

A Methodology to Support the Flexibility Maximization for Multi-Energy Systems to Provide Services to the Electrical Distribution System

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Abstract

The paper proposes the Energy-Lattice methodology designed to model and analyse multi-energy systems (MES) as energy transformation flows. A mixed-integer linear programming algorithm supports the methodology to set short-term planning for MES to satisfy the multi-energy demand, and the provision of services, like ancillary services to the power system. The methodology is based on the notion of energy-layers associated to energy carriers. An energy-layer represents the provision of services and the satisfaction of the external demand, by the operation of suitable devices, like generators, storages and loads related to an energy-carrier. Energy layers are related each other by conversion nodes. This work was partially carried out in the European project H2020 MANGNITUDE (n. 774309). The paper illustrates the main features of the Energy Lattice methodology and the underlying algorithm that model the behaviour of the MES in the short term. This algorithm is a mathematical mixed integer linear programming composed of two steps. The former copes the energy demand and the latter, according to the results of the first one, verifies the economic convenience to provide ancillary services according to the identified flexibility margins.

1 Introduction

The transformation of energy landscape towards decentralized low-carbon energy systems is leading to redesign the generation devices to supply the demand and revise the electricity system management strategies [1].

In this respect, the strong commitment arising from power system operators concerns the even more availability of resources for regulation exchanged as ancillary services (AS) [2]. The set of ASs consists of different procedures to control the stability and balance the power system. These bring in action active power control resources like primary, secondary and tertiary reserve, power balancing and congestion resolution.

Traditional resources devoted to system regulation are progressively reducing in number, and substituted by variable renewable energy sources (vRES), which are the main responsible of the issues currently occurring on the electrical systems [2]. This trend can be fruitfully mitigated by the available resources, acting on the electrical (distribution) system and on other energy systems like gas, heat, etc. which can share flexibility to support the electrical system. Multi-energy systems (MES), [3] and [4], are systems that can share flexibility to support power system. The integration of technologies like generation, energy storage, renewable energy, short distance transmission and natural gas, is considered an effective way to improve the energy utilization efficiency, accommodate more renewable energy and satisfy the multiple energy demands [5].

The physical and commercial coupling enables great synergies among the energy carriers but at the same time introduces a higher level of complexity to be managed. Several complexity-streams can be identified:

- spatial* : a MES can be a converter device, or a pool of devices, as well as an energy area, an entire country or a region;
- temporal* : different functionality like operation, balancing and planning of a MES, in the “very-short” and “short” term with seconds, minutes, hours-time resolutions; and hours, days, weeks-time horizons;
- networks*: integration of energy networks (for electricity, gas, DH -district heating- and cooling, hydrogen, and so on). This is currently one of the main barrier to completely get benefits from MES integration.

A strong commitment arises from power system to ask the availability of resources for regulation organized by ancillary services (AS) products. Power system stability and balance procedures are implemented by several market products like primary, secondary and tertiary reserve, power balancing, congestion resolution, etc. (Multi)-Energy systems are able to provide ASs in a flexible way combining generators and loads, and in some cases even storage systems, across several energy carriers.

The complexity in modelling and analyses of MES represents a barrier to the complete exploitation of the benefits arising from their integration. Delimit this complexity is the key goal addressed in this paper. Complexity reduction will be dealt

with from several perspectives: the identification of services, the demand and the different devices composing the MES. Devices are modelled to meet the requirements posed by a planning scheme, which are mainly associated to the spatial and temporal streams previously introduced, as addressed in [6]. The work proposed in this paper, currently carried on by RSE and ACS within the European H2020 project MAGNITUDE (n. 774309) and the Research Fund for the Italian Electrical System, investigates how to identify and design the optimization strategies to maximize the synergies among multi-energy systems for the provision of services to the electrical system.

The paper is organized as follows: in section 2 the energy-lattice methodology is introduced, in section 3 the two stage-algorithm is sketched and in section 4 the exemplification of the methodology, based on the Milan district-heating case study, is proposed.

2. The Energy Lattice Methodology

The complexity of the MES modelling phase is mainly due to coordination of multiple devices - operating on different energy carriers, like: electricity, gas, heating, cooling etc.; - to satisfy the multiple-carrier demand, and to provide multiple-services. Devices taken into account include: energy converters (e.g., gas turbine, gas boiler, , electric chiller, absorption chiller), energy storages - electricity and heat storages - transformers [4]. The energy transformation process to satisfy the demand can result in energy losses and demand-not-met.

The diffusion of *modelling languages* to express mathematical programming problems (e.g., AMPL, GAMS, CPLEX/OPL, etc.) are leading to abstract the design point of view from “low-level coding” related to the mathematical programming paradigm, to a more abstract one, based on algebraic equations, possibly associated to graphs, to represent the transformation of energy fluxes through system devices and network-carriers. Furthermore, the possibility of providing a common framework covering different levels from planning to control is an increasingly requested feature.

- The Energy Lattice

The methodology links each energy carrier managed by the MES to an *energy-layer* (EL). An energy-layer hosts the energy process related to the associated carrier devoted to provide external services and satisfy the carrier-demand. A general representation of an energy-layer is proposed in Fig.1. The energy transformation/production is modelled by interactions of elementary entities like: generators (GEN), energy storages (STO), loads (LOAD). The carrier’s demand satisfaction is represented by the withdrawal of energy, while service provision is an energy contribution, or a withdrawal, or both. An energy-layer quantifies losses and demand-not-met. In general, the model of a MES involves as many energy-layers as many energy carriers it manages. Energy layers are linked together by energy *conversion-nodes* (CN). Each CN represents the conversion of energy performed by a conversion device, like for instance a combined heat and power generator (CHP), a chiller, etc. A conversion device

provides as many CNs as many energy conversions it performs.

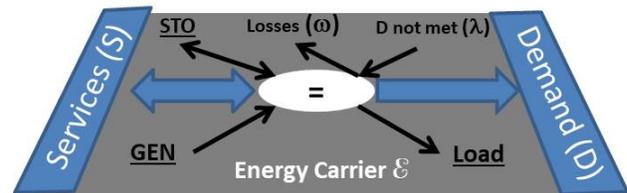


Figure 1 : Energy (Carrier) Layer: main constituents

- Balancing node/carrier network

The simplest way to model the flow among services, generators, storage, loads and demand is by a single balancing node. Each entity is linked with an energy flux with a specific direction. However, if the complexity or the features required to model the energy fluxes cannot be represented by a single node, the detail of the network is introduced. In this methodology formulation just the case of balancing-node is taken into account. Energy equilibrium for balancing nodes is solved according to the Kirchhoff’s current law, set for electric circuits. That is, the algebraic sum of energy inflows (contributions) to the node must be equal to the algebraic sum of corresponding energy outflows (withdrawals), accounting losses and demand-not-met.

- Conversion nodes to link energy-layers

Each coupling-device operates an energy conversion among two or more energy carriers, this is represented by as many suitable conversion-nodes (CNs) as needed. According to a functional view, a CN is a bidirectional-rule that relates input and output energy flows together. In case the input energy flow to the CN is the input energy flow to the device and the output energy flow to the CN is the output energy flow to the device the CN denotes the efficiency.

- Carrier process and the lattice model

The complete model of a MES consists of as many energy-layers (ELs) as many energy-carriers (ECs) are involved in its energy processes, ELs are linked together by suitable CNs. Within each energy layer a node, or a graph, links together GENs, STOs and Loads and coupling devices allow to link energy layers through CNs. The model gained is a graph. This graph ensures the soundness of energy-transformation processes held in the model. That is, the balance acquired in one EL must be coherently reflected in all the other connected ELs while providing services and satisfying the demands.

- MES and operational flexibility identification

As previously shown, the model of a MES expressed by the energy-lattice methodology ensures balancing among the different entities. The methodology also supports the identification of (operational) flexibility owned by a MES, to gather extra resources to cover extra-services. For instance, this suites well to the case extra-flexibility margins are identified to be offered on the ancillary market services after the participation to the day-ahead electricity market. In fig. 2

the energy-layer is integrated with the information regarding the flexibility margins the MES entities own.

Operational flexibility was deep investigated in [7]. Here the quantification of a MES operational flexibility is expressed through the flexibility metric parameters: “ramp-rate” (ρ , [MW/min]), “power capacity” (π , [MW]) and “energy” (ϵ , [MWh]).

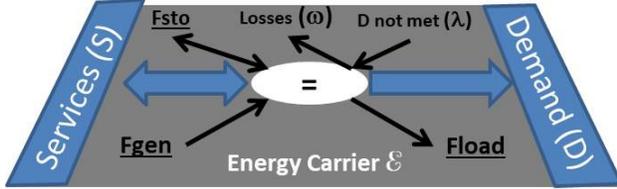


Figure 2 : Energy (Carrier) Layer: flexibility extensions

3 The underlying framework

The set of energy carriers involved in the MES operation (i.e., the energy-layers), are,

$$\mathcal{E} = \{\mathcal{E}_1, \mathcal{E}_2, \dots, \mathcal{E}_n\} \quad (1)$$

For each EL (\mathcal{E}_i) the range of values for each physical (input or output) variable of the device d is set as follows:

$$\{(uc_d(t) \cdot \bar{P}_d \geq P_d(t) \geq uc_d(t) \cdot \underline{P}_d)\}_{\mathcal{E}_i} \quad (2)$$

where, uc_d denotes the unit-commitment of d , and $P_d(t)$ is a d -physical (input or output) variable at time t ; \underline{P}_d and \bar{P}_d denote, respectively, the lower (min) and the upper (max) limit value. For each device d power shifting (in upward or downward direction) must be within the maximum power variation allowed for d (the ramp-rate ρ),

$$\rho_d \geq |P_d(t) - P_d(t + \tau)| \quad (3)$$

For a coupling device that links energy carriers \mathcal{E}_j and \mathcal{E}_i , the conversion coefficient is,

$$\{P_d^{out}(t)\}_{\mathcal{E}_i} = \{P_d^{in}(t)\}_{\mathcal{E}_j} \cdot \sigma_d^{\mathcal{E}_j, \mathcal{E}_i} \quad (4)$$

where P_d^{out} is the output power (\mathcal{E}_i), P_d^{in} is the input power (\mathcal{E}_j); $\sigma^{\mathcal{E}_i, \mathcal{E}_j}_d$ labels the CN, it specifies the conversion to get the P_d^{out} from P_d^{in} , in this case σ identifies the efficiency η of d to convert P_d from \mathcal{E}_i to \mathcal{E}_j . The state of charge for storage devices at each time instant depends on the history and on the current charging contribution and discharging withdrawal, and is computed by the equation:

$$SOC_d(t + \tau) = SOC_d(t) \cdot \omega_d + P_d^{CH}(t) \cdot \eta_d^{CH} \cdot \tau - P_d^{DCH}(t) \cdot \frac{1}{\eta_d^{DCH}} \cdot \tau \quad (5)$$

where SOC denotes the state-of-charge of storage d , ω_d denotes the losses of the storage in the time unit, P_d^{CH} and P_d^{DCH} denote, respectively, the charging and discharging power of d . η_d^{CH} and η_d^{DCH} denote, respectively, the charging and discharging efficiency value for d .

The balancing equation for each energy-layer \mathcal{E}_i , taking into account service provision and demand satisfaction (with suitable management policies [8]) is,

$$\left\{ \sum_{g \in gen} P_g(t) + \sum_{s \in sto} P_s^{DCH}(t) + \sum_{sr \in S} P_{sr}^{IN}(t) + \lambda(t) = \sum_{l \in Ld} P_l(t) + \sum_{s \in sto} P_s^{DCH}(t) + \sum_{sr \in S} P_{sr}^{OUT}(t) + D(t) + \omega(t) \right\}_{\mathcal{E}_i} \quad (6)$$

where on the left side (contributions) there are the GENs P_g , discharging STO P_s^{DCH} , the service-S- P_{sr}^{IN} and the demand-not-met λ . On the right side (withdrawal) there are the LOADs P_l , charging STO P_s^{DCH} , the services-S+ P_{sr}^{OUT} , the demand D and the losses ω .

Both first and second-stage algorithm require the cost reduction of energy production P_g , an increasing of revenue due to demand satisfaction P_l and to electricity market participation (for electricity energy carrier, [9]).

$$J_1 = \min_p \left[\sum_{\mathcal{E}_i} \left\{ \sum_{d \in Gen} P_d(t) \cdot cost_d(t) - D(t) \cdot rem_D(t) + \sum_{sr \in S} P_{sr}^{IN}(t) \cdot cost_{sr}^{IN}(t) - \sum_{sr \in S} P_{sr}^{OUT}(t) \cdot rem_{sr}^{OUT}(t) \right\}_{\mathcal{E}_i} \right] \quad (7)$$

The term $cost_d$ represents the unitary production cost and P_d , the power generated by d , rem_D represents the unitary remuneration due to supply the demand D , $cost_{sr}^{IN}$ and rem_{sr}^{OUT} represent, respectively, the unitary cost and remuneration due to import and export of power due to some service provided by the MES.

The second stage algorithm differs from the first one because it looks for extra services to be provided and at this aim computes flexibility margins for GENs, STOs and LOADs. Flexibility is distinguished between upward (up) and downward (dw) margins (identified with M1 and M2), for generation and load modes:

$$\{FLEX_d^{M1}(t) \equiv uc_d(t) \cdot (\bar{P}_d - P_d(t))\}_{\mathcal{E}_i} \quad (8)$$

$$\{FLEX_d^{M2}(t) \equiv uc_d(t) \cdot (P_d(t) - \underline{P}_d)\}_{\mathcal{E}_i} \quad (9)$$

where in case the device d is a generator: M1= up and M2= dw , while in case is a load: M1= dw and M2= up .

3 Methodology exemplification

In this section a sketch of the Energy-Lattice methodology testing is proposed. This refers to the analysis of the (real) case study of the Milan district-heating (DH) system. This plant includes 9-devices to feed the district heating network linking 700 buildings. Plant devices includes: 3 Combined Heat and Power - CHP gas engines, 1 water/water heat pump, 3 gas boilers, 2 heat storages (operated as a single unit) and 1 electric boiler. The next table illustrates the essential technical characteristics of these devices.

Table 1 : Devices installed in the Milan DH-Plant

device	Pmin [MW]	Pmax [MW]	Eff/COP	Energy [MWh]
3-CHP (th)	2.5 (2.75)	5 (4,55)	0.43 (0.41)	
1-HP	11.2	15	2.5	
3-GsB	0	15	0.93	
1-EIB	2.5	5	0.95	
2-HS	0	11		35

The Energy-Lattice multiple-layer representation is proposed in the next figure.

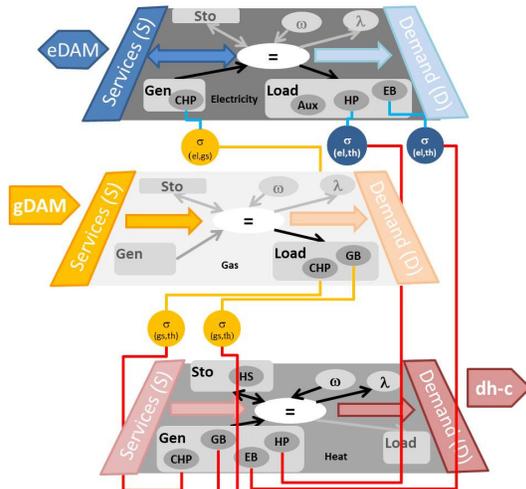


Figure 3 : Milan District-Heating: Energy-Lattice model

Light grey entities in EL are not used. The first stage of the EMS allows to cope the (forecasted) daily heat demand. At this stage, the electrical carrier exchanges the extra-electrical production on the day-ahead market. During the winter season this that is a relevant amount as the satisfaction of heat demand requires to operate almost all the generators.

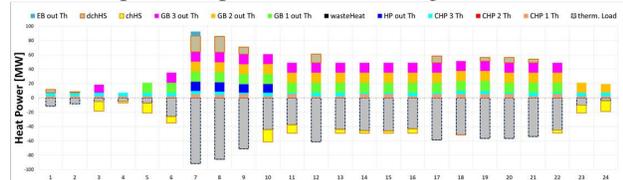


Figure 4 - Milan DH: heat-carrier balancing

The electrical daily program is represented in the next figure.

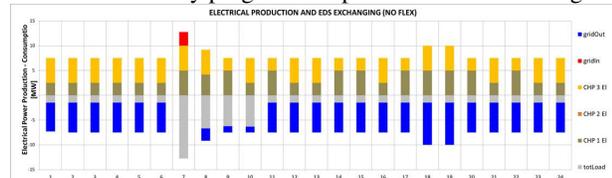


Figure 5. Milan DH: electrical-carrier balancing

The second stage algorithm computes the (electrical) flexibility and checks which ancillary service can be provided, as shown in fig.6.



Figure 6: 2-stage identifies flexibility and services to be provided

Ancillary services taken into account include: frequency containment reserve (FCR), automatic frequency regulation

reserve (aFRR) and manual frequency regulation reserve (mFRR) in both *up* and *dw* directions.

6. CONCLUSIONS

The paper proposed a methodology to support the short-term planning for multi-energy systems. The methodology is designed to ensure the balancing equilibrium across several energy carriers, and at the same time to associate to each energy carrier its own resources. The methodology owns a two steps algorithm to analyse and operate MES. This case study is a fragment of the Milan district-heating system.

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