Multi-energy systems as enablers of the flexible energy transition

ABBÀ ILARIA
TEBE-IEEM Research Group,
Energy Department,
Politecnico di Torino, Italy.
Corresponding author:
ilaria.abba@polito.it

LA BELLA ALESSIO
Technologies for
Generations and Materials
Department, Ricerca sul
Sistema Energetico - RSE
S.p.A., Milano, Italy

The growing deployment of renewable sources is having a relevant impact on the whole energy chain, and much more flexibility is required to continuously ensure the power balance between generation and demand. In line with this, the paper focuses on the analysis of Multi-Energy Systems, recognized as a key solution to efficiently match final users' needs by exploiting flexible interactions between different energy vectors.

Keywords: Multi-Energy Systems, Flexibility, Energy Transition, Multi-Generation Technologies, Energy Models, Simulation.

Overview Of Multi-Energy Systems

The current energy transition is having a huge impact on the whole energy chain and the progression towards carbon neutrality is affecting supply, transmission, conversion, and demand sides. In particular, the increasing diffusion of controllable distributed generation technologies enables to better exploit renewable energy sources (RESs), transforming consumers from passive to active actors (i.e., the so-called prosumers). The shifting in the way energy is produced and consumed clearly represents a challenge for transmission and distribution networks, leading the concept of power flexibility to play a crucial role in future power systems [1], [2]. According to [2], flexibility is defined as "the ability to adjust generation or consumption in the presence of network constraints to maintain a secure system operation for reliable service to consumers". This means that the availability of an adequate power flexibility becomes a prerequisite to foster the effective integration of RESs, enabling to tackle their volatility and uncertainty strongly dependent on weather conditions. In this framework, the necessity of more flexible energy players puts the attention on the efficient exploitation of the interaction between different energy vectors, converging towards the so-called Multi-Energy Systems (MESs). According to [3], MESs are defined as systems "whereby electricity, heat, cooling, fuels, transport, and so on optimally interact with each other at various levels for instance, within a district, or a city, or at a country level". In other words, the main idea of MESs is to manage different energy vectors as a whole, exploiting the synergies between them. An example of MES can be an electric network coupled with a thermal network, or a building where electrical, thermal and gas utilities are jointly regulated to improve the overall energy efficiency. MESs can perform better than traditional separate energy systems in terms of technical, financial, and environmental performances, allowing higher conversion efficiencies, efficient exploitation of local energy sources, reduction of greenhouse gases emissions and opening to new business and market opportunities [3], [4]. Nevertheless, MESs ask for the effective and optimal management of different energy sources and power interfaces; this is challenging since it increases the complexity of the systems and involves different dynamics [5; the same holds for design, modelling and simulation tasks concerning MESs [4], [6], [7]. For the above reasons, MESs and their provided flexibility are a current and trending research field, with significant interest both from the academic and in the industrial sector, in order to foster their integration in the energy system [3], [7]. In this context, a European project named MAGNITUDE has been recently carried out, with the objective of developing market mechanisms and tools to enhance MESs providing flexibility to the European power system, exploiting and optimizing the synergies among different energy vectors (i.e., electricity, heating and gas) [8]. Fitting into the context, this paper aims to provide a complete overview of the main features and modelling issues of MESs, proposing also a dynamic simulation approach, allowing a quick evaluation of a MES performances and suitable for testing control/optimization algorithms.

Multi-energy technologies and systems

A key role in enabling and practically allowing interactions between energy commodities is played by conversion technologies. In MESs, there exist several possibilities to transform one energy vector into another [7], each with related efficiency, technical features, emissions and costs. In line with the growing electrification of final uses [9], power-to-X technologies are increasing their relevance and diffusion, being able to exploit electricity coming from local RES. Nevertheless, gas technologies are still the most widespread and affirmed on the market and are improving their efficiency to reduce their environmental impact. In this regard, Guelpa et al. [7] offered a complete review on the conversion technologies suitable for MESs applications, classifying them into the following classes: *(i)* gas-to-heat, cooling and power (e.g. condensing gas boilers, chillers or trigeneration systems), *(ii)* power-to-gas (e.g. electrolysers), *(iii)* power-to-heat (e.g. electric boilers, heat pumps or polyvalent heat pumps), and *(iv)* power-to-commodities (e.g. mobility or desalination), with a final focus on storages considered fundamental to decouple supply and demand phases. Witkowski et al., [1], using a similar classification, added information about technical features of technologies (e.g., operating temperature level, efficiencies, partial load conditions, etc.), financial data and information about ramp rates and response time in case of flexibility demand. Concerning the technological sphere, the presence of multiple energy technologies in a single system can be challenging. Indeed, complexity comes from *(i)* the different sources of energy that can be used, from fossil to renewable sources; *(ii)* the level of maturity and readiness of technologies (e.g. gas vs hydrogen) with related financial and environmental implications; *(iii)* the different networks they need to use (i.e. power, gas or district heating and cooling networks) and finally *(iv)* the necessity to satisfy several types of energy demand simultaneously (i.e., heating, cooling and electricity) [4].

Modelling and simulation challenges

While technologies seem to be ready for their implementation into multi-energy systems, the design and operation phases ask for new approaches, models, and simulation tools to properly describe the operation of MESs and to optimally manage the interaction between energy vectors. Such tools are fundamental to provide science-based support to decision-makers, to effectively plan the development and optimization of MESs at different scales of analysis. Building an energy model is firstly a goal-driven process; indeed, all models are developed for a very specific purpose, which in turn determines the diverse characteristics of the models, from the level of abstraction and simplification to the spatial and temporal scale and resolution [10]. According to [11], models "could be categorized according to their purpose, methodology, assessment criteria, and structural and technological detail. They also take different analytical and mathematical approaches and vary according to their reusability.". In addition, diverse models' classifications are present in literature, depending on several factors, among which geographical coverage, spatial and temporal resolutions, as well as time horizon [11].

Focusing on the complex framework of MESs, the most challenging issue is that the different energy vectors involved may require the application of different time scales, resolutions and approaches to be addressed in the right way, in particular when dealing with modelling of networks or renewables [6]. According to [10], models can be defined as integrated or integral; the former are built assembling already existing models, the latter are usually built as a whole from scratch, giving more interest on the dynamics of the overall system, while devoting less attention to the detailed analysis of single components. The selection of proper modelling techniques for MESs is not an easy task, since it is not trivial to synthetize complex and bigger systems from small pieces and deduce or extend the properties of the MES from the features of the components. Considering that technologies and networks involved in MESs operations are well known and already modelled in separate environment, it could be easier to build an integrated model, using already existing models and adding links between them. Nevertheless, it has to be considered that the link between existing models, if not properly implemented, can increase the overall complexity [10]. This aspect, coupled with the challenge of mixing models with different requirements in terms of temporal and spatial granularity, could make it more beneficial to use an integral approach, building the entire MESs model from scratch; in this way, the management of a unique model with different energy vectors and their synergies in the same simulation environment could be easier. Several recent review papers facing the problem of modelling and simulating an MES are present in literature. Drivers, requirements, opportunities and drawbacks of modelling the interactions between energy vectors under the MES framework were discussed in [6]. The paper also reported examples of existing models and tools. Mavromatidis et al. tried to address the challenges of modelling Distributed-MES by answering ten questions on the most relevant topics [4]. The importance of choosing the proper level of detail when describing components of complex systems was stressed, to reach a good trade-off between model accuracy and computational time. In [7], a review on the state-of-the-art of modelling aspects and trends concerning the integration of gas, heat and electricity was conducted, with a focus on networks infrastructures; starting from a separate and detailed analysis of energy networks, highlighting differences and similarities between them, authors addressed the issue of optimizing and designing an MES as a whole. Finally, [11] presented a review on energy models and existing tools to optimize MESs in mixed-use districts, concluding that few already existing tools are able to answer the research question.

A "quick and dirty" simulation method for multi-energy systems

In line with the above, this section presents a proposal of a new simulator well suited for the efficient and dynamic simulation of MESs. The main objective of the tool is to give a quick answer about the performances of a MESs, which is a crucial feature when testing energy optimization and control algorithms. For this reason, the developed simulator is defined as "quick and dirty", giving outcomes in reasonable time and therefore requiring less detailed systems' modelling. The simulation methodology is here presented considering the case study of a small district heating network, named AROMA network [12], connected to the electrical utility through a CHP plant. In detail, this benchmark system is composed of a central power station (with a gas boiler and a CHP system), five residential users and several supply and return pipes to link demand and supply sides. As said before, the choice of the proper simulation tool is crucial for a good quality analysis [11]. According to the model purpose, the Simscape environment from MATLAB®

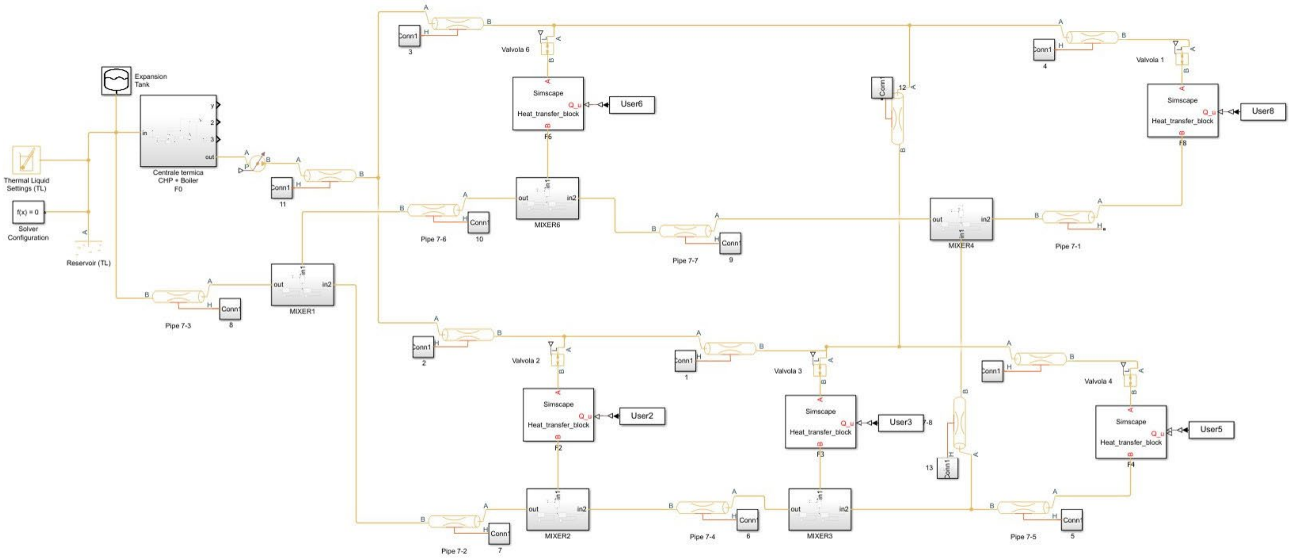


Figure 1. AROMA network scheme on Simscape.

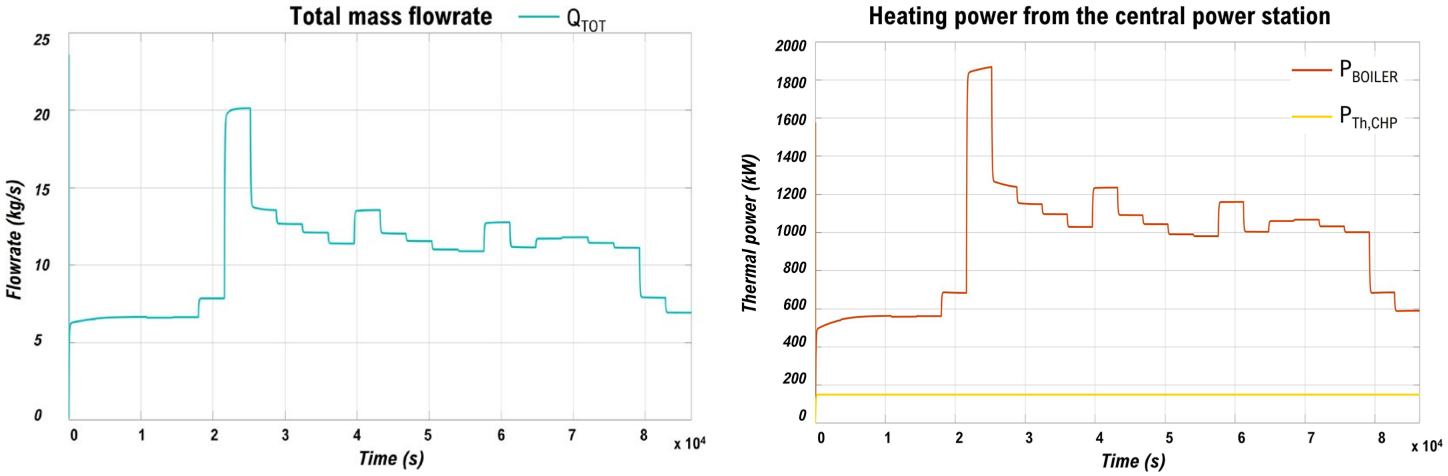
was selected [13]. Simscape enables building models of physical components based on physical links that integrate directly with block diagrams and other modelling paradigms. Moreover, thanks to its several libraries, it allows to cover all the physical domains involved in MES analysis (electricity, thermal fluids, gas and eventually hydrogen).

Figure 1 shows the global architecture of the designed simulation model for the district heating network, developed using the thermal liquid domain of Simscape.

In detail (**Figure 1**), the following components were used:

- a central power station, composed by a CHP plant, power-regulated, and a gas boiler in series; the boiler outlet water temperature is regulated by properly designed controllers tracking an imposed reference temperature, in this case 90 °C. CHP and gas boiler blocks are manually designed as heat exchangers.
- a water-pump (derived from the Simscape foundation library), to impose a desired pressure difference;
- supply and return pipes (taken from the Simscape foundation library), able to simulate temperature and pressure dynamics, as well as to account for the thermal losses through the pipe walls. Data concerning pipe lengths and diameters were selected according to [12];
- users' valves, regulating the water flow entering the users' substation to maintain the return temperature as close as possible to a reference (here 65°C), through a properly designed control system;
- users' substations, modelled as heat exchangers, in which the water supply network deliver to users the required amount of power; thermal loads are distributed on the five users following [12] distribution, while the users' power profiles come from the real experimental data provided by RSE;
- adiabatic water mixers (self-made components), which mix mass flowrates at different pressure and temperature conditions;
- an expansion vessel, giving the reference for the regulation of water pressure in the circuit.

For the sake of exemplification, a simulation for one day with a resolution of one second is carried out and the simulation time is around one minute. Supposing variable load profiles, **Figure 2**(a) shows the total water mass flowrate, while **Figure 2**(b) depicts thermal powers exiting from the central power station. The total flowrate circulating in pipes is the result of the valve regulation at the users' substations in order to keep the return temperature at 65°C, as previously reported. Therefore, the flowrate is set so that all users, even the furthest from the supply plant, can receive the desired amount of heat at the proper temperature. Concerning thermal powers, looking at **Figure 2**(b), it is possible to notice that the profile of the CHP heating power is almost constant during the day as it is controlled to track a predefined power reference. On the other hand, the boiler integrates the heat delivered by the CHP to satisfy the users' demand. Its power profile recalls the flowrate one, since both are imposed by the users' cumulated heating request.



(a) (b)

Figure 2. Total mass flowrate of the district heating network (a) and thermal powers exiting from the central power station (b).

Conclusions

The need for more flexible energy systems in response to the volatility and uncertainties coming from the deployment of local renewable energy sources opens the way to the so-called Multi-Energy Systems in which different energy vectors optimally interact with each other. The paper investigates some fundamental aspects concerning MESs, from technological readiness, to modelling and simulation opportunities and challenges. It emerged how from a technological point of view, even if with different levels of maturity, technologies are ready to be implemented in MESs, while the same cannot be stated for models and simulation tools, needed to support the development of such systems from operation and management standpoints. As witnessed by the literature, MES modelling is a current and open research topic, still difficult to solve. In line with this, a proposal of a "quick and dirty" MES simulator has been presented, with promising results in properly simulating the dynamics of the system. The first step has been the development of a base district heating system, with the perspective of integrating it with electric power and gas networks. ■

Acknowledgements

This work has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development - General Directorate for the Electricity Market, Renewable Energy and Energy Efficiency, Nuclear Energy in compliance with the Decree of April 16th, 2018.

References

[1] Witkowski, K., Haering, P., Seidelt, S., & Pini, N. (2020). Role of thermal technologies for enhancing flexibility in multi-energy systems through sector coupling: technical suitability and expected developments. *IET Energy Systems Integration*, *2*(2), 69-79.

[2] Ulbig, A., & Andersson, G. (2015). Analyzing operational flexibility of electric power systems. *International Journal of Electrical Power & Energy Systems*, *72*, 155-164.

[3] Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, *65*, 1-17.

[4] Mavromatidis, G., Orehounig, K., Bollinger, L. A., Hohmann, M., Marquant, J. F., Miglani, S., ... & Carmeliet, J. (2019). Ten questions concerning modeling of distributed multi-energy systems. *Building and Environment*, *165*, 106372.

[5] La Bella, A., Del Corno, A., & Scaburri, A. (2021, October). Data-driven modelling and optimal management of district heating networks. In *2021 AEIT International Annual Conference (AEIT)* (pp. 1-6). IEEE.

[6] Mancarella, P., Andersson, G., Peças-Lopes, J. A., & Bell, K. R. (2016). Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities. In *2016 Power Systems Computation Conference (PSCC)*. IEEE, pp. 1-22.

[7] Guelpa, E., Bischi, A., Verda, V., Chertkov, M., & Lund, H. (2019). Towards future infrastructures for sustainable multi-energy systems: A review. Energy, 184, 2-21.

[8] MAGNITUDE European Project, avaible at: https://www.magnitude-project.eu/

[9] Kraan, O., Chappin, E., Kramer, G. J., & Nikolic, I. (2019). The influence of the energy transition on the significance of key energy metrics. *Renewable and sustainable energy reviews*, *111*, 215-223.

[10] Voinov, A., & Shugart, H. H. (2013). 'Integronsters', integral and integrated modeling. *Environmental Modelling & Software*, *39*, 149-158.

[11] Klemm, C., & Vennemann, P. (2021). Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. Renewable and Sustainable Energy Reviews, 135, 110206.

[12] Krug, R., Mehrmann, V., & Schmidt, M. (2021). Nonlinear optimization of district heating networks. Optimization and Engineering, 22(2), 783-819.

[13] Simscape tool, available at: https://it.mathworks.com/products/simscape.html