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Retrofit design and numerical modeling of bidirectional substations for the empowerment of thermal prosumers in district heating networks[#]

Federico Gianaroli[1*], Mattia Ricci[1], Paolo Sdringola[1], Mauro Pipiciello[2], Diego Menegon[2], Francesco Melino[3]

1 Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Energy Efficiency Department Research Center Casaccia, Via Anguillarese 301, 00123 Rome, Italy

2 Eurac Research, Institute for Renewable Energy, Viale Druso 1, Bolzano, 39100, Italy

3 Alma Mater Studiorum University of Bologna, Department of Industrial Engineering, Viale Del Risorgimento 2, Bologna, 40136, Italy

(Corresponding Author: federico.gianaroli@enea.it)

ABSTRACT

The global energy landscape is undergoing a crucial transition towards renewable energy solutions, underlining the importance of decentralizing energy systems. This complex and long-term process has facilitated the emergence of energy communities, enabling a wide range of actors, including citizens, to actively participate in the energy transition. A key element of this transition is the role of prosumers, individuals who consume and produce energy from renewable sources. Thermal prosumers can be integrated into district heating networks through bidirectional thermal substations, allowing excess thermal energy – produced locally from renewable sources, such as solar thermal systems, or recovered from industrial processes – to be injected into the network.

In this framework, the study introduces a novel approach to adapt traditional district heating substations to bidirectional heat exchange devices, enabling prosumers to actively use thermal energy for their needs and contribute surplus energy to the network. Using an existing network in northern Italy as a case study, an optimized layout in a “supply-to-return” configuration is proposed. To evaluate the performance and potential of the proposed bidirectional device, a detailed numerical model of the substation was implemented in Dymola software for multi-domain simulation. The model was designed to analyze the system’s summer operation, with customized systems and control logics developed from standard library models to accurately reproduce the substation’s behavior under specific conditions.

The results showed that the bidirectional substation allows for the utilization of previously unused thermal potential, due to the mismatch between demand and production, and makes it available to the network, particularly on days with high solar irradiance. This innovative approach finally extends the concept of energy sharing to thermal energy flows, at the community level, opening up new opportunities for a more integrated and sustainable management of energy resources.

Keywords: district heating network, bidirectional substation, energy community, numerical modelling, renewable energy source

1. INTRODUCTION

District heating networks (DHN) are experiencing global growth with a significant increase in heat production worldwide, playing a crucial role in decarbonizing the sector by integrating large amounts of renewable and waste heat energy [1], [2]. This approach broadens the concept of energy sharing, extending beyond just electrical flows as outlined by the European Directive RED II [3], to also include thermal flows through efficient district heating and the development of thermal energy communities.

In this framework, the active participation of prosumers — individuals who are both consumers and producers of energy [4] — may balance energy demand and supply, optimize self-consumption, and encourage the production of energy from local renewable sources. This transformation allows users to exchange, sell, or

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purchase energy based on their needs and production capacity, thus promoting the creation and expansion of local energy communities [5].

Thermal prosumers can be integrated into the DHN through a bidirectional thermal substation, which allows locally produced excess thermal energy — whether from renewable sources like solar thermal panels or recovered from industrial processes as waste heat — to be transferred into the network. Several studies in the scientific community have explored the operation and potential of these substations.

Some researchers have conducted experimental laboratory tests on a bidirectional substation prototype, aimed at maximizing thermal energy from renewable sources or waste heat [6], [7]. Other scholars have used modeling approaches, developing numerical models of bidirectional substations with Dymola [8] or TRNSYS [9]. [10] validated a control method for prosumer bidirectional substations through case study analysis, while [11] developed and monitored a thermal network model with various prosumers.

Starting from the configuration of an existing substation in a DHN in northern Italy, this work aims to develop a method for retrofitting the substation and utilizes the dynamic model of the new bidirectional substation, designed by The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and the Alma Mater Studiorum University of Bologna (UNIBO) using the Modelica language with Dymola software.

2. MATERIAL AND METHODS

2.1 Implementation of retrofit in bidirectional substations

The analyzed substation, located in a DHN in Turin, Italy, serves 34 residential buildings with a two-pipe system: the supply pipe delivers thermal power for space heating (SH) and domestic hot water (DHW), while the return pipe carries cold fluid back to the thermal power plant. The supply temperature is 80°C in winter and 70°C in summer with a ΔT of 20°C. 16 of these buildings are equipped with flat-plate solar collectors which cover part of the DHW needs through a storage system made up of five thermal tanks.

Fig. 1 shows the new layout of the substation with the retrofit components highlighted in orange. The layout includes an additional heat exchanger (HE3) in a “supply to return” configuration. The fluid is taken from the supply line of the primary circuit and reintroduced into the return line at a higher temperature after exchanging thermal power with solar collectors.

The following circuits are essential for the interaction between the DHN and the end user:

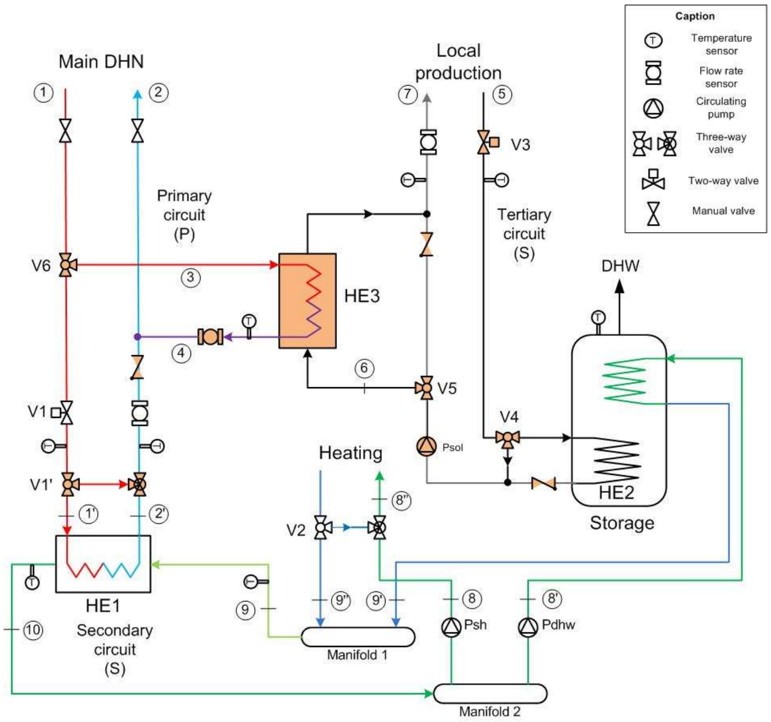


Fig. 1 Layout of bidirectional heat exchange substation

- The *primary circuit* allows heat to be transferred from the main DHN to the secondary circuit through the HE1, satisfying the user load.
- The *secondary circuit* allows heat to be transferred from HE1 to the user's SH circuit and the upper heat exchanger of the DHW tank.
- The *tertiary circuit* allows heat to be transferred from the local production (solar collectors) to the lower heat exchange of the DHW tank.

For the retrofit of the current configuration, some limits have been considered. In particular, the inability to act on the main DHN branch outside the substation room requires operating in a limited space. Furthermore, the control logics of the existing valves (described below) have not been modified.

Valve V1 activates the heat exchange on HE1 when one of the following conditions occurs: heating season (October 15th-April 15th) 6-22; storage temperature (Ttank) < 70°C.

Valve V1' regulates the flow from the supply branch of primary circuit to HE1, based on the temperature in section 10. This is done in order to maintain a constant value of the supply temperature (T10 = T10,obj) through PID control. In detail: if T10 > T10,obj, it diverts the fluid, bypassing HE1; if T10 < T10,obj, valve V1' increases the flow sent to HE1; if T10 = T10,obj, valve V1' maintains its current opening position; if valve V1 is closed, then V1' does not work.

The V3 valve fully opens (on/off) if: Ttank < 70 °C and solar temperature (T5)> Ttank + ΔT (5°C) or T5 > DHN supply temperature + ΔT (5°C).

Valve V6 deviate the flow from the supply (primary) branch to heat exchanger HE3: if T6 > supply temperature + ΔT (5°C), valve V6 diverts partially the flow to HE3; if T6 < supply temperature + ΔT (5°C), the valve closes.

The V4 (when Ttank is 70°C) and V5 valves instead follow the same control logic as V6, working simultaneously. To avoid intermittent on/off cycles of heat exchangers HE1, HE2, and HE3, and hysteresis of 2°C is added to the nominal control value used for activation.

2.2 Modelling

To develop and simulate the numerical model of the bidirectional substation, Dymola software was employed. For this model, the open-source libraries Modelica and IBPSA were used.

To facilitate connections between key devices and components in the substation, *StaticPipe* models were used, while to model the boundary conditions, *MassFlowSource_T* (mass flow source model) and *Boundary_pT* (model that prescribes pressure and temperature) were used. Regarding the sensors, *TemperatureTwoPort* (temperature sensor) and *MassFlowRate* (mass flow rate sensor) were used.

A crucial element in developing the bidirectional thermal exchange substation is the heat exchanger, which handles thermal power transfers between different flows. The *ConstantEffectiveness model* (from IBSA Fluid library) heat exchanger operating at constant efficiency according to Equation 1, was used to represent this component.

$$Q = eps \cdot Q_{max} \qquad (1)$$

Where eps represents the heat exchange efficiency, while Q_{max} represents the maximum amount of power that can be transferred, simulating an infinite exchange area in the heat exchanger.

Effort was spent to model the storage tank with double internal exchanger, as it plays a significant role in the bidirectional substation. To allow the simultaneous operation of the solar collectors and the network to produce hot water, a new tank model with double internal exchanger has been implemented. This model was developed starting from the *StratifiedEnhancedInternalHex* model, a storage tank with a single exchanger integrated from the IBSA library.

To model and characterize the substation's valves, the *ThreeWayValveLinear* from the IBPSA library was used. In one case, the valve regulates the flow rate entering HE1, while in the other case it diverts the flow rate of the supply branch of the primary and tertiary circuit towards HE3. The PI regulator manages the opening of the valve until the set-point temperature is reached while to configure the diverter mode, the flows through the three fluid ports were reversed compared to the standard model.

The dynamic model of the bidirectional substation for DHN in summer configuration is shown in Fig. 2. Similarly to the layout of the bidirectional substation shown in the Fig. 1, the same colours were used to represent the branches of the primary, secondary and tertiary circuit, while the dotted lines indicate the control signals, the logic of which is explained in paragraph 2.1. Dynamic tests include simulations in which the demand profile for the DHW and the production profile of the solar generation system are dynamically varied, implementing all the necessary control systems. In the model developed in Dymola to set time-varying boundary conditions, a data table is used as an input signal.

2.3 Simulated Scenarios and Optimization

The setup conditions, including the input data, were derived from a prototype of a bidirectional substation, which has been tested at the Energy Exchange Laboratory of Eurac Research. For detailed information on the prototype specifications and experimental setup, please refer to [12].

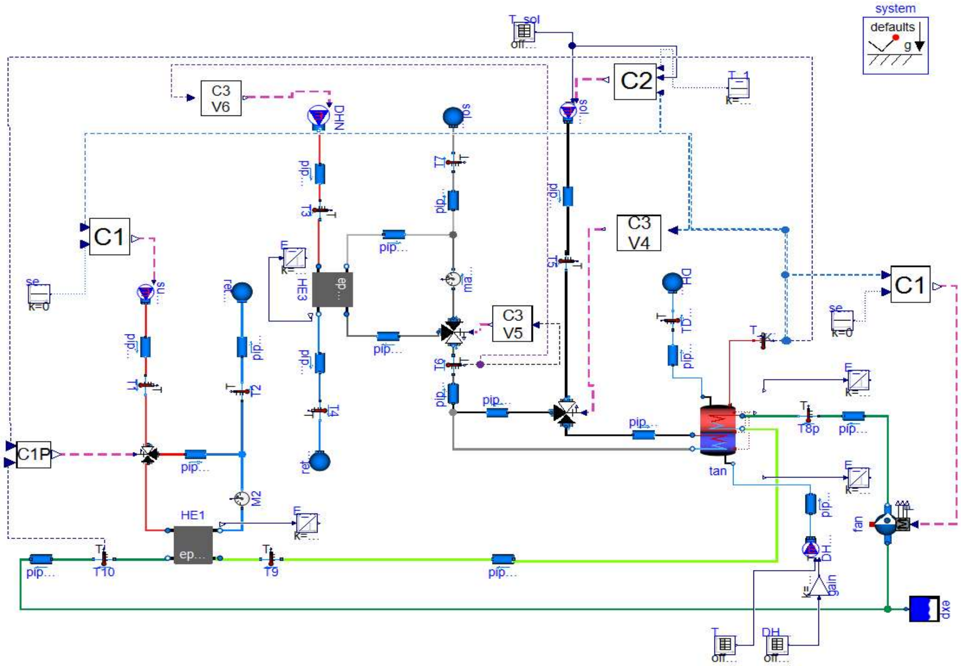


Fig. 2 Dynamic model of the substation, including the control logics

To evaluate the performance of the substation, two non-consecutive representative days were selected to capture the variations in weather conditions , following the procedure described in [13]. The selected test days, their average ambient temperature, the average irradiance on the horizontal surface, and the number of days belonging to each cluster considered are illustrated in Table 1.

To conduct a comparative analysis between different test days, key performance indicators (KPIs) were calculated daily. The analysis included the self-consumption (S_C), which indicates the percentage of locally produced thermal energy consumed on-site (Equation 2); the self-sufficiency (S_S), indicative of how much thermal demand is satisfied by local production (Equation 3); and the useful energy coefficient (U_{ec}), which indicates the percentage of locally generated thermal energy used by the user or fed into the network (Equation 4).

$$S_C = 100 \cdot \frac{E_{DG\ to\ user}}{E_{DG}} \tag{2}$$

$$S_S = 100 \cdot \frac{E_{DG\ to\ user}}{E_{User}} \tag{3}$$

$$U_{ec} = 100 \cdot \frac{E_{DG\ to\ user} + E_{DG\ to\ DHN}}{E_{DG}} \tag{4}$$

Where E_{DG} is the energy produced by the distributed generation, $E_{DG\ to\ DHN}$ is the energy produced by the distributed generation and feed into the grid, $E_{DG\ to\ user}$ is the energy produced by the distributed generation to the end-user, and E_{user} is the thermal load for end-user.

Table 1. Characteristics test days

Test days	Average daily T [°C]	Average daily radiation [W/m²]	N° of days in the cluster
24 May	20.1	153	67
1 August	24.4	287	74

3. RESULTS

In order to dynamically test the model, simulations have been performed at a daily level on the two days described in the previous paragraph.

Fig. 3 and Fig. 4 show the powers exchanged in the heat exchangers (HE1, HE2, HE3), the temperature of the tank (measured at approximately 3/4 of height) in relation to the solar temperature and the DHW flow rate requested by the user respectively on the day 1 and 2.

It is clear how the control logics implemented in the model influence the trend of the thermal powers in the three exchangers. On both days, the tank is mainly charged via HE1, while HE3 feeds most of the heat produced into the network. This is because most of the demand for domestic hot water occurs in the early morning and evening hours, when there is no solar production.

Analyzing Fig. 3, in particular the trend of HE2, it can be noted that the tank is charged only twice a day (around 11:00 and 15:30), when the water temperature drops below the set-point value, having a lot of thermal power from DG available when there is no demand. In fact, between 14:00 and 16:30, a large amount of thermal power is fed into the network. The same considerations can be applied to Day 2 in Fig. 4, although the heat provided through, HE is higher than Day 1, as it results from the energy flows in Fig. 5.

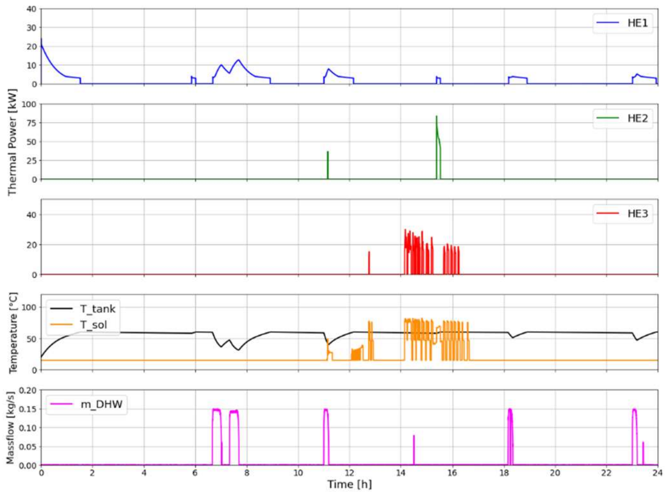


Fig. 3. 24 May: power exchanged in HE1, HE2, HE3, the tank and solar temperature, the flow rate required for the DHW

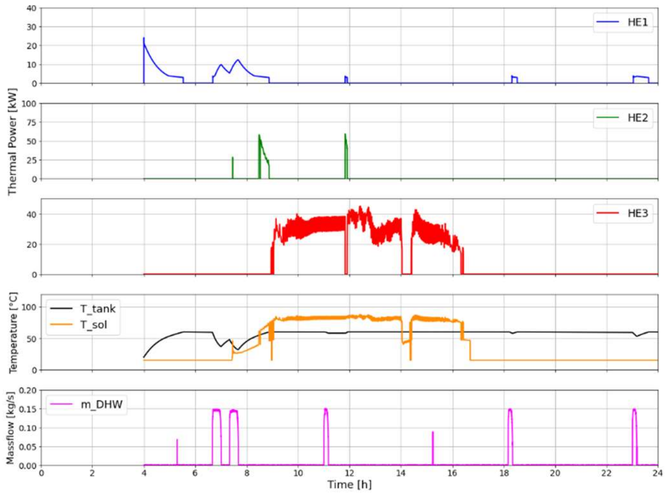
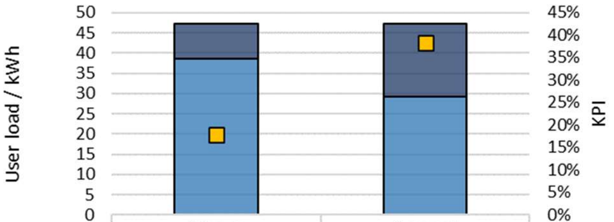


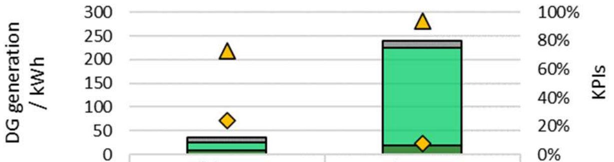
Fig. 4. 1 August power exchanged in HE1, HE2, HE3, the tank and solar temperature, the flow rate required for the DHW

Fig. 5 and Fig. 6 illustrate the energy flows and KPIs on days 1 and 2. Fig. 5 illustrates the total daily load, highlighting how, on both days, a large part of the demand for the DHW is satisfied by the DHN. Fig. 6 shows the total daily production, outlining the amount of energy fed into the network, the amount of energy used by the user for DHW, and the energy not used by the substation. There is a significant difference between the amount of energy produced on day 1 and day 2. On the summer day, thanks to the bidirectional configuration via HE3, the substation is able to exploit the 49% and 86% (day 1 and 2 , respectively) of the solar production, that would otherwise remain unused, feeding it into the network.



	24 may	1 august
■ from DG	8.5	18.1
■ from DHN	38.7	29.1
■ Ss	18%	38%

Fig. 5 User load energy flows and KPIs



	24 may	1 august
■ DG not used	9.6	14.3
■ to DHN	17.0	207.9
■ to user	8.5	18.1
◆ Sc	24%	8%
△ Uec	73%	94%

Fig. 6. Local generation energy flows and KPIs

4. CONCLUSIONS

Integrating thermal prosumers through bidirectional substations into District Heating Networks enhances the use of renewable energy and promotes thermal energy sharing at the community level. The article outlines a method to retrofit traditional thermal substations based on existing network with bidirectional heat exchange technology. In particular, a dynamic model of bidirectional heat exchange substation has been implemented. The potential of the new substation in different configurations has been evaluated by dynamically simulating two typical days, in mid-season (May) and in summer (August), with varying levels of irradiation. The results highlighted that the majority of the DHW demand is mainly satisfied by the district heating network (HE1), due to the mismatch between user demand and solar production. In fact, much of the DHW demand occurs in the early morning and evening hours, so the tank's solar exchanger (HE2) works less than solar production potential. However, this potential is exploited thanks to the installation of the new heat exchanger (HE3) which feeds a large amount of thermal power into the network, especially in August. In general, the bidirectional setup significantly enhances the substation's energy performance, particularly on days with high solar radiation, where previously much of the energy would be unused. This improvement increases the self-consumption rate from 8% to a useful coefficient of 94%. Future developments include extending the tests to winter and mid-seasonal days, also exploring innovative renewable technologies.

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