unit-commitments-*uc* and the setpoints-*sp*).

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These commands result from the transformation of an operational planning program (OPP), calculated by a short-term planning tool, into an equivalent program expressed on a seconds-based time scale. Each unit-commitment is a scalar (binary) while each setpoint is a vector including several control items.

Each timed automaton is defined by a set of states, a set of input commands/variables, a set of output variables and a set of transitions δ. The automaton's set of states has 4 items: *stop* (0), *starting* (1), *running* (2), *changing set-point* (3), and *stopping* (4). The states stop and running are stationary (i.e., the system can remain there, indefinitely) and their outputs do not change. The states starting, changing set-point, and stopping are non-stationary states, the automaton remains in a non-stationary state for the duration of the transition (δ). The value of δ is calculated on the physical characteristics of the device and the difference between the current output and the new setpoint required. Each conversion device is modelled by a TA in this way. The devices with energy storage ability (i.e., electrochemical battery (EBS), thermal energy storage (TES), etc.) are modelled by specialized TA such that the 5 stated mentioned above are associated to the charging and discharging phases of the device and the full and the empty states of energy are added to the model. When the device is in the full or empty state the only action allowed is, respectively, discharging or charging.

Furthermore, the model of the MES conversion devices requires further details to support the simulation step, specifically the energy carriers involved and the classification of generation and load ability of the device. The set of energy carriers managed in a MES are gathered into the set: $\mathcal{E} = \{\mathcal{E}_1, \mathcal{E}_2, .., \mathcal{E}_n\}$. Each conversion device in a MES shows *generation* or *load* ability with respect to a specific energy carrier (e.g., a CHP gas-engine is a generator on the electricity and the heat carriers while it is a load on the gas carrier). Identified by $\mathcal{D}_i$ the set of MES devices, the set of generators-$\mathcal{G}_i$, storages-$\mathcal{B}_i$ ($\mathcal{B}$ stands for batteries) and loads-$\mathcal{L}_i$ are associated to the carrier $\mathcal{E}i$ and $\mathcal{D}_i = \{\mathcal{G}_i, \mathcal{B}_i, \mathcal{L}_i\}$.

1) The model of the X-to-heat conversion devices (e.g., chp, heat pump, gas boiler, electric boiler)

The model of conversion devices will require an optimization step endowed in several control strategies for control the MES commitments and that will constitute the subject of the next section. For this purpose, a '*grey box*' modelling approach was adopted. The simulation tool is based on an optimization problem coded in Python in combination with Cplex mixed-integer linear solver. The MPC models for each system component are described below.

For each conversion device *d* involved in the heating production (X-to-heat) holds,

$$\{p_{d,t}\}_{heat} = (T_{d,t}^{in} - T_{d,t}^{out})c_{p,w}\dot{m}_{d,t} \tag{1}$$

Where $\{p_{d,t}\}_{heat}$ is the generated heat power by *d* at time *t*, $T_{d,t}^{in}$ and $T_{d,t}^{out}$ are the in(let) and out(let) temperatures of *d*, $c_{p,w}$ is the heat capacity of water and $\dot{m}_{d,t}$ is the water flow rate in *d* at *t*. The model also defines the power heat output in terms of the input power that depends on the technology. For gas-to-heat device *d* (i.e., chp, gb) the conversion is,

$$\{p_{d,t}\}_{heat} = \{p_{d,t}\}_{gas}\eta_d^{gas,heat} \tag{2}$$

In case of CHP the conversion also includes the electricity production due to the gas power,

$$\{p_{chp,t}\}_{elect} = \{p_{chp,t}\}_{gas}\eta_{chp}^{gas,elect} \tag{3}$$

The power heat output calculated in terms of input electricity power for power-to-heat technologies is defined by the next equations; for heat pumps this is calculated by the Coefficient of Performance (COP),

$$\{p_{hp,t}\}_{heat} = \{p_{hp,t}\}_{elect}COP_{hp} \tag{4}$$

In case of an Electric Boiler it is expressed by the efficiency,

$$\{p_{eb,t}\}_{heat} = \{p_{eb,t}\}_{elect}\eta_{eb}^{elect,heat} \tag{5}$$

Electricity, gas and heat powers are bounded by the device *d* characteristics:

$$\left\{\underline{p}_d \le p_{d,t} \le \overline{p}_d\right\}_i \ \forall i \in \mathcal{E} \tag{6}$$

Where $\underline{p}_d$ and $\overline{p}_d$ the minimum and the maximum power of *d* on the energy carrier *i*.

2) The stratified Thermal Energy Storage

The model of the stratified thermal model is borrowed from [16] where the TES tank is divided into multiple nodes. The simulated results for temperatures are used to estimate the heat stored in the tank. The mass and energy balances are considered for all the nodes. The discharging and charging of the tank are described by eqs(7-8),

$$Q_{dc} = \dot{V}(\rho_{top}h_{top} - \rho_{DHret}h_{DHret}) \tag{7}$$

$$Q_{ch} = \dot{V}(\rho_{CHP}h_{CHP} - \rho_{bot}h_{bot}) \tag{8}$$

Q is heating content [kW], $\dot{V}$ is volume flow [m^3/s], ρ is density [kg/m^3], and *h* is enthalpy [kJ/kg] of the inlet and outlet streams of the tank. The temperature change in each node is calculated by eq (9):

$$\frac{dT_i}{dt} = \frac{\dot{m}_{i.in}h_{i.in} - \dot{m}_{i.out}h_{i.out} + HT_{(i+1)\to i} - HT_{i\to(i-1)} - Q_{los}}{Cp_iV_i\rho_i} \tag{9}$$

where: T is temperature [K], $\dot{m}_{i.in}$ is the mass flow for the i-th node [kg/s], h_i is enthalpy for the *i* th node in [kJ/kg], HT is transferred heat and its direction is indicated in the subscript, Q_{los} is the heat loss to the environment from the tank, Cp is the specific heat capacity of water [kJ/(kg•K)], and V_i is volume of each node [m3]. The state of heat energy (SoE) stored in the tank is calculated by the next equations:

$$SoE_t = \sum_j cp_jm_j\Delta T_j = \sum_j cp_jV_j\rho_j\Delta T_j \tag{10a}$$

$$SoE_{t+1} = SoE_t + p_{b,t}^{ch}\eta^{ch} - p_{b,t}^{dc}/\eta^{dc} \tag{10b}$$

where: ΔT_j is the temperature difference between the temperature in the j-th node and a pre-defined temperature as the lowest operating temperature of the TES, and m_j is mass of water in the *j*-th node; $p_{b,t}^{ch}$ and $p_{b,t}^{dc}$ are the power in charging and discharging the storage and η^{ch} and η^{dc} are the efficiency in charging and discharging power.

B. The control strategies

The model of the MES behaviour is completed by a set of Control Strategies (CSs) that adapt the behaviour of devices to satisfy the MES commitments and specific technical constraints. In a sector coupling perspective, the MES commitments require to satisfy the demand(s) and fulfil import and export bids set on the electricity and gas day-ahead and intraday markets. Control strategies help in facing these commitments adapting the dispatching of devices to fit the balancing. Further specific control strategies regard system technical constraints that must be satisfied to prevent the infeasibility of the operational program. This last category is specific of the devices in the MES.

The set of CSs is managed at the coordination layer in a lazy-closed loop scheme such that the strategies are evaluated separately from each other. The decisions taken are selected from those calculated by CSs according to the priority setup and at any rate in to avoid infeasibility. The coordination layer is based on a Model Predictive Control (MPC) framework, taken from the TA representation.

1) Strategies to control the fulfilment of commitments

Schematically, each control strategy in this category is composed of an Error definition (E_{CS}) with a threshold ($\mathcal{T}_{CS}$) to recognize the mismatch and a set of recovery actions (RA_{CS}) to reduce the mismatch. At each computation cycle, the coordination layer verifies the satisfaction of the commitments assumed by the MES in a closed-loop scheme.

First, the error associated to each CS is defined.

- Error definition

$$\left\{E_t^{CS_i,*} = \sum\nolimits_{g\in\mathcal{G}_i} p_{g,t} + \sum\nolimits_{b\in\mathcal{B}_i} p_{b,t}^{dc} + p_{M,t}^{imp} - \left(\sum\nolimits_{\ell\in\mathcal{L}_i} p_{\ell,t} + p_{\mathbb{D},t} + \sum\nolimits_{b\in\mathcal{B}_i} p_{b,t}^{ch} + p_{M,t}^{exp}\right)\right\}_i \tag{11}$$

Eq (11) is an energy balancing equation. The symbol '*' stands for: '+', positive, or '-', negative; error $E_t^{CS1,+}$ is positive in case the generation terms are greater than the consumption terms, otherwise $E_t^{CS1,-}$ is negative. $p_{b,t}^{dc}$ and $p_{b,t}^{ch}$ represent the discharging and the charging powers of b at t; $p_{\mathbb{D},t}$ is the demand $\mathbb{D}$ on i; $p_{M,t}^{imp}$ and $p_{M,t}^{exp}$ represent the importing and exporting bids on the market M at time t, respectively. The index i identifies the power and gas energy carriers.

- Recovery Action(s)

Given the set of devices $\mathcal{D}_{RA,i}$, the recovery actions are specified through a first equation that sets the contributions to cover the error,

$$\left\{E_t^{CS_i,+/-} = \sum_{d\in\mathcal{D}_{RA,i}} p_{d,t}^{-/+}\right\}_i \tag{12}$$

Eq(12) specifies in case the error has positive sign ($E_t^{CS_i,+}$), or negative sign ($E_t^{CS_i,-}$), it faced by the summation of the negative, positive, flexibility contribution, $p_{d,t}^{-}$or $p_{d,t}^{+}$ from the device(s) d in $\mathcal{D}_{RA,i}$, respectively. On any other energy carrier j, different from i, further recovery actions are required for balancing energy carrier to avoid rebound effects. This is operatively carried out by the device $d2$ in the set $\mathcal{D}_{RA,i}^2$ (such that $\mathcal{D}_{RA,i}^2 \subseteq \mathcal{D}_{RA,i}$),

$$\left\{\sum_{d\in\mathcal{D}_{RA,i}} p_{d,t}^{-/+} \cdot \sigma_d^{i,j} = p_{ID,t}^{ex/im} + \sum_{d2\in\mathcal{D}_{RA,i}^2} p_{d2,t}^{+/-}\right\}_i \tag{13}$$

The recovery action scheme proposed by eq (13) requires that each rebound effect on the energy carrier j due to the error compensation on the energy carrier i, represented by $p_{d,t}^{-/+} \cdot \sigma_d^{i,j}$, is compensated either by some $d2, p_{d2,t}^{+/-}$, or by accessing the intraday market $p_{ID,t}^{ex/im}$ in exporting or importing mode. The term $\sigma_d^{i,j}$ defines the conversion operated by the device d from the energy carrier i on the energy carrier j. In case i is the input energy carrier and j the output energy carrier, conversion is the device efficiency: $\sigma_d^{i,j} = \eta_d^{i,j}$.

- The objective function

The objective function (eq (14)), associated to each control strategy, drives the selection of devices to reduce costs related to error recovery and keeping the energy carriers in balance. The last term in eq (14) represents the possible bids for intraday markets, for releasing (<u>ex</u>port) or acquiring (<u>im</u>port) resources. These bids are suggested to avoid penalties at MES run-time.

$$\min_p \left\{\sum_{d\in\mathcal{D}_{RA,i}} p_{d,t}^{-/+}\mathbb{C}_{d,t}^{-/+} + \sum_{d2\in\mathcal{D}_{RA,i}^2} p_{d2,t}^{+/-}\mathbb{C}_{d2,t}^{+/-} + p_{ID,t}^{ex/im}\mathbb{C}_{ID,t}^{exp/imp}\right\}_z \tag{14}$$

2) Specific control strategies: energy storage operation

Energy storage devices represent powerful means for balancing the energy carrier during operation. Nevertheless, if the contributions asked by recovery actions is polarized, that is always in charging or in discharging, it is more likely the device falls in completely empty or completely full states, respectively, frustrating any other control action. Furthermore, the original program of the device becomes infeasible, and this is not acceptable. A very rough control strategy to be adopted to save the original program of the storage device is to constrain its flexibility, and then the impact on the State of Energy (SoE), to stay within an upper and downward bounds. This condition is based on the calculation of the percentage error,

$$\left\{E_t^{CS_i,*} = \left(SoE_t - SoE_t^{plan}\right)/SoE_t^{plan}\right\}_i \tag{15}$$

The percentage error calculates the percentage distance between the original SoE (SoE_t^{plan}) set in the plan and the new SoE (SoE_t) obtained by the flexibility margins. Recovery Actions associated to this control strategy may require the contribution from the energy storage is accepted if it falls within the bounds identified.

The description of the coordination layer sketched in this section, will be defined in the next section for the specific study case proposed.

III. The validation study to check a daily plan

The analysis of one-week daily operation plan was studied regarding a 3rd generation multi-energy district heating (DH). This plant is really operating in Milan (Italy) area and includes several conversion devices:

- *gas*-to-*heat*: 3 gas boilers (GB), each 15.1 MW heat power output; 3 combined heat & power (CHP) gas engines, each 5 MW electric power output;
- *power*-to-*heat*: one geothermal heat pump (HP), with 13 MW heat power and COP 2.5; one HP exploiting recovery heat from CHPs with 3 MW heat power and COP 3; one electric boiler (EB) with 10 MW heat power output;
- one *heat storage* (HS) with 58 MWh heat energy capacity

The MES maximum heat power capacity is about 110 MWt and the maximum electricity generation is 15 MWe. The plant participates in the DA and ID energy markets. Data used for the simulations regarding the energy market prices and costs for electricity and gas are taken from the website of the Italian manager of energy markets, for the winter day January 22nd 2025.

A. The 'lazy' evaluation of CSs defined in this study-case:

The set of CSs defined for the district heating MES consist of 4 elements, whose characteristics are reported in the next list. Each CS is evaluated at each cycle, as a single strategy, and the set of resulted RAs is successfully reduced, by heuristic criteria, to get an effective and coherent set of actions.

a) CS_1 checks the electricity markets bids provision: the instantiation of this scheme exploits the control device $\mathcal{D}_{RA,1}$ ={CHPs}; eq(11) and eq(12) are instantiated on the electricity carrier; eq (13) is instantiated on the heat ($\mathcal{D}^2_{RA,i}$={GBs,TES}) and on the gas ($\mathcal{D}^2_{RA,1}$={GBs}) carriers.

b) CS_2 checks the gas markets bids provision: the instantiation of this scheme exploits the control device $\mathcal{D}_{RA,2}$ ={GBs}; eq(11) and eq(12) are instantiated on the gas carrier; eq (13) is instantiated on the heat carrier ($\mathcal{D}^2_{RA,2}$={TES}).

c) CS_3 checks the DH-heat demand provision: the instantiation of this scheme exploits the control devices $\mathcal{D}_{RA,3}$ ={GBs,TES}; eq(11) and eq(12) are instantiated on the heat carrier; eq (13) is instantiated on the gas carrier ($\mathcal{D}^2_{RA,3}$={GBs}).

d) CS_4 checks the percentage mismatch between the planned SoE and the measured one: the control device $\mathcal{D}_{RA,4}$ ={TES}, and hold $\left|E_t^{CS_i,*}\right| < 0.25$ and $\underline{SoE} + 3 \leq SoE_t \leq \overline{SoE} - 3$ (where $\underline{SoE}$ and $\overline{SoE}$ are, respectively, the minimum and the maximum SoE of the energy storage device);

After the evaluation of the set of CSs, the heuristic criteria are applied on the set of resulted RAs. These criteria first apply the priorities ($' \succcurlyeq '$ means greater priority) set among the CSs.

- CS priority specification

$$CS_4 \succcurlyeq CS_1 \succcurlyeq CS_3 \succcurlyeq CS_2 \qquad (16)$$

Eq(16) means: CS_4 has the greatest priority, it is always applied on the flexibility of the storage devices under control. Afterwards, if CS_1 runs eq(12) on the electricity carrier and eq(13) on the heat carrier are set, while setting eq(13) on the gas carrier depends on the other CSs. Then, CS_3 is set in case of DH-demand error on the heat carrier by eq(12) and eq(13), eq(13) on the gas carrier is not necessarily set but depends on the other actions. Finally, CS_2 is evaluated, eq(12) and eq(13) are set just in case there are no conflicts with the other CSs. The priority specification among CSs suggests that the electricity carrier is the most important one, while the gas carrier acts like a slack term that always ensure matching between the other constraints.

B. The day-simulation of the MES

- Input data for simulation

The daily plan calculated by [6] consists of *uc* and *sp* values associated to the devices of the MES to fulfil the heat demand, and with hourly resolution. This program also specifies for electricity and gas the importing and in exporting bids in the day-ahead and intraday markets. The program also specifies the electrical consumptions that must be met such that the plant is as self-sufficient as possible.

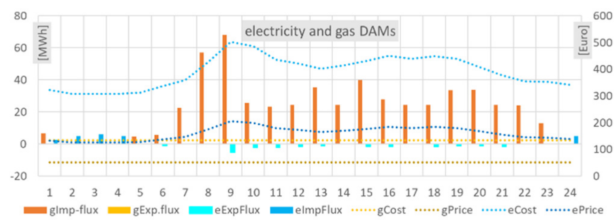

Figure 1 – The daily program of importing and exporting bids on day-ahead gas and electricity markets, with prices and costs (y-axis left [MWh], y-axis right [Euros])

Figure 1 shows the bids calculated to import the gas (orange bars) to sustain the production of the gas-to-X technologies. This figure also shows the bids to export the excess of the electricity production to reduce the cost of the heat production.

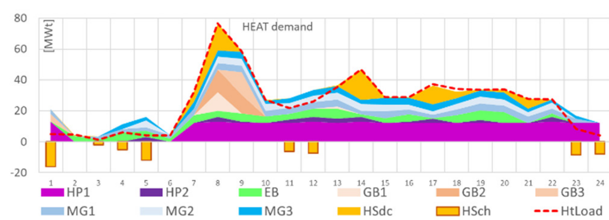

Figure 2 - Heat carrier, with dh-demand and device schedules

Figure 2 shows the daily heat demand profile (red dashed line) together with the scheduled devices to satisfy it. The contributions of the different technologies are represented by stacked coloured areas: gas boilers (GBs) are shown in red, heat pumps (HPs) in purple, combined heat and power units (CHP) in blue, and electric boilers (EB) in green. The heat storage system (HS) is represented in yellow, where positive yellow areas correspond to the discharging phase, while negative yellow columns represent the charging phase.

- Outcomes of simulations

Figure 3 reports the behaviour of one of the CHPs along the daily operation horizon.

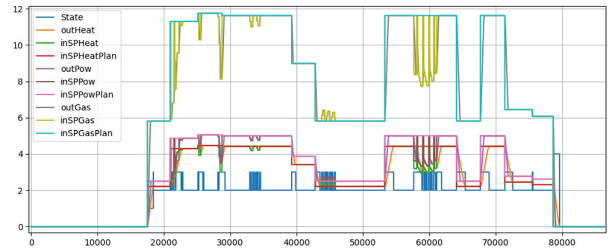

Figure 3 - CHP operation, original program and recovery actions due to electricity CS (powers are expressed in [MW])

In the figure above, a (standard) start and stop sequence is represented, during the CHP operation some setpoints of the original program (i.e., red, pink and light blue lines for heat, electricity and gas, respectively) are substituted by setpoints (i.e., green, brown and light green lines for heat, electricity and gas, respectively) calculated by the recovery actions, activated by the control strategies, to keep the electricity carrier balanced.

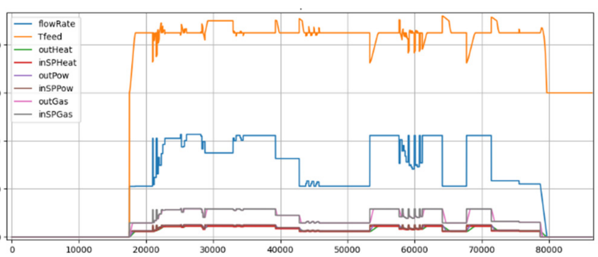

Figure 4 - CHP operation with details about flow rate and feeding temperature (Tfeed) (Tfeed is expressed in [°C], flow rate is expressed in [m^3/h] and power associated to electricity and heat are expressed in [MW])

Figure 4 details the trends of flow rate and Tfeed of the CHP during the daily operation. These variables are calculated by the heat balance equation specified by eq (1).

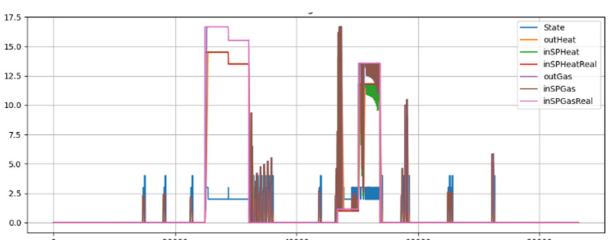

Figure 5 – GB daily operation with original plan setpoints and setpoints decided by recovery actions due to electricity and heat control strategies (powers are expressed in [MW])

Figure 5 shows the daily operation of a GB. The original program (the red and pink lines for heat and gas setpoints, respectively) are integrated by the setpoints decided by control strategies devoted to keep heat and gas carriers balanced. The graph shows the modification to the original program and the device switched on not originally foreseen. Indeed, recovery actions can switch on GBs to increase the upward flexibility on the heat carrier. GBs are the only devices that are operated in this way by CSs.

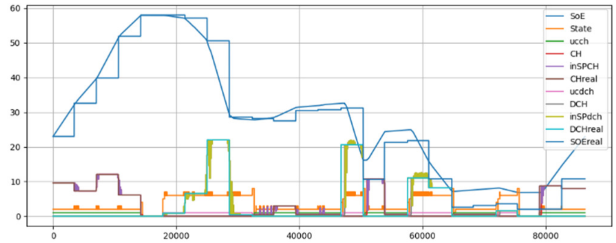

Figure 6 - Thermal Energy Storage participating in the daily program and in control strategy to keep heat carrier balanced, Power values are expressed in [MW] while energy values are expressed in [MWh].

Figure 6 reports the simulation of the thermal energy storage. As GBs, TES is operated by control strategies to keep the heat carrier balanced. During the charging and discharging phases (represented by the red and grey lines), changes are very frequent. The control strategy aimed at bounding the variations of SoE within a feasible interval, with respect to the real SoE (set in the original program), ensures the feasibility operation of this device. In fact, the two SoEs are strictly linked and unexpected deadlock due to *full* or *empty* states of energy are avoided.

Figure 7 reports the trends of the energy errors associated to electricity, heat and gas. The Energy errors are the summation of power errors at each time instant (eq(12)) from the beginning of each hour until the end. Energy errors are reset at the beginning of the new hour. Energy errors are more informative than the power ones because provide the total amount of excess/lack of energy within a time slot associated to energy market bids, or the schedule of the demand. Based on the results proposed in this graph, an error that overcomes the penalty threshold requires a change in the original plan. This means that a revision of the device schedules or extra bids on intraday markets can be set.

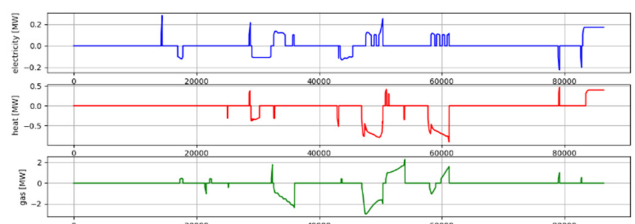

Figure 7 - The result of the errors in energy (electricity, heat and gas represented by blue, red and green lines) calculated in a winter day DH operation

Figure 8 proposes the detail about the energy error for the electricity carrier. This graph witnesses the impact of the priority set on CSs such that the CS dedicated to keep the electricity carrier balanced has a great effect. The result highlights as the electricity market bids are satisfied and no penalties are dealt with.

The errors obtained for gas bids suggest that maintaining the daily plan without corrective actions may lead to operational drawbacks, while energy errors measured on heat and electricity do not represent issues. To quantitively assess the impacts of errors for each energy carrier specific penalty factors were defined. For electricity, if the energy error (eERRp_f) measured at the end of each energy slot is greater than 0 the penalty factor is 2.5 times the day-ahead electricity price. If eERRp_f<0, the penalty factor is 1.25 times the day-ahead cost.

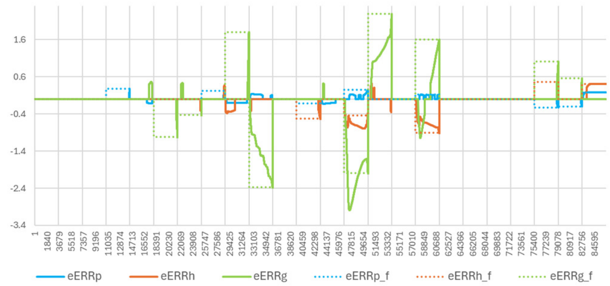

Figure 8 - The result of the error in energy for electricity, heat and gas carriers (energy values are expressed in [MWh])

For heat, if the energy error (eERRh_f) is greater than zero leads to customer dis-comfort, quantified as follows: in case eRRh_f>0 the penalty is equal to 0.5 time the error; if eRRh_f is negative the discomfort on the demand is greater and the penalty factor is 2 time the error. In the case of gas, if eERRg_f > 0, penalty factor is 1.4 with respect to the hourly price market and if eERRg_f < 0, the penalty factor is 1.1 of the hourly cost market. Table 1 reports the penalties associated to the errors calculated on the simulated case, dark grey cells suggest the need to integrate the original daily plan (e.g., by setting up suitable gas bids on intraday market).

Table 1 - Outliers of the penalties calculated on the errors

hour	Electric penalty (Euro)	Heat penalty (Discomfort)	Gas penalty (Euro)
4	89.11	0	0
6	0	0	151.06
7	0	0	62.43
8	93.83	0	0
9	0	0	128.25
10	0	0	352.3
12	60.49	1.05	0
14	107.96	0.87	295.41
15	0	0	164.91
16	0	0.81	0
17	52.04	1.82	115.44
22	99.73	0	72.1
23	88.05	0	39.59
24	60.52	0	0

CONCLUSIONS

This paper proposed a simulation framework for multi-energy systems based on timed automata (TA). TA are well suited to model the behaviour of the conversion devices of a MES and easily implement real-time operational constraints. The primary goal of this tool is to validate at the operation level the (daily) short-term plan elaborated by a suitable planner. This is pursued transferring the short-term plan (i.e., device unit commitments, setpoints and energy market bids) on the very fine second time scale. To adequate the short-term plan to the technical characteristics of devices several control strategies were identified. These control strategies measure the mismatch between generation and consumption in each energy carrier and in case of relevant errors put in place recovery actions designed according to a model predictive control (MPC) borrowed from the device thermal and dynamic characteristics. Furthermore, the implementation of the recovery actions is performed according to a 'lazy' mechanism that avoid as far as possible inconsistencies and infeasibilities. The tool was tested against a winter day, and the results gained seem promising. A penalty mechanism was set-up to quantify the energy errors that overcome threshold defined. Future work will focus on developing models to simulate energy carrier networks.

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