A Multi-Agent framework to evaluate energy flexibility in District Heating networks

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***Abstract*—Modelling and simulating urban energy facilities and their interactions is becoming a crucial topic in order to better assess policies and decision making in cities. District Heating (DH) is one of the key enabler for energy transition in cities and, in literature, several tools address its analysis and modelling. Usually the focus in analysing energy systems in cities is oriented on the specific fields and thus models and simulation tools are too sectorized and unable to interact in a larger perspective. Therefore, co-simulation paradigm is exponentially gaining attention as well as Multi Agent Systems (MAS). The lack of multidisciplinary approaches holds especially when dealing with DH and the interconnected subsystems that belongs to different domains. Therefore our proposition consists on a MAS-based co-simulation framework to simulate DH system behaviour while easily integrating models of other subsystems (e.g. buildings and storage). We have tested this distributed and modular framework with two case studies to asses a peak reduction strategy exploiting thermal storage. In conclusion, we have showed the flexibility of our tool while analysing benefits of a simple peak reduction strategy.**

***Index Terms*—District heating, energy flexibility, Multi Agent system, Distributed co-simulation, Demand Response**

I. Introduction

District heating (DH) represents a key technology to reach sustainable urban areas in the next future. By relying on DH, it is possible a) to exploit the renewable energy sources available in urban areas and on the surrounding areas, such as biomass, solar and geothermal; b) to valorize waste heat of industrial plants and data centres; c) to have at disposal a source of flexibility for the electricity grid [1]. The last point will be soon crucial, since electricity grids are increasingly supplied by renewable energy sources, that are characterised by a fluctuating nature [2]. In this context, the flexibility of the energy infrastructure represents a crucial point in both future and present perspectives. Indeed, in the future, using renewable energy sources and waste heat to supply fixed and unalterable loads is challenging. At the same time, currently, large DH systems are still supplied using combined heat and power plants. The occurrence of large and unmodifiable peaks in the energy demand causes various issues: a) the adoption of less efficient technologies to supply the peak load; b) the necessity of larger capacity installed; c) the presence of water congestion in the pipelines, limiting either the supply temperature reduction or the connection of further buildings. For these reasons in last years the attention has been focused on the new solutions to increase the DH network flexibility. A commonly used approach is the installation of sensible heat [3] thermal energy storage [4]. These can be installed in buildings, substations or in strategic areas of the network (especially in cases of large-scale storage systems). Another approach consists in smart modifications of the end-user demand side management actions. As concern demand side management, several attempts have been done in the electricity field [5]. Despite modifications in thermal demand of DH can provide great benefits as well as in the power grid, demand side management to DH has still not been completely investigated. The first attempts are reviewed in [6]. In [7], it has been proved that the combination of demand response along with thermal storage in DH allows an overall cost saving of about 1.4%. In order to address the increasing complexity of DH networks and the large variety of interconnected subsystems when studying these networks in the larger perspective of Multi Energy Systems (MES) a multi-domain approach is needed. In particular, as highlighted in [8], there is a lack of multi-domain platform to address the heterogeneity of involved systems. Co-simulation approaches are powerful tools when dealing with different domain simulators, making them really widespread in the Smart Grid context [9] [10]. In addition to that, MES and DH network could be seen as a composition of different subsystems that can be easily represented as agents in a co-simulation environment, thus a Multi-agent system (MAS) architecture seems a suitable structure for framework assessing these problems. In particular, three remarkable literature examples used MAS: i) to study peak reduction techniques in electricity and thermal grids focusing on both market and economic incentives perspectives [11]; ii) to assess building demand optimisation in DH networks through alternating direction method of multipliers solution method [12] and iii) to study building energy flexibility through thermal inertia in smart grid environment [13]. In general, modelling approaches based on agents allow a distributed control of the system easing the scalability, and the division of computational resources of the tool [14].

In this context we propose a Multi-agent co-simulation platform that by means of its modularity can be considered Plug&Play in terms of model exchange. The platform distributed architecture ensure high scalability in terms of number of agents and consequently of case study size. We are proposing a general framework with high configurability and ready to be used as a test-bed for different strategies or models in the DH context. There are three main strengths: i) integrating a transient thermal fluid dynamic model for the simulation of the thermal-dynamic inside the pipelines; ii) the possibility of dealing with different kind of network, also very large-scale, that are usually very difficult to be modelled, by easily combining transport and distribution networks; iii) the possibility of integrating models of different components such as buildings, substations, storage and thermal plants.

The paper is structured as follows, Section II describes the proposed methodology and the framework structure with its principal layers and components. Section III and Section IV present the case study used to test the framework and the results of performed simulations, respectively. Finally, Section V provides concluding remarks.

II. Methodology

The proposed framework is a Multi-agent co-simulation environment to be used as a test-bed for different analysis in the DH field. It allows to couple the thermofluid analysis of the grid with other simulation models representing the involved systems in MES (e.g. building simulation models, Demand response models, Storage models). It allows to distribute simulations ensuring scalability, modularity, Plug&Play model exchange and flexibility. Fig. 1 depicts the framework structure.

The framework consists of two layers: the *Scenario layer* and the *Co-simulation layer*. The *Scenario layer* creates the case study and manages all its physical information. The *Co-simulation layer* runs the co-simulation environment with all its interactions and models, it is implemented in PYTHON exploiting the AIOMAS library [15]. This library allows an easy implementation of request-reply channels, remote procedure calls (RPC) and MASs, exploiting ASYNCIO [16] library that allows asynchronous and concurrent code execution. In particular, *Co-simulation layer* is the framework core and is composed by three sub-layers: *Operational*, *Agent* and *Communication* layers, which are synchronised by an *External Clock*. The rest of this section provides a more in depth description of each individual layer.

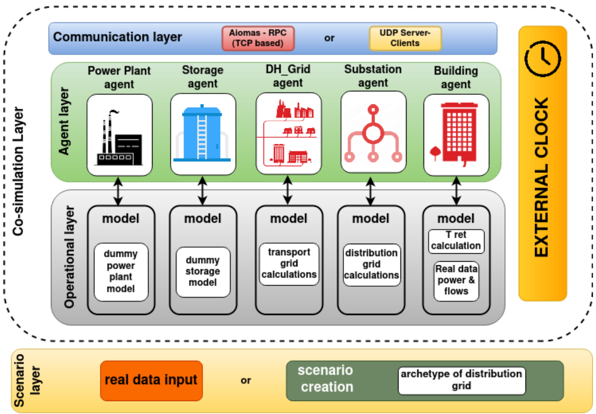


Fig. 1: Schema of the proposed framework

A. Scenario layer

The *Scenario layer* is in charge of the data management of system physical information. It contains the grid network representation and buildings information. The DH grid data are collected in a graph structure which represents topology, lengths and diameters of the network. The DH network is a closed systems of pipelines that can be divided in a *Delivery* portion and a *Return* one. The former brings hot water from the power plants to the final users to perform heat exchange, while the latter is in charge of bringing back the cooled water from buildings to power plants. In our representation the DH network is modelled as a directed graph representing both portions of the grid, namely Delivery and the Return. They only differs on the water flow direction, which is one the opposite to the other. Indeed, on the Delivery network, water flows from the power plant to the buildings; whilst on the Return network, the water flows from buildings to the power plant. On the other side, the data collected for the buildings can be the thermal power demands and the mass flow rates at their interfaces with the DH grid. This layer enables high usage configurability, it is possible to decide whether to use real data or not. Furthermore, for the district heating network topology and components (number of power plants, number of storage, number of users and division in transport and distribution grids), it is possible to use external case study or to create realistic networks exploiting an editable configuration file and a sample of a real distribution grid.

B. Co-simulation layer

As previously mentioned, the *Co-simulation layer* is the core of our framework. It performs the actual simulation for a configurable time period with a modifiable time resolution. It consists of three sub-layer: *Operational layer*, *Agent layer* and *Communication layer*.

The **Operational layer** consists of all the models to carry out calculations and simulate operational behaviours of the DH. One of the most important aspects of this framework is the separation between agents and operational modules, which enables modularity. Indeed, the *Operational layer* is a sort of empty box where users can integrate their own modules, with the only constraint of matching the input/output (I/O) requirements from the framework. Therefore, it is possible to co-simulate thermodynamics of the grid with building demand models, as well as power plant and storage models.

In particular, for this work we built up a transient one dimensional network model for the grid thermodynamics (see block *distribution grid calculation* and *transport grid calculations* in Fig. 1), while the topology is modelled through a graph-based approach. This model is used to solve the energy problem, i.e. the estimation of the temperatures within the network pipelines, taking into account the thermal inertia, as well as the thermal losses. This is particularly important in case of significant thermal transient (e.g. large DH networks) in which neglecting the pipe thermal masses leads to bad approximations [17]. Following this approach, the energy problem can be divided into different sub-problems, one for each portion of the grid, thus enabling possible parallelization paradigms. The fluid dynamic model is analysed through a quasi-steady state model, as usually done in district heating applications, since pressure perturbations travel within the network at sound velocity; therefore the time pressure wave, taken to reach furthest areas, is much smaller than the time step considered in the simulations. The same does not apply to the temperature that travels at the velocity of water that is small (usually 0.5-4 m/s). In large networks the water flow can take up to an hour or more to reach the furthest areas of the network. The graph approach for the description of the network topology consists in considering pipelines as branches and junctions as nodes. The topological interconnections are taken into account by means of the incidence matrix A, as shown in [18] along with a more in depth description of the model. The model includes mass, momentum and energy equations applied to all the network pipes (momentum) and nodes (energy and mass). The result is a set of the matrix equations: Equation 1 for computing the mass, Equation 2 for the momentum and Equation 3 for the energy.

$$A \cdot G + G_{ext} = 0 \tag{1}$$

$$G = Y \cdot A^T \cdot P \tag{2}$$

$$M \cdot \dot{T} + K \cdot T = g \tag{3}$$

where:

A = incidence matrix;
G = vector of mass flow rate within each branch;
G_{ext} = vector of the mass flow rate entering and exiting each node;
Y = conductance matrix (inverse of the fluidynamic resistance);
P = is the vector of pressures in the nodes;
M = the mass matrix;
K = the stiffness matrix;
T = vector of temperatures at the nodes;
g = the known-term vector of the equation.

Beside the thermodynamic calculations performed in the network model, in this work the other models are simplified representation of power plants, storage and buildings. Thus, the storage systems are modelled as ideal, with complete separation between hot and cold water and zero losses through time (see *dummy model storage* in Fig. 1). The buildings simply calculate the return temperature (see *T_ret calculation* in Fig. 1) through the discretized heat exchange basic formulation $Q = m * cp * \Delta T$, where the mass flow rate (m) is multiplied times the water specific heat capacity (cp) and the difference between in and out temperatures (ΔT) to obtain the thermal power (Q). Then, buildings take power and flow values from real data (see *Real data power& flows* in Fig. 1). Instead, the power plant fixes a water dispensing temperature, regulates the mass flow rate based on the demand and then calculates the needed thermal power through the above mentioned equation (see *dummy model power plant* in Fig. 1).

The **Agent layer** consists of the entities that represent the system components, it provides the fixed structure in which components interacts among themselves. The agents are implemented exploiting the AIOMAS-API [15] and are distributed to ensure parallelization of processes. This is done by exploiting containers as shown in Fig.2 which are distributed thanks to multiprocessing in python. Each container runs one or multiple agents offering all the functionalities to enable the communication among them.

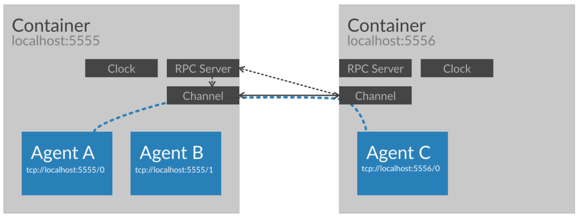


Fig. 2: Agents-Containers architecture [15]

Five typologies of actors have been individuated inside the DH network and modelled as agents:

(i) The *Power Plant Agent* is the virtualisation of a power plant in the network located at some injection node in the transport grid. It is aware of the mass flow rate demand at every time instant of the simulation, thus it exploits the *dummy power plant model* as its operational module to regulate the inlet of water in the grid. It communicates with the DH Grid Agent to exchange information about temperature and mass flow rate at the specific node.

(ii) The *Storage Agent* can be located in a network node or in the premises of other agents (e.g. buildings or power plants). It is modelled by exploiting the *dummy storage model* as operational module and communicates with the agent in charge of the thermodynamic calculations of the grid portion in which the storage is located. It knows only of the temperatures at its injection/extraction node and of its operational state, i.e. if it is *'charging'* or *'discharging'*, thanks to a configurable schedule.

(iii) The *DH Grid Agent* is the core agent of the simulation, it coordinates all the other agents by triggering their tasks and gathering operational information (e.g. temperatures and mass flow rates). It acts as a sort of orchestrator for the simulation time-flow. The DH Grid Agent has knowledge of the overall system, it keeps information of the physical parameters and components as well as the information of the agents (e.g. addresses, proxies). Furthermore, it computes the calculations for the transport grid, exploiting the *transport grid calculations* model, by gathering the needed information from all the agents and by coordinating the calculation workflow with the Substation Agents.

(iv) The *Substation Agent* is the coordinator of one distribution portion of the DH network reaching the final users. It is located at the interface between transport grid and distribution allowing the decomposition of the thermodynamic calculations. Indeed, it exploits the *distribution grid calculations* module to compute the energy problem in the distribution grid of its competence. It communicates with the Building Agents and the DH Grid Agent.

(v) The *Building Agent* represents a final user building that is locate in one of the leaf nodes of a distribution grid. In particular it exploits modules in the operational layer to model the heat exchange that is performed in building premises, the thermal power demand and the needed mass flow rate. The Building Agent communicates thermal power and mass flow rate to both the belonging Substation Agent and to the DH Grid Agent, in order to pass the information needed for the thermodynamic calculations.

The **Communication layer** ensures interactions among all the agents in the simulation by implementing the AIOMAS library. Fig. 2 shows the basic communication infrastructure, which AIOMAS exploits a two level of abstraction architecture. It is composed of a channel component and a Remote Procedure Call (RPC) module on top. Each container implements an RPC server that is used by each agent to trigger events and gather/set information with respect to remote agents that can run in the same container or in others. This is possible because the communication is implemented over the TCP/IP protocol stack through unique address assignment. This layer guarantees the distribution of agents, and thus the whole proposed frameworks, across different servers, making our solution scalable.

Finally the **External Clock** allows the external updating of the agents clocks at every time-step. It is in charge of the time synchronisation and becomes more fundamental when time-based simulators are integrated.

C. Co-simulation workflow

The simulation process is event-based, it proceeds through time by triggering all the events that compose a time-step. Beside that, agents are implemented to allow also some time-based process. The workflow of a single time-step is depicted in Fig. 3, where performed tasks are divided into a *Preliminary stage* and a *Calculation stage*. At the beginning of each time-step, the *Preliminary stage* performs the following tasks: i) Building Agents estimate the demand and the mass flow rate for the current step; ii) Storage Agents check if they are idle or in charge/discharge states; iii) Substation Agents calculate the mass flow rate passing through their nodes; iv) Power Plant Agents fix the delivery temperature and calculate the mass flow rate to be injected in the network.

Then, the Calculation stage is performed. This phase is strictly related to the thermodynamic calculations in the DH network, in which the energy problem is solved following the water flow from the power plants to the users and backwards, i.e. delivery/return. The coordinator for these operations is the DH Grid Agent. The first task is to solve the problem for the transport grid during delivery. The DH Grid Agent collects the mass flow rates from external nodes of the grid (i.e. the power plants, the substations and the storage if in discharging mode), then collects the inlet temperatures (i.e from both power plants and storage if this is in discharging mode). Once these information are gathered, the DH Grid Agent computes the calculation for the transport grid (during delivery). The solution consists of the temperatures in the transport grid nodes, thus all these values are communicated to the respective connected agents. Solved the problem for the

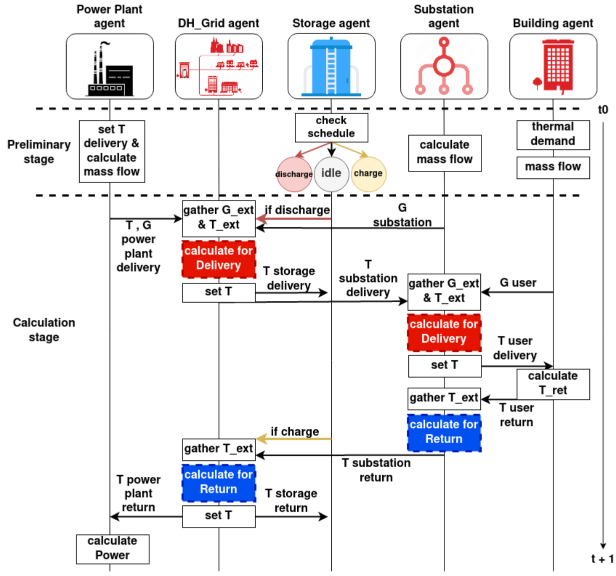


Fig. 3: Schema of the co-simulation workflow

transport grid during delivery, it comes the turn of distribution grids, which are managed by the Substation Agents. Each Substation Agent has received its delivery temperature from the previous calculation, thus it knows the inlet temperature for its sub-problem. It collects the mass flow rates from buildings and solves the energy problem for the distribution grid during delivery. As a result of this calculation, inlet temperatures in buildings premises are known and thus Building Agents are able to calculate the resulting temperatures for the return section after the heat withdrawn. With these new temperatures Substation Agents revert the problem to solve it for the return. The inlet temperatures are now those from buildings and the mass flow rates are the same of the delivery but with opposite signs. Substation Agents calculate and estimate their return temperatures. The DH Grid Agent gather these temperatures and use them to finally compute the calculations for transport grid during return.

Finally, Power Plant Agents know the returning water temperature in one time-step and use it to calculate the amount of power withdrawn from the whole system.

III. Experimental set-up

In order to test our framework we built up a case study which consists of a typical medium size DH network. The network power is about 240 MW, and the mass flow of about 603 kg/s is supplied. The network includes one thermal plant and provide heat to 1300 buildings. As usually done in DH, pipelines diameters are designed to have proper velocities in the pipelines. The value selected for the application is 2 m/s. The overall network is divided in one transport grid and 20 substations (i.e., distribution grids) each of them supplying 65 buildings. For the simulations the thermal power demand from buildings as well as the mass flows are taken from real data, that belongs to real-world buildings in Turin (IT) for a typical winter day of thermal consumption. These consumption profiles are well representative of the problem we want to analyse. As shown in Fig. 4 the load profile from a building in a 24h window presents an early-morning peak. This depends, especially in the less harsh areas, from the fact that the heating devices are switched-off (or attenuated) during night hours. Therefore in the morning the terminal masses of the system must be heated [19].

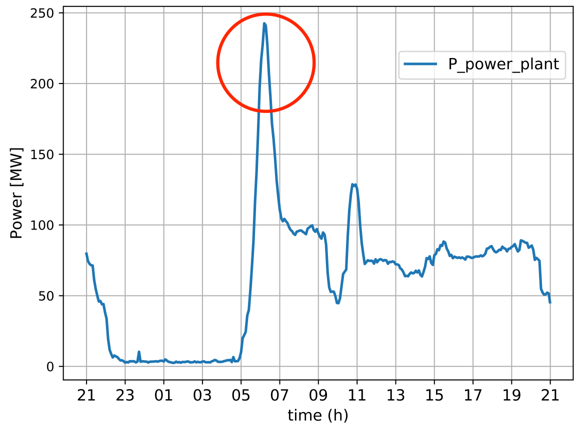
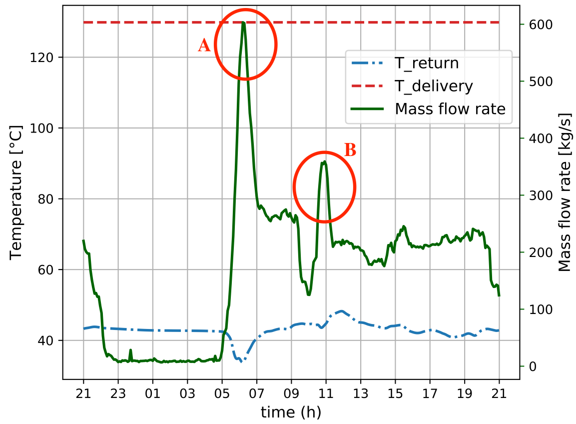


Fig. 4: Power plant power profile in 24h

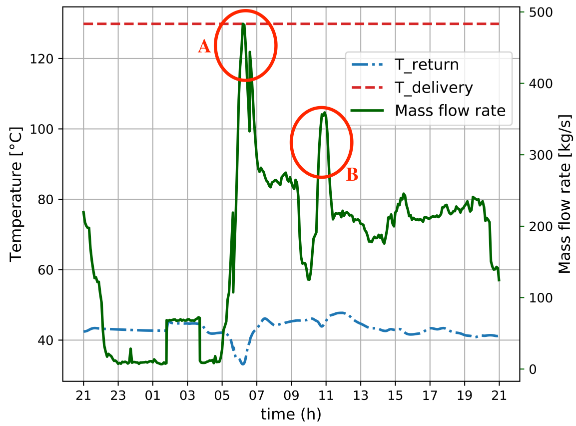
By the point of view of smart energy management, load peaks must be avoided in order to reduce prices and to keep the power level of production plants as constant as possible. A straightforward method for reducing the peaks is the integration of storage systems, thus we analyse a simple peak reduction strategy, exploiting storage. Therefore, we have performed two different simulations for two different scenarios: i) *without storage* and ii) *with storage*. Both simulations have been performed for a 24 hour period with a time resolution of one minute. The simulation *without storage* treats the system as it is with only buildings and power plants to inject or extract mass flow rate. Instead, in the simulation *with storage*, three storage systems have been integrated, each one with a capacity of 144 m^3. The storage systems are represented as additional external node in the transport grid strategically placed and they have a pre-assigned schedule for charge and discharge: a) charging from 02:00 to 04:00 with a mass flow rate of 20 kg/s; b) discharging from 06:00 to 07:00 with a mass flow rate of 40 kg/s.

IV. Experimental results

In this section, we present the results of the performed simulations. In Figure 5, the outcomes of the two simulations (Fig. 5a without storage and Fig. 5b with storage) are presented in terms of Delivery temperature (see dashed red line), Return temperature (see dot-dashed blue line) and mass flow rate (see continuous green line) at the Power Plant node. Analysing the standard case in which the DH system works in absence of storage systems(Fig. 5a), we can easily individuate the mass flow rate peak (label A), which is localised between 5:00 am and 7:00 and reaches in a short time period about 600 kg/s. This is due to the sudden morning request of thermal power from buildings that is fulfilled by increasing the mass flow. The chosen model for the power plant only addresses mass flow rate regulation, thus the power plants inject hot water at a constant temperature and can only act on the water quantity. Simply exchanging the presented generic model for the power plant with a more specific one will enable to inspect different regulation methods. The morning peak consists of a sudden power request that comes after a night period of inactivity (from 22:00 to 5:00 in Fig 5a), and it coincides with the switching on of the centralised heating systems at the buildings premises.



(a) Simulation scenario *without storage*



(b) Simulation scenario *with storage*

Fig. 5: Temperature trends for Delivery/Return and mass flow rates at the Power plant in 24h in both simulation scenarios

With the first simulation we assess the compliance of the simulated environment with a realistic behaviour of a DH network. Indeed, looking at Fig. 5a we can see that the temperature difference between delivery and return water, even if slightly higher than the norm, is in a reasonable range ($\Delta T \approx$ 40-90°C). It is possible to see that in presence of the mass flow rate peak, we have a drop in the return temperature because all the buildings from the distribution grids are extracting thermal power from the delivery water. The inverse proportionality between mass flow rate increase and return temperature decrease is observable only on the highest peak that we could consider as an extreme condition, while in lower peaks we can notice a direct proportionality between those two variables (see label B in Fig. 5a and the slightly delayed increase in the return temperature).

Then, Fig. 5b shows the outcome of the simulation in which the three storage systems have been integrated. It is possible to highlight the charging phase (see the mass flow rate increase between 02:00 and 04:00 i.e. label A) and the discharging phase (see the reduced peak between 05:00 and 07:00 i.e. label B). By simply looking at the scale of the mass flow rate axis in 5b the peak reduction is visible, however, Figure 6 gives a better representation in order to compare the two simulations. Therefore, Figure 6 presents the power profiles at power plants for both simulations and the effect of the storage integration coincides with the mismatching portion of the curves (see the grey regions in Fig 6). The peak has been reduced but due to the simplicity of the tested mass flow rate regulation in the storage systems some oscillations are present right before and after the main peak (5:00 - 7:00).

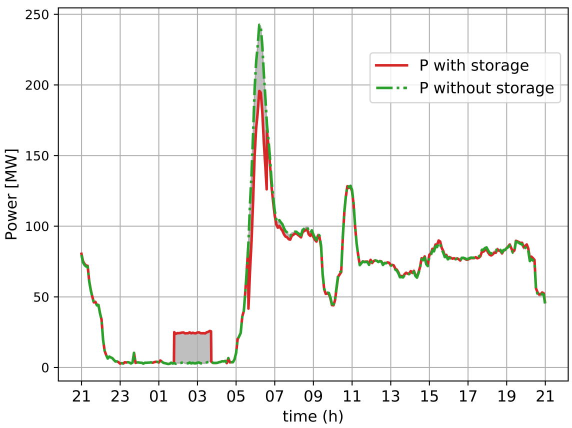


Fig. 6: Comparison of the power measured in the Power Plant between the two simulation scenarios: *with storage* and *without storage*

V. Conclusions

The main objective of this work was the design and development of a MAS-based co-simulation environment for the DH network and its connected components. In particular, we have configured and tested our platform in order to analyse a peak reduction strategy involving storage systems. Real consumption data have been used to profile load curves for Building Agents and a real grid topology has been used as baseline for the creation of an artificial DH network. The performed simulations have shown the flexibility of the platform in simulating realistic scenarios and, in particular, by showing two different case studies we have demonstrated configurability and flexibility of the platform. Indeed, we have performed simulations integrating different models in a Plug&Play fashion, this feature allows further extensions to other different models. For what concern the analysis performed we have discussed how the simplest storage system could reduce the load demand peak. Thus, as future works, we are planning to integrate more complex models for storage (e.g. taking into consideration losses, water mixing and mass flow rate regulation strategies) and for power plants. In conclusion, the concept of a scalable and flexible test-bed makes smarter the analysis process allowing easy bench-marking and expanding the analysis perspectives on a single problems. The almost endless possibilities created by co-simulation tools such as the one we propose, makes clear their usefulness when studying DH networks and, as a next step, Multi Energy Systems.

References

[1] P. Mancarella, "Mes (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, 2014.

[2] H. Lund, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, "Smart energy and smart energy systems," *Energy*, vol. 137, pp. 556–565, 2017.

[3] J. Hennessy, H. Li, F. Wallin, and E. Thorin, "Flexibility in thermal grids: A review of short-term storage in district heating distribution networks," *Energy*, vol. 158, pp. 2430–2434, 2019.

[4] E. Guelpa and V. Verda, "Thermal energy storage in district heating and cooling systems: A review," *Applied Energy*, vol. 252, p. 113474, 2019.

[5] L. Gelazanskas and K. A. Gamage, "Demand side management in smart grid: A review and proposals for future direction," *Sustainable Cities and Society*, vol. 11, pp. 22–30, 2014.

[6] E. Guelpa and V. Verda, "Demand response and other demand side management techniques for district heating: A review," *Energy*, vol. 219, p. 119440, 2021.

[7] S. Salo, A. Hast, J. Jokisalo, R. Kosonen, S. Syri, J. Hirvonen, and K. Martin, "The impact of optimal demand response control and thermal energy storage on a district heating system," *Energies*, vol. 12, no. 9, p. 1678, 2019.

[8] M. Abugabbara, S. Javed, H. Bagge, and D. Johansson, "Bibliographic analysis of the recent advancements in modeling and co-simulating the fifth-generation district heating and cooling systems," *Energy and Buildings*, vol. 224, p. 110260, 2020.

[9] T. Godfrey, S. Mullen, D. W. Griffith, N. Golmie, R. C. Dugan, and C. Rodine, "Modeling smart grid applications with co-simulation," in *2010 IEEE SmartGridComm*. IEEE, 2010, pp. 291–296.

[10] P. Mihal, M. Schvarcbacher, B. Rossi, and T. Pitner, "Smart grids co-simulations: Survey & research directions," *arXiv*, 2021.

[11] H. K. Nunna, A. M. Saklani, A. Sesetti, S. Battula, S. Doolla, and D. Srinivasan, "Multi-agent based demand response management system for combined operation of smart microgrids," *Sustainable Energy, Grids and Networks*, vol. 6, pp. 25–34, 2016.

[12] H. Cai, S. You, and J. Wu, "Agent-based distributed demand response in district heating systems," *Applied Energy*, vol. 262, p. 114403, 2020.

[13] P. Rando Mazzarino, C. De Vizia, E. Macii, E. Patti, and L. Bottaccioli, "An agent-based framework for smart grid balancing exploiting thermal flexibility of residential buildings," in *2021 EEEIC/I&CPS Europe).* IEEE, 2021, pp. 1–6.

[14] A. Vandermeulen, B. van der Heijde, and L. Helsen, "Controlling district heating and cooling networks to unlock flexibility: A review," *Energy*, vol. 151, pp. 103–115, 2018.

[15] "Aiomas," https://aiomas.readthedocs.io/en/latest/, accessed:2021-01-24.

[16] "Asyncio," https://docs.python.org/3/library/asyncio.html, accessed:2021-01-24.

[17] E. Guelpa, "Impact of network modelling in the analysis of district heating systems," *Energy*, vol. 213, p. 118393, 2020.

[18] E. Guelpa, A. Sciacovelli, and V. Verda, "Thermo-fluid dynamic model of large district heating networks for the analysis of primary energy savings," *Energy*, vol. 184, pp. 34–44, 2019.

[19] E. Guelpa, "Impact of thermal masses on the peak load in district heating systems," *Energy*, vol. 214, p. 118849, 2021.