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# Setup and testing of smart controllers for small-scale district heating networks: an integrated framework

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## Abstract

Nowadays, the growing availability of renewable energy resources is an opportunity to reduce carbon emissions but also a challenge, as advanced control technologies are required. The new generation of smart district heating and cooling networks, for instance, pledges efficient energy distribution, flexibility and low-carbon energy integration. However, in the literature it is hard to find comprehensive frameworks for the integrated setup and testing of smart control strategies. This paper defines and demonstrates a framework that involves all steps of the controller development for small-scale district heating networks: from conceptualization to prototype testing. The innovative controller prototype, which relies on Model Predictive Control and aims to minimize operating costs and/or energy, is demonstrated in three original case studies, one in a simulation environment and two in real systems of different complexity in operational conditions. Compared to the control approaches previously adopted, based on predefined rules and operator experience, the smart solution achieves 6 % reduction in cost and up to 34 % reduction in energy consumption while meeting user requirements. The fast replicability of the proposed integrated methodology can foster the transition toward the next generation of smart heating networks.

*Keywords:* Model Predictive Control; District Heating and Cooling network; dynamic simulation; library of energy system components; experimental case study; Smart Energy Systems

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## 1. Introduction

Nowadays, reduction in carbon emissions is identified as one of the key global targets for future years, in order to mitigate climate change and human environmental impact and, moreover, to improve air quality. Building air conditioning (i.e. heating and cooling) is responsible for about 40 % of global energy consumption [1], with heating representing the leading demand in 25 out of 28 countries in the European Union [2]. Hence, research works that focus on the improvement of energy efficiency [3] and total costs [4] in heating and cooling energy distribution networks have to be carried out. In this context, a significant opportunity for energy saving is given by existing district heating and cooling networks (DHC), which are designed to distribute thermal energy from various decentralized production plants to the end-users more efficiently than individual boilers [5]. As a matter of fact, a DHC can be a multi-source system as different available energy resources, including renewables, can be integrated [6]. Moreover, the production of thermal energy in centralized plants allows the economy of scale to be exploited and carbon dioxide emissions to be reduced.

It is assessed that DHC networks and their production units require proper control devices due to the necessity to cope with the growing penetration of fluctuating resources and the high weather variability caused by climate change. Conventional controllers based on time-scheduling are not able to deal with these challenges, since they do not provide solutions customized to the actual conditions. Moreover, at present the most part of heating systems is still managed by relying on the experience of operators and technicians. These methods can guarantee neither a fast adaptability to the rapidly varying boundary conditions nor the optimal solution. However, recent studies show that it is possible to reduce the energy consumption of DHC by applying innovative control approaches without any changes to the system hardware configuration [7–9]. This is one of the key steps in the transition

toward the next generation of heating grids, namely 4<sup>th</sup> generation [10], in which lower distribution temperatures, lower losses and higher efficiency lead to affordable cost and lower energy consumption. Hence, these systems have to become smart [11], optimized, sustainable and connected [12].

Research on real-time smart controllers for energy systems has increased, especially as far as individual building systems are concerned, and various innovative techniques have been exploited to optimally operate their air conditioning systems and enable a rational use of primary energy. For instance, the Model Predictive Control strategy has been successfully implemented both in real field tests on residential [13] and commercial buildings [14], and in simulation cases, where a detailed model emulates the behavior of the system [15,16]. Machine learning predictive features (e.g. based on neural networks [17]) and Internet-of-Things architectures [18] have demonstrated to improve the adaptability, reliability and efficiency of the control systems. Moreover, there are many projects in the early development phase that include blockchain technologies concerning the transition of the role of different households from end-users to prosumers [19]. This is further demonstrated by the growing number of research and innovation projects funded by the European Union (e.g. within the Horizon 2020 Framework Programme) with the aim of developing smart management and optimal control strategies for DHC. For instance, the projects INDIGO [20] and OPTi [21] have incorporated advanced modeling and predictive controllers for cooling and heating networks, respectively, supplying two hospital sites. Other projects aim to quantify the energy saving of the proposed solutions in relevant environments, from building level [22] to municipality level [23]. Further investigations on these applications are required.

Nonetheless, at present it is hard to find research works that cover all steps related to the development of specific controllers for DHC or that propose general guidelines for treating different types of heating system. Indeed, the most part of the research regarding DHC focuses on the development of models for the fast representation of system dynamics [24–26]; their design and operation [27]; or

the optimization of long-term production planning [28] and scheduling [6] without including real-time control. Moreover, the effective testing and demonstration of smart controllers in a real district environment are still lacking. For instance, Guelpa *et al.* [29] optimize a district heating system by (i) adopting a clustering approach in order to identify the relevant characteristics of the connected buildings and (ii) scheduling the switch-on of the heating system to shave peak loads. Another work proposed by Kazagic *et al.* [30] optimizes the design and hourly production planning of a district heating solution under construction in the Visoko Municipality, located in Bosnia and Herzegovina.

Some interesting articles have recently proposed the control of large-scale DHC, for instance by controlling the return temperature of the network through a feed-forward predictive controller to reduce thermal losses [31] or by operating the peak load management to exploit the production units in a more rational and efficient way [32]. Oftentimes, however, the methods proposed are case-dependent and the possibility to extend the analysis to real scenarios is not straightforward.

Furthermore, as previously mentioned, the cited works base their analysis on large-scale districts (e.g. cities and large regions) in which the end-users cannot be considered as separate individual elements. Nonetheless, systems characterized by smaller dimensions (e.g. campus scale) are promising as well, considering that they are widespread in the territory, have a great potential for energy saving and are hardly tackled in the literature.

### 1.1 Scope of the work

This paper aims to fill the scientific gap outlined above by presenting an integrated framework for the setup and testing, both in simulation and experimental environments, of a novel predictive controller suitable for small-scale DHC. The controller is based on a Dynamic Programming algorithm developed by the authors [33]. Contrary to old control techniques that rely on operator experience or pre-defined rules, the MPC can be considered smart for several reasons:

- It forecasts the external conditions and accurately predicts the system behavior by means of a model. This allows unexpected changes and phenomena to be considered in the control.
- It calculates the optimal control action based on this knowledge by means of an optimization algorithm and, therefore,
  - It is able to optimize multiple variables simultaneously and directly include the operating constraints (while usual DHC controllers can typically act on single variables and cannot consider the correlations between them).
  - It updates the prediction and control variables at every time-step, in order to compensate model inaccuracies and additional uncertainties.
  - It automates system operation and enables digitalization.

Firstly, a Model-in-the-Loop (MiL) platform has been developed and described for testing and comparing different control strategies whenever the real system is not available or the testing phase may jeopardize the indoor comfort of the occupants. This platform comprises a library of detailed models suitable for the dynamic simulation of DHC developed by the authors in the MATLAB®/Simulink® environment. The novel control approach is then evaluated and demonstrated in three case studies with different specifications: one based on simulation using the MiL platform, and two real cases in operational conditions.

The simulation case study shows the potentialities of the MiL platform as a tool for the development and evaluation phase of a control strategy or for when the actual system is still under construction. Indeed, it is a multi-agent hierarchical application performed to test the applicability of the controller in a more complex virtual case, verify its performance and identify the potential challenges. The application comprises a small-scale district heating network supplied by a Thermal Energy Storage tank (TES) which, in turn, is supplied by the recovered heat from an Organic Rankine Cycle (ORC) power plant. ORC plants are versatile due to the possibility of exploiting a wide variety of heat sources [34] in the evaporator (e.g. waste heat recovery, biomass boilers and solar thermal collectors).

Moreover, they can meet the electrical demands and, at the same time, supply heat distribution networks in an efficient way. Hence, **within** this case it is possible to verify the controller performance in the multi-agent (i.e. each end user is controlled by a dedicated module [33]), hierarchical (i.e. the power plant is managed by a supervisory module) architecture.

Lastly, the proposed control system **is** prototyped and used to effectively control the heating system and the distribution network of two experimental case studies: a school complex in Podenzano and the Parma University Campus, **both located in northern** Italy. **These are on-field tests of different complexity, aimed to demonstrate the controller up to a Technology Readiness Level (TRL) of 7. According to the scale defined by the European Commission to assess the maturity of a technology [35], TRL 7 indicates that the system prototype is demonstrated in an operational environment and is close to being qualified and introduced on the market.**

## **1.2** *Main contribution*

The main innovation features of the proposed work are summarized as follows:

- A **general** methodology for the setup of smart controllers that can be extended to a **variety of** systems and **networks**. The methodology spans over the entire procedure from the development and simulation phases to prototyping and testing.
- **An inhouse library of physics-based dynamic models of the main components in an energy network.** The modularity allows different layouts and system configurations to be easily assembled and simulated. Moreover, the direct causality of the sub-models reflects the physical causality and, therefore, enables the testing of different control approaches. **The usefulness of this tool is investigated through the simulation case study.**
- A **controller prototype** based on economic Model Predictive Control which **proved to be** versatile and modular in its applicability. Indeed, it can be applied to the branches of the

distribution side of the network in a multi-agent logic as well as to the production units in a hierarchical configuration.

- *Two real case studies of small-scale district heating networks*, in which the controller has been successfully demonstrated up to TRL 7, guaranteeing energy and cost saving.

To the best of the authors' knowledge, an integrated procedure comprising the aforementioned novelties has not been proposed yet in the current state-of-the-art research on DHC. Furthermore, the literature lacks the assessment of innovative controllers for DHCs up to TRL 7, which is achieved in this paper in two cases with varying complexity and boundary conditions. The replication of this work to other small-scale district heating systems (e.g. hospitals, campuses and residential neighborhoods) potentially enables the digitalization of the heating and cooling sector with a consequent significant reduction in its impact on the environment.



## 2. The District Heating Network Library

The on-site **testing** of a new control strategy is not always possible **due to compliance with** service requirements, technical issues or economic feasibility. Hence, the mathematical modeling of a district heating network – for MiL applications – represents a good option, since it allows the control strategy to be implemented, tested and refined, with potential significant savings in time and money. **For this purpose**, a library of dynamic models has been developed by the authors in the MATLAB®/Simulink® environment **assembling** the models of all the common components of a district heating network. **Notwithstanding the simplifications**, the library has proved to be a reliable tool for the development of accurate **simulators**, suitable for testing and assessing new control strategies without affecting the real system.

The library exploited in this work is an improved version [36] of the preliminary one proposed in [37], extended with additional features and components. The relevant characteristics of the main components, reported in detail in Table 1, are:

- **Algebraic/Dynamic:** the component is algebraic (Al) if it does not involve a storage term and can be described by algebraic relations, while it is dynamic (Dy) if the storage term or memory (i.e. system state) is present and the evolution in time of the variables is described by means of differential equations.
- **Lumped/Discretized:** the component can be represented by a lumped parameter model (L) or can be discretized, typically along one dimension (1D).
- **Inputs, Outputs and States of the model**, according to the chosen causality. It is worth recalling that algebraic models do not have any state.
- **Governing and additional equations**, which constitute the mathematical model of the component.

A survey of the corresponding component models is given below.

Table 1. Summary of the relevant characteristics of the component models of the District Heating Network library.

| Component           | Algebraic<br>Dynamic | Lumped<br>Discretized | Inputs   | Outputs  | State                     | Governing equations  |
|---------------------|----------------------|-----------------------|--|--|---------------------------|--|
| Boiler              | Al                   | L                     | Fuel mass flow<br>rate   | Thermal<br>power                                     | -                         | $\dot{Q} = \eta_{\text{eff}} \cdot (\dot{m}_f \cdot LHV) \quad (1)$ $\eta_{\text{eff}} = \frac{\Lambda - \Lambda_{\min}}{1 - \Lambda_{\min}} \cdot (\eta_{\text{nom}} - \eta_{\min}) + \eta_{\min} \quad (2)$  |
| Pump                | Al                   | L                     | Pump rotational<br>speed, pressure<br>head                                       | Water mass<br>flow rate                              | -                         | <p>Characteristic curve based on the parameters:</p> $\pi_1 = \frac{g \cdot H}{n^2 \cdot D^2} \quad \text{and} \quad \pi_2 = \frac{\dot{V}}{n \cdot D^3} \quad (3)$  |
| Expansion<br>vessel | Dy                   | L                     | Inlet and outlet<br>water mass flow<br>rate                                      | Water pressure                                       | Water<br>volume           | $p_w = p_a = p_{a,0} \cdot \left( \frac{V_{a,0}}{V_{a,0} - \frac{dV_w}{dt}} \right)^k \quad (4)$   |
| Pipeline            | Dy                   | 1D                    | Inlet water mass<br>flow rate<br>pressure and<br>temperature,<br>outlet pressure | Outlet water<br>mass flow rate<br>and<br>temperature | Pipe water<br>temperature | $M \cdot c_w(T_{w,\text{in}}) \cdot \frac{dT_w}{dt} = \dot{m} \cdot c_w(T_{w,\text{in}}) \cdot (T_{w,\text{in}} - T_w) - A \cdot U \cdot (T_w - T_{\text{ext}}) \quad (5)$ $\Delta p = \Delta p_{\text{geo}} + \Delta p_{\text{dist}} + \Delta p_{\text{conc}} \quad (6a)$ $\Delta p_{\text{geo}} = \rho_w \cdot g \cdot (z_{\text{in}} - z_{\text{out}}) \quad (6b)$ $\Delta p_{\text{dist}} = \lambda \cdot \rho_w \cdot \left( \frac{L}{\phi_{\text{in}}} \right) \cdot \left( \frac{v^2}{2} \right) \quad (6c)$ $\Delta p_{\text{conc}} = \rho_w \cdot \frac{v^2}{2} \cdot k_r \quad (6d)$ $\frac{1}{\rho_w \cdot A_{\text{in}(1)}} \cdot \frac{d\dot{m}}{dt} = \frac{(p_{\text{max}} - p_{\text{min}} - \sum_i (\Delta p)_i) \cdot A_{\text{in}(1)}}{\sum_i M_i} \quad (7)$ |

|                        |    |    |   |                                       |                      |   |              |
|------------------------|----|----|---|---------------------------------------|----------------------|---|--------------|
| Junction               | Dy | L  | Inlet water mass flow rates and temperatures  | Water outlet pressure and temperature | Water volume         | Eq. (4) for the pressure calculation<br>$T_{\text{out}} = \frac{\sum_{i=1}^n (\dot{m}_{\text{in}} \cdot c_w(T_{\text{in}}) \cdot T_{\text{in}})_i}{c_w(T_{\text{out}}) \sum_{i=1}^n (\dot{m}_{\text{in}})_i}$   | (8)          |
| Control valve          | A  | L  | Valve opening, inlet water mass flow rate, temperature and pressure                     | Water outlet pressure                 | -                    | $\Delta p_{\text{valve}} = \frac{\dot{m}^2}{\rho_w(T_{\text{in}}) \cdot (\varphi \cdot K_v)^2} = \frac{\dot{m}^2}{\rho_w(T_{\text{in}}) \cdot (K_v')^2}$<br>Coefficient $K_v'$ obtained by valve characteristic curve   | (9)          |
| Heat exchanger         | Dy | L  | Inlet water mass flow rate, pressure and temperature, thermal power                     | Outlet water pressure and temperature | Water temperature    | Eq. (6d) for pressure drop calculation<br>$M \cdot c_w(T_{w,\text{in}}) \cdot \frac{dT_w}{dt} = \dot{m} \cdot c_w(T_{w,\text{in}}) \cdot (T_{w,\text{in}} - T_w) + \dot{Q}$   | (10)         |
| Thermal energy storage | Dy | 1D | Inlet and outlet water mass flow rates, inlet pressure and temperature                  | Outlet water pressure and temperature | Node temperature     | $\dot{V}_{\text{vert,out}} = \frac{\dot{m}_{i,\text{in}}}{\rho(T_{\text{in}})} + \dot{V}_{\text{vert,in}} - \frac{\dot{m}_{i,\text{out}}}{\rho(T_i)}$<br>$M \cdot c \cdot \frac{dT_i}{dx} = \sum \dot{m}_{i,\text{in}} \cdot c \cdot T_{\text{in}} - \sum \dot{m}_{i,\text{out}} \cdot c \cdot T_i - \dot{V}_{\text{vert,out}} \cdot \rho(T_{\text{vert,out}}) \cdot c \cdot T_{\text{vert,out}} + \dot{V}_{\text{vert,in}} \cdot \rho(T_{\text{vert,in}}) \cdot c \cdot T_{\text{vert,in}} + k \cdot (T_{i-1} - T_i) - k \cdot (T_i - T_{i+1}) - U \cdot A \cdot (T_i - T_{\text{ext}})$ | (11)<br>(12) |
| Building               | Dy | L  | Supply water mass flow rate and temperature, heat gains, control input of space heaters | Return water temperature              | Building temperature | $\frac{dT_{\text{bldg}}}{dt} = \alpha \cdot (T_{\text{ext}} - T_{\text{bldg}}) + \beta \cdot (\dot{Q}_{\text{hs}} + \dot{Q}_{\text{ir}} + \dot{Q}_{\text{oc}}) + \gamma \cdot (T_{\text{ext}} - T_{\text{bldg}}) + \delta \cdot (T_{\text{air}} - T_{\text{bldg}})$   | (13)         |
| ORC plant              | A  | L  | Thermal power to ORC evaporator   | Electric and recovered thermal power  | -                    | $P_{\text{el}} = (P_{\text{in}} \cdot \eta_{\text{th}}) \cdot \eta_{\text{el}} \cdot \eta_{\text{m}}$<br>$P_{\text{rec}} = P_{\text{in}} \cdot (1 - \eta_{\text{th}}) \cdot \eta_{\text{rec}}$  | (14)<br>(15) |

**Boiler** The boiler is represented by an algebraic, physics-based model that evaluates the effective thermal power  $\dot{Q}$  produced by the combustion of a given amount of fuel  $\dot{m}_f$ , as in Eq. (1). In order to consider the critical influence of the load conditions on the boiler efficiency  $\eta_{\text{eff}}$ , this is corrected through a linear interpolation between the nominal and minimum load conditions as in Eq. (2), in accordance with the most common technical standards [38]. The correction is based on the dimensionless parameters  $A$  and  $A_{\text{min}}$ , which are the ratio of actual to nominal heat and the ratio of minimum to nominal heat generated by the boiler, respectively. It should be noted that minimum and nominal operating conditions are usually defined in the manufacturer's datasheet.

**Pump** The pump is an algebraic model based on a heuristic modelling approach. Considering the Buckingham  $\pi$  theorem, a dimensionless curve – drawn from a set of measured operating points for a specific rotational speed – can be used to describe the performance of a series of geometrically similar pumps at various operating speeds, by means of the head coefficient  $\pi_1$  and flow coefficient  $\pi_2$  (Eqs. (3)). Once the dimensionless map has been set, the model evaluates the volumetric flow rate  $\dot{V}$  processed by the pump – with an impeller diameter  $D$  – operating at a rotational speed  $n$  for a given pressure head  $H$ .

**Expansion vessel** Expansion vessels are fundamental elements of any closed water heating system since they handle pressure fluctuations related to thermal expansions and mass flow rate transients. Basically, an expansion vessel is a tank partially filled with air, the function of which is to act like a pressure buffer. The proposed dynamic model represents the air damping effect by means of a differential equation, derived from the continuity equation Eq. (4). As a simplification, air is assumed as an ideal gas in adiabatic conditions. The water volume  $V_w$  is the model state-variable: it evolves over time depending on both the initial condition and the differences between incoming and outgoing mass flow rates. It must be noticed that, from a computational point of view, this state-determined model is required for decoupling algebraic models, which might otherwise give rise to undesirable algebraic loops.

**Pipeline** The developed pipeline model considers both the thermal dynamics and the hydraulics of the heat transfer fluid. Several pipeline models can be interconnected, so that even a complex distribution layout can be split into a sequence of pipeline segments with their own characteristics. Thermal losses and pressure drops are critical since they can deeply affect the efficiency of the whole system. In this respect, the thermal losses are determined by means of the energy conservation equation for each pipeline segment (Eq. (5)), considering the net enthalpy flow and heat transfer with the surroundings. The latter is influenced by the pipeline geometry and by the thermal characteristics of the metal wall and insulation material. Similarly, pressure drops are calculated for each pipeline segment by summing up all the contributions: geodetic, distributed and concentrated (Eqs. (6)). The distributed and concentrated pressure losses are calculated by means of the Darcy-Weisbach equation, while the related flow and resistance coefficients are given by the Haaland empirical correlation and datasheets, respectively. Unlike thermal losses and pressure drops, the circulating mass flow rate is calculated once for the entire pipeline sequence, by means of a differential equation derived from the momentum continuity equation Eq. (7) and depending on the pressure values upstream and downstream of the pipeline. In this case, the total pressure drop is calculated as the sum of all the segment contributions.

**Junction** A district heating network is usually made up of several pipeline branches. For every intersection, a junction is needed since it allows the flow to be mixed or split. The proposed junction model is dynamic and relies on the energy balance and continuity equations for the pressure and temperature calculation of the water outflow. As regards the pressure, the junction model behaves in the same way as that of the abovementioned expansion vessel. The incoming mass flow rate is calculated as the sum of two or more contributions, depending on the number of converging branches. On the other hand, the model represents an ideal junction without dissipation, since neither heat accumulation nor thermal losses are considered. Indeed, the temperature of the water outflow is determined by means of an algebraic form of the energy balance equation, as in Eq. (8). In the case of flow splitting, the temperature of the outflow equals that of the inflow since there is no mixing.

**Control valve** In a distribution system, valves are used to control energy flows toward the thermal users. For this specific purpose, valves can be seen as controllable fittings that regulate fluid pressure drop by completely or partially obstructing the pipeline cross-section. The developed algebraic model relies on a derived form of the Darcy-Weisbach equation in Eq. (9). The flow coefficient  $K'_v$  is corrected – compared to the nominal flow coefficient  $K_v$  – by means of the factor  $\phi$  representing the effects of valve opening on the actual flow coefficient. This relationship is made explicit by the valve characteristic curve which is usually provided by the valve manufacturer. The proposed model is pre-set with linear, equal percentage and quick opening characteristic curves, but other curves can be easily entered by the user. Similarly to the junction, thermal losses across the valve are neglected.

**Heat exchanger** In this case, a heat exchanger model is exploited to simulate the interactions between the boiler and the heat transfer fluid. The dynamic model relies on the differential form of the energy conservation equation as in Eq. (10). The heat flow from the boiler  $\dot{Q}$  is conventionally positive when entering the control volume. The pressure drops are evaluated with the equivalent length method in order to simplify the model setting. Regardless of heat exchanger type, once the rated values of pressure drop and fluid velocity are known, the overall resistance coefficient  $k$  and the pressure drop are calculated as a function of the operating conditions, according to Eq. (6d). In summary, beside the nominal values of pressure drop, fluid velocity and density, which are usually given in the manufacturer's datasheet, no other information about the heat exchanger is needed.

**Thermal energy storage** The TES is useful for decoupling heat generation and consumption in the district heating systems, providing an additional degree of freedom in heating management. Indeed, the operation scheduling of the heat generation systems can be varied – regardless of thermal demand profile – in order to match the most favorable conditions. The proposed model is suitable for the simulation of a sensible heat water TES, typically used in district heating applications, with a special focus on thermal stratification. It is a multi-node, one-dimensional, plug-flow model designed to be part of a district heating network [39]. The tank is divided into a customizable number of layers,

namely nodes, in which the temperature is considered uniform. Only the vertical temperature gradient inside the tank is considered. The nodes are sorted in decreasing order of temperature starting from the top to the bottom of the tank. The continuity and energy balance equations (Eqs. (11) and (12), respectively) are implemented for the generic  $i^{\text{th}}$  node [40]. The tank water inflow rate is automatically allocated to the node with the closest temperature. The outflow rates are defined as model inputs, except for that of the lowest node, which is calculated by the model through the conservation equation applied to the whole tank. The energy balance determines the node temperature  $T_i$  differential by considering the net enthalpy flow, heat transfer between adjacent nodes (due to convection and conduction) and thermal losses through the tank wall.

**Building** Buildings can be considered as the final users of the system. The aim of the proposed model is to give a simplified but reliable representation of end-user thermal behavior. For this purpose, the building is considered as a system with a given mass, exchanging heat with the external environment, the district heating system and the air flow due to natural and mechanical ventilation. These contributions are taken into account by means of a parametrized form of the energy conservation equation, given by Eq. (13). The indoor building temperature variation depends on four different terms: heat dissipation through the building envelope, the main thermal power contributions (heating system  $\dot{Q}_{\text{hs}}$ , solar heat gain  $\dot{Q}_{\text{ir}}$  and heat gain from occupants  $\dot{Q}_{\text{oc}}$ ), natural ventilation (or infiltrations) and mechanical ventilation influenced by the presence of a heat recovery ventilation system. These terms are characterized by performance coefficients – i.e.  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$  – which can be determined from experimental measurements or proper simulations with a detailed building model. Together with the indoor temperature variation, the building model determines both the amount of heat withdrawn from the district heating system  $\dot{Q}_{\text{hs}}$  and the water return temperature from the distribution side. The former is affected by the space heater operation (e.g. radiators and fan coil units), which is determined by an input variable regulating the actual value of the overall heat transfer coefficient. The latter is determined throughout the application of the energy balance equation to the heat interface unit, that allows the district heating network and the local heating system to be interconnected.

**Organic Rankine Cycle plant** The exploitation of low-temperature heat sources is one of the most common applications for ORC technologies. Indeed, thanks to the relatively low boiling point of the working fluid, it allows electrical and thermal power to be produced by energy sources that would otherwise be wasted. The presented algebraic model evaluates the electric power production (Eq. (14)) and heat recovery (Eq. (15)) depending on the heat flow from the source and all the efficiency contributions. The thermodynamic efficiency is corrected on the basis of the ORC plant operation, with a linear interpolation between the nominal and minimum load efficiency values. The heat provided to the district heating network is influenced by the recovery efficiency  $\eta_{\text{rec}}$  of the heat exchanger.



### 3. Control approach

The smart controller implemented in this work is based on Model Predictive Control, which is a technology that emerged in the field of chemical and process industry and is becoming more widespread in other engineering areas. According to the MPC control strategy, a dynamic model of the controlled system predicts its behavior over a defined horizon in the future, and an optimization algorithm calculates the sequence of optimal inputs that should be applied to the system to optimize a cost function over the aforementioned time horizon. The modeling approximations and the influence of the disturbances are overcome by means of the receding time horizon approach, which is typical of the MPC. Indeed, the first element of the optimal input sequence is effectively exploited to control the system while the remaining elements are dismissed. The time horizon for the prediction is then moved one step forward, the model variables and disturbances are updated with new measurements and predictions, and a new optimization problem is solved. This approach allows a system with multiple inputs, multiple outputs and constraints to be controlled in real-time and in an optimal way by taking advantage of new information about the system that is acquired at each time-step.

As mentioned in Section 1.1, all these factors make it possible to potentially overcome the limitations of the standard control approaches that, in thermal systems, are still raw. Indeed, the system operation is made automatic, the interconnections between the control variables are considered and optimal performance is expected also when the conditions vary significantly.

The feasibility of the real-time implementation of an MPC is highly dependent on the computational effort required to solve the optimization problem at each time-step. Therefore, since the dynamic model of the system is run many times by the optimization algorithm for each calculation step, one of the main requirements for the application of this method is a low computational burden of the used model.

The development and analysis of the MPC controller has been extensively described in previous studies by the authors [33,41]. It is an economic MPC that optimizes the control actions to satisfy an

economic or performance cost function. In particular, optimization is performed by means of a novel algorithm, the parameters of which have been selected through sensitivity analysis [33]. The algorithm is based on the concept of Dynamic Programming, which relies on the discretization of the system state-space and the division of the optimization problem in smaller sub-problems that are solved recursively backward in time. The knowledge gained by solving the various sub-problems is exploited for the following calculation steps in order to create a map that associates the optimal inputs with each feasible state at each time-step. A subsequent forward calculation that starts from the initial condition allows the optimal inputs to be selected by using this map.

The developed algorithm is suitable for models in a state-space form with a single state and a variable number of inputs and disturbances. Hence, the controller can be exploited for individual building applications [42] by considering a model with one state (i.e. building internal temperature), two inputs (i.e. mass flow rate and temperature of the water to the building substation heat exchanger) and the environmental conditions as disturbance. Nonetheless, it is easily replicable to larger networks with a multi-agent approach already outlined in [33].

The multi-agent approach consists of splitting the system into smaller sub-systems, each managed by a representative agent and communicating with a central controller. According to this assumption, each building is managed by a dedicated MPC controller, namely building-MPC, which communicates in a hierarchical way with a supervisory-MPC controller. This, in turn, operates the production side of the system by minimizing the global energy consumption or the operating cost.

It is possible to implement this approach with different goals, represented by a properly defined objective function. In this study, it is firstly applied to a simulation case study where the objective function of the production side is the total cost, including the fuel purchase and the electricity sold or bought from the national power grid (Section 4). It is also tested in two operational cases: the former considers the energy consumed for the end-user side and the cost of fuel for the production side as objective functions (Section 5.1), while the latter considers only the energy supplied (Section 5.2).

## 4. Simulation case study

A preliminary study to test the feasibility of the developed controller in an MiL application concerning the heat distribution network of a single building has been conducted in [42]. In order to demonstrate the replicability of the approach in a multi-agent hierarchical perspective, a more complex simulation study is presented in this work. The main scope of this case is to investigate the MiL simulation platform as a tool for the development, evaluation and comparison of new control strategies in complex systems that are yet to be designed, yet to be commissioned or not available for testing. It can also provide insights into the system operation while it is being proposed and designed and, therefore, be helpful in improving system layout and sizing accordingly.

The system model is built within the MATLAB<sup>®</sup>/Simulink<sup>®</sup> environment by means of the components of the library described in Section 2. The system model is operated firstly with a conventional control approach and secondly with the controller described in Section 3 with the same external conditions. The technical and economic results of the two methods are then compared.

### 4.1 Case study description

The virtual case study, represented in Figure 1, is the district heating network of a school complex comprising three education buildings, located in northern Italy. The network is supplied by an ORC plant which is powered by a biomass boiler and works with a condenser temperature equal to 90 °C [43]. The ORC produces electrical power to supply the building appliances or the grid while the heat transferred from the condenser is recovered and fed to a TES, which decouples production and utilization. A supply manifold collects hot water from the TES and dispatches it to the distribution pipelines of the buildings. Once the thermal power has been transferred to the building substation heat exchangers, the water is partly recirculated to the building itself and partly collected by the return manifold of the TES. The internal temperature of the buildings has to be maintained at the comfort value of 20 °C when the buildings are occupied. The values of the main system parameters are

reported in Table 2. The ORC system is sized according to [44], in which the thermal power recovered from a Rankine cycle is around two thirds of the overall end-user thermal peak demand. The efficiency parameters of the ORC are taken from [45]. The size of the TES is designed according to [44], which indicates that a profitable sizing is given by the storage ability to fulfill the circuit peak load for 1.5 hours to 2 hours.

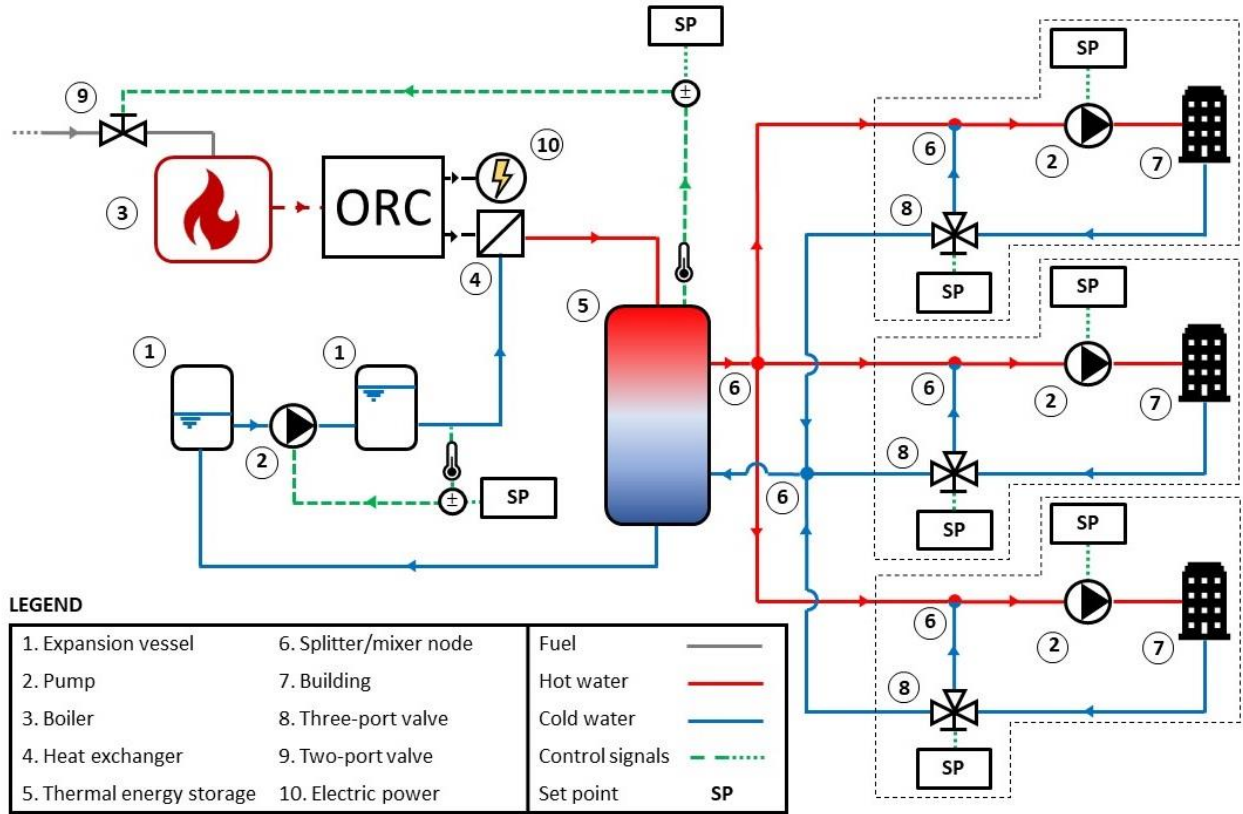


Figure 1. Schematic representation of the district heating network.

The set-points of the pumps and valves of the system are defined *a priori* in the conventional control strategy (hereinafter referred to as PID, for the sake of brevity). The conventional control strategy is based on the following features:

- A PI controller (i.e. proportional integral) regulates the pump rotational speed of the ORC condenser cooling circuit in order to guarantee that the thermal power is correctly retrieved, and the temperature of the water supplied to the TES is kept at 80 °C.

- A proportional controller regulates the biomass boiler in order to maintain a state of charge of the TES, i.e. the temperature in the upper fifth of the tank is kept between 70 °C and 80 °C.
- The internal air temperature of each building is controlled by regulating – through the pump rotational speed – the water mass flow rate sent to the building heat exchangers. The recirculation is disabled; thus the supply temperature is that exiting the TES upper node. This control is activated according to time-scheduled set-points which assume that the maximum thermal power is sent some hours before the building is occupied, i.e. five hours in this application.
- A proportional controller regulates the building space heaters in order to maintain the water return temperature at the design value of 60 °C.

Table 2. Main system parameters.

| Element          | Parameter   | Value                 |
|------------------|---|-----------------------|
| TES tank         | Inner diameter [m]                                | 6                     |
|                  | Height [m]  | 6                     |
| ORC unit         | Nominal electric power [kW]                       | 400                   |
|                  | Nominal thermodynamic efficiency [%]              | 16                    |
|                  | Minimum load electric power [kW]                  | 60                    |
|                  | Minimum load thermodynamic efficiency [%]         | 10                    |
| Sports hall      | Envelope heat loss coefficient [h <sup>-1</sup> ] | 0.0262                |
|                  | Supplied power coefficient [°C/kJ]                | 7.53·10 <sup>-7</sup> |
| Secondary school | Envelope heat loss coefficient [h <sup>-1</sup> ] | 0.0126                |
|                  | Supplied power coefficient [°C/kJ]                | 9.08·10 <sup>-7</sup> |
| Primary school   | Envelope heat loss coefficient [h <sup>-1</sup> ] | 0.0081                |
|                  | Supplied power coefficient [°C/kJ]                | 1.35·10 <sup>-7</sup> |

On the other hand, in the innovative control approach, the set-points are calculated by the MPCs at each time-step. The algorithm of each end-user receives the actual building internal temperature and returns the optimal set-points for water (i) mass flow rate, which is maintained by controlling the pump rotational speed with a feedback loop, and (ii) supply temperature, which is maintained by setting the recirculation valve with an open-loop controller (e.g. look-up table). The supervisory-MPC receives – as disturbances – the predicted thermal demands over the prediction horizon as calculated by the building-MPCs and returns the optimal set-point to operate the plant in order to guarantee that the TES is able to fulfill the total thermal demand.

As stated in Section 3, the MPC controllers for both the building and the production plant require simplified models of the systems in order to perform real-time optimization and control, as follows:

- i. The building-MPC adopts a gray-box model of the building based on performance coefficients as presented in [33];
- ii. The supervisory-MPC adopts a thermocline assumption for the TES model [46]: the tank is split into two zones at a defined high temperature  $T_h$  (80 °C) and low temperature  $T_l$  (60 °C). The position of the virtual separation surface – referred to the top of the tank – between the zones is the thermocline and represents the TES state of charge and system state, constrained between 0 and the TES total height. The thermal power to the ORC, the boiler on-off signal and the electricity bought from the grid are the inputs. The cost function  $C_{tot}$  calculated for each time-step of the algorithm is the total operating cost, given by the sum of the costs for the biomass  $\dot{m}_f$  to the boiler, electricity bought from the grid  $P_b$  and the revenues resulting from the sale of electricity to the grid  $P_s$ . It is reported in Eq. (16):

$$C_{tot} = C_b P_b \Delta t - C_s P_s \Delta t + C_f \dot{m}_f \Delta t \quad (16)$$

where  $C_b$ ,  $C_s$  and  $C_f$  are the specific costs of the bought and sold electric power and of the fuel, respectively.

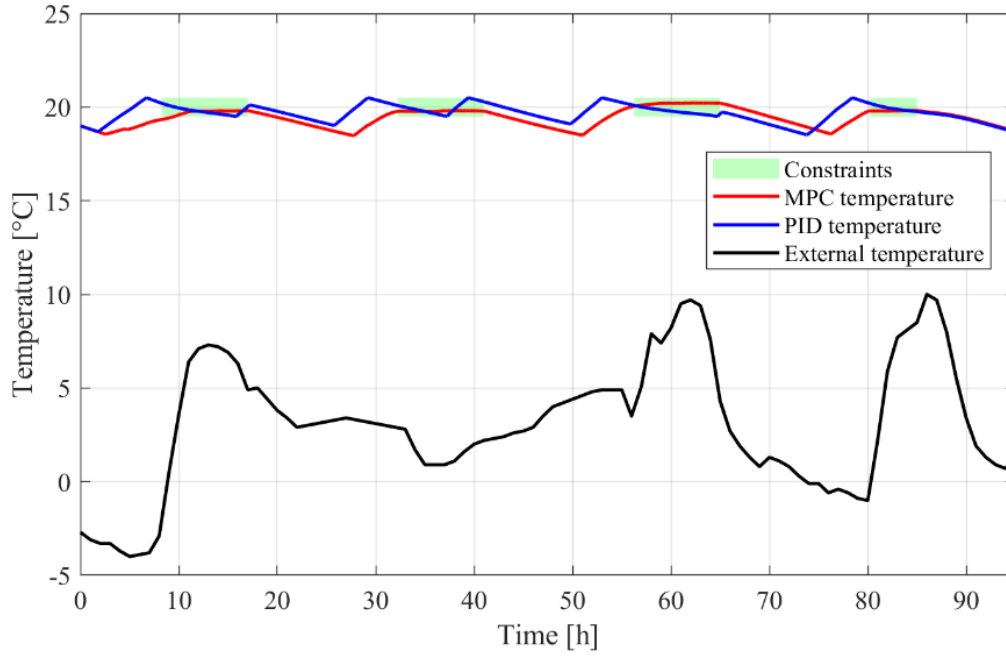
## 4.2 Simulation results

The network is simulated for four days in January. The results of the MiL simulations concerning the indoor temperature of one of the end-users are shown in Figure 2. It is important to verify that, when the building is occupied (green shaded areas), the indoor temperature is kept within the constraints. Instead, when the building is not occupied, the building temperature is left unconstrained. In the constrained periods, the average temperature with the conventional control is 19.86 °C, while it is 19.88 °C with the MPC. Hence, the difference between the two control methods is negligible as far as the indoor thermal comfort is concerned.

Furthermore, it is possible to notice that the conventional controller (blue line) generally results in the required comfort temperature being reached several hours before it is needed with consequent energy wastage, as it is based on set-points established by a pre-defined rule. Whereas, the MPC controller can send the exact amount of energy required to keep comfort at the minimum allowed temperature (i.e. in order to minimize heat loss). At the same time, when necessary, it manages the thermal inertia of the building by establishing the right time to supply heat and by using the heat capacity as storage. Similar considerations can be drawn for the other buildings.

This confirms the results obtained in the previous works concerning the capability of the MPC controller to efficiently control buildings with different thermal characteristics, fulfilling the indoor comfort requirements while reducing the thermal losses.

The two control approaches show significant differences also in the management of the production plant. Figure 3 depicts the electrical output of the ORC power plant compared to the power demand of the school complex. The electrical power produced by the plant is not always enough to fulfill the total demand, but it should be remembered that the main goal of the plant is to fulfill the thermal demand of the buildings. The electricity is bought from the power grid to cover the demand when self-production is not sufficient, while it is sold to the grid when in excess.



**Figure 2.** Indoor temperature of one of the buildings with the MPC and conventional (PID) controllers.

The graph shows that the ORC is managed in an on-off way by the conventional controller. The MPC, instead, is able to define the operating strategy that minimizes the cost function (i.e. total cost, in this application) and modulates the plant output. The graph shows that, when the indoor comfort of the building is maintained, the production is regulated by the MPC in order to cover as much electrical demand as possible, while avoiding the complete charge of the storage. Indeed, the innovative controller also optimizes the management of the TES to make sure that, at each calculation step, there is enough stored thermal energy to guarantee the energy supply to the circuits downstream over the prediction horizon, while minimizing the thermal losses from the tank. Figure 4 represents the temperature of the five nodes in which the TES model is discretized. The comparison between the TES temperature evolution in the two control strategies shows that the MPC charges the storage when there is thermal request from the end-users while trying to keep the temperature as low as possible to reduce energy loss.



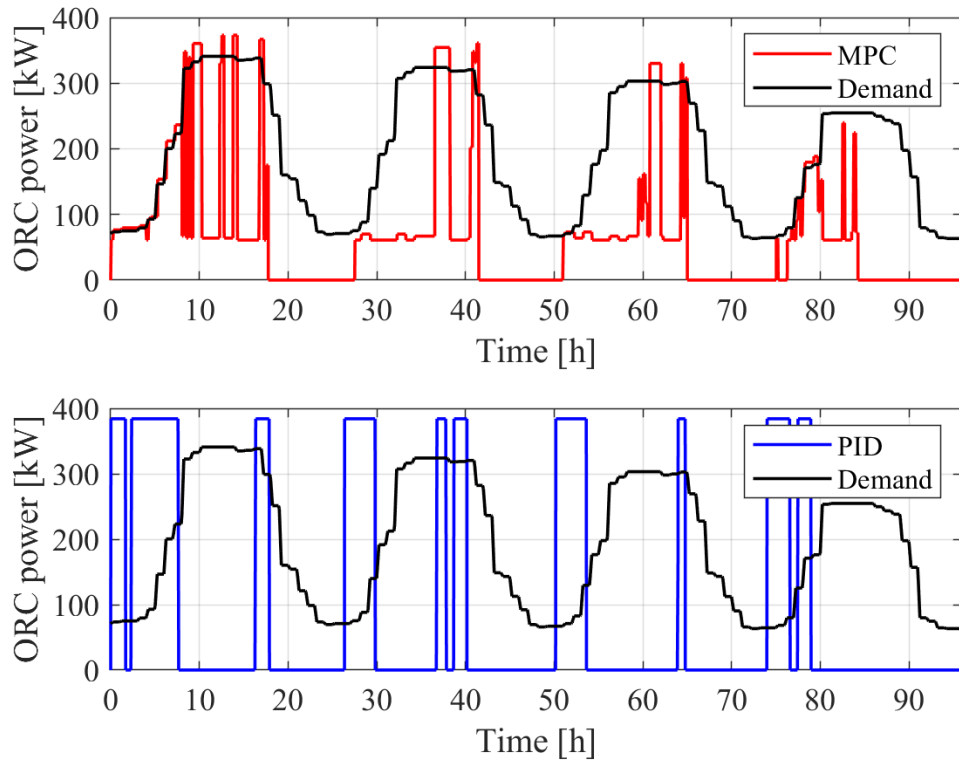


Figure 3. ORC power plant electrical power output and electrical demand with the MPC and conventional (PID) controllers.

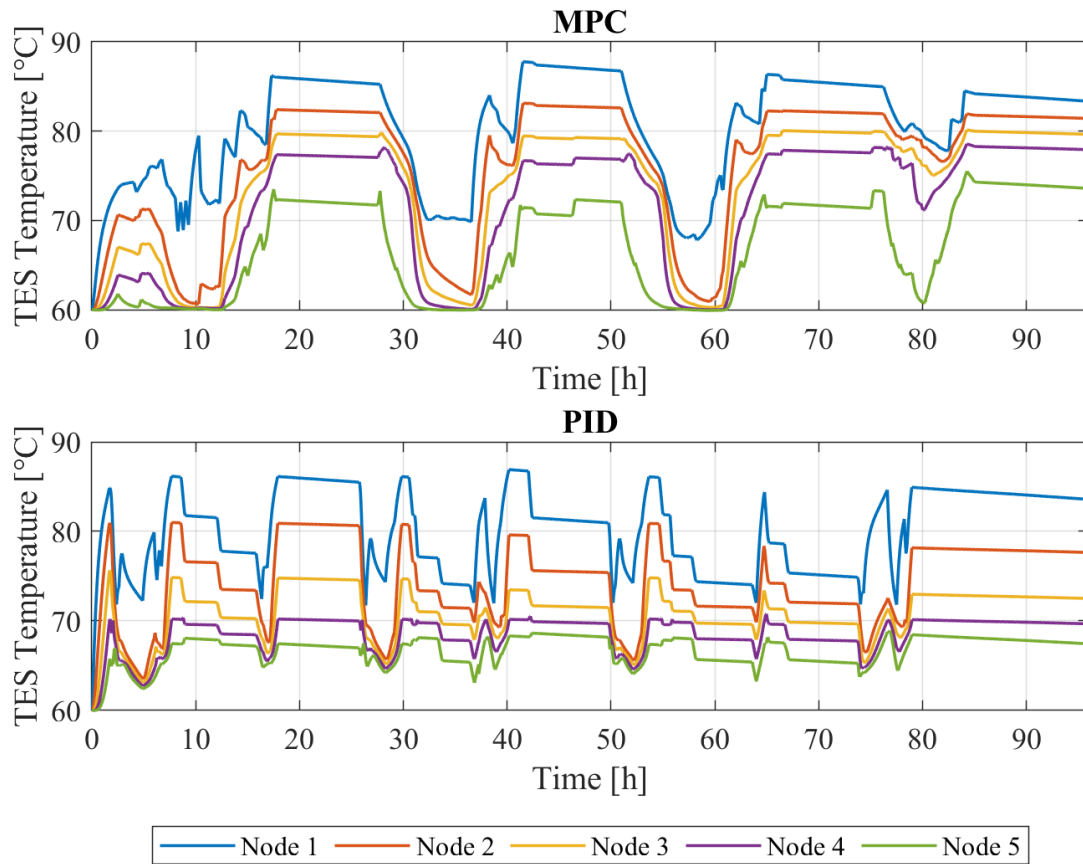


Figure 4 Node temperatures of the thermal energy storage tank with the MPC and conventional (PID) controllers.

The economic and energy results of the analysis are reported in Table 3. As expected, the MPC shows a 7 % reduction in total energy cost, since this is the objective function to be minimized. In addition, fuel consumption is reduced by 13 %. The total primary energy, obtained by considering a grid overall efficiency equal to 0.4, slightly increases (i.e. 1.3 %) with the new control strategy. Other promising results might be obtained by implementing the minimization of the total energy consumption. In any case, it should be underlined that the self-consumed electricity, which is the percentage of the total electric demand of the school complex satisfied by the ORC production, is increased by more than 70 % in the case of the MPC. Moreover, it is produced from biomass which can be considered a renewable primary energy source.

Table 3. Energy and economic results of the simulation.

| Parameter   | PID results | MPC results | MPC compared to PID |
|---|-------------|-------------|---------------------|
| Total cost [EUR]                                      | 4360        | 4053        | - 7.0 %             |
| Bought electricity [kWh]                              | 15043       | 12627       | - 19 %              |
| Sold electricity [kWh]                                | 5398        | 667         | - 87 %              |
| Produced electricity [kWh]                            | 8773        | 6457        | - 23 %              |
| Self-consumed electricity [kWh]                       | 3375        | 5791        | + 72 %              |
| Self-consumed electricity compared to user demand [%] | 18.3        | 31.5        | + 72 %              |
| Fuel mass [kg]  | 14905       | 13039       | - 13 %              |
| Total primary energy [kWh]                            | 87553       | 88697       | + 1.3 %             |

## 5. Experimental case studies

After its **successful** development and **evaluation** in the simulation environment described in Section 4, the MPC controller has **been further** demonstrated in two real case environments **in operational conditions**. They differ from the simulation case study and present different complexity and challenges. Moreover, they are subjected to the requirements of the system operator. The first case study is a school complex located in northern Italy and is described in Section 5.1. The second case study is the Parma University Campus, described in Section 5.2.

### 5.1 School complex in Podenzano (Italy)

#### 5.1.1 Site description

The proposed MPC algorithm was implemented for the heating management of the school complex of Podenzano, in the province of Piacenza, Italy. The complex, **depicted in Figure 5**, is supplied by a small-scale district heating network aimed to provide heat to three school buildings with different intended uses (primary school, secondary school and sports hall). The district heating system is composed of three **energy** conversion systems (two natural gas boilers with a nominal thermal power of 350 kW and a biomass boiler with a nominal thermal power of 300 kW), a thermal energy storage tank with a capacity of 6 m<sup>3</sup>, two collectors (supply and return) and three secondary circuits, as described in **[47]**. The user **occupation hours are different**: the primary school heating schedule is set from 8:30 a.m. to 5:30 p.m., that of the secondary school from 8:30 a.m. to 12:30 a.m. and, lastly, that of the sports hall from 10:00 a.m. to 11:00 p.m.

#### 5.1.2 **Traditional system control**

Before the MPC application, the plant management was conducted by means of a standard Building Management System (BMS), composed of four control units: the first for the energy conversion systems, and the other three for the three secondary circuits of the district heating network.

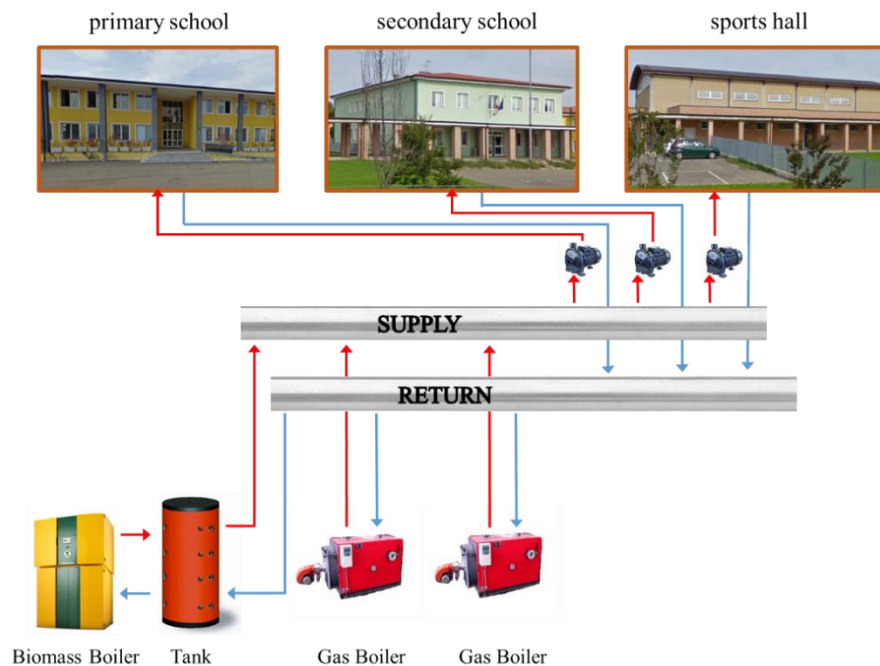


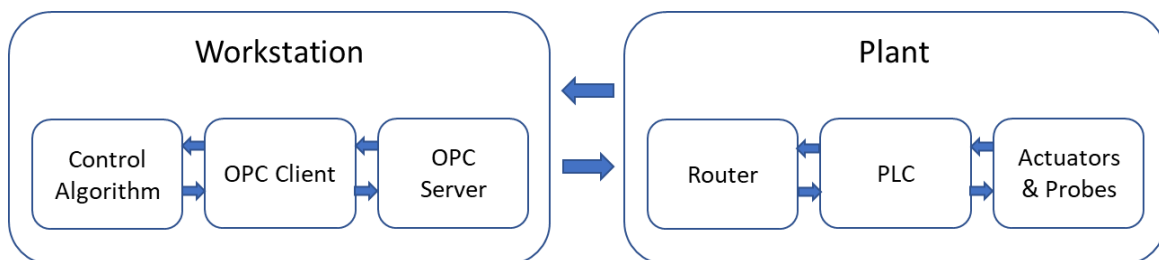
Figure 5. Schematic representation of the school plant [47]

Each building was managed by a dedicated control unit, which set the supply temperature and the pump operation in order to comply with the indoor temperature threshold. Then, the control unit of the production plants imposed the maximum supply temperature among the secondary loops as the set-point for the three boilers during the activation period. Therefore, the boilers were sequentially turned on or off – according to the cascade control logic – in order to keep the main collector supply temperature at the set-point value. This control method requires the plant activation schedule to be manually set up through the BMS software interface. Every month, the operators had to set the plant activation schedule for the next month remotely. Since the operators could not forecast the plant behavior, they had to rely on their own personal experience which, although extensive, could not guarantee optimal management of the system.

### 5.1.3 Controller prototype

Modifications in the communication network layout were required for the implementation of the MPC-based system control. In fact, in the original configuration, the set-points and time schedules were set through the BMS. Then, the actual control was made by means of Programmable Logic Controllers (PLC). Since the MPC algorithm is not supported by the BMS, a new workstation has been installed and designated for managing the plant. An Open Platform Communication (OPC) client-server **platform** has been used to interact with the existing communication protocol. These two **programs** are installed in the workstation and exchange data from the algorithm to the plant and vice versa.

The following example is given to provide a better understanding of the control chain. The control algorithm calls back the OPC client to **collect** the initial information about **the** internal temperature of the buildings. In order to obtain this information, the OPC client sends a request to the OPC server **which**, in turn, interrogates the plant control units through **the** TCP/IP (i.e. Transmission Control Protocol – Internet Protocol) communication protocol. Once the calculation of the control algorithm is finished, the OPC client sends the control signals to the OPC server that sets the new set-point in the real plant through the control units. This simple communication architecture, summarized in **Figure 6**, allows the real plant to be controlled in an easy and **versatile** way.



**Figure 6.** Communication architecture of the new controller **prototype** for the school complex of Podenzano [47].

The new MPC control software – developed in the MATLAB® environment for this first application – is installed in the workstation. There are two main reasons for choosing the MATLAB® software: firstly, for this first version of the MPC, the Dynamic Programming algorithm developed by Sundström and Guzzella in the MATLAB® programming language [48] has been used; and, secondly, the technicians working on the project had already an in-depth knowledge of the software. This communication and software architecture, even if prototypical, ensures the right functionality of the plant on a daily basis.

#### *5.1.4 Controller performance*

A preliminary monitoring campaign was carried out for four days in order to register the variations in the operating parameters and is reported in [47]. The network was operated for two days with the standard control strategy and for the other two days with the MPC control strategy. The second day of each period was chosen as significant, in order to neglect the effect of the initial transients on the operation. As regards the energy conversion system, the results of the trial showed that, in both cases, the biomass boiler is turned on during the start-up phase in the morning. Then, during the day, the MPC strategy activates the natural gas boilers rather than the biomass boiler to maintain the indoor temperature of the buildings. Regarding the pump activation, in the original configuration, the pumps are activated depending on specific timetables, while the MPC strategy varies the pump activation depending on the building thermal requirements. In this way, the improved control strategy allows the indoor temperature set-point to be reached with remarkable electrical energy saving.

The demonstration of this case proceeded further and is presented in this paper. Indeed, the MPC control system performances were assessed for an entire winter season (from November 2017 to the end of March 2018) and were compared with those of the original control system during the same period of the previous year (November 2016 – March 2017). Similarly to the simulation case study described in Section 4, the mass flow rate and supply temperature of each building loop are controlled

by a dedicated MPC with the aim of minimizing the energy supply. A supervisory controller operates the boiler station to minimize the operating cost (i.e. fuel cost) while fulfilling that demand.

The main and most significant result is the energy saving that the MPC has brought to the district heating application. The old and new management performances are compared by means of the dimensionless energy consumption parameter (Figure 7). The energy consumption is calculated as the sum of the energy produced by the different conversion systems in the boiler station, as measured by the instruments over each month. In order to have a reliable comparison of the performance of the control strategies in different weather and external conditions, it is necessary to refer to specific values of consumption. Therefore, the monthly energy consumptions  $E_{\text{cons}}$  is divided by the monthly heating degree days ( $HDD$ ) to evaluate the specific monthly energy consumption  $e_{\text{cons}}$ , given by Eq. (17). Since they are sensitive date and the requirements of confidentiality of the system operator have to be respected, the values of specific energy consumption are made dimensionless with respect to their maximum value, as expressed by Eq. (18).

$$e_{\text{cons}} = \frac{E_{\text{cons}}}{HDD} \quad (17)$$

$$\Psi = \frac{e_{\text{cons}}}{\max(e_{\text{cons}})} \quad (18)$$

The comparison between the 2017/18 and 2016/17 heating seasons points out that an average 13 % reduction in specific energy consumption is achieved by means of the MPC application. Specifically, the new management strategy records its best performance during the mid-season (e.g. November), when the difference between indoor and outdoor temperature is relatively low but the higher variability should be addressed. Under these circumstances, the MPC identifies – thanks to the outdoor temperature forecast and mathematical model of the system – the right time to turn the heating system on or off in an optimal way. Hence, the minimization of energy produced by the boilers and delivered to the network is assessed.

Figure 7 also shows the percentage distribution of the production between the biomass and natural gas conversion systems during the heating season with the standard control (2016/17) and with the MPC control (2017/18). This is represented by the pie charts above the bars of the specific energy consumption. The main result from the boiler control strategy is the increased use of gas boilers at the expense of the biomass boiler. The main reason could be the long biomass boiler start-up time – especially when coupled with a TES – in contrast with the gas boilers which are typically faster. Thus, the latter are selected by the control system to handle the daily fluctuations in indoor temperature.

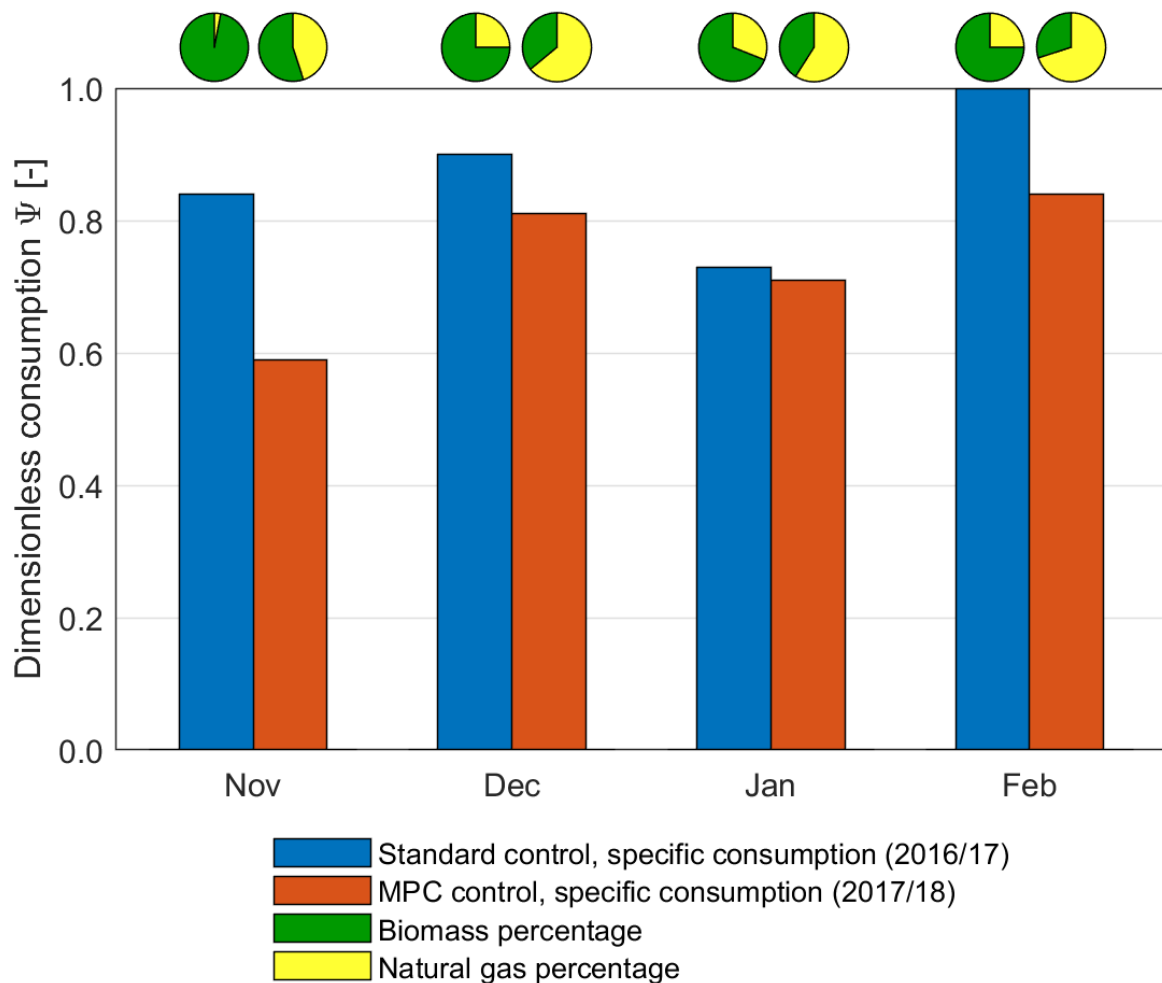


Figure 7. Comparison of the dimensionless specific energy consumption obtained with the standard control and with the MPC control. The pie chart above each bar represents the percentage distribution of the energy produced by the biomass boiler and natural gas boiler.



These results seem to be in contrast with one of the general objectives for energy systems to increase the share of renewable energy resources. However, it should be noted that, in this preliminary test application, the main requirement of the system operator was to minimize the operating cost that included the price of the fuels (i.e. biomass and natural gas). On the one hand, the MPC controllers of the network circuits minimize the energy sent to the end-users, and the consequent energy reduction is demonstrated by the results. On the other hand, the boiler station management is based only on an economic criterion to comply with the system operator request: additional contributions such as, for instance, the environmental cost of carbon emission or the priority of the biomass boiler have not been considered up to now. For this reason, this application is relevant as a demonstration case study in an operational environment of the innovative control strategy (with significant energy saving), but not as an example of an increased share of renewables in heating networks. The inclusion of priority criteria and incentives for renewables as well as environmental costs will be the subject of future developments and applications of this approach.

A further goal of this experimental application was to perform an endurance test. In real applications, it is critical to guarantee reliability and **safety** in the long term. In the first test developed during the heating season, failures of the proposed control system were detected only due to interruptions in the Internet connection.

## *5.2 University Campus in Parma (Italy)*

### *5.2.1 Site description*

Since the first MPC application has pointed out the importance of distribution on the overall system optimization, a second test case has been **carried out**, in order to better investigate this issue. The second application of MPC was carried out in a building **on** the Parma University Campus, in Italy (**Figure 8**). This case is more relevant than the school complex for its **size** and internal heating system complexity. Indeed, the building has a volume equal to 50 000 m<sup>3</sup> and the Heating Ventilation and

Air Conditioning system (HVAC) is composed of six air treatment units, 36 fan coil units and 30 radiators, all served by the district heating network. This starts from the main boiler station and, after approximately 1 km of pipeline, enters the building and feeds the secondary heating circuit through the substation heat exchanger characterized by 800 kW of heat power. The control system has the difficult task of preserving internal comfort by managing the high variability of the thermal demand of the facilities.

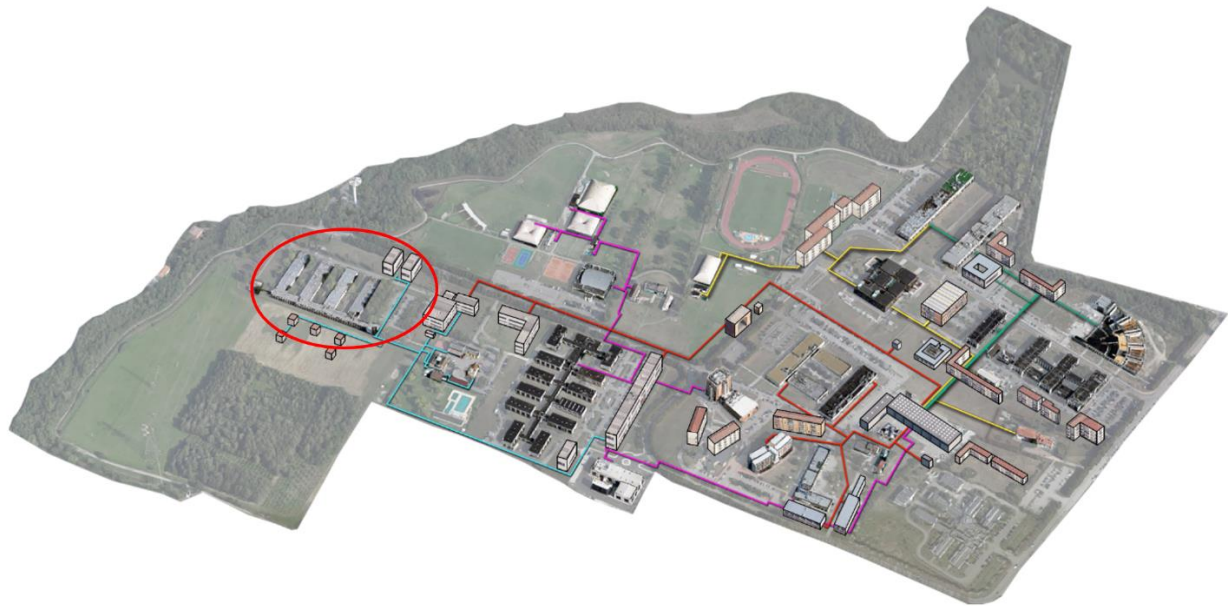


Figure 8. District heating network of Parma University in Italy and the MPC test building (circled in red).

The energy demand of the building changes both daily and weekly due to external temperature variation, irradiation and occupancy: the heating system must fulfill the user requirements from 8:00 a.m. to 18:00 p.m. during working days, whereas it is turned off during the weekend.

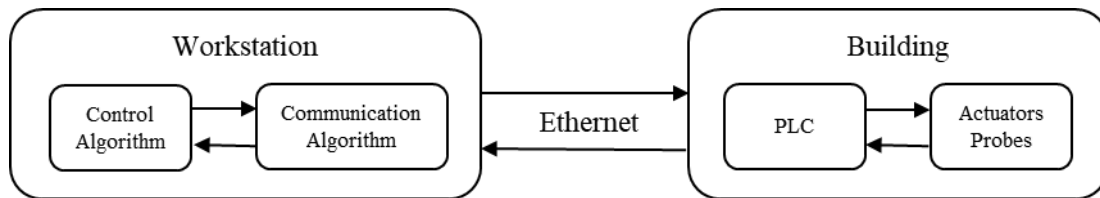
### 5.2.2 Current system control

The current system control of the Parma University Campus is summarized in this section: each of the 33 buildings is managed by a dedicated control unit, which regulates the HVAC and heat exchanger operation. These control units allow the activation schedules to be set manually for the

pumps and HVAC systems, while the supply temperature of the secondary loops is determined through the application of the climatic curves. Each heat exchanger is fed – on the primary circuit side – by a three-way valve, which **regulates** the amount of hot water **taken** from the distribution network in order to fulfill user thermal requirements. As regards heat generation, a single control unit is in charge of the management of all the energy conversion systems. In this case, the activation schedule and set points are determined for each system by a full-time dedicated operator.

### 5.2.3 Controller prototype

The heating and cooling plants are managed by a single BMS, which is composed **of** several control units installed in each building substation. All of them are linked, by means of an Ethernet LAN, to a server located in the **boiler** station. Thanks to this communication standard, an industrial workstation was installed and linked to the Ethernet network. Then, a communication algorithm (based on the **BACnet** protocol) was developed in order to exchange data between the MPC and standard BMS. Therefore, the MPC algorithm – originally developed in the MATLAB<sup>®</sup> environment – was **translated** in the open-source Python<sup>™</sup> code. The new communication architecture is schematized in **Figure 9**.



**Figure 9.** Communication architecture of prototype of the new controller for the Parma University Campus.

Once implemented, the MPC and communication algorithms were **wrapped** in a single LabVIEW<sup>®</sup> application in order to assure real-time control reliability and **to** make troubleshooting easier. As **a**

future development, the real time application will be performed in C++ programming language to improve versatility and reduce runtime.

#### 5.2.4 Controller performance

The new control system was installed in March 2019 and its performance was assessed for two months (until the end of April), during which it ran without issues, complying with the user thermal requirements. In this second MPC application, the results are even more significant than in the previous case, in terms of energy saving. The main goal, in this case, was to minimize the energy delivered to the branch of the network. Figure 10 presents the comparison of the old and new management performance during a two-month test period in terms of dimensionless specific energy consumption. This quantity is calculated in a similar way as it was in the previous case study: the total energy sent to the end-user by means of the distribution system is measured and divided by the monthly heating degree days, in order to allow different months, seasons and conditions to be effectively compared. The values of specific consumption are then made dimensionless by dividing them by the maximum value. In the results, a relevant decrease in specific consumption can be observed between the conventional and new control strategy.

Specifically, the comparison between the dimensionless energy consumptions – as calculated according to Eq. (18) – pointed out that an average 34 % reduction was achieved through the MPC application compared to the old management system (January – February 2019). Again, a promising performance is registered during the mid-season, when the weather is typically subjected to higher variations, and a management strategy based on a pre-defined rule is not able to react efficiently to the rapidly varying conditions. Indeed, the great advantage of MPC is that it can calculate the optimal switch on/off scheduling of the heating system throughout its operation, by means of the forecast of the external temperature and the mathematical models of the system.

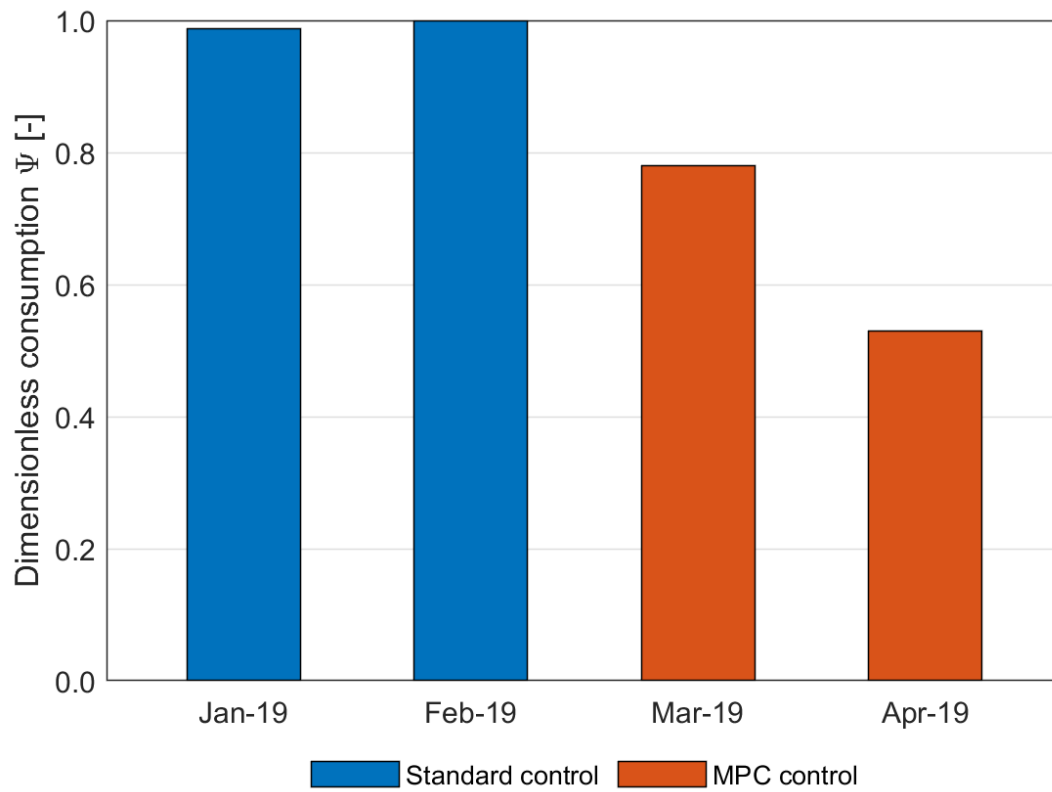


Figure 10. Dimensionless energy consumption comparison. The blue bars (January and February) represent the previous control approach while the green bars (March and April) represent the MPC.

## 6. Conclusions

This paper proposed an integrated framework for the setting and testing of an innovative predictive control algorithm (MPC), intended for the management of small-scale district heating systems. The control strategy was demonstrated in three original case studies, one in a simulation platform and two in real operational environments. As a first step, a collection of models for the simulation of a fully customizable network was developed by the authors in the MATLAB®/Simulink® environment: all the standard components were modeled through a physics-based modular approach and then gathered into a dedicated library. Since on-site testing is not always a feasible option, the library represents an effective tool for the Model-in-the-Loop applications of a new control strategy: as a remarkable example, an ORC powered network was simulated, which feeds a school complex with three buildings. A dedicated MPC module was in charge of the thermal demand optimization of each building, while a supervisory MPC controlled the ORC plant with the task of minimizing the total energy cost without affecting compliance with the thermal requirements.

Moreover, two real applications of the MPC-based algorithm were carried out in order to assess the control performance when dealing with existing facilities. In the first case, the MPC was implemented with the same hierarchical structure for the management of two natural gas boilers, a biomass boiler and a TES supplying a school complex composed of three buildings (Podenzano case). In the second case, the smart controller application focused on distribution and was applied to a building connected to the district heating system of the Parma University Campus. The objectives were to minimize energy consumption for the end-user side and fuel cost for the production side.

The main results of the three case studies confirmed the potential of the MPC for future smart applications as summarized as follows:

- The simulation results pointed out the smart controller effectiveness, showing significant reduction in operating cost (i.e. 7 %), and its capability of dealing with variable boundary conditions. In particular, the electricity produced, sold and bought from the grid is reduced by

23 %, 87 % and 19 %, respectively, while the amount of self-consumed electricity is increased by 72 %. The fuel is reduced by 12 %. Thus, it is not considered cost-effective to produce electricity in order to sell it to the grid. This case also showed the utility of the MiL simulation platform as a tool for evaluating and comparing control strategies in complex configurations. An additional benefit is also the possibility to analyze costs and energy factors more in detail, which is not always feasible when private stakeholders are involved.

- The Podenzano case study demonstrated an average 13 % reduction in specific energy consumption with better mid-season performance.
- Similarly, the Parma University Campus case study showed that the energy supplied to the considered network branch is reduced by 34 %.

The presented integrated methodology can be useful to foster the transition of existing heating networks towards 4<sup>th</sup> Generation District Heating and to develop new smart energy systems. The change of the control system architecture to a predictive approach enables the digitalization of the heating sector. This can lead to a globally connected system, in which the various grids – electricity, heating, cooling and gas – are coupled and the energy is produced, converted and distributed in an optimal way.

The experimental case studies involve a first prototype, but future works on the demonstration and validation of the proposed control approach in more complex real energy networks will be carried out. New configurations with waste heat recovery and new cost functions that include environmental costs and renewable share will be investigated. Furthermore, a research line that aims to scale the proposed procedure in a fractal way is ongoing. The scope of this further development is to enable the application of a single demonstrated methodology potentially to any kind of heating network, from the micro-scale (i.e. building level) to the macro-scale (i.e. city level). This can constitute a valid tool for researchers and industrial partners in the area of smart energy networks.

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## Nomenclature

|                    |  |
|--------------------|--|
| $A$                | surface <b>area</b> [ $\text{m}^2$ ]   |
| $A_{\text{in}(1)}$ | cross-sectional area of first pipeline segment [ $\text{m}^2$ ]                          |
| $C$                | specific cost [EUR/kWh] or [EUR/kg]  |
| $C_{\text{tot}}$   | total cost [EUR]   |
| $c$                | water specific heat capacity [ $\text{kJ kg}^{-1} \text{K}^{-1}$ ]                       |
| $D$                | impeller diameter [m]  |
| $E$                | monthly energy consumption [kJ]  |
| $e$                | specific monthly energy consumption [ $\text{kJ } ^\circ\text{C}^{-1} \text{day}^{-1}$ ] |
| $g$                | gravitational acceleration [ $\text{m s}^{-2}$ ]   |
| $H$                | pressure head [m]  |
| $HDD$              | <b>heating</b> degree days [ $^\circ\text{C day}$ ]                                      |
| $k$                | heat capacity ratio [-]  |
| $k_r$              | resistance coefficient [-]   |
| $K_v$              | flow coefficient [ $\text{m}^3 \text{s}^{-1} \text{Pa}^{-1/2}$ ]                         |
| $K_v'$             | corrected flow coefficient [ $\text{m}^3 \text{s}^{-1} \text{Pa}^{-1/2}$ ]               |
| $L$                | pipe length [m]  |
| $LHV$              | fuel lower heating value [ $\text{kJ kg}^{-1}$ ]   |
| $M$                | water mass inside the pipe [kg]  |
| $\dot{m}$          | mass flow rate [ $\text{kg s}^{-1}$ ]  |
| $n$                | rotational speed [ $\text{s}^{-1}$ ]   |

|               |   |
|---------------|---|
| $p$           | pressure [Pa]   |
| $P$           | power [kW]  |
| $\dot{Q}$     | thermal power [kW]  |
| $T$           | temperature [°C]  |
| $t$           | time [s]  |
| $U$           | heat transfer coefficient [kW m <sup>-2</sup> K <sup>-1</sup> ] |
| $v$           | speed [m s <sup>-1</sup> ]                                      |
| $V$           | volume [m <sup>3</sup> ]  |
| $\dot{V}$     | volumetric flow rate [m <sup>3</sup> s <sup>-1</sup> ]          |
| $x$           | spatial discretization scale [m]                                |
| $z$           | height [m]  |
| $\alpha$      | first building performance coefficient [s <sup>-1</sup> ]       |
| $\beta$       | second building performance coefficient [°C kJ <sup>-1</sup> ]  |
| $\gamma$      | third building performance coefficient [s <sup>-1</sup> ]       |
| $\delta$      | fourth building performance coefficient [s <sup>-1</sup> ]      |
| $\varepsilon$ | roughness [m]   |
| $A$           | ratio between actual and nominal load [-]                       |
| $\lambda$     | friction factor [-]   |
| $\eta$        | efficiency [-]  |
| $\rho$        | water density [kg m <sup>-3</sup> ]                             |
| $\pi_1$       | dimensionless head coefficient [-]                              |



|             |   |
|-------------|---|
| $\pi_2$     | dimensionless flow coefficient [-]            |
| $\phi_{in}$ | pipe diameter [m]                             |
| $\Psi$      | dimensionless specific energy consumption [-] |

### *Subscripts*

|      |                |
|------|----------------|
| a    | air            |
| a,0  | initial air    |
| air  | forced air     |
| b    | bought         |
| bldg | building       |
| conc | concentrated   |
| cons | consumption    |
| dist | distributed    |
| eff  | effective      |
| el   | electric       |
| ext  | external       |
| f    | fuel           |
| geo  | geodetic       |
| hs   | heating system |
| in   | inlet          |
| ir   | irradiance     |
| m    | mechanical     |

|     |                     |
|-----|---------------------|
| max | maximum             |
| min | minimum             |
| nom | nominal             |
| oc  | building occupation |
| out | outlet              |
| rec | recovered           |

s sold

|       |               |
|-------|---------------|
| th    | thermodynamic |
| valve | valve         |
| vert  | vertical      |
| w     | water         |

### *Acronyms*

|      |   |
|------|---|
| BMS  | Building Management System                      |
| DHC  | District Heating and Cooling                    |
| HVAC | Heating and Ventilation Air Conditioning system |
| MiL  | Model-in-the-Loop                               |
| MPC  | Model Predictive Control                        |
| OPC  | Open Platform Communication                     |
| ORC  | Organic Rankine Cycle                           |
| PID  | Proportional-Integral-Derivative controller     |

PLC Programmable Logic Controllers

TES Thermal Energy Storage tank

TRL Technology Readiness Level