EMPOWERING PROSUMERS IN DISTRICT HEATING NETWORKS: EXPERIMENTAL ANALYSIS AND PERFORMANCE EVALUATION OF A BIDIRECTIONAL SUBSTATION

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ABSTRACT

The European Union highlights the crucial role of district heating and cooling, prompting innovations for prosumer-driven energy communities. The significance of thermal prosumers lies in their ability to contribute to the district heating network by utilizing locally sourced energy from renewables or industrial processes, thereby reducing fossil fuel usage, and enhancing district heating sustainability. In this framework, the document outlines an innovative approach aimed at establishing a pre-commercial setup for retrofitting traditional substations in bidirectional substation for district heating networks. These devices allow prosumers to actively consume thermal energy for their internal needs and share any surplus to the network. Based on an existing network in northern Italy, an optimized layout is proposed in a "supply-to-return" configuration: it includes a heat exchanger at the interface between the end-user and the network, supplying space heating and domestic hot water through thermal storage, which can also be charged by the distributed generation system (i.e., solar panels). An additional heat exchanger is intended to feed the network with surplus energy locally produced. To assess the performance and advantages of the proposed setup, an extensive experimental campaign was conducted, modifying, and integrating a pre-existing substation prototype in real-time with data-driven thermal loads and production profiles using the hardware-in-the-loop technique. The results show that while the deployment of evacuated tube solar collectors may not have significantly impact in term of local self-consumption in comparison to flat collectors due to energy demand disparities, it does offer a notable advantage in terms of energy fed into the network. This advantage is nearly 25 times greater than that of flat panels, particularly noticeable during winter days. This results in a significant advantage at the local level as well, enabling the achievement of 100% self-consumption when the DHN serves as thermal storage, especially during mid-season days. These findings underscore the effectiveness of evacuated tube collectors in maximizing energy utilization and reinforcing the role of bidirectional substations in promoting renewable energy integration within urban heating systems.

1 INTRODUCTION

The global energy landscape is currently undergoing a transition towards clean energy solutions, with a strong emphasis on national energy policies. The decentralization of energy systems, shifting from centralized fossil sources to renewable ones, is crucial (Gielen et al., 2019); however, it is important to note that energy transitions are complex and long-term processes, as emphasized by (Sovacool, 2016). In recent years, energy communities have emerged as crucial players in the shift from centralized fossil fuel-dominated energy markets to decentralized and democratized ones. These initiatives aim to empower citizens and actively involve them in the energy transition (Brisbois, 2020; Mucha-Kuś et al.,

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2021). In Europe, these projects have led to the creation of new governance models that facilitate the comparison and support the growth of different community-based models, as acknowledged by the European Commission in the Clean Energy Package for all Europeans in 2016 (*Clean energy for all European packages*). In this changing landscape, the active participation of prosumers plays a significant role, as "consumers" and "producers" of energy (Schuitema et al., 2017). Prosumers allow for balancing energy supply and demand, maximizing self-consumption, and promoting the generation of energy from local renewable sources. This paradigm shift enables users to exchange, sell, or acquire energy according to their needs and production capabilities, generating a growing interest in promoting the aggregation of energy users at the local level (Volpato et al., 2022). While electric energy communities have received significant attention in the scientific literature, it is essential to consider the importance of heating and cooling systems (Fouladvand, 2023; Papatsounis et al., 2022). These systems account for approximately 75% of non-transport energy consumption among households, yet thermal energy communities are widely underestimated (Fouladvand et al., 2022; Persson et al., 2014). In this historical context, it is crucial to broaden the focus of energy communities to include thermal energy systems, especially to manage the growing number of renewable energy producers capable of supplying heat to thermal networks. Simultaneously, the adoption of district heating networks (DHN) is experiencing global growth, with a significant increase in global heat production for these networks. In 2022, it reached approximately 17 EJ, marking a 10% increase from 2020 and a 17% increase over the last decade ("District Heating - Energy System," n.d.; "Power to heat and cooling: Status," n.d.). Expanding the concept of energy sharing at the community level can be facilitated through the integration of thermal prosumers into DHN, enabling them to become active contributors of surplus heat from renewable sources. Similar to electrical prosumers, thermal prosumers can integrate into the DHN through a bidirectional thermal substation. This system allows to feed into the DHN the thermal energy exceeding the current consumption, locally produced from renewable sources such as solar thermal plants or recovered from industrial processes i.e., waste heat. Several studies have investigated the capabilities and operation of such substations.(Sdringola et al., 2023) focused on the development of a bidirectional substation for DHN with thermal prosumers. In particular, a dynamic model using Dymola was developed and validated based on experimental sessions conducted on a substation prototype as presented in the work of (Pipiciello et al., 2021). Similarly, based on the same work, (Dino et al., 2023) developed a dynamic model of the bidirectional substation using TRNSYS. (Licklederer et al., 2024) presented a control approach for bidirectional prosumer substations, which was validated through case studies analysis. (Testasecca et al., 2023) developed a thermal network model featuring various prosumers and dynamically monitored the main thermohydraulic parameters of the network. Furthermore, (Pipiciello et al., 2024) tested and analyzed the prototype of the bidirectional substation to maximize the thermal energy from renewable sources or waste heat. The research on DHN holds significant importance in Italy: a technical-economic potential of efficient DHC for 2030 has been estimated at 20.9 TWh of delivered thermal energy (approximately doubling the 9.8 TWh of 2018), pushing for new networks and the renovation of existing ones, enhanced in terms of distribution temperature, integration of RES/waste heat, and third-party access. Additionally, the favourable climatic conditions, driven by high levels of solar irradiation ("joint research centre.ec.europa.eu," n.d.), promote the use of solar thermal panels. The objective of this work is to develop a method for retrofitting conventional substations within DHN into bidirectional heat exchange substations. Through the testing of an existing substation prototype, the study aims to analyze the potential advantages of this configuration in a widespread context and with a high degree of replicability, facilitating the integration of prosumer users into the next generation DHN. Starting from the design of an existing substation in a northern Italian DHN, a layout for a bidirectional substation in a "supply-return" configuration is proposed. To test the new proposed layout for the retrofit of existing substations, the prototype of a bidirectional substation, originally designed by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) and the Alma Mater Studiorum University of Bologna, was modified accordingly, and tested in the Energy Exchange Laboratory of EURAC. Various scenarios were evaluated across two typical winter and mid-season days, including a unidirectional configuration employing flat-plate solar collectors, a bidirectional configuration with identical collectors, and finally, configurations featuring evacuated tube solar collectors. This study aims to examine the contribution of the bidirectional substation in three different scenarios: In the first

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scenario (E0), the use of flat solar collectors was considered, with the substation in passive configuration (no feed into DHN). In the second scenario (E1), the substation turns into active, with bidirectional flows in the presence of the same flat solar collectors. Finally, in the third scenario (E2), the effectiveness of an alternative configuration, characterized by the use of evacuated solar collectors, combined with the bidirectional substation, was examined.

2 MATERIALS AND METHOD

2.1 DHN and substation description

The DHN under investigation serves no. 34 residential buildings located in the city of Turin, in northern Italy. Each building features its own substation, equipped with heat exchangers that provides thermal power for space heating (SH) and domestic hot water (DHW). The supply temperature of the network is set water is sent to 80°C in winter and 70°C in summer, while the fluid returns to the generation plant at a 60°C in winter and 50°C in summer (with a ΔT of 20°C). The network has a two pipes configuration, a supply pipe that provides heat for heating and DHW to the substations, and a return pipe that carries the cold fluid from the users back to the heat production facility. To cover part of the demand for DHW, no. 16 buildings served by the network are currently equipped with flat solar collectors, totalling no. 652 residential units. The substation examined is of the indirect type, which involves the interposition of a heat exchanger between the DHN and the end-user. The current configuration includes a heat exchanger for SH and DHW service and a storage system made up of five thermal tanks for the DHW service only. Part of the DHW thermal load is covered by the production of thermal energy from the solar collectors installed on the roof of the building, whose solar circuit powers exchanger in the lower part of the thermal storage tanks. In case of insufficient solar radiation to heat the water, the DHN provides the thermal energy necessary to reach the desired temperature inside the thermal tank. Figure 1 shows the simplified scheme of the substation currently located in the DHN of Turin. The scheme presents only the essential components crucial to the interaction between the DHN and end-user, identifying three main circuits: the primary circuit for the thermal energy exchange between the DHN and the secondary circuit, which then distributes the exchanged thermal energy to the final appliances for heating and DHW; the tertiary circuit supplies the thermal storage for the production of DHW from solar panels. The substation investigated in this study is shown in Appendix A, Figure A.1.

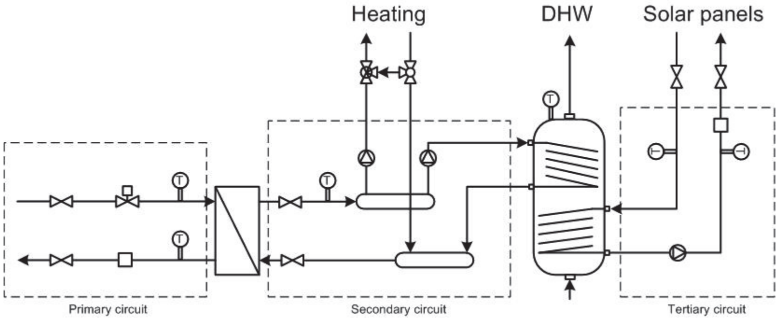

Figure 1: grouped schematic of the "passive" substation.

2.2 Prosumer layout

Based on the existing substation within the DHN described in the previous paragraph, the conversion of the consumer into a prosumer involves an additional exchanger able to feed the excess heat into the network, thus resulting in a bidirectional substation. In order to evaluate qualitative benefits resulting from this intervention, Authors also proposed this layout to be implemented in a real substation prototype; however, it is important to note that there is no direct similarity between the traditional existing substation and the prototype developed and tested at the EURAC laboratory, in terms of devices installed, capacity, etc. The prototype was originally designed by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) and the Alma Mater Studiorum University of Bologna, in order to interact with both conventional DHN and distributed generation systems, such as solar thermal panels or heat recovery plants. The selected configuration is "supply to return" as it represents the optimal solution for this type of substation, evolving from the existing prototype by adding a storage system for the DHW. This modification allows us to avoid further derivations from the ridge and the introduction of further pumping systems. In this configuration, the heated fluid is extracted from the supply line and reintroduced into the DHN return line. Figure 2 represents the simplified layout of the prototype bidirectional substation, highlighting three main circuits: the primary circuit connected to the supply pipeline (in red) and the return pipeline (in blue) of the main DHN; the secondary circuit related to the user with the supply pipeline to the heating and DHW collector (dark green) and the return pipeline from the collector (light green); the tertiary circuit connected to the solar collectors for local generation (gray and black). The heat exchange between the circuits takes place through heat exchangers HE1 and HE3 and through the lower exchange in the thermal storage named HE2. Temperature and flow sensors are installed in key sections, while interception, diversion, and mixing valves enable precise control over the system's operation. There is a variable speed circulation pump that supplies heat to the emission terminals for heating, a circulation pump that transfers heat to the upper exchange of the thermal storage for DHW. In this configuration, the heating demand of the user is exclusively satisfied by the main distribution network, while the demand for DHW can be satisfied by the solar collectors or the distribution network through heat exchanger HE1 and the thermal storage with HE2. When the solar collectors produce more thermal power than required by the DHW demand, the substation allows – if temperature levels permit – to transfer this surplus to the grid through heat exchanger HE3. As mentioned earlier, this configuration is of the "supply to return" type: in fact, a three-way valve diverts the flow of the primary circuit and re-introduces it onto the return line after passing through heat exchanger HE3, increasing the temperature of the flow. The prototype substation is shown in Appendix A, Figure A.2.

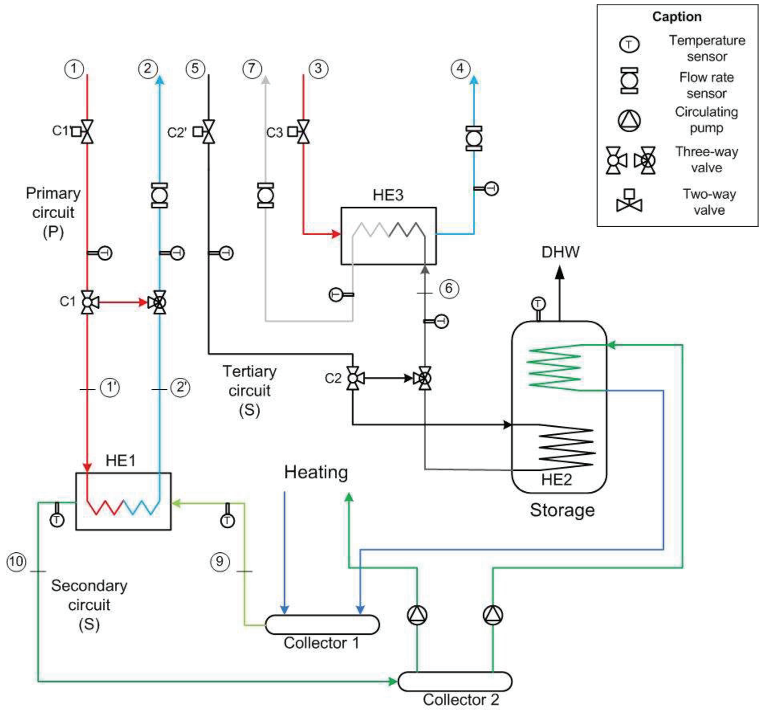

Figure 2: Simplified layout of the prototype bidirectional heat exchange substation.

The substation control is achieved through a thermo-electric system based on flow. This system is managed by valves and circulators in the various circuits, employing proportional-integral controllers and preset nominal values. The control system includes the 2-way valve C1', which opens during the winter season and when there is a demand for thermal power from the thermal storage; the 2-way valve C2', which opens when the solar temperature is sufficient to exchange thermal power with HE2 and there is a thermal demand from the thermal storage; the 3-way valves C1 and C2, designed to regulate the hot flow to the heat exchangers based on the target temperature of the fluid leaving HE1 and HE2; and a 2-way valve C3, designed to regulate the flow from the district heating supply to HE3 when sufficiently high temperatures are reached with the solar collectors. To prevent intermittent cycling of the heat exchangers HE1, HE2, and HE3, a hysteresis of 1-2 °C is added to the nominal control value used for activation. Table 1 shows the nominal values of main control variables.

Table 1: Nominal values for substation control variables

Control Variable	Nominal Value
Solar system flow rate (M5&M7)	3 m^3/h
Flow rate from DHN to HE1 (M1&M2)	1.8 m^3/h
User flow rate (M9&M10)*	4.7-3.7-1 m^3/h
User supply temperature	Variable
DHN supply temperature (T1&T1')	80°C

* Differentiated by type of load. The three values respectively represent the flow rate when there is a simultaneous request for heating and DHW storage loading, in case of heating only and in case of DHW loading only.

2.3 Test methodology and scenarios

The experimental campaign was conducted at the Energy Exchange Laboratory of EURAC Research, equipped with a small-scale DHN. The bidirectional substation was hydraulically connected to this test facility, allowing independent control of flow and inlet temperatures at four connection points: district heating supply and return, user return, and solar generator supply. End-user thermal loads and solar collector production profiles (both flat plate and evacuated tube collectors) were dynamically emulated using numerical models and coupled with the entire system in hardware-in-the-loop (HIL) mode. TRNSYS was the dynamic simulation software employed to emulate building loads and solar collector generation. Input data for the simulation model were transmitted by the substation, which measured temperature and flow rate at each data acquisition interval. The substation was then coupled in real-time with the building and solar generation models, enabling assessment of performance, management, and control characteristics under various operational and dynamic conditions. In order to assess the annual performance of the substation, two representative non-consecutive days were selected to capture variations in weather conditions during winter and spring, following the procedure described in (Menegon et al., 2017). Table 2 illustrates the two selected test days, their average ambient temperature, average horizontal surface irradiance, and the number of days belonging to each considered cluster.

Table 2: characteristics test days

Test days	Average daily temperature [°C]	Average daily radiation on the horizontal surface [W/m^2]	Number of days in the cluster
5 January (day 1)	3.7	63	83
9 April (day 2)	15.8	243	47

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2.4 KPIs and calculations

During the test phases, several data were measured and recorded, including the heat generated by the solar collectors and the heat exchanged by HE1, HE2, and HE3. These data were used to establish a correlation between the energy flows and the energy exchanged by the three heat exchangers in the bidirectional substation. Furthermore, the mechanism of net-metering enables local energy producers to store unused thermal energy in the DHN, thereby covering part of the demand in the absence or not enough solar generation. In order to conduct a comparative analysis between the two reference days (day 1 and day 2) and assess the contribution of the bidirectional substation with E0, E1, and E2 scenarios, key performance indicators (KPIs) were calculated on a daily basis. The self-consumption rate (S_C), indicating the percentage of locally produced energy consumed on-site, the self-sufficiency rate (S_S), indicative of the extent to which the thermal demand is met by local consumption, and the useful energy coefficient (U_{ec}), indicating the proportion of locally generated energy used by the user or feed into DHN for net metering, were included in the analysis. From equation 1 to equation 3 the definitions of the present coefficients are reported.

$$S_C = 100 \cdot \frac{E_{DG} - E_{DG\ to\ DHN}}{E_{DG}} \tag{1}$$

$$S_S = 100 \cdot \frac{E_{DG} - E_{DG\ to\ DHN}}{E_{User}} \tag{2}$$

$$U_{ec} = 100 \cdot \frac{E_{DG\ to\ user} + E_{DG\ to\ DHN}}{E_{DG}} \tag{3}$$

Where:

- E_{DG} is the thermal energy produced by the distributed generation (DG) systems, i.e. solar panels
- $E_{DG\ to\ DHN}$ is the thermal energy generated by distributed generation (DG) systems and feed into to the DHN
- E_{User} is the thermal load of the end-user
- $E_{DG\ to\ user}$ is the thermal energy supplied by the distributed generation (DG) systems and distributed to the end-user

3 RESULTS

For day 1 and day 2, the energy flows in the three heat exchangers in scenarios E1 and E2 are shown in Figure 3 and Figure 4, respectively. During the two days, there is a demand for energy for space heating and domestic hot water, in addition to the availability of energy from flat-plate solar panels (E1) and evacuated tube solar panels (E2). Consequently, the operation of HE1 (heat from the DHN to the user), HE2 (exchanger inside the storage tank for DHW), and HE3 (heat from DG to the DHN) is foreseen. The graphs in Figure 3 illustrate the variation in user heating load during day 1, particularly the demand starts at 6:00 and ends at 22:00, remaining nearly constant around 20 kW. Furthermore, the graphs illustrate the impact of DG production on HE2. In scenario E2, solar panels initiate power generation earlier than in E1, leading to an earlier charge of the DHW tank (between 9:00 and 10:00). Additionally, there is an extra charging period around 15:30 due to a longer production in E2 than E1. The most notable aspect pertains to the extended duration during which excess solar energy is fed to the grid. In

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scenario E2, solar panels feed energy into the grid from 10:00 to 15:00, reaching a peak of about 45 kW. In contrast, in E1, solar panels contribute to the grid from 12:00 to 13:30, with a peak of 25 kW. The graphs in Figure 4 shows the variations in user heating load during day 2, with values generally lower than the previous day. In this context, it is observed that solar production in E2 is slightly higher than in E1, presenting a similar profile but with a greater amount of energy fed into the grid, extending until 17:45, whereas in E1 it ends at 17:00.

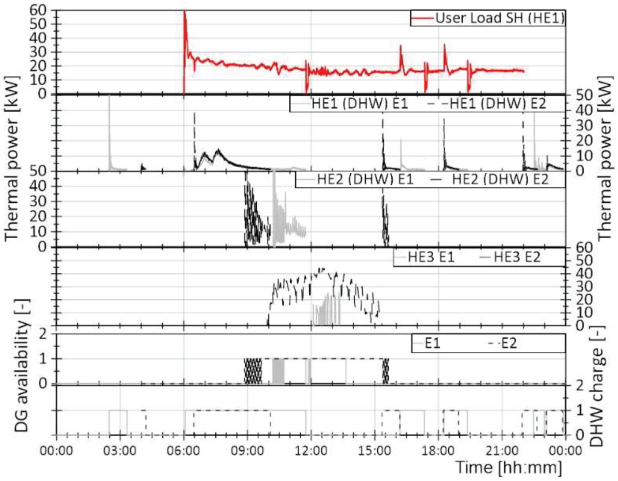

Figure 3: day 1. Top graph shows the user load for SH. Second and third graph show the user's load for DHW provided by HE1 (from DHN) and HE2 (from DG). The fourth graph shows the heat from DG fed into DHN. Bottom graphs show the two binary control signals: one indicating the availability of useful solar energy and the other reflecting the user's request for charging the DHW storage tank.

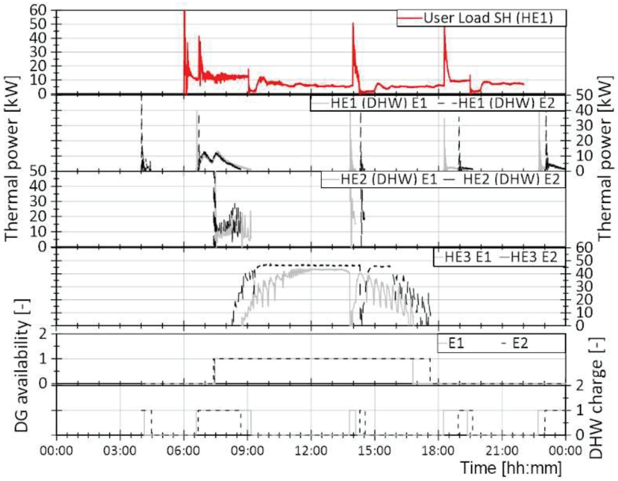

Figure 4: day 2. Top graph shows the user load for SH. Second and third graph show the user's load for DHW provided by HE1 (from DHN) and HE2 (from DG). The fourth graph shows the heat from DG fed into DHN. Bottom graphs show the two binary control signals: one indicating the availability of useful solar energy and the other reflecting the user's request for charging the DHW buffer.

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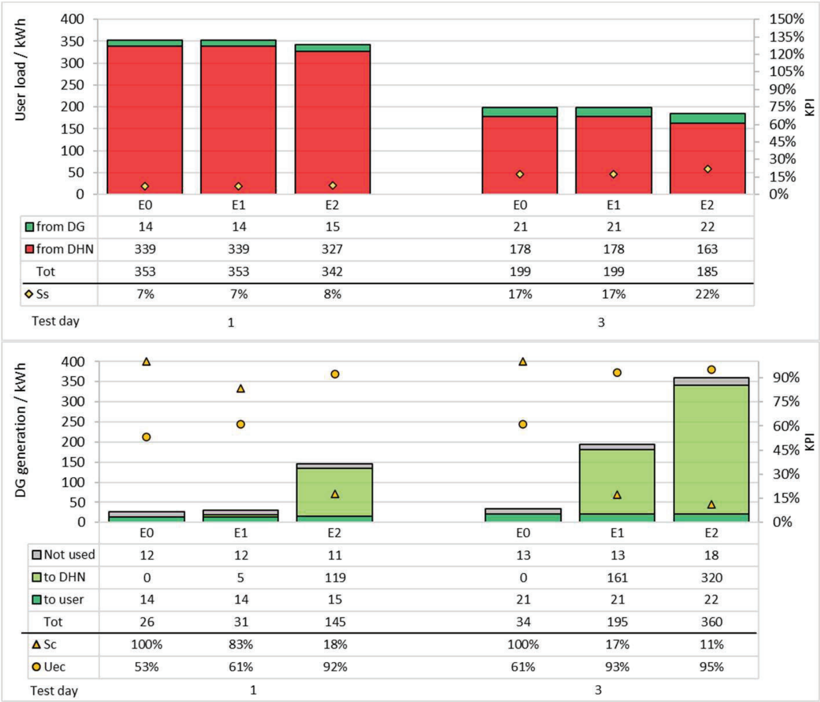
Figure *5* and **Figure *6*** illustrate the energy flows and key performance indicators (KPIs) observed in the substation over the two experimental test days, for the above-described scenarios E0, E1, and E2; unlike **Figure *5***, **Figure *6*** accounts net metering. The first graph of each figure illustrates the total daily load of the user, showcasing the amount of energy supplied from both the DHN and solar panels (DG), along with the self-sufficiency coefficient. The second graph provides an overview of the total daily production of DGs, delineating the amount of DG generation feed into the DHN, the amount directly supplied to the user, and the solar field-produced energy not used by the substation. Additionally, the self-consumption coefficient and the useful energy coefficient are presented in the graphs.

Figure *5* reveals that on both days, the user load was primarily satisfied by DHN. The contribution of the solar panels (DG) to the user load remains nearly constant across the three scenarios, despite E2 having greater energy availability but not a higher synchronization between DG energy and user load for DHW. This trend is also reflected in the self-sufficiency rate, which is below 10% in winter (day 1) and between 17% and 22% in spring (day 2). Particularly evident on day 1 is how the asynchrony between DG energy and user load for DHW allows for greater energy injection into the DHN in scenario E2 compared to E1 (E0 injects nothing as it is in passive configuration), resulting in a significant increase in the useful energy coefficient from 61% to 92%. In fact, observing day 1, the ratio between the energy produced by the flat panels and the evacuated tube panels is 21%, the same ratio calculated on day 2 is 54%, this means that the performance of the tube panels evacuees is more significant on a winter day.



	E0	E1	E2	E0	E1	E2
🟩 from DG	14	14	15	21	21	22
🟥 from DHN	339	339	327	178	178	163
Tot	353	353	342	199	199	185
◇ Ss	7%	7%	8%	17%	17%	22%
Test day		1			3	

	E0	E1	E2	E0	E1	E2
⬜ Not used	12	12	11	13	13	18
🟩 to DHN	0	5	119	0	161	320
🟩 to user	14	14	15	21	21	22
Tot	26	31	145	34	195	360
△ Sc	100%	83%	18%	100%	17%	11%
○ Uec	53%	61%	92%	61%	93%	95%
Test day		1			3	

Figure 5. Contribution to user load from DG and DHN, DG generation use and KPIs during the two test days without net-metering

Figure *6* highlights the significant benefits arising from adopting the DHN as a thermal storage system through net metering. Particularly, an important increase in self-sufficiency during day 1 in E2 can be observed if compared to scenario E1. This change in self-consumed energy arises from the utilization of the DHN as a thermal storage, enabling the partial fulfillment of SH requirements through solar panels. Thanks to the installation of vacuum solar panels, 43% of the user's energy load is satisfied by solar production, a substantial increase compared to E1's 9%, where winter production is very low. E1

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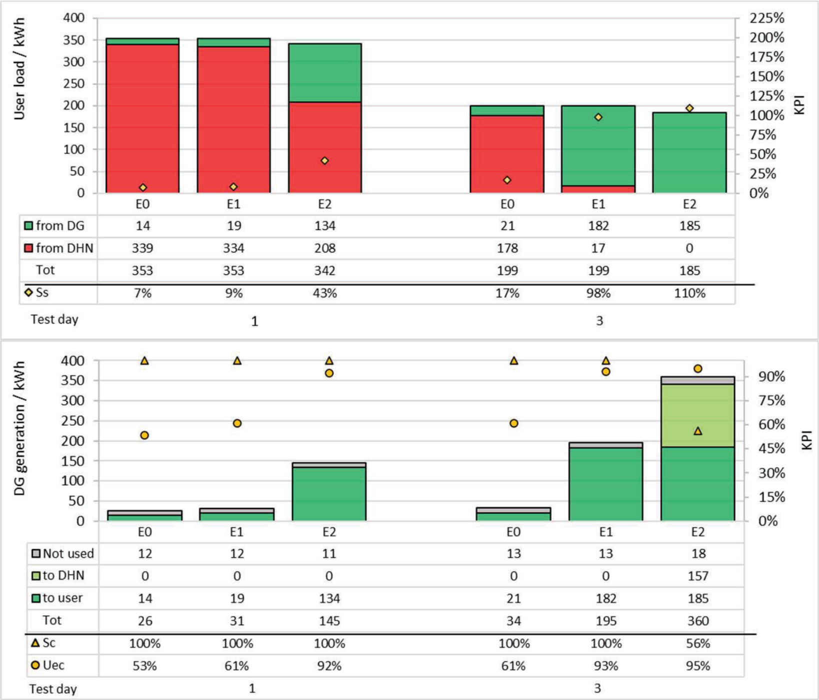
and E2 show a less significant difference during day 2; however, in E2, solar production fully satisfied the user's energy load. This behavior results in a zero balance by solar panels on day 1 for both E1 and E2, as they consume all locally produced energy during the entire day-time period of net-metering. However, on day 2, only in E2 is there the possibility to fed energy into the DHN through the bidirectional substation, as self-consumption reaches 56% in this case.



	E0	E1	E2	E0	E1	E2
🟩 from DG	14	19	134	21	182	185
🟥 from DHN	339	334	208	178	17	0
Tot	353	353	342	199	199	185
◇ Ss	7%	9%	43%	17%	98%	110%
Test day		1			3	

	E0	E1	E2	E0	E1	E2
▨ Not used	12	12	11	13	13	18
🟩 to DHN	0	0	0	0	0	157
🟩 to user	14	19	134	21	182	185
Tot	26	31	145	34	195	360
△ Sc	100%	100%	100%	100%	100%	56%
○ Uec	53%	61%	92%	61%	93%	95%
Test day		1			3	

Figure 6. Contribution to user load from DG and DHN, DG generation use and KPIs during the two test days with net-metering

4 CONCLUSION

The global energy landscape is evolving, with a strong focus on national energy policies and transitioning from fossil fuels to renewable sources. Energy communities have emerged as key players in this transition, actively engaging citizens as prosumers. Integrating thermal prosumers through bidirectional substations into DHN maximizes the potential of renewable sources, extending the concept of thermal energy sharing at the community level. The article proposes an approach to retrofit traditional substations in DHN with bidirectional heat exchange substation. Based on an existing network in northern Italy, a bidirectional substation prototype was developed and subjected to an experimental campaign. Various scenarios were analyzed, including the unidirectional configuration with flat-plate solar collectors, the bidirectional configuration with the same collectors, and finally with evacuated tube solar collectors. The results highlight that the installation of evacuated tube solar collectors does not yield significant benefits in terms of local self-consumption compared to flat-plate collectors, due to the mismatch between energy demand for DHW and solar production. However, there is a notable increase in energy fed into the DHN, especially in winter days with evacuated tube solar collectors, which is nearly 25 times higher than with flat-plate collectors. This disparity tends to decrease during the midseason days. The adoption of DHN as energy storage through net metering mechanism proves to be extremely advantageous, enabling local energy self-consumption close to 100% during midseason days, both with flat-plate and evacuated tube solar collectors. However, it emerged as well on winter days, there is a significant increase in self-consumption with evacuated tube collectors compared to flat-plate collectors. In conclusion, retrofitting traditional substations into a bidirectional setup maximizes the utilization of renewable sources, overcoming challenges associated with their intermittency. This technology can also incentivize the installation of solar panels with enhanced energy performance, reducing reliance on fossil fuels. The observed benefits imply that policies focused on these solutions could enhance energy sustainability, facilitating further integrations of renewable energies into urban heating systems through targeted net metering incentives.

NOMENCLATURE

Acronyms

DG	Distributed Generation
DHC	District Heating and Cooling
DHN	District Heating Network
DHW	Domestic Hot Water
HE	Heat Exchanger
RES	Renewable Energy Sources
SH	Space Heating

Symbols

En	Nth scenario
E_{DG}	Energy produced by the distributed generation
$E_{DG\ to\ DHN}$	Energy produced by the distributed generation and feed into the grid
$E_{DG\ to\ user}$	Energy produced by the distributed generation to the end-user
E_{user}	Thermal load for end-user
S_C	Self-consumption rate
S_S	Self-sufficiency rate
U_{ec}	Useful energy coefficient

Subscripts and superscripts

C	Consumption
ec	Energy coefficient
S	Sufficiency

Appendix A

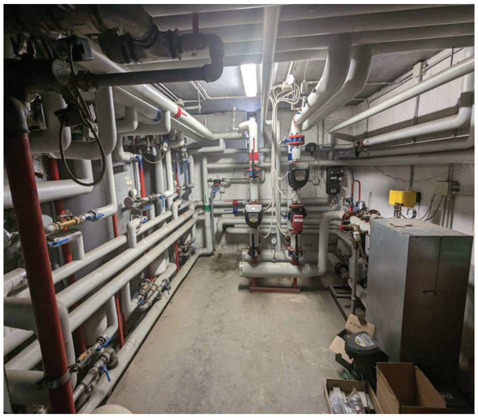


Figure A.1: Substation in the district heating network of northern Italy

Figure A.2: Bidirectional substation prototype object of the experimental campaign

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