Multi-energy systems and flexibility markets: benefits and boundaries

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***Abstract*—The progressive transformation of power systems driven by decarbonization policies is asking for new contributions and new actors. Multi-energy systems operating on the distribution grids and linking several energy vectors represent an ideal mean to support the transition in a reliable and fruitful way. Indeed, these systems act on multi-markets and provide high performance services with their devices, taken as single, or aggregated units. In this paper, a study is proposed regarding the efficacy and the economic impact of MES provision of ancillary services to flexibility markets. This is carried out by several simulations along different seasons, adopting the Italian regulation and balancing rules. The results show that MESs own high flexibility availability but receive little economic revenue, markets show a low capacity to get this flexibility.**

***Index Terms*-- Co-Optimization, decarbonization, Energy Markets, Flexibility, Flexibility Markets.**

I. INTRODUCTION

A profound transformation is currently underway in European power systems, driven by the requirements of the Climate and Energy Package and related European Union directives [1]. Decarbonization policies are significantly increasing the share of renewable energy generation, necessitating the deployment of new resources for ancillary service provision and requiring all energy sector actors to respond more dynamically to market signals. Traditional providers of regulation services are progressively diminishing, replaced by variable renewable energy sources (vRES), which are a primary source of increased operational uncertainty. To address these challenges, numerous solutions have emerged in recent years, ranging from technological innovations—such as electrical energy storage systems—to enhanced system capabilities, including demand response mechanisms [2]. Among these, the concept of multi-energy system (MES) has gained traction. MESs integrate multiple energy carriers and function as interconnected nodes within the broader energy system [3]. These nodes can utilize fuels that are economically and environmentally advantageous or locally available to meet diverse energy demands, delivering various energy carriers accordingly.

A key feature of MESs is the ability to switch between energy carriers, making them essential for sector coupling [4]. Furthermore, this interconnection enables the transfer of stored energy from one carrier to another, enhancing operational flexibility. According to [5], *flexibility* is meant the upward and downward margins from a baseline. In the case of MESs, flexibility margins exist across all managed energy carriers, making MES flexibility inherently multidimensional. There is a growing body of literature addressing MESs and their flexibility potential. [6] explores the aggregate flexibility of MESs using dynamic network models, [7] investigates coordinated operation and optimal dispatch strategies. In [8], comprehensive classification of flexibility types and the key influencing factors are discussed and [9] evaluates the economic opportunities available to industrial facilities through participation in frequency regulation (FR) markets.

This paper presents an optimization model for simulating the short-term operational planning of a MES. The model incorporates both the technical and economic characteristics of the system's devices and formulates market bids for participation in energy and flexibility markets. Key innovations of the proposed model include: (*i*) detailed representation of ancillary service products, which may be provided by individual devices or coordinated pools; and (*ii*) internal balancing actions designed to maintain equilibrium across all energy carriers during each MES operational phase. While the capability of the model to represent participation in electricity and gas day-ahead and intra-day markets was introduced in [10], the present study aims to highlight the role MESs can play in advancing the decarbonization agenda particularly by leveraging the higher flexibility potential. To this end, we simulate MES operations across all four seasons, focusing on the provision of flexibility to both Transmission System Operators (TSOs) and Distribution System Operators (DSOs). The case study involves a real-world 3rd-generation district heating system operating in the Milan area, located in northern Italy. The simulation results demonstrate that MESs can reliably provide flexibility throughout most of the year. However, existing market regulations sometimes significantly constrain this potential. These findings contribute to the ongoing regulatory review processes by

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highlighting the need to adapt flexibility market rules to fully leverage MES capabilities in future energy systems.

The paper is organized with section II describing the current revision of the Italian regulation, section III defining the MES operational planning model, section IV proposing the results of the simulations of the model, and conclusions.

II. FLEXIBILITY AND EVOLUTION OF REGULATION

The Italian electricity system is managed by Terna, the TSO, which adopted a central dispatching scheme [11]. In central dispatching systems consumption schedules as well as power generating facilities are determined by the TSO within the integrated scheduling process. In 2023 the new rules for dispatching and balancing the Italian electricity system were published by the National Regulatory Authority (NRA) in the resolution named ‘TIDE’ [12]. This document started a complete and deep revision process that is currently ongoing and should be accomplished within February 2026. TIDE provides relevant changes in balancing and dispatching:

- A new classification of the units devoted to the provision of flexibility services
- differentiate the balance responsible party (BRP) and balance service provider (BSP) roles to identify operators of the energy and flexibility markets, for a single or aggregated unit
- the transition on spot markets from ‘unit bidding offers’ to ‘portfolio bidding offers’
- the introduction of the Nomination Platform to ensure the Italian's participation in continuous trading on XBID (the European platform for intra-day market)
- the classification of global national ancillary services is deeply revised, to be compliant with the nomenclature adopted in [13] and [14]
- the former TSO flexibility market ‘MSD’ is redefined to be compliant with the requirements and characteristics posed by [14]

The actions put in place by the Italian NRA and TSO follow the European revision of the electricity regulation [14]. This impacts on the electricity day-ahead and intraday markets [15] as well as on the flexibility markets and products traded in. The goal is widening the participation in flexibility markets and standardizing the (main) ancillary service products. Standardization of flexibility products focuses on sharing common parameters like full activation/deactivation times (FA/DTs), shape (i.e., symmetry feature), time duration (ψ) and minimum power. The flexibility products considered (set in [16]) include Frequency Containment Reserve (FCR), *replacement reserves* (RR), *frequency restoration reserves* with manual activation (mFRR) and automatic activation (aFRR) balancing energy, and support for the imbalance netting process. Once activated these products are paid by the *pay-as-bid* (PAB) mechanism on national flexibility markets.

III. THE OPERATIONAL PLANNING MODEL

The operational planning model (OPM) is developed to determine the optimal *unit commitment* and *energy dispatch* of Multi-Energy System (MES) devices, with the objective of minimizing the economic costs associated with meeting energy demand over the short term (e.g., day-ahead or intra-day time horizons). It is assumed that the necessary resources to meet demand are procured through participation in energy markets, specifically the day-ahead (DA) and intra-day (ID) markets for electricity and gas. To demonstrate the capability of MESs to provide flexibility to the power system, one of the primary objectives of this study, the model is extended to include a flexibility module that enables participation in dedicated flexibility markets. While it is possible to formulate a single-stage optimization problem that jointly solves demand satisfaction and market participation (energy and flexibility), a two-stage structure is adopted for the sake of conceptual clarity and to clearly define the MES operational baseline.

In the first stage, the model addresses demand satisfaction and energy market participation, aiming to minimize fuel procurement costs, maximizing revenue from surplus electricity generation. The result is a comprehensive operational program for the MES devices, alongside market bids that determine interactions with the electricity and gas grids. This outcome defines the MES baseline, as established in [10]. In the second stage the model exploits the potential deviations from the baseline to provide upward and downward electrical flexibility. These adjustments must also ensure that energy carrier balances are maintained and demand is continuously met.

A. *The basic stage: demand satisfaction*

- The 1st stage objective function

The first stage objective of the OPM minimizes costs due to acquiring fuels on day-ahead (DA) energy markets for demand satisfaction. Eq(1) sets the MES objective function (OF) that minimizes MES operative (*opr*) costs of device *r* and the costs associated with importing (*imp*) energy and maximizes the revenue for exporting (*exp*) energy, for electricity and gas on DA market.

$$\min_{p} \sum_{t\in T, i\in \mathcal{E}} \left\{ \sum_{r\in \mathcal{R}, M\in\{DA,ID\}} p_{r,t}\mathbb{C}_{r,t}^{opr} + p_{M,t}^{imp}\mathbb{C}_{M,t}^{imp} - p_{D,t}\mathbb{P}_{D,t} + \sum_{M\in\{DA,ID\}} -p_{M,t}^{exp}\mathbb{P}_{M,t}^{exp} \right\}_{i} \tag{1}$$

In eq(1), $p_{r,t}$ is the setpoint of device *r* at time *t* for each device $r\in \boldsymbol{\mathcal{R}}=\{\boldsymbol{\mathcal{G}},\boldsymbol{\mathcal{B}},\boldsymbol{\mathcal{L}}\}$, $\boldsymbol{\mathcal{R}}$ is the set of devices in the MES constituted by generators $\boldsymbol{\mathcal{G}}$, storages $\boldsymbol{\mathcal{B}}$ and loads $\boldsymbol{\mathcal{L}}$ (consumptions required by the MES internal needs), *t* is any time instant of the plan time horizon *T*, $\mathbb{C}_{r,t}^{opr}$ is the operative (*opr*) unitary cost of *r* at *t*, the terms $p_{M,t}^{imp}$ and $p_{M,t}^{exp}$ represent the power exchanged with the grid through any energy market M$\in\{DA, ID\}$, and the terms $\mathbb{C}_{M,t}^{imp}$ and $\mathbb{P}_{M,t}^{exp}$ represent the economics, that is the unitary costs and prices for importing and exporting, respectively, from/to energy market *M*, finally, $i\in \boldsymbol{\mathcal{E}}$ the set of energy carriers processed in the MES (in the following variables *i*, *j*, and *z* will represent generic energy carriers in $\boldsymbol{\mathcal{E}}$).

- Equilibrium of energy carriers

Eq (2) sets the MES balance where the contributions must be in equilibrium. Contributions are from generators $\boldsymbol{\mathcal{G}}$, storages $\boldsymbol{\mathcal{B}}$, loads $\boldsymbol{\mathcal{L}}$ (consumptions of MES internal needs), the demand

$\mathcal{D}$ (consumptions required by MES external entities) and the (importing and/or exporting) participation to DA and ID energy markets for any energy carrier *i* in $\mathcal{E}$:

$$\left\{\sum_{g\in\mathcal{G}} p_{g,t} + \sum_{b\in\mathcal{B}} p_{b,t}^{d} + p_{DA,t}^{imp} + p_{ID,t}^{imp} = \sum_{b\in\mathcal{B}} p_{b,t}^{c} + \sum_{\ell\in\mathcal{L}} p_{\ell,t} + p_{\mathcal{D},t} + p_{DA,t}^{exp} + p_{ID,t}^{exp}\right\}_i \forall i \in \mathcal{E} \tag{2}$$

The terms $p_{g,t}$ $p_{\ell,t}$ are the setpoint of generator *g* and load $\boldsymbol{\ell}$ at time *t* and the terms $p_{b,t}^{d}$ and $p_{b,t}^{c}$ are the discharging (*d*) and charging (*c*) power at time *t* for the storage *b*, for each device *r* holds $\underline{p}_r z_{r,t} \leq p_{r,t} \leq \overline{p}_r\, z_{r,t}$, where $\underline{p}_r$ and $\overline{p}_r$ are the minimum and nominal power of *r*, while $z_{r,t}$ represents the *r-on-off* variable, $p_{\mathcal{D},t}$ is the MES-demand (e.g., the demand in a district heating). The conversion of the device power value across two energy carriers *i*, *j* is set by the *conversion factor* σ: $\{p_{r,t}\}_i = \{p_{r,t}\}_j \sigma_r^{i,j}$(e.g., this sets the relationship between gas input and heat output in a gas boiler). In case *j* is an input and *i* is an output for device *r*, conversion equals efficiency: $\sigma_r^{i,j} = \eta_r^{i,j}$. Eq(3) sets the evolution of $e_{b,t}$ representing the energy stored in the device *b* at time *t*,

$$e_{b,t} = (1 - \lambda_{b,\Delta t}^{losses}) e_{b,t-\Delta t} - + \frac{p_{b,t}^{c}}{\eta_b^{c}} \Delta t - \eta_b^{d} p_{b,t}^{d} \Delta t \tag{3}$$

Where, $\lambda_{b,t}^{loss}$ is the energy loss of *b* during Δ*t*, η_b^{c} and η_b^{d} are the efficiency of charging and discharging and Δ*t* is the time interval. The energy stored boundaries are: $\underline{e}_b \leq e_{b,t} \leq \overline{e}_b$.

B. The flexibility provision

OPM calculates the flexibility resulting from the baseline and elaborates the bids for ancillary services. Bids for ancillary services on flexibility markets are set preserving the reliability of demand satisfaction, and possible new bids for ID market are set to solve possible imbalances caused by ancillary service provision. Basically, the upward '+' and downward '-' modes flexibility for each device *r* is defined, unless for storages and in line with [5], for each energy carrier *i*∈$\mathcal{E}$ by eqs (4a-4b),

$$\{\mathcal{F}_{r,t}^{+} = z_{r,t}(\overline{p}_r - p_{r,t})\}_i \tag{4a}$$

$$\left\{\mathcal{F}_{r,t}^{-} = z_{r,t}\left(p_{r,t} - \underline{p}_r\right)\right\}_i \tag{4b}$$

where $z_{r,t}$ is the on/off status of *r* (in case of very fast units this term can be dropped), $\overline{p}_r$ and $\underline{p}_r$ are, respectively, the upper and lower operating limits of *r*, on the energy vector *i*.

- The 2nd stage objective function

The objective function of the second step is focused on bids regarding the ancillary service products S_k belonging to the set S. Each product S_k is subdivided into S_k^{+}, the upward, and S_k^{-}, the downward, components (if any). Then FO maximizes the revenue from the provision of S_k^{+} and minimizes the costs of provision of S_k^{-} to the flexibility (ancillary service AS) markets.

$$\min_{p_t^{\mathcal{S}^*}} \left\{\sum_{S_k\in\mathcal{S}} p_t^{S_k^-} \mathbb{C}_{AS,t}^{S_k^-} - p_t^{S_k^+} \mathbb{P}_{AS,t}^{S_k^+} + \mathbb{E}_{ID,t}\right\}_i \forall i \in \mathcal{E} \tag{5}$$

where $\mathbb{C}_{AS,t}^{S_k^-}$, $\mathbb{P}_{AS,t}^{S_k^+}$ and. $p_t^{S_k^-}$, $p_t^{S_k^+}$ represent are the unitary cost and price, and the downward and upward powers for providing the downward product S_k^{-} and the upward product S_k^{+}, respectively. The term $\mathbb{E}_{ID,t}$ represents the importing costs and exporting revenues from the participation in the ID market.

- The flexibility bounded by ramp rate

The maximum amount of flexibility for each device is bounded by eqs(4a-4b) and by the ramp rate ρ_r^{*} characteristics of *r*:

$$\mathcal{F}_{r,t}^{*,k} \leq \rho_r^{*} \cdot t_k^{a} \tag{6}$$

Where '*' stands for upward (+) or the downward (-) mode, t_k^{a} is the full activation/deactivation time (FAT/FDT) characteristics of the product S_k^{*}.

- Flexibility from a pool of devices

The set of devices $\underline{\mathcal{R}}\subset\mathcal{R}$ includes devices involved in the provision of the set of ancillary service products S. The flexibility of this pool is algebraically calculated, according to [5], as follows:

$$\left\{\mathcal{F}_{\underline{\mathcal{R}},t}^{*} = \sum_{r\in\underline{\mathcal{R}}} \mathcal{F}_{r,t}^{*}\right\}_{i} \tag{7}$$

Given the set of products S, the corresponding bids are represented by $p_t^{\mathcal{S}}$, formally: $p_t^{\mathcal{S}} = \sum_{\mathcal{S}_k\in S} p_t^{\mathcal{S}_k}$. The provision of S from $\underline{\mathcal{R}}$ is defined by, $p_t^{\mathcal{S}} = \sum_{\mathcal{S}_k\in S} p_{\underline{\mathcal{R}},t}^{\mathcal{S}_k}$. The flexibility of $\underline{\mathcal{R}}$ bounds the provision of S. The next equation details the provision of S by the contribution of each device in $\underline{\mathcal{R}}$,

$$\left\{p_t^{\mathcal{S}} = \sum_{\mathcal{S}_k^*\in S, r\in\underline{\mathcal{R}}} p_{r,t}^{\mathcal{S}_k^*}\right\}_x s.t.\, p_{r,t}^{\mathcal{S}_k} \leq \mathcal{F}_{r,t}^{*} \tag{7a}$$

The provision of $p_t^{\mathcal{S}}$ is further constrained by the characteristics of each product in S, that is: symmetry, duration and minimum power required, respectively,

$$\left\{p_{\underline{\mathcal{R}},t}^{\mathcal{S}_k^+} \cdot \varrho_k = p_{\underline{\mathcal{R}},t}^{\mathcal{S}_k^-} \cdot \varrho_k\right\}_i \forall \mathcal{S}_k \in \mathcal{S} \tag{7b}$$

$$\left\{p_{\underline{\mathcal{R}},t}^{\mathcal{S}_{k,t}} = p_{\underline{\mathcal{R}},t+\alpha}^{\mathcal{S}_{k,t}}\right\}_i \forall \alpha \leq \psi_k\, \forall \mathcal{S}_k \in \mathcal{S} \tag{7c}$$

$$\left\{p_{\underline{\mathcal{R}},t}^{\mathcal{S}_k} \geq \underline{p}_k\right\}_i \tag{7d}$$

Where, for each product S_k, ϱ_k is the on/off symmetry requirement, ψ_k is the minimum duration required and $\underline{p}_k$ is the minimum power value, respectively.

In case of multiple instantaneous activations of products in S the maximum power is potentially further reduced. At short-term planning stage the sequence of product activations is unknown, and to avoid any inconsistency the available flexibility must be reduced by the duration of the operative time interval τ (e.g. 15 minutes) to be compliant with the summation of the activation time of each product, as follows,

$$\left\{\sum_{\mathcal{S}_k\in S} p_{r,t}^{\mathcal{S}_k^*} \leq \rho_r^{*} \cdot \tau\right\}_i \forall r \in \underline{\mathcal{R}} \tag{8}$$

- Flexibility provision and balancing energy carriers

The provision of S_k on the carrier *i* possibly requires balancing actions on any other energy carrier *j*. These actions must be performed by suitable devices, in the set $\overline{\mathcal{R}} \subseteq \mathcal{R}$ such that $\underline{\mathcal{R}} \cap$

$\overline{\mathcal{R}} = \emptyset$, not involved in the provision of S_k (this reduces the complexity). Then the balancing equation is set as follows,

$$\left\{\sum\nolimits_{r\in\underline{\mathcal{R}}} p_{r,t}^{\mathcal{S}_k^*} = \sum\nolimits_{r\in\overline{\mathcal{R}}} p_{r,t}^{\mathcal{S}_k^{*(+/-)}} + p_{ID,t}^{*}\right\}_j \; \forall \mathcal{S}_k^* \in \mathcal{S}^* \qquad (9)$$

Where the contribution of $r \in \overline{\mathcal{R}}$ in balancing the provision of $\mathcal{S}_k^*$ is distinguished into increasing (+) and decreasing (-), $p_{ID,t}^{*}$ represents the bids on the ID market to increase/reduce the production due to the provision of $\mathcal{S}_k^*$.

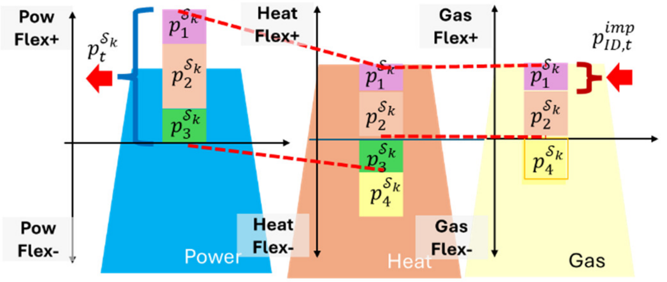

Figure 1 - Balancing the heat and gas carriers while providing the product Sk on the electricity carrier.

Figure 1 exemplifies eqs (4-9) focusing on the provision of product S_k on the power carrier, and associated balancing actions on heat and gas carriers. Starting from the left-hand side, the product S_k is provided on the electricity grid (the blue layer) by the upward contribution $p_t^{S_k}$ from the pool of devices 1, 2 and 3 (the pink, red and green boxes). Devices 1 and 2 are supposed *gas-to-heat-&-power* technologies while device 3 is *power-to-heat* technology. The provision of S_k creates an imbalances the heat carrier (the middle red layer). In response, devices 1 and 2 provide upward heat flexibility, while device 3 provides downward heat flexibility and the result is an upward imbalance. Device 4 (the yellow box) which is not involved in the provision of S_k, can balance heat carrier and it is as *gas-to-heat* technology. Device 4 reduces provides heat (-) flexibility until the heat carrier equilibrium is reached. Devices 1, 2 and 4 provide upward flexibility on the gas carrier, the yellow layer on the right-hand side, producing an imbalance. Devices 1, 2 provide upward gas flexibility and 4 provides negative (-) gas flexibility, device 3 has no impact on gas. To restore balance on the gas carrier, the bid $p_{ID,t}^{imp}$, representing the quantity imported from ID market at time t, is activated.

The model is implemented as a Mixed Integer Linear Programming and coded in Cplex.

IV. THE SIMULATION OF THE MODEL OVER ONE YEAR

This section proposes the simulation of the model to demonstrate the ability of MESs in providing flexibility. The model is instantiated with a real 3rd generation district heating plant, operating in the Milan-East area. Simulations cover several seasons of the year to demonstrate the ability of this MES in providing flexibility and adopt (average) prices/costs taken from the outcomes of the Italian day-ahead, intraday and TSO flexibility markets in 2023.

A. *The MES adopted for simulation*

The model was simulated by implementing a district heating system with the following characteristics:

- *gas*-to-*heat*: 3 gas boilers (GB), with 16.1 MW heat power; 3 combined heat & power (CHP) gas engines with 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;
- one *heat storage* (HS) with a heat energy capacity of 58 MWh.

The MES maximum heat power capacity is about 110 MW and the maximum electricity generation is 15 MW. The plant participates in the DA and ID energy markets. Devices directly involved in the provision of flexibility products are CHPs (ρ=0.125 MW/*min* each) and EB (ρ=14 MW/*min*).

B. *The use cases to be tested*

In a first run the model defines the daily baseline by scheduling the devices to face the foreseen heat demand and elaborating the bids for DA energy markets, for electricity and gas. In the second run, the bids for the flexibility markets (i.e., the TSO and the DSO markets) are set to exploit possible opportunities, according to the baseline set in the first run. As previously said, the two runs are a choice and don't depend on the characteristics of the model. The flexibility products considered for simulations include FCR, aFRR, mFRR, TSO and DSO congestion management (TCONG and DCONG, respectively).

The input data include daily heat demand (with hourly time resolution) and energy and flexibility products prices, from 2023 market outcomes, along 4 weeks, taken in winter, spring, summer, and autumn. Flexibility market prices and costs refer to the average prices resulted in the day-ahead flexibility market session for the Italian north market area. FCR is currently a mandatory product, the prices adopted here are set as a hypothesis. aFRR, mFRR and TSO congestion management are traded in the day-ahead flexibility market session as a single product, at the activation time the operator specifies the product needed. Then simulations are carried out associating the same price and cost to these three products. All data have hourly time resolution.

A. *Simulations and assessment*

- Outcomes of the first run

First run calculates in calculating the daily plan of the MES fitting the heat demand and setting the bids on day-ahead energy markets, as shown in Figure 2 for a winter season.

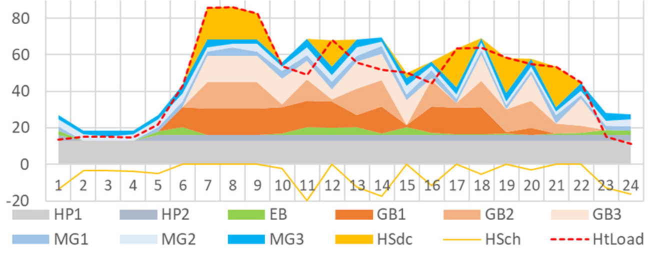

Figure 2 - The daily scheduling of the MES, with hourly resolution, on a winter day (abscissa heat power [MW])

Figure 2 shows the scheduling of the MES units (the different colored areas) to face the heat demand (dotted red line). The yellow area and (negative) line represent the HS discharging and charging phases, respectively.

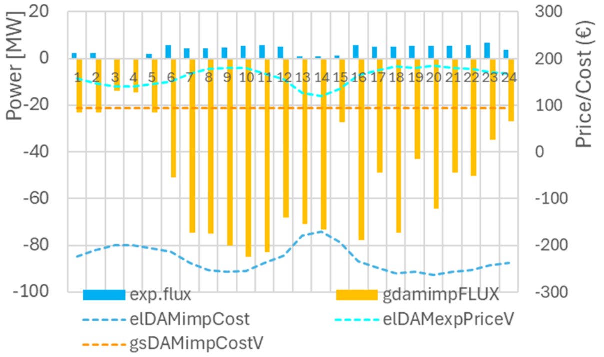

Figure 3 - The daily bids on the electricity and gas day-ahead markets

Figure 3 reports the import bids on the gas DAM (the negative yellow bars) and the exporting bids on the electricity DAM (the positive blue bars) calculated by the model in the first run.

- Outcomes of the second run

The second run includes as input the outcomes of the first run (the day-ahead electricity and gas markets bids) and calculates the bids for flexibility products on TSO and DSO flexibility markets.

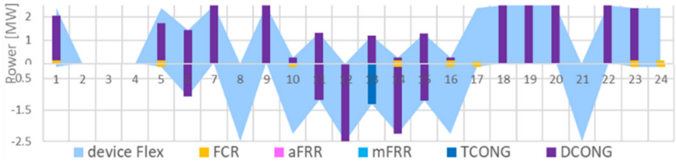

Figure 4 – The available daily upward and downward flexibility margins (the light blue areas) and the scheduling of the flexibility products for a CHP in the MES.

CHP daily flexibility program outcomes are reported in Figure 4. This consists of the bids for the different flexibility products, FCR (yellow bars), the *up* and *dw* DCONG (purple bars), and the *dw* TCONG (negative blue bar).

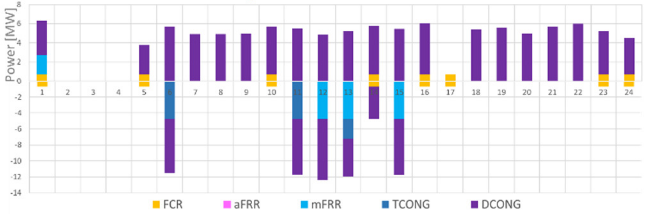

Figure 5 – The daily scheduling of the flexibility products in the winter season for the MES.

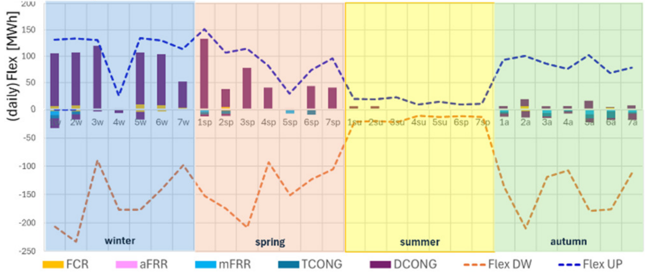

Figure 6 – The annual results of the flexibility markets along the four weeks of the 4 seasons.

Figure 5 shows the complete set of bids scheduled for a winter day. Figure 6 proposes the flexibility markets bids set along the 4 weeks in the 4 seasons (distinguished by the colored areas). The daily cumulative available flexibility is represented by blue and red dashed lines, in the upward and downward modes, respectively. The MES flexibility is highly exploited in the upward mode in the winter (blue area, days 1*w*-7*w*), and in the spring (red area, days 1*sp*-7*sp*) periods, is poorly exploited in autumn (green area) and almost non-existent in summer (yellow area).

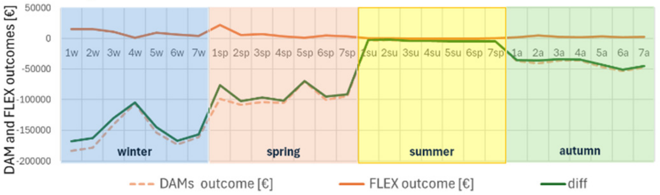

Figure 7 – The yearly trend of daily costs (in €) of the production program to face the heat demand (the green line) with the possible reduction costs due to flexibility bids, supposed to be accepted by the market managers and activated by the SOs.

In Figure 7 the yearly economic results, with daily resolution, show a little revenue arising from flexibility provision (red line) with respect to the total costs due energy markets trading (yellow dotted line). Moreover, the revenues from flexibility provision is calculated (optimistically) assuming that all the flexibility products are activated by the system operators at the maximum foreseen power (flexibility products are remunerated by the pay-as-bid mechanism when activated).

V. CONCLUSIONS

This paper presents a model designed to manage the provision of flexibility by Multi-Energy Systems (MESs) in markets operated by both TSOs and DSOs. The model was tested using representative data from a 3rd generation district heating system, simulating MES behavior within the context of the Italian electricity and gas markets, as well as participation in flexibility markets. As demonstrated in Section IV, the MES is capable of providing substantial flexibility across nearly all seasons of the year. However, despite this potential, the current market price structures and cost parameters hinder the full exploitation of MES flexibility. Downward flexibility remains underutilized in existing flexibility markets. This is due to cost assumptions that still reflect the economics of large-scale power plants, which can offer downward flexibility at very low prices, typically representing an avoided cost of generation. In contrast, MESs provide downward flexibility by reducing power output and simultaneously maintain the balance of all other energy carriers, with additional operational constraints and costs. An example is provided in Section III. The summer season warrants special attention. In this period, 3rd generation district heating systems, designed with high-temperature heat delivery, supply domestic hot water, a small fraction of the winter heat demand. As a result, flexibility provision during summer is significantly limited. Nevertheless, this outcome also underscores an important insight: heating must be coupled with cooling to increase the yearly efficiency of the system. These findings offer valuable insights for energy regulatory authorities.

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