DISTRHEAT

Digital intelligent and scalable control for renewables in heating networks

Deliverable D2.2

Report on the development of the small scale DHC system model

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Executive summary

The deliverable summarizes the results from task “T2.2 Modeling and validation”, the goal of which was to develop and validate dynamic physics-based models of the small DHC network studied and analyzed in T2.1.
The research group of the University of Parma has developed an in-house library of models for integrated energy systems to developed their digital twins, i.e. models that emulate the behavior of the real system with high-detail and typically faster than real-time. Each block represents a physical component that can be found in multi-energy networks, covering various domains, i.e. heat, electrical energy, fuels.
The aim, features and governing equations of the sub-models of the components are described with specific reference to the elements of the case study: the thermal power station (boilers, cogeneration plant, absorption chiller), district heating and cooling circuits (pumping station, pipelines, heat exchangers), and outdoor conditions.
The library has shown to be a reliable tool for accurate simulations of distribution networks and thermal power stations with different energy domains. Thus, a digital twin of the small-scale DHC (Cona Hospital) has been built by combining together the components from the library.
The control logic implemented in the digital twin represents the traditional way in which the energy system of the real-world hospital is operated:

- The **cogeneration plant** is generally operated continuously at nominal load, except for the maintenance periods during which it is switched off. The **absorption chiller** is operated only during the summer months.
- The water temperature in the supply pipeline of the **district heating circuit** is maintained at the set-point value of 85 °C by activating the boilers in cascade if it is lower and dissipating heat from the cogenerator if it is higher.
- The water temperature in the supply pipeline of the **district cooling circuit** is maintained at the set-point value of 6 °C by activating the absorption and electric chillers in cascade if it is higher.
- The pump rotational speed of the pumps is controlled in order to match the reference temperature difference between supply and return.

All relevant variables of the system (e.g. mass flow rates, temperatures, pressures, powers) can be monitored to produce datasets of system operation. These data determine the complete energy and environmental performance of the system in given operating conditions and allow to verify if the technical requirements of the distribution systems are maintained.
The digital twin is significantly faster than real time, reliable and useful for several purposes. It can be simulated for an entire operating year, as long as the evolution over time of the heating, cooling and electrical load of the hospital is provided, and it can be exploited as a virtual testbed for verifying different management strategies.

1. Introduction

This report is the deliverable D2.2. of work package WP2 of the DISTRHEAT project, led by University of Parma. The work package "WP2 – System study, modeling and algorithm development for small DHC" aims to develop a system model of a small-scale District Heating and Cooling network (DHC), in particular of the small-scale case study, and an optimization algorithm suitable for its optimal management within a Model Predictive Controller.
The coordinated activities of WP2 are illustrated in Figure 1.

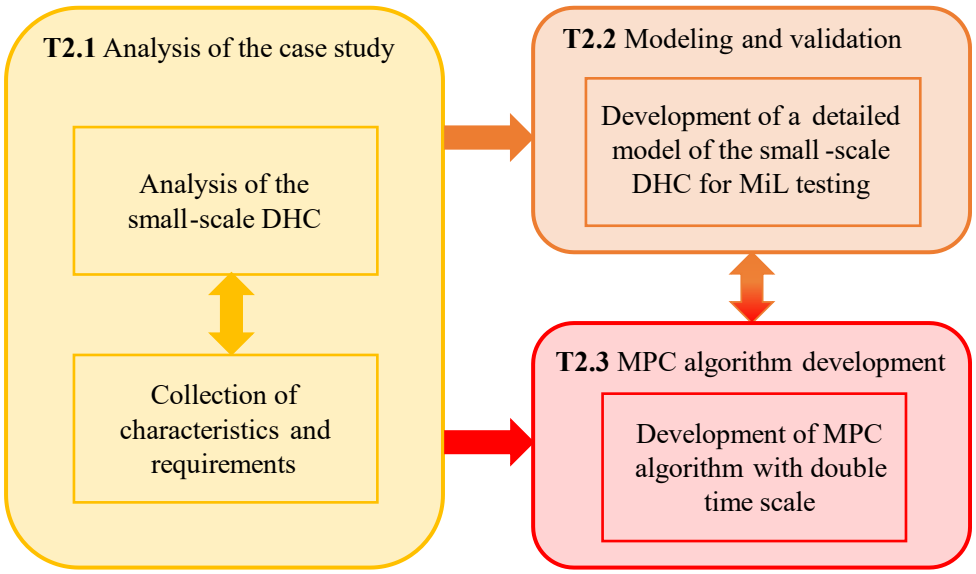


Figure 1. Schematic representation of main tasks and activities of WP2. The present deliverable focuses on T2.2.

The deliverable summarizes the results from task "T2.2 Modeling and validation", the goal of which was to develop and validate dynamic physics-based models of the small DHC network studied and analyzed in T2.1. It was also stated that both production and distribution sides of the network, as well as all energy carriers (i.e. electricity, heating and cooling, steam), would be considered.
The proposed model is built by means of a library developed by the research group of the University of Parma involved in the project. The library is developed in the MATLAB®/Simulink® environment and collects the most common components that can be found in integrated energy networks.
The deliverable describes firstly the library concept and the sub-models of energy system components, and then the way in which these components were assembled to represent the system selected as small-scale case study and analyzed in T2.1. The model developed in this deliverable will be useful in combination with the output of task T2.3, since it will be used to perform Model-in-the-Loop tests of the Model novel optimization algorithm for Model Predictive Control.
The work has been conducted from M13 to M19 of the project.

2. Library of energy systems

2.1. Library concept

Detailed mathematical models of integrated energy systems are also called digital twins, as they emulate the behavior of the real system with high-detail and typically faster than real-time. For these reasons, they can serve for several purposes:

- Simulating the system;
- Monitoring the system key parameters with desired boundary conditions;
- Creating datasets of some system variables in order to train simplified models or machine learning models;
- Testing control strategies in simulation environment, which is particularly important for large systems that are not available at laboratory scale.

The research group of the University of Parma has developed an in-house library of models for integrated energy systems (De Lorenzi et al., 2020) for the abovementioned reasons. The selected environment is MATLAB®/Simulink® because it is a block diagram environment for system level design and dynamic simulation and it is equipped with a graphical editor for customizing and developing specific blocks. Each block represents a physical component that can be found in multi-energy networks, covering various domains, i.e. heat, electrical energy, fuels. The library and its components are shaped according to the direct causality, which considers the physical flows of matter and energy that enter, exit or are stored within each component. Moreover, both fluid dynamics and thermal aspects are modeled, and mass flow rate, temperature and pressure (and composition, in case of gas flows) are involved as representative variables Hence, each element is described in a physical way by means of the conservation equations in differential or algebraic form, depending on whether there is accumulation of mass, momentum or energy or not. This guarantees a proper physical representation, which is well suited to simulation and monitoring purposes (Saletti, 2021).
A selection of the most common components in district heating and cooling networks and of the blocks producing the environmental conditions (e.g. solar radiation, outdoor and soil temperature) is shown in Figure 2.

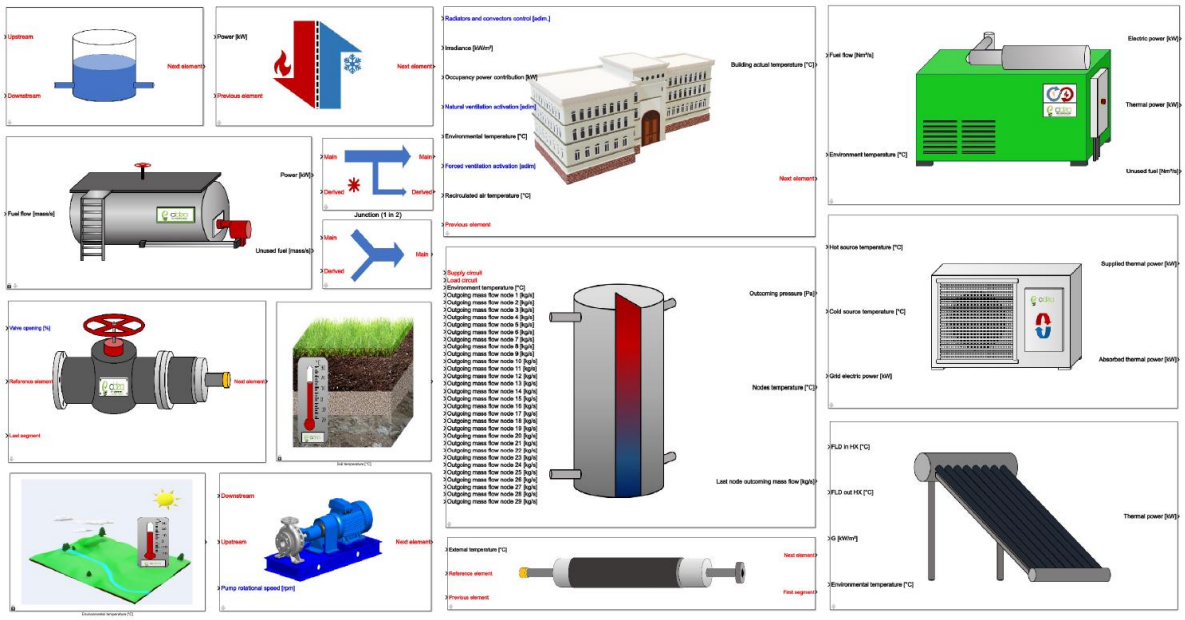


Figure 2. Selection of components of the library of energy systems developed in MATLAB®/Simulink®.

These component sub-models can be easily assembled with a *drag and drop* interface and in a modular way in order to reproduce different types of networks and configurations.

2.2. Sub-models of energy system components

In the following paragraphs, the aim, features and governing equations of the sub-models of energy system components are described.
The explanation is limited to the blocks that were used to model the case study (Section 3). In particular:

- For the **thermal power station**, the blocks related to all energy conversion units are required (i.e. trigeneration plant, heat-only boilers, electric chiller).
- For the **district heating and cooling network,** the blocks related to the pumping station, distribution pipelines, and substation heat exchangers are required, since the flows of hot and cold water from the thermal power station have to be pressurized by a set of hydraulic pumps and sent to the hospital buildings.

2.2.1. Thermal power station

Boilers. The boilers are represented by algebraic, physics-based models that evaluate the thermal power produced by the combustion of a defined amount of inlet fuel. The reference equation is Eq. (1):

$$\dot{Q}_{\mathrm{b}} = \dot{m}_{\mathrm{f}}\, LHV\, \eta_{\mathrm{b}}\, SW \tag{1}$$

where $\dot{Q}_{\mathrm{b}}$ is the outlet thermal power, $\dot{m}_{\mathrm{f}}$ and LHV are the fuel mass flow rate and lower heating value respectively, η_{b} is the boiler actual efficiency, and *SW* is the on-off switch (which is 1 is the plant is operating or 0 otherwise).
The boiler efficiency is corrected with respect to the actual load, in order to account for the critical influence of the load on the unit performance. This is done by means of the linear interpolation between the nominal and minimum load conditions, which are usually defined in the boiler manufacturer datasheets, defined in Eq. (2). The correction is in agreement with the most common technical standards, and is based on the dimensionless parameters Λ and Λ_{min}, which are the ratio of actual to nominal heat and the ratio of minimum to nominal heat generated by the boiler, respectively.

$$\eta_{\mathrm{b}} = \frac{\Lambda - \Lambda_{\mathrm{min}}}{1 - \Lambda_{\mathrm{min}}} \cdot (\eta_{\mathrm{nom}} - \eta_{\mathrm{min}}) + \eta_{\mathrm{min}} \tag{2}$$

where η_{nom} and η_{min} are the values of the efficiency at nominal and minimum load, respectively. In case of a nonlinear correlation between the actual load and the boiler efficiency, the block can be customized by introducing a piecewise linear correction through a look-up table.

Trigeneration plant. A trigeneration plant converts the chemical energy of a fuel into three energy forms, i.e. heating, cooling and electrical energy. It comprises a cogeneration plant, also known as **Combined Heat and Power plant (CHP)**, which produces heat and electricity, and an absorption chiller, which is fed by part of the heat recovered from the CHP and exploits it within a refrigeration cycle to produce cooling energy.
The CHP is represented by an algebraic model that evaluates the electric power and thermal power produced (P_{CHP} and $\dot{Q}_{\mathrm{CHP}}$, respectively) depending on the inlet fuel flow rate, the on-off

switch *SW* and the unit efficiencies. The key parameters are the first principle efficiency and electrical efficiency, defined in Eqs. (3a) and (3b), respectively:

$$\eta_{\mathrm{I}} = \frac{P_{\mathrm{CHP}} + \dot{Q}_{\mathrm{CHP}}}{\dot{m}_{\mathrm{f}}\, LHV} \tag{3a}$$

$$\eta_{\mathrm{el}} = \frac{P_{\mathrm{CHP}}}{\dot{m}_{\mathrm{f}}\, LHV} \tag{3b}$$

$$\dot{Q}_{\mathrm{CHP}} = \dot{m}_{\mathrm{f}}\, LHV\, (\eta_{\mathrm{I}} - \eta_{\mathrm{el}})\, SW \tag{4a}$$

$$P_{\mathrm{CHP}} = \dot{m}_{\mathrm{f}}\, LHV\, \eta_{\mathrm{el}}\, SW \tag{4b}$$

The first principle efficiency is again corrected on the basis of the plant modulation, with a linear or piecewise linear interpolation between the nominal and minimum load efficiency values (which can be found in the datasheets), similarly to the boiler efficiency correction. In addition, the CHP efficiency is generally influenced by the outdoor temperature. This correction was implemented in the model by means of the possibility to specify the ratio between the actual and nominal efficiency in three outdoor temperature conditions, i.e. minimum, nominal and maximum temperature. In this way, the efficiencies are corrected with a piecewise linear interpolation between these three operating points.
Similarly, the **absorption chiller** is represented by algebraic model that evaluates the outlet cooling power $\dot{Q}_{\mathrm{ABS}}$ based on the inlet thermal power $\dot{Q}_{\mathrm{in,ABS}}$, the on-off switch and the actual Coefficient of Performance (COP). A linear performance curve between minimum load and nominal load conditions is determined starting from the unit characteristics available from the manufacturers' datasheets. The governing equation is reported in Eq. (5):

$$\dot{Q}_{\mathrm{ABS}} = \dot{Q}_{\mathrm{in,ABS}}\, COP_{\mathrm{ABS}}\, SW \tag{5}$$

Since the chiller cannot operate below the minimum load condition and above the nominal load condition, the portion of the inlet thermal power that is actually exploited within the refrigeration cycle is also evaluated by the block and returned as a block output.

Electric chiller. The electric chiller is a unit that produces cooling power through a compression refrigeration cycle. It is represented by the model of a reversible heat pump developed with reference to the UNI-TS 11300-4 Italian legislation, with an overturned causality. Indeed, it has the electrical power as an input and the exchanged thermal power as an output, rather than the opposite as in the legislation.
The cooling power produced by the electric chiller $\dot{Q}_{\mathrm{c,EC}}$ is defined by Eq. (6)

$$\dot{Q}_{\mathrm{c,EC}} = P_{\mathrm{in,EC}}\, EER\, SW \tag{6}$$

where $P_{\mathrm{in,EC}}$ is the electrical power that feeds the unit and *EER* is the Energy Efficiency Ratio when the unit operates in chiller mode. This, in turn, is calculated through Eq. (7):

$$EER = \frac{\dot{Q}_{\mathrm{c,EC}}}{P_{\mathrm{in,EC}}} = \frac{\dot{Q}_{\mathrm{h,EC}} - P_{\mathrm{in,EC}}}{P_{\mathrm{in,EC}}}\, COP - 1 \tag{7}$$

where $\dot{Q}_{\mathrm{h,EC}}$ is the thermal power supplied to the environment and the COP is the performance coefficient of the unit in heat pump mode. The latter can be calculated according to the legislation through the following equation:

$$COP = \frac{COP_{\mathrm{nom}}}{C_{\mathrm{c}}} \cdot \left[1 - \frac{P_{\mathrm{in,nom}}}{P_{\mathrm{in}}} \cdot (1 - C_{\mathrm{c}})\right] \tag{8}$$

where $P_{in,nom}$ is the nominal inlet electrical power and Cc is a correction factor declared by the producer. The nominal coefficient COP_{nom} at the actual operating temperatures is obtained through the following procedure:

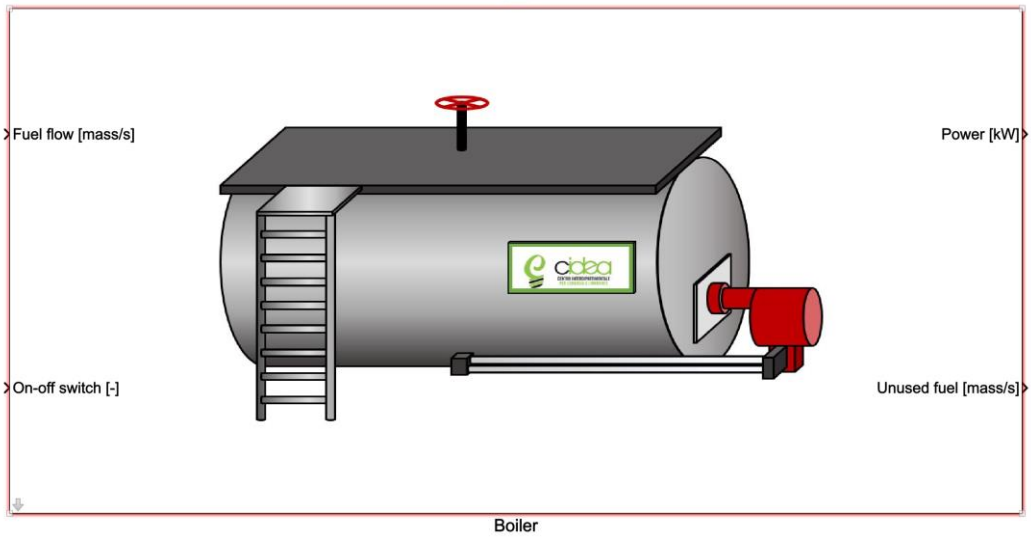
$$\eta_{II} = \frac{COP_{\mathrm{nom,ABCD}}}{COP_{\mathrm{max}}|_{ABCD}} \tag{9a}$$

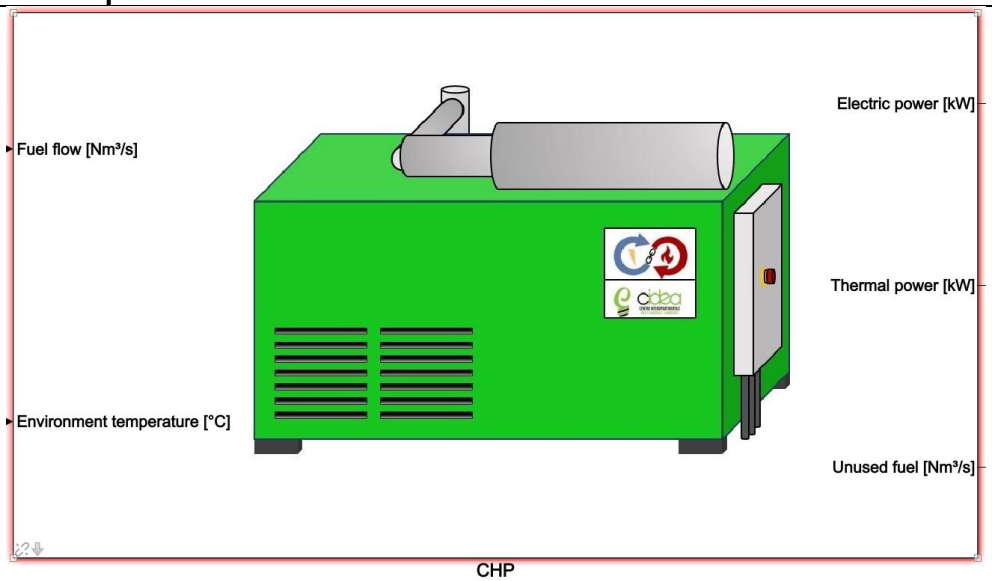
$$COP_{\mathrm{max}} = \frac{\vartheta_H + 273.15}{\vartheta_H - \vartheta_C} \tag{9b}$$

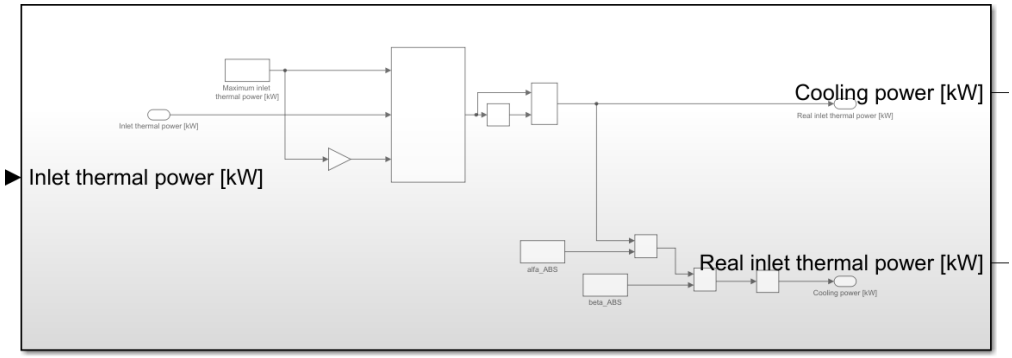
$$COP_{\mathrm{nom}} = \eta_{II_{\mathrm{int}}} \cdot COP_{\mathrm{max}}|_{\vartheta_H, \vartheta_C} \tag{9c}$$

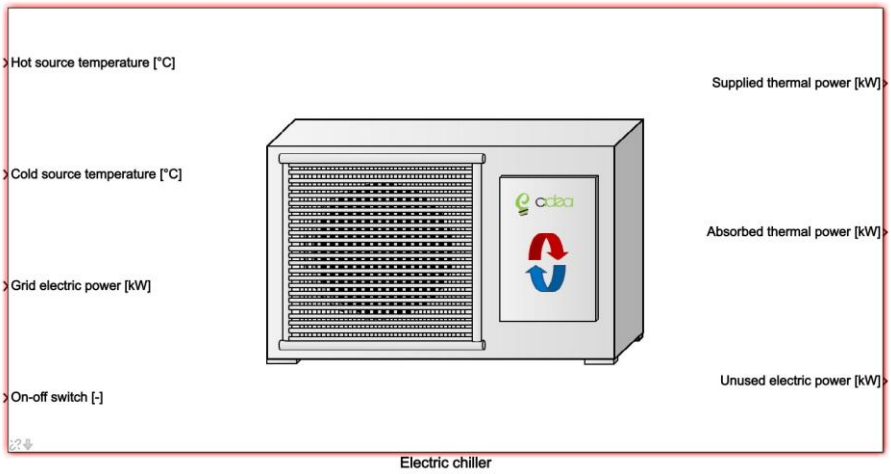
Basically, the user defines the COP value in specific reference conditions A, B, C and D (defined by the legislation) related to the temperature of the hot and cold source, ϑ_H and ϑ_C (in °C) respectively. These temperatures are exploited to determine the second principle efficiency in these reference conditions and to setup a lookup table. Finally, the nominal COP is found by interpolating the second principle efficiency according to the actual temperatures.
Overall, the inputs of the model are the actual electrical power and on-off switch regarding the unit operation, and the temperatures of hot and cold source regarding the fluid conditions. The outputs of the model when it is in electric chiller mode are the absorbed thermal power (i.e. cooling power), supplied thermal power (i.e. heat released to the environment) and the unused electrical power, which derives from the actual load conditions.

The main characteristics of the thermal power station units detailed above are summarized in the following factsheets.

Boiler

Inputs: fuel mass flow rate, on-off switch
Outputs: thermal power, unused fuel mass flow rate
Model type: algebraic, physics-based
Description: the block evaluates the effective thermal power produced by a given amount of inlet fuel, according to the boiler efficiency.

Cogeneration plant

Inputs: fuel mass flow rate, environment temperature
Outputs: electrical power, thermal power, unused fuel mass flow rate
Model type: algebraic, physics-based
Description: the block evaluates the effective electrical and thermal power produced by a given amount of inlet fuel, according to the CHP efficiency.

Absorption chiller

Inputs: inlet thermal power (i.e. generation of the absorption refrigeration cycle)
Outputs: cooling power, actual inlet thermal power according to the load
Model type: algebraic, physics-based
Description: the block evaluates the effective cooling power produced by an absorption refrigeration cycle, given an inlet thermal power for generation.

Electric chiller

Inputs: hot source temperature, cold source temperature, inlet electrical power, on-off switch
Outputs: supplied thermal power (to the environment), absorbed thermal power (cooling power), unused electrical power
Model type: algebraic, physics-based
Description: the block evaluates the cooling power and thermal power released to the environment, produced by a given inlet electrical power. The model is built with reference to the UNI-TS 11300-4 Italian legislation,

2.2.2. District heating and cooling networks

Pumping station. According to the concept of the library, the pumping station of a distribution network loop is composed of a pump and two expansion vessels.
The **pump** is an algebraic model based on a heuristic modeling approach. Considering the Buckingham π theorem (Buckingham, 1914), a dimensionless curve, drawn from a set of measured operating points for a given 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 and flow coefficients π_1 and π_2, given by:

$$\pi_1 = \frac{g \cdot H}{n^2 \cdot D^2} \tag{10a}$$

$$\pi_2 = \frac{\dot{V}}{n \cdot D^3} \tag{10b}$$

with g being the gravity acceleration. The model parameters are the impeller diameter D and the dimensionless map for the pump type. The model calculates the volume flow rate $\dot{V}$ processed by the pump for a defined pump rotational speed n and pressure head H, which are the block inputs.
The expansions vessels are fundamental elements of a closed-loop water heating systems since they handle pressure fluctuations related to thermal expansion and mass flow rate transient regimes. The expansion vessel is modeled as a tank partially filled with air, the function of which is to act like a pressure buffer: the higher the water level, the higher the air pressure and, consequently, the water pressure. On the other hand, a water discharge leads to a vessel pressure reduction. The model is dynamic and physics-based and is derived from

the continuity equation Eq. (11), which allows for the calculation of the pressure of the water and of the air within the vessel (i.e. p_w and p_a, respectively):

$$p_{\mathrm{w}} = p_{\mathrm{a}} = p_{\mathrm{a,0}} \cdot \left(\frac{V_{\mathrm{a,0}}}{V_{\mathrm{a,0}} - \int V_{\mathrm{w}}\, dt} \right)^{k} \tag{11}$$

Here, the water volume V_w (i.e.model state variable) evolves over time depending on the initial condition and on the difference between incoming and outgoing mass flow rates. Air is assumed as an ideal gas which is compressed or expanded in adiabatic conditions, starting from the initial air pressure and volume in the vessel $p_{a,0}$ and $V_{a,0}$, respectively. Finally, k is the specific heat capacity ratio.

Pipeline. The pipeline is modeled by considering both the thermal dynamics and the hydraulics of the heat transfer fluid. Several pipeline models can be interconnected, so that a generic complex distribution topology can be split into a sequence of pipeline segments with several different features. Moreover, different subsequent pipeline blocks can form a discretized pipeline. The circulating mass flow rate $\dot{m}$ is calculated once for the entire pipeline sequence, by means of a differential equation derived from the momentum continuity equation Eq. (12) and depending on the differential pressure between upstream (p_{max}) and downstream (p_{min}) of the pipeline:

$$\frac{1}{\rho \cdot A} \cdot \frac{d\dot{m}}{dt} = \frac{(p_{\max} - p_{\min} - \sum_i (\Delta p)_i) \cdot A}{\sum_i M_i} \tag{12}$$

with A being the cross-sectional area of the pipeline, M_i the fluid mass contained within the i-th pipeline segment. The total pressure drop Δp is calculated as the sum of all the pipeline segment contributions and considers geodetic, distributed and concentrated losses.
As for the thermal domain, the outlet temperature T_w from each pipeline is determined by means of the energy conservation equation for a lumped-parameter pipeline:

$$M \cdot c_{\mathrm{w}}(T_{\mathrm{w,in}}) \cdot \frac{dT_{\mathrm{w}}}{dt} = \dot{m} \cdot c_{\mathrm{w}}(T_{\mathrm{w,in}}) \cdot (T_{\mathrm{w,in}} - T_{\mathrm{w}}) - UA \cdot (T_{\mathrm{w}} - T_{\mathrm{soil}}) \tag{13}$$

where c_w is the specific heat capacity of the water at the inlet temperature $T_{w,in}$, UA is the product between the global heat transfer coefficient and perimetral surface of the pipe, and T_{soil} is the soil temperature. This equation includes the net enthalpy flow and heat transfer towards the soil, which is influences by the pipeline geometry and thermal properties.

Heat exchanger. The heat exchanger is modeled as a dynamic element relying on the differential form of the energy conservation equation, in similarity with the pipeline thermal equation:

$$M \cdot c_{\mathrm{w}}(T_{\mathrm{w,in}}) \cdot \frac{dT_{\mathrm{w}}}{dt} = \dot{m} \cdot c_{\mathrm{w}}(T_{\mathrm{w,in}}) \cdot (T_{\mathrm{w,in}} - T_{\mathrm{w}}) + \dot{Q} \tag{14}$$

Here, $\dot{Q}$ is the heat transferred to or from the primary fluid within the unit and can derive from a heat source (e.g. boiler) or a heat sink (e.g. substation heat exchanger).

2.2.3. Outdoor conditions

When simulating energy systems with high detail, it is paramount to define the conditions of the environment dynamically, in order to estimate the exchange between system and environment accurately. The library of energy system components developed by the University of Parma contains specific blocks for this purpose, represented in Figure 3 and described as follows:

- The **soil temperature** is determined through correlations that depends on the simulation day and time, the depth and the coldest day of the year generally recorded for the given area, as well as on the average, minimum and maximum air temperatures. These can be defined through the user interface of the block.
- The **solar radiation** is calculated accurately according to the day and time of the year, the latitude of the area, the altitude and the inclination of the surface on which irradiance occurs.
- The **outdoor air temperature** can be defined by the user as a model input with the preferred time resolution, e.g. minute, hour or day.

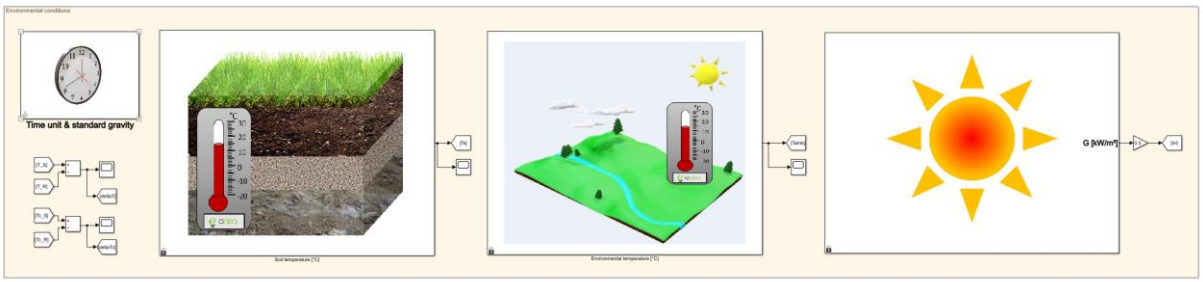


Figure 3. Blocks of the library representing the evaluation of environment conditions.

3. Digital twin of the case study

3.1. Model of the case study

The library has been presented and exploited in other studies (Cadau et al., 2018; De Lorenzi et al., 2022) as a reliable tool for accurate simulations of different distribution networks and thermal power stations with different conversion units. Since it has been enhanced to include different energy domains (i.e. not only the thermal domain, but also the electrical and gas domains), it is also suitable for representing multi-energy systems in a sector integration perspective.
For these reasons, a digital twin of the small-scale DHC has been built by combining together the components from the library. The digital twin emulates the dynamic behavior of the real system in a simulation environment and, therefore, can be useful as a test bench for verifying different management strategies. Moreover, all relevant variables of the system (e.g. mass flow rates, temperatures, pressures) can be monitored to produce datasets of system operation.
As described in D2.1, the small-scale DHC case study is the Sant'Anna Hospital of Cona located close to the city of Ferrara, in the north-east of Italy (Emilia-Romagna region). The system comprises (i) the thermal power station and (ii) a small-scale district heating and cooling network, with the heating loop and the cooling loop. The involved energy vectors are heat, cold, electricity, steam, and gas as a fuel. All details related to units in the system can be found in D2.1.
Since the three steam generators that have to meet the hospital steam demand are located in a dedicated area, which do not interact with the rest of the system and cannot be controlled from remote at the present moment, this section has been omitted from the model without hindering the generality of the approach.

The global model of the hospital in the MATLAB®/Simulink® environment is illustrated in Figure 4. It is possible to recognize the different sections of the system:

- The **boiler** section, comprising four identical boiler blocks. The main output of this section is the total thermal power produced by the boilers, which is sent to the district heating circuit. The four blocks are arranged in cascade: the natural gas flow rate enters the first boiler, while the unused gas flow rate exiting the first boiler enters the second boiler, and so on.
- The **trigeneration** section, comprising the CHP block and the absorption chiller block. The thermal power recovered from the CHP is sent partly to the district heating circuit and partly as an input to the absorption chiller. The remaining part is dissipated to the environment. The control strategy of these values is detailed in Section 3.2. In parallel, the effect of the absorption chiller is that thermal power is extracted from the district cooling circuit, in order to maintain the cold water supply temperature.
- The **electric chiller** section, comprising four identical electric chiller blocks. The main output of this section is the total cooling power, i.e. heat extracted from the district cooling circuit. Similarly to the boilers, the four blocks are arranged in cascade: the electrical power enters the first block, while its unused electricity enters the second chiller, and so on until the forth.
- The **outdoor conditions** section, in which soil temperature, outdoor air temperature and solar radiation are evaluated.

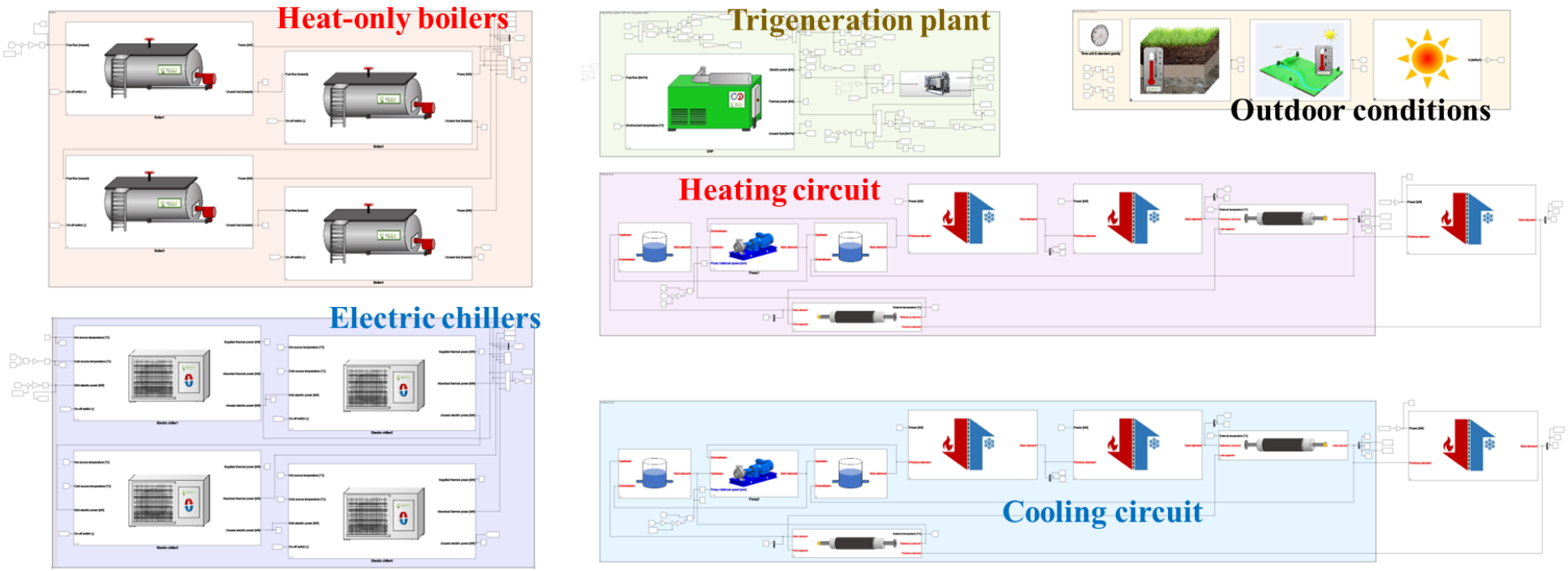


Figure 4. Digital twin of the Cona Hospital.

- The **heating circuit**, comprising a pumping station, the supply and return pipelines, and three heat exchangers. Two of them receive the thermal power from the CHP and boilers, respectively, while the third represents the hospital substation heat exchanger, in which the thermal load of the end-users is extracted from the water circulating in the pipeline.
- The **cooling circuit**, comprising a pumping station, the supply and return pipelines, and three heat exchangers. Two of them receive the cooling power from the absorption chiller and electric chillers, respectively. This means that the corresponding heat is extracted from the water circulating within these units. The third block represents the hospital substation heat exchanger, in which the cooling load is supplied to the end-users, i.e. heat is transferred from the building to the circulating water.

The parameters of the energy conversion unit are defined in the masks of the blocks according to the characteristics and requirements identified in D2.1.
The parameters of each pipeline block of the heating and cooling circuits are reported in Table 1.

Table 1. Main parameters of the pipelines in the district heating and district cooling circuits.

Parameter	Unit	District heating	District cooling
Pipe external diameter	mm	258	258
Pipe thickness	mm	9	9
Pipe length	m	50	50
Insulation thickness	mm	25	25
Insulation thermal conductivity	W/m K	0.04	0.04
Roughness	mm	0.05	0.05
Water initial temperature	°C	80	10
Pipeline configuration	-	Underground	Underground

3.2. System control

The system can be simulated for the desired time interval, as long as the evolution over time of the heating, cooling and electrical load of the hospital is provided. The main goal of the thermal power station is to fulfill these requirements, as follows:

- The heating load of the hospital is extracted from the water of the primary heating circuit by means of the third heat exchanger, representing the substation of the hospital buildings. The temperature of the circulating water is lowered in the process.
- Similarly, the cooling load of the hospital is extracted from the water of the primary cooling circuit. Since a “negative heat” is extracted, this means, the temperature of the cooling water increase between supply and return.
- As for the electrical load, this is fulfilled by means of the electricity balance equation implemented in the model

$$P_{\mathrm{CHP}} + \left(P_{\mathrm{EC}} - P_{\mathrm{EC,unused}}\right) + P_{\mathrm{gb}} = P_{\mathrm{el,dem}} + P_{\mathrm{gs}} \tag{15}$$

where P_{EC}, $P_{EC,unused}$, P_{gb}, P_{gs} and $P_{el,dem}$ are the total electrical power supplied to the chillers, the unused electrical power of the chillers, the power purchased and sold to the grid and the user electrical demand, respectively.

The control logic implemented in the digital twin represents the traditional way in which the energy system of the real-world hospital is operated (Saletti et al. 2022).
The CHP is an electrical-load-following unit which is generally operated continuously at nominal load, except for the maintenance periods during which it is switched off. The absorption chiller is operated only during the summer months.

The water temperature in the supply pipeline of the **district heating circuit** has to maintained at the set-point value (e.g. 85 °C). For this purpose, the energy conversion units are regulated as follows:

- If the temperature of the supply water is higher than the set-point, the boilers are switched off and part of the heat recovered from the CHP is dissipated to the environment through a feedback proportional controller (this regulator is highlighted in red in Figure 5);
- If the temperature of the supply water is lower than the set-point, a feedback proportional loop supplies fuel to the boilers which are then activated in cascade.

In addition, the reference temperature difference between supply and return in the user substation (e.g. 25 °C) is maintained though a feedback loop that varies the rotational speed of the pump.

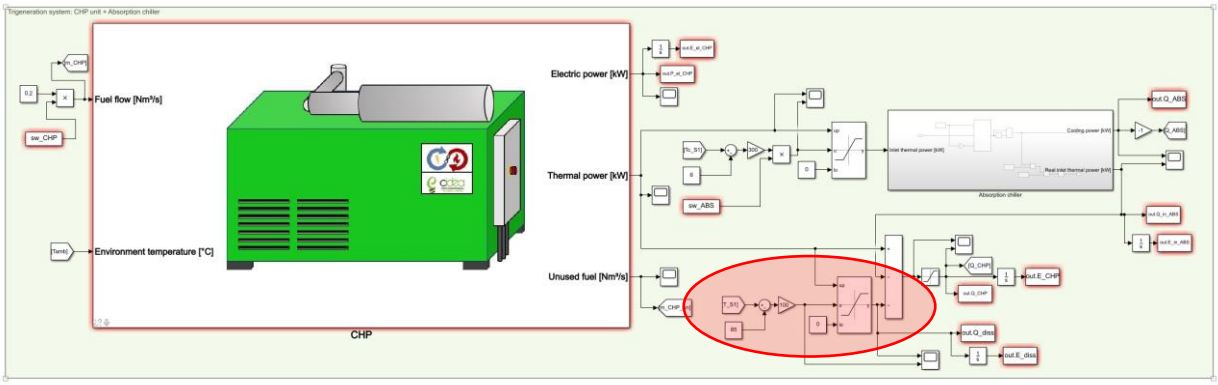


Figure 5. Zoom of the trigeneration plant comprising the Combined Heat and Power unit and the absorption chiller. The red circle highlights the control of the heat dissipation with respect to the supply temperature of the water in the heating circuit.

Similarly, the water temperature in the supply pipeline of the **district cooling circuit** has to meet the set-point value of 6 °C. The regulation is as follows:

- If the temperature of the water exiting the first heat exchanger is lower than the set-point, the absorption chiller and the electric chillers are switched off;
- if the temperature of the supply water is higher than the set-point, the electric chillers are activated in sequence to provide sufficient cooling power until the desired value is reached.

Another feedback loop varies the pump rotational speed of the cooling circuit in order to match the reference temperature difference between supply and return (e.g. 6 °C).

The abovementioned controllers and the details of the related manipulated and control variables are summarized in Table *2*.

Table 2. Summary of the controllers implemented to operate the digital twin of the Cona Hospital.

Manipulated variable	Control variable	Control type
Head dissipation from CHP	Temperature of water exiting the first heat exchanger (heating circuit)	Feedback (P)
Fuel mass flow rate to boilers	Temperature of water exiting the second heat exchanger (heating circuit)	Feedback (P)
Absorption chiller on-off	Temperature of water exiting the first heat exchanger (cooling circuit)	Feedback (P)
Electrical power to the electric chillers	Temperature of water exiting the second heat exchanger (cooling circuit)	Feedback (P)
Pump rotational speed in the heating circuit	Temperature difference in the heating circuit	Feedback (P)
Pump rotational speed in the cooling circuit	Temperature difference in the cooling circuit	Feedback (P)

As reported in D2.1, the centralized Building Management System automatically monitors and controls the plants in the thermal power station and the parameters of the distribution network. In order to simulate and verify the implementation of innovative control strategies, also in the simulation with the digital twin it is possible to dynamically modify the set-points of CHP modulation, absorption chiller modulation, and activation of boilers and electric chillers.
The optimal control logic based on Model Predictive Control that is reported in D2.3 can be tested in this way (Saletti et al., 2022).

3.3. Simulation analysis

During the simulation of the entire system, the following model variables related to the thermal power station can be monitored:

- The fuel mass flow rate entering the group of boilers, the portion of it that is left unused, and the produced thermal power;
- The fuel mass flow rate entering the CHP unit, the portion of it that is unused, and the produced electrical and thermal power, as well as the dissipated heat;
- The thermal power entering the absorption chiller and the output cooling power;
- The electrical power entering the group of electric chillers and the total output cooling power;
- The exchange with the power grid that fulfill the electrical balance.

These data and the related cumulated energy parameters determine the complete energy and environmental performance of the system in given operating conditions.
As for the heating and cooling distribution circuits, the monitored variables are the following:

- Mass flow rates of the heating and cooling water;
- Inlet and outlet temperatures from all thermal power station heat exchangers;
- Supply and return temperatures of the user substation heat exchangers.

These data allow to verify if the technical requirements of the distribution systems are maintained. One example of the supply and return temperatures of the heating circuit during a winter week is illustrated in Figure 6.
The simulation times for three days, one week, one month and an entire year are reported in Table 3.

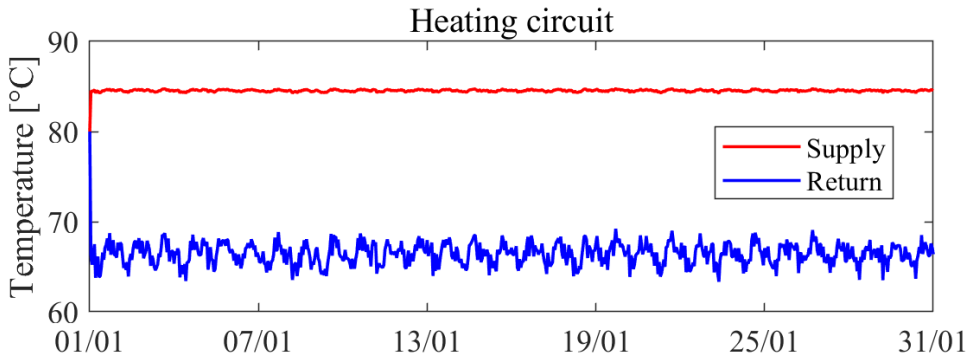


Figure 6. Supply and return temperature of the district heating network during a winter month.

Table 3. Summary of the controllers implemented to operate the digital twin of the Cona Hospital.

Time interval	Simulation time
Three days	20 s
One week	30 s
One month	2 min
One year	55 min

The developed digital twin of the Cona Hospital is significantly faster than real time, reliable and useful for several purposes. In particular, as mentioned above, it can be simulated for an entire operating year and it can be exploited as a virtual testbed to demonstrate the performance of the control algorithm developed and described in the subsequent task of the WP. It also has to be remarked that this validation procedure is valid not only for the present case, but also for generic multi-energy systems.

4. Conclusions

In this report, the activities of the second task of WP2 are reported. The detailed dynamic model of the small-scale district heating and cooling network case study (identified in T3.1) was built in the MATLAB®/Simulink® simulation environment. A library of energy system components developed by the research group of the University of Parma was used.
Firstly, the main sub-models representing the energy conversion units in the thermal power station (boiler, cogeneration plant, absorption chiller, electric chiller) and the components of a district heating and cooling network were described. Then, the way in which these modular components were assembled to form the digital twin of the case study was illustrated. All components were implemented according to the characteristic identified in T2.1. Finally, the low-level controllers implemented to achieve the desired operation were summarized and a preliminary analysis of the computational feasibility of the simulator was carried out.
The output of the task is a complete simulation platform representing the energy system of the small-scale district heating and cooling network selected as Italian case study. The model will be used to test the new control strategy with the double time scale developed in T2.3 and to compare it with the traditional control approach currently used. The simulations will be carried out for an entire operating year.

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