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Optimizing Thermal Energy Sharing in Smart District Heating Networks

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Abstract: The constant attention to sustainability aimed at reconciling economic and social development with environmental protection is the driving force of the continuous growth of renewable energy in the energy sector. Among the numerous actions taken by the European Commission (EC) in this direction, an important initiative towards the complete decarbonization is represented by the Renewable Energy Communities (RECs). According to the EC, "energy communities enable collective and citizen-driven energy actions to support the clean energy transition. They can contribute to increasing public acceptance of renewable energy projects and make it easier to attract private investments in the clean energy transition". At the European level, numerous energy communities are emerging, although they are all based on photovoltaic production and, consequently, focus only on electricity flows. The aim of this paper is to define a thermal energy community in which thermal energy sharing can be achieved by exploiting the concept of the smart district heating network. Starting from a small existing district heating network, its conversion into a smart one will be analyzed and optimized with the aim of studying the sharing of thermal energy between the various prosumer and non-prosumer users connected to the district heating network.

Keywords: thermal energy community; smart district heating; shared energy; allocation algorithms

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1. Introduction

One of the major changes occurring within the ongoing energy transition is the shift from a centralized to a decentralized energy system, where the end users are not merely consumers but also increasingly play an active role in the generation of distributed energy, thereby becoming prosumers [1,2]. This term describes individuals who, alongside consuming from the grid, produce energy locally using small-scale renewable sources in order to self-consume it immediately, store it for later on-site consumption, or even feed it into the national grid [3,4]. In such a scenario, emerging collaborative economies have developed in recent years [5] and the concept of energy communities has gained prominence. These initiatives enable consumers and prosumers to foster a new energy–social model, based on sharing locally generated energy from renewable sources through either power grids or decentralized systems [6,7]. This paradigm shift empowers users to trade energy, by selling the surplus or acquiring residual needs, according to their consumption and production profiles [8,9].

The scientific literature offers a wide range of in-depth studies on energy communities: definitions, meaning, and purpose of these communities [10,11]; socioeconomic and environmental goals of these communities [12], highlighting both positive and critical impacts [13]; geographical area of development [14,15], including regional and local influences on their growth pattern; business models and legal framework [16,17]; etc. A comprehensive systematic review of the scientific literature has revealed that the progress of energy communities faces several significant barriers, including regulatory hurdles, related to the complexity and inflexibility of existing regulatory frameworks; financial challenges, due to the substantial investment necessary for infrastructure and technology; and managerial obstacles, related to the organization and administration of energy communities. Addressing these barriers requires an appropriate institutional and legal framework capable of providing the necessary support to overcome them and foster widespread adoption of energy communities. Further details can be found in [18].

The European Union has embarked on a significant transition towards a low-carbon energy system [19,20]. To achieve it, the EU has implemented policies targeting both energy demand (aiming to reshape consumption patterns) and energy supply (supporting innovative technologies and mechanisms). Within this framework, the EU is actively promoting solutions that encourage self-consumption and sharing of local energy production, notably through the establishment of energy communities. One pivotal initiative is the EU Directive 2018/2001 on the promotion of the use of energy from renewable sources [21], commonly referred to as REDII, which introduced the Renewable Energy Community (REC), defined as "a legal entity, which is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity"; jointly acting renewables self-consumers are users located in the same building or multi-apartment block. The main objective is to generate environmental, economic, and social benefits for the community or local areas in which they operate, rather than financial profits. These aggregation models serve as key tools of collective collaboration for energy production and sharing within a limited area. They enable more efficient management of distributed generation, as they reduce losses [22,23], while also facilitating access to renewable sources for those hindered by geographic constraints (e.g., urban centers with limited available area) or experiencing energy poverty. Regardless of the configuration, the valorization and incentive system under the Italian legislation is based on the definition of "shared energy": the minimum value, assessed on an hourly basis, derived from the total electricity actually fed into the grid and the total electricity withdrawn through the connection points between the REC users and the national grid [24]. Consequently, the model adopted is based on a virtual sharing, lacking a physical basis for calculating actual energy exchanges between users. As a result, the scientific literature and the grey literature document numerous studies and tools aimed at managing the costs and benefits, associated with community participation among users, related to energy, environmental and social purposes [25].

Most papers focus on Renewable Energy Communities based on solar energy for electricity production, often combined with storage systems and heat pumps. While EU directives encompass all forms of renewable energy, the attention on energy communities emphasizing thermal energy production is still limited [26]. These studies predominantly investigate technical aspects, related to design and optimization, production and distribution technologies (mainly district heating and cooling), and user consumption patterns [27,28]. However, there is a recognized interest in further exploring interactions and internal dynamics among different stakeholders, including the willingness of final users [29], business models [30], and development of potential case studies.

District heating and cooling (DHC) systems play a crucial role as key infrastructure in enabling decarbonization and facilitating the efficient integration of energy sectors. The recast Energy Efficiency Directive (EED) [31] introduces a more ambitious definition of "efficient district heating and cooling" along with specific deadlines. Enhancing the efficiency and competitiveness of DHC systems to enable greater integration of waste heat and renewable energy sources, thus fostering conditions for their further expansion, stands out as one of the principal challenges.

In this regard, Smart District Heating Networks (SDHNs) can present further opportunities to increase overall production and distribution efficiencies and the integration of renewable sources in the thermal production sector. In order to ensure a bidirectional flow from a District Heating Network (DHN) to users and vice versa, four possible hydraulic connections between the substation and the network can be adopted [32]:

- Supply to return: mass flow rate from the supply of the network; it is heated using a decentralized production system and then reintroduced via the return pipe of the DHN;
- Supply to supply: the introduction of heat into the network via decentralized generation occurs by using only connections located at the supply lines;
- Return to return: connections between the DHN and the prosumer, who introduces heat into the network, are all located at the return lines;
- Return to supply: in this case, a mass flow rate is taken from the return circuit, heated via the decentralized production system, and reintroduced via a decentralized pumping station into the supply of the network.

The use of 'supply to return' and 'return to return' configurations can imply an increase in temperature in the return circuit of the network, causing heavy management issues for the grid. Increasing the supply circuit temperature (supply to supply configuration) is not an optimal configuration for downstream utilities (when they need constant-temperature flow) and/or any others decentralized systems (which can be excluded from the possibility of thermal energy feed-in due to the increase in supply temperature) [32]. The 'return to supply' configuration allows no temperature increase as this scheme is based on realizing a feed-in temperature almost equal to that of DHN. It follows that the 'return to supply' configuration is the best option for SDHNs, particularly if decentralized solar (or, generally speaking, renewable sources) are integrated into the network, as confirmed in [33]. It must be highlighted that 'return to supply' is the most complex among the four configurations, since it can lead to reverse flow in the network caused by the change in pressure distribution [34].

In this study, the 'return to supply' configuration has been chosen to convert an existing DHN into a SDHN. To evaluate the performance of the network in both traditional and smart configuration, the software I.H.E.N.A. 9.3 (Intelligent Heat Energy Network Analysis) has been used. This software was developed by the University of Bologna, and it is based on the Todini–Pilati algorithm [35], generalized using the Darcy–Weisbach equation.

In more detail, the aim of this study is to analyze a Thermal Energy Community, with particular attention on the estimation of shared energy. Regarding Electrical Energy Communities, the adoption of allocation algorithms is a widely used approach to account for Virtual Shared Energy. In the case of Thermal Energy Communities, this is not the optimal approach due to the evidence that thermal energy can be traced across the district heating network. A comparison between a flow approach and the use of various algorithms will be presented and discussed.

2. Case Study

In this section, a brief overview of the selected district heating network will be given together with a performance estimation of its design point.

2.1. Network Description

The district heating network chosen for this study is presented in Figure 1, which shows its extension and planimetry. The network is located in the north of the city of Tourin in an *E* climatic zone, according to the Italian classification.

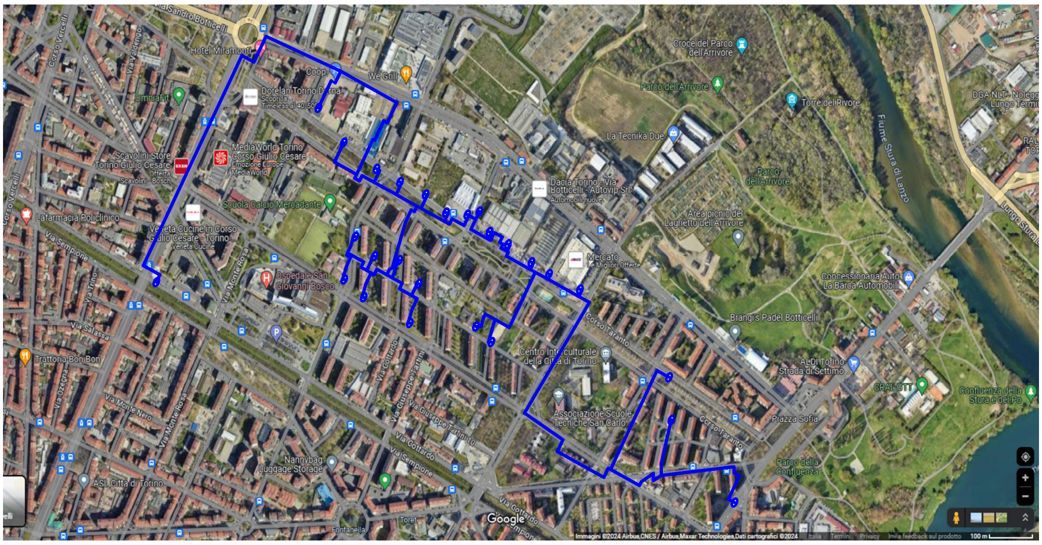


Figure 1. District heating network (original image from Google Maps).

It is a small network, with a total length (considering supply and return circuit) equal to less than 7 km, serving only residential users in a neighborhood of a city in northern Italy. The network provides space heating and hot water services to 25 condominium users and is powered by a single thermal production plant (TPP). The temperature and pressure of the heat transfer fluid introduced into the network are, respectively, equal to 85 °C and 6.3 bar. The network has a variable flow rate and a constant temperature difference at the primary circuit of the users equal to 20 °C. More details about this district heating network can be found in an authors' previous study [36].

The district heating network has been modelled in I.H.E.N.A. 9.3 (Intelligent Heat Energy Network Analysis) [37], an in-house-developed software able to estimate the performance of district heating (or cooling). In more detail, I.H.E.N.A. 9.3—with respect to other commercial software—is able to estimate the performance of a district heating network by considering all four schemes of smart substations and solving the Todini–Pilati algorithm by considering the Darcy–Weisbach approach for the estimation of pressure losses across the network.

The realized model is presented in Figure 2. It consists of 140 nodes (one source, 25 users, and 114 mixers/splitters) and 139 pipes.

2.2. Design Conditions Performance Evaluation

Considering the design conditions, the total thermal power required for space heating and hot water by the 25 utilities is equal to less than 13 MW, divided as represented in Figure 3.

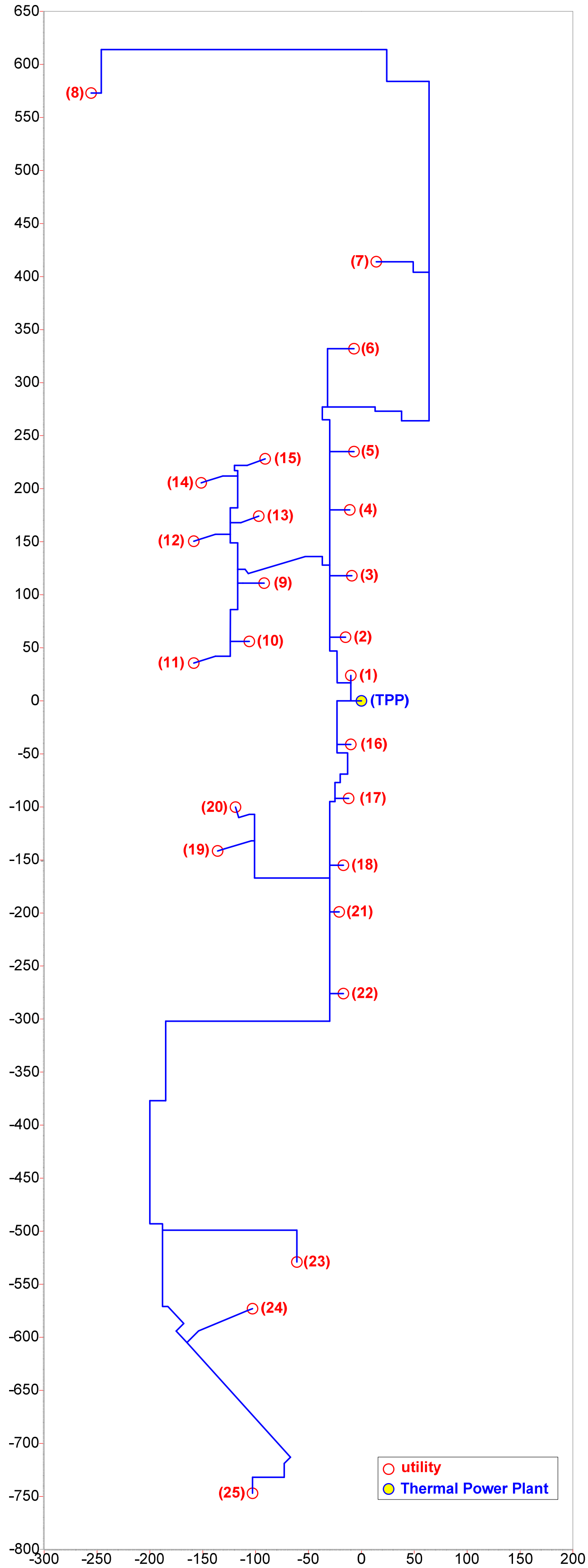


Figure 2. District heating network model in IHENA 9.3.

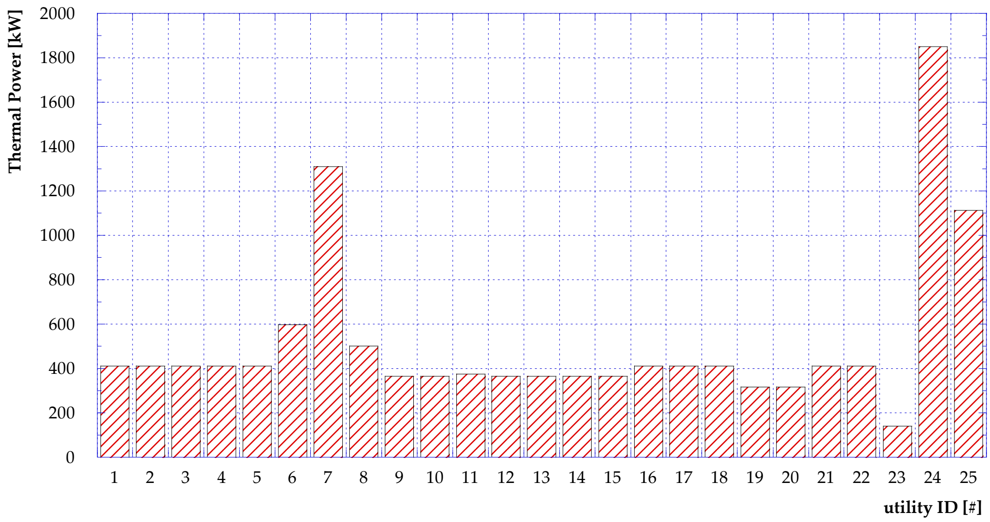


Figure 3. Utilities and thermal need in the design condition (at external reference temperature equal to −8 °C).

The main performance of the network is listed in Table 1, as calculated using the IHENA 9.3 Software.

Table 1. District heating network main performance in design condition.

Overall water mass flow rate at DH inlet [kg/s]	$\dot{m}_{DH,in}$	153
Overall Thermal Power to the utilities [kW]	$Q_{TH,U}$	12,839
Overall Produced Thermal Power [kW]	$Q_{TH,TPP}$	15,805
Electrical Power for Pumping Station [kW]	$P_{PMP,EL}$	59

From the table, it can be estimated that the total efficiency of the network ($\eta_{DH,TH} = Q_{TH,U}/Q_{TH,TPP}$) is equal to more than 80%.

From the network pressure analysis distribution, the available pressure drops (Δp) at users' substations have been calculated (see Figure 4). From this figure, it can be noted that user #25 (who is characterized by a minimum Δp equal to about 0.5 bar) can be individuated as the critical user. Users 8 and 15 are the substations (with immediately lower Δp than user 25), characterized by pressure differences available to their exchangers equal to 1.0 bar and 1.2 bar, respectively.

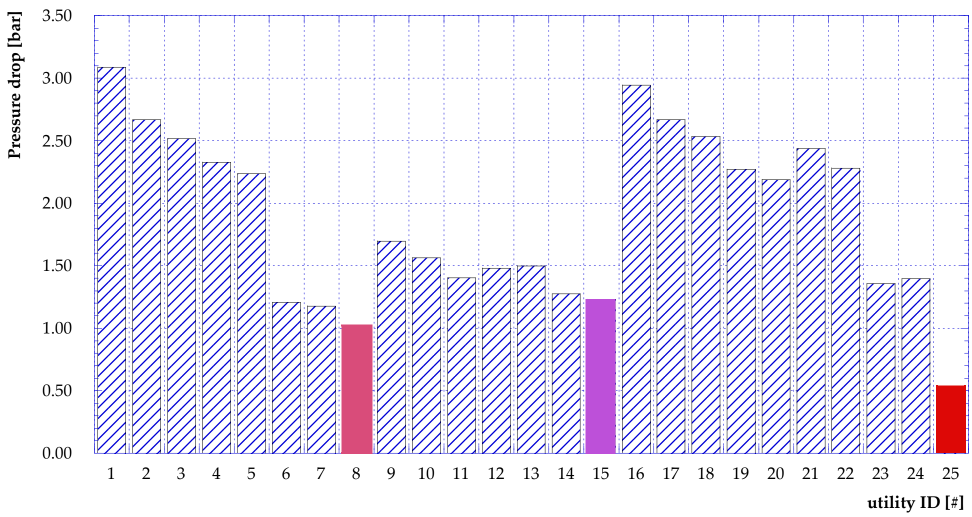


Figure 4. Available pressure drop at users' substations in design condition.

On the basis of the previous evidence, the critical path (i.e., the path that, starting from the source, presents the highest pressure losses) can be drawn, as presented in Figure 5. Finally, the pressure profiles along the critical path of the network for both the supply and the return circuit are represented in Figure 6.

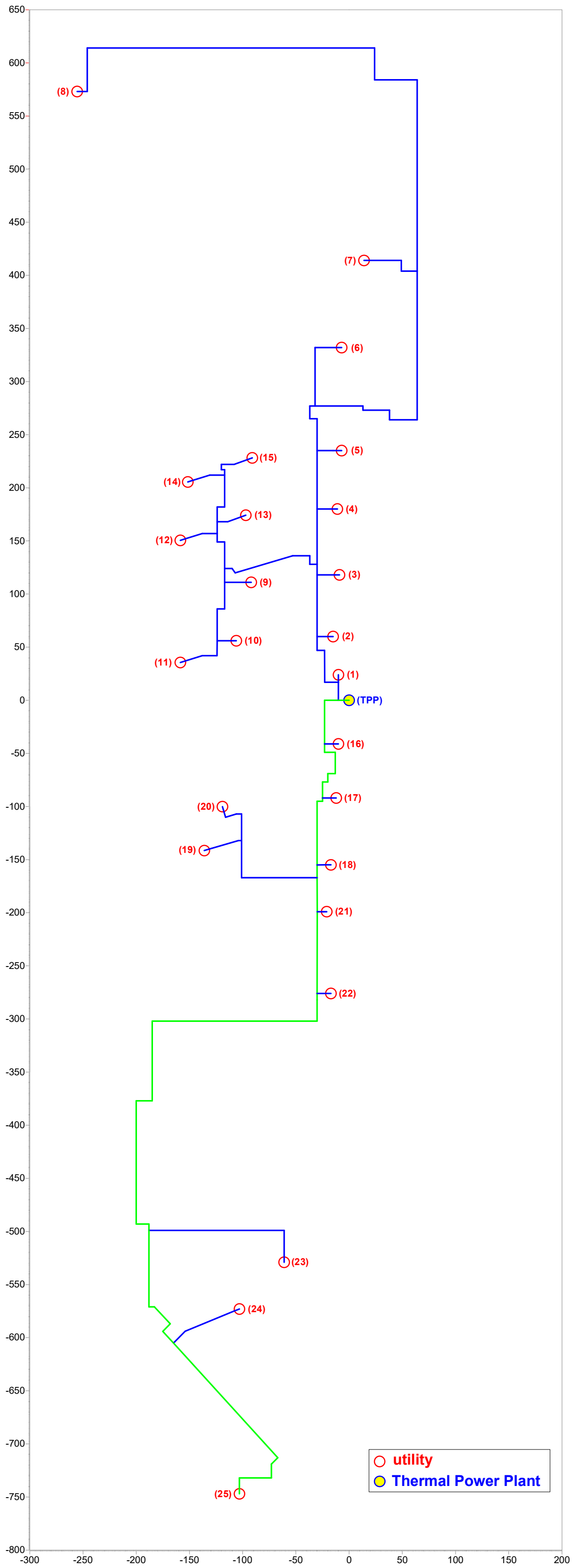


Figure 5. Critical path (in green) in design condition.

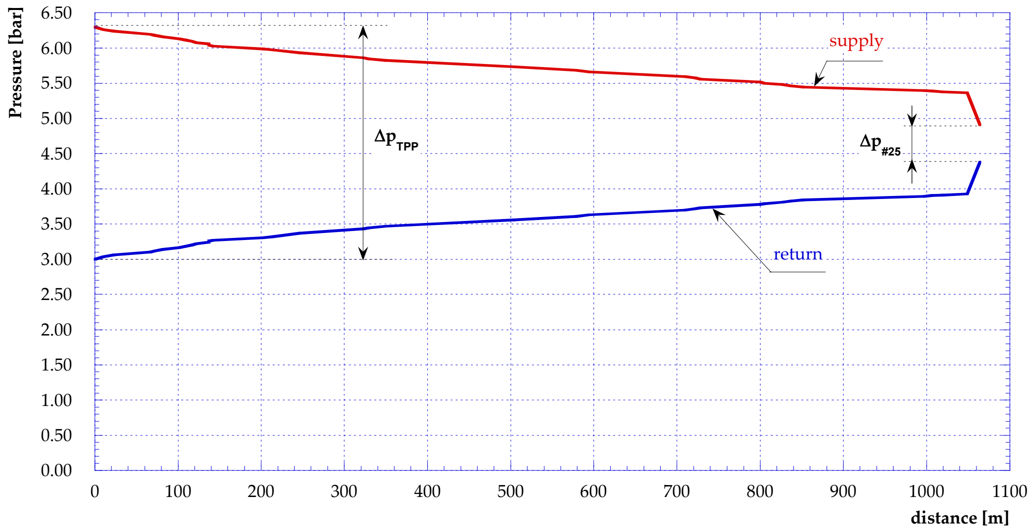


Figure 6. Pressure profile for critical path in design condition.

3. Smart District Heating Configuration and Performance Evaluation

In order to study the performance of a Thermal Energy Community, the conversion of the district heating network into a smart one is defined and analyzed. In this regard, three smart users can be considered with the aim of decentralizing thermal production at the terminal points of the network with minimum pressure difference at the exchangers (i.e., user #25, #8, and #15). For all the smart users, a bidirectional 'return to supply' substation is assumed. IHENA 9.3 Software was applied to find the equilibrium point of the network with three smart users, as presented in Figure 7.

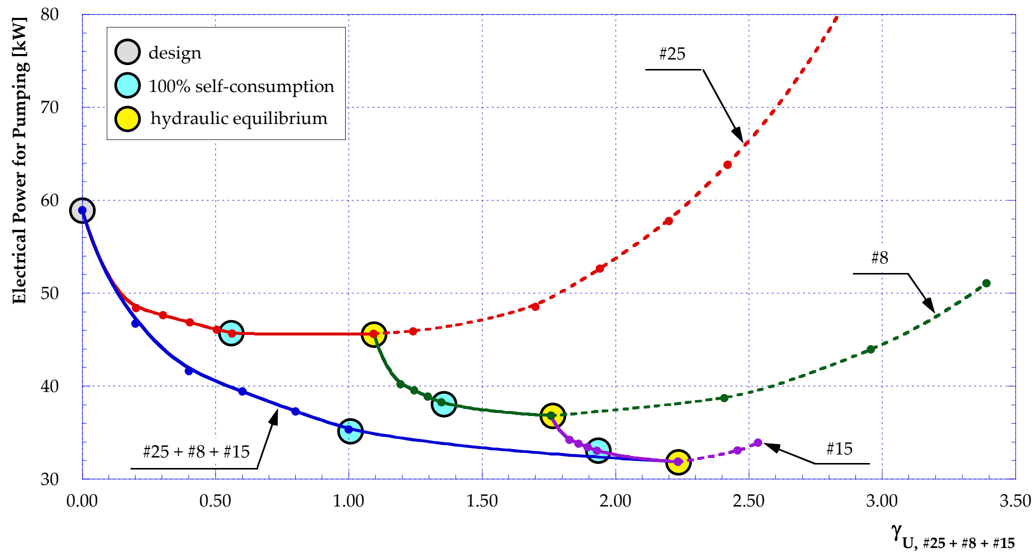


Figure 7. Overall electrical power for pumping.

The figure shows the change in electrical power required for pumping as a function of the parameter γ (defined as the user smart index), which represents the ratio between the thermal power produced ($Q_{TH,P}$) and required ($Q_{TH,R}$) by the same users of the network.

Starting from the design point (see the red curve in Figure 7), if only user #25 produces thermal power—i.e., $\gamma = Q_{TH,P,\#25} / (Q_{TH,R,\#25} + Q_{TH,R,\#8} + Q_{TH,R,\#15})$—the electrical power for pumping reduces due to the lower demand until it reaches the 100% self-consumption. Starting from this point, a further increase in production of user #25 involves the introduction of thermal power into the district heating network, which causes a further reduction in pumping costs until a minimum value, defined as the hydraulic equilibrium, is reached. The hydraulic equilibrium represents the balance of the network between TPP and, in this first case, user #25. If user #25 introduces further thermal power, exceeding the hydraulic equilibrium leads to a new increase in pumping costs. From the hydraulic equilibrium of user #25, keeping constant its thermal production, user #8 can be considered (green line in Figure 7). Using the same approach as the previous case—$\gamma = (Q_{TH,P,\#25} + Q_{TH,P,\#8})/(Q_{TH,R,\#25} + Q_{TH,R,\#8} + Q_{TH,R,\#15})$—the 100% self-consumption of user #8 and a new hydraulic equilibrium point (among TPP and users #25 and #8) can be reached. Finally, the purple curve in Figure 7 represents the introduction of the last of the smart users (#15) and the final network hydraulic equilibrium point (among TPP and all the smart users: #25, #8 and #15).

The methodology just explained, which allows us to identify the smart network operating point that minimizes the required pumping electrical power, can be defined as "series inserting of active users". The alternative is the "parallel inserting of smart users", which is represented by the blue curve in Figure 7. In this case, (as in the last one of the series), γ can be calculated as it follows:

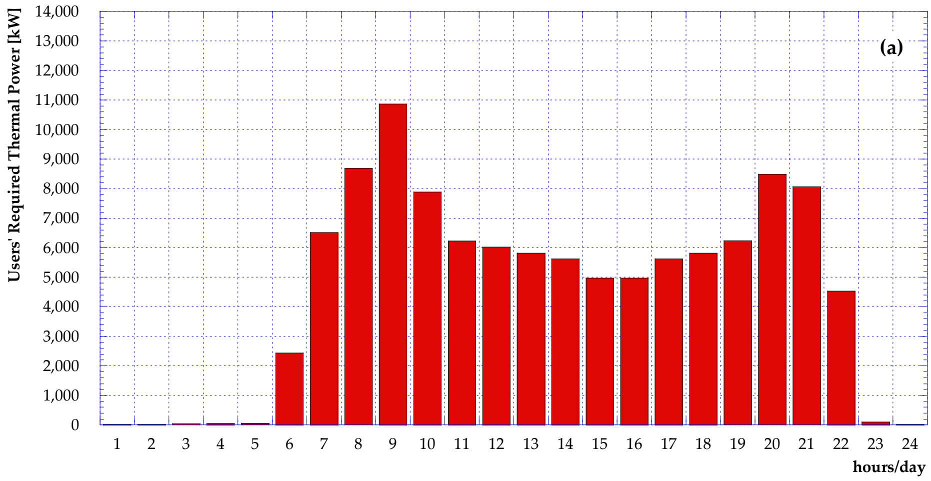
$$\gamma_{U,\#25+\#8+\#15} = \frac{Q_{TH,P,\#25} + Q_{TH,P,\#8} + Q_{TH,P,\#15}}{Q_{TH,R,\#25} + Q_{TH,R,\#8} + Q_{TH,R,\#15}}. \quad (1)$$

Figure 7 demonstrates that the two procedures are equivalent because they allow the same hydraulic equilibrium point to be determined.

Therefore, a smart user index equal to 2.23 can be defined as the optimal operating point, where the pumping electrical power is 45% lower than the design value.

On this basis, the performance of the smart district heating network can be evaluated by considering two typical days (for winter period and for summer/middle season period) of thermal load, as presented in Figure 8. In more detail, the aim of this analysis is the estimation of the thermal energy shared by the three smart users with the network and then with the other utilities. In particular, the shared thermal energy has been estimated considering the total mass flow rate and temperature difference between supply and return into the network by the three smart users—less the thermal dispersed energy—and the corresponding values of each utility, taking into account the paths of the network for the flow due to the smart operation with three smart users in hydraulic equilibrium with the TPP.

In Figure 9, the distribution of the thermal power produced by the TPP and by the three smart users is presented, respectively, for the typical winter and middle season/summer day. Smart users—according to this study—are able to produce from 18% to 22% of the total thermal power introduced into the network. Regarding shared thermal energy, a scheme of the energy fluxes during the smart district heating operation is provided in Figure 10. As an example, from the figure, it can be highlighted that user ID #14 is completely fulfilled by the production of prosumer ID #15; prosumer 15 also supplies part of the energy requested by user ID #13, whose needs are integrated with the TPP. The results of the distribution of the energy shared by the three smart users without thermal losses are presented in Figure 11, with reference to the typical winter and middle season/summer day. It follows that the total energy shared by the three smart users for one year of operation is slightly higher than 5000 MWh, divided as presented in Figure 12.



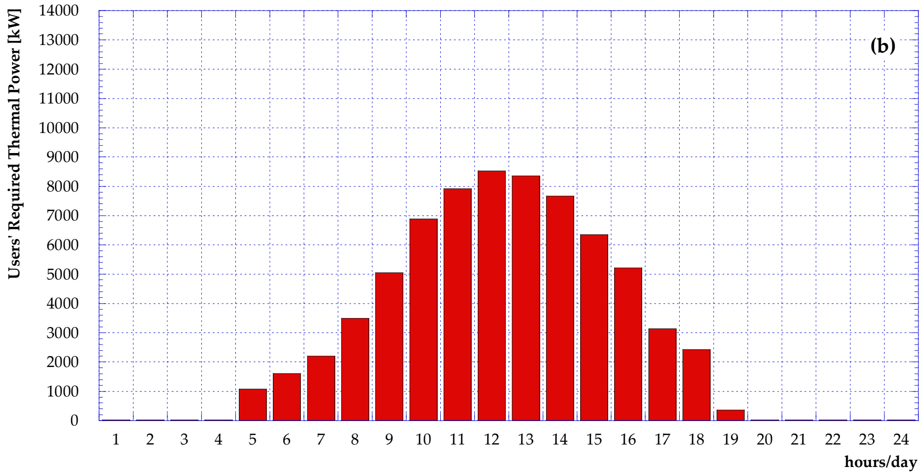


Figure 8. Users' required thermal power for (**a**) typical winter day and (**b**) middle season and/or summer day.

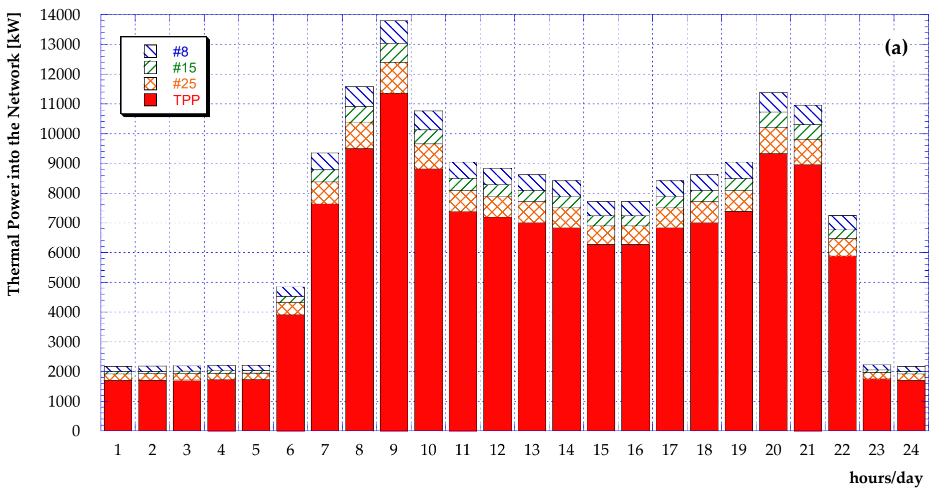


Figure 9. *Cont.*

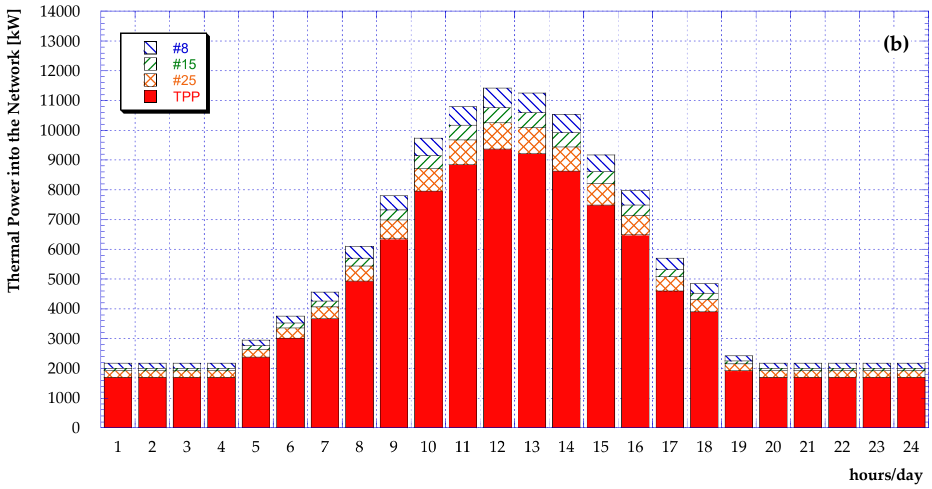


Figure 9. Thermal power introduced into the network via TPP and smart users for (**a**) typical winter day and (**b**) middle season and/or summer day.

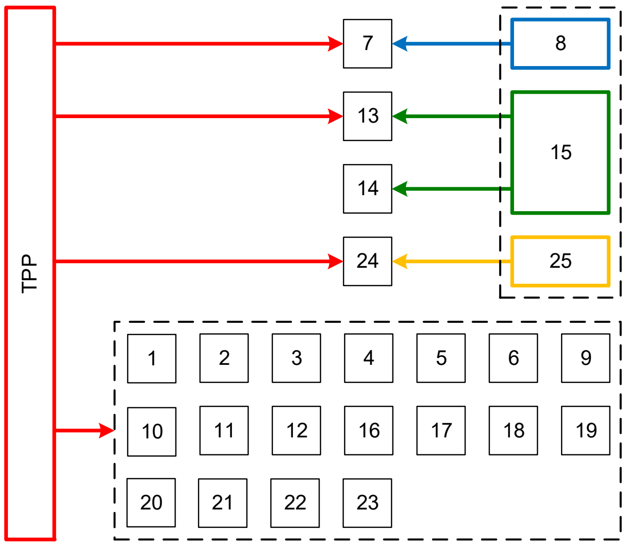


Figure 10. Energy flux distribution between TPP and smart users.

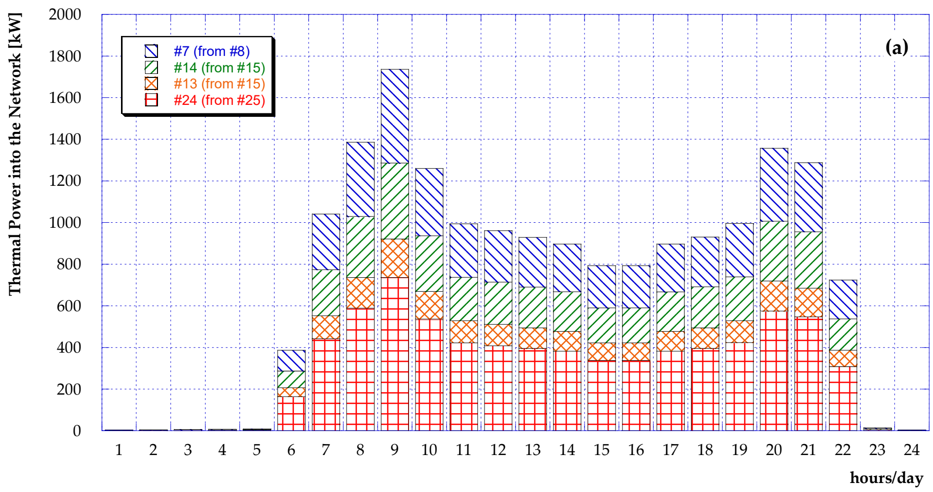


Figure 11. *Cont.*

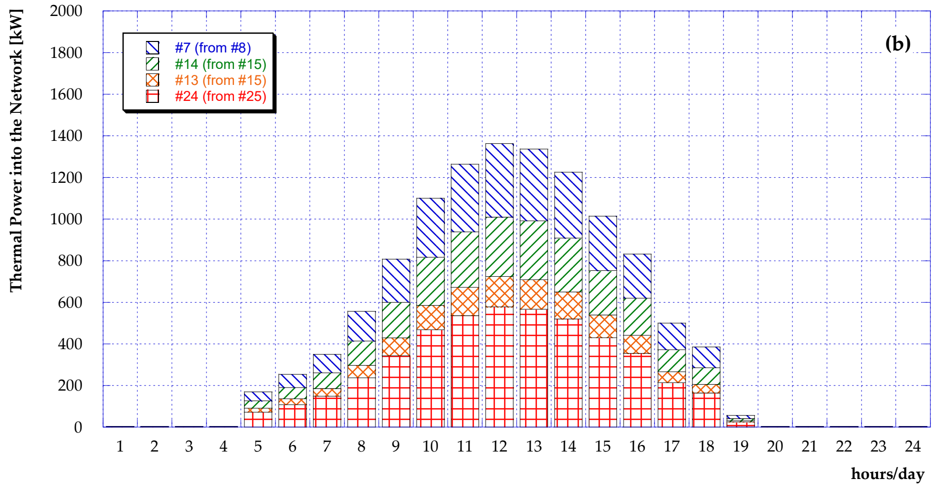


Figure 11. Shared thermal power: served users and sharing smart users for a (**a**) typical winter day and (**b**) middle season and/or summer day.

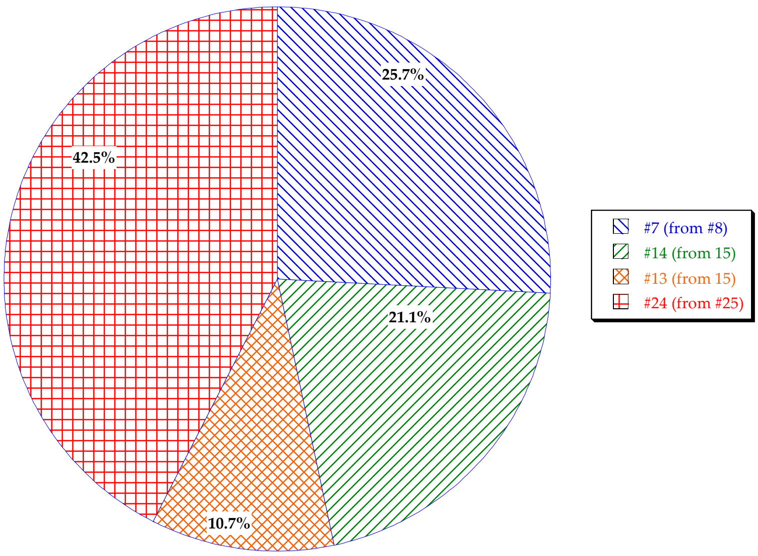


Figure 12. Total shared energy (5236 MWh) for one year of operation.

4. Virtual Shared Energy Allocation Algorithms

In general, depending on the topology of the district heating network, the energy fluxes starting from active users and directed to consumers (as reported in Figure 10) might not be so easy to trace. When this producer-to-user association is not trivial, a different approach that can be adopted in order to distribute the thermal energy injected into the network among the users can take inspiration from the methodologies adopted in the field of electric energy communities [14]. Indeed, differently to what happens in the framework of district heating networks, when the electric grid is considered, the concept of active users (or prosumers) is quite widespread and different techniques are present in the scientific literature that deal with the problem of shared energy allocation [21]. In fact, when the electric grid is considered, the introduction of the virtual concept of shared energy becomes necessary since it is not straightforward to identify the users who directly consume the energy injected into the grid by the active users. Therefore, the concept of virtual shared energy arises, and it is defined as follows:

$$\sum_{i}^{N} SH_{i,j} = min\left(E_{inj,j}, \sum_{i}^{N} C_{i,j}\right) \tag{2}$$

where $\sum_{i}^{N} SH_{i,j}$ is the total shared energy of the community each *j* (hour) to each *i*-th member (N is the total number of members), $E_{inj,j}$ is the total energy fed into the grid by the production plants (each *j*-hours), and $\sum_{i}^{N} C_{i,j}$ is the total energy purchased by the energy community members.

It can be interesting to borrow this concept from the field of electric energy communities and use it in the field of district heating networks, particularly when active users are present. Based on the work described in [21], the thermal shared energy is computed for the two typical days described in Section 3 and distributed among the users adopting method 1 and method 5, as they are described in [21] and briefly recalled here.

Method 1 assigns an amount of shared energy (for each hour analyzed) to each member, proportional to their consumption. As a result, this approach might not provide incentive for members to reduce their energy consumption. In order to take into account both the correlation between the energy consumed by the *i*-th member and the energy injected into the grid by production plants as well as to penalize users who consume more energy than is produced by the community production plants, method 5 has been developed. The results presented in the present paper are, therefore, analyzed by considering these two methodologies. In particular, Figures 13 and 14 show the results of the shared energy allocation among the users adopting method 1 and method 5, respectively.

As can be observed, method 1 assigns more energy to user 7 with respect to method 5, since user 7 is the one with the highest consumption. Method 5, on the other hand, tends to redistribute the shared energy equally among the users. This might be due to the fact that consumption is generally lower than the injected energy and that the time correlation of the consumption profiles is very similar among the users. These considerations are also reflected in Figure 15, which compares method 1 and method 5 for a typical winter day. In this figure it is apparent that the shared energy allocated by means of method 5 is higher than the one allocated to method 1 for the majority of the users.

Regarding results obtained for a typical middle season and/or summer day, Figures 16 and 17 show the results of the shared energy allocation among the users adopting method 1 and method 5, respectively.

Also, in this case, as previously observed for a typical winter day, method 5 provides a uniform allocation of the shared energy among the users, and this is also reflected in Figure 18.

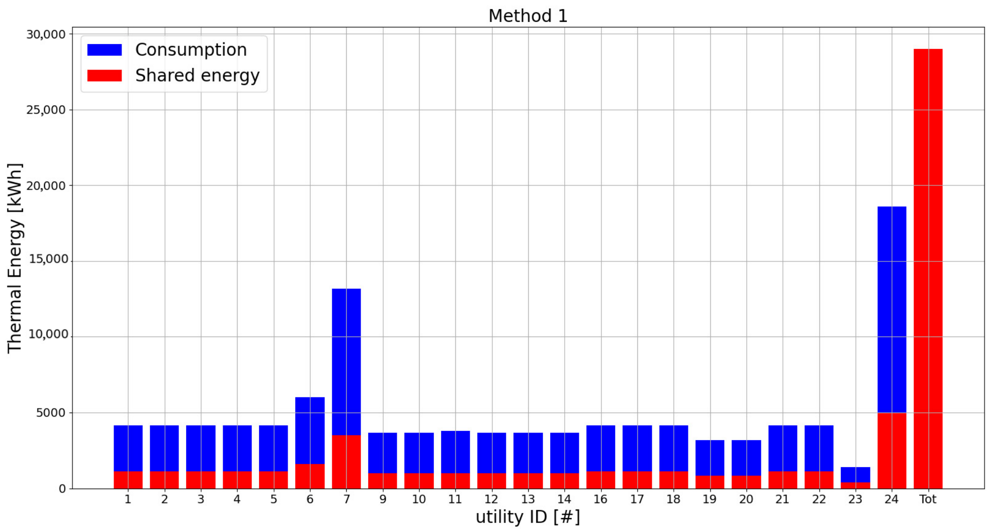


Figure 13. Shared thermal energy allocation according to method 1 [21] for a typical winter day.

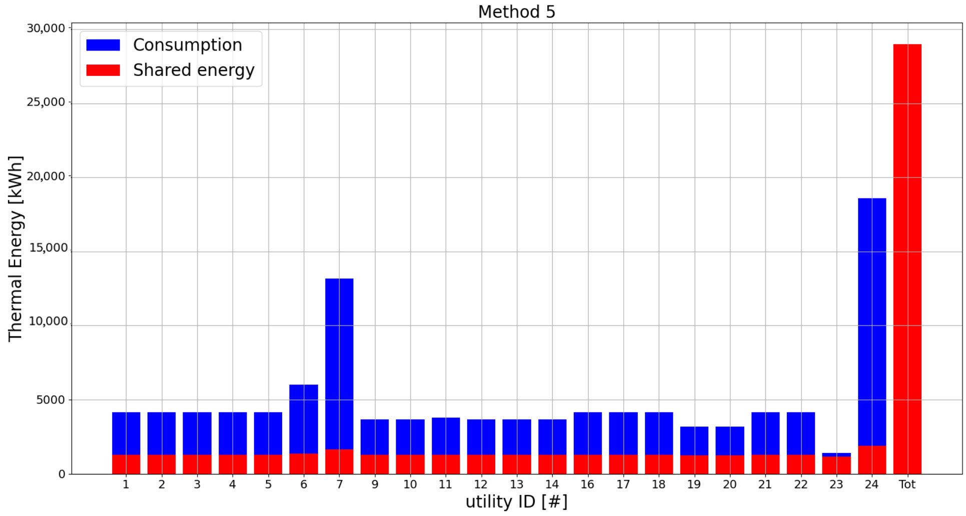


Figure 14. Shared thermal energy allocation according to method 5 [21] for a typical winter day.

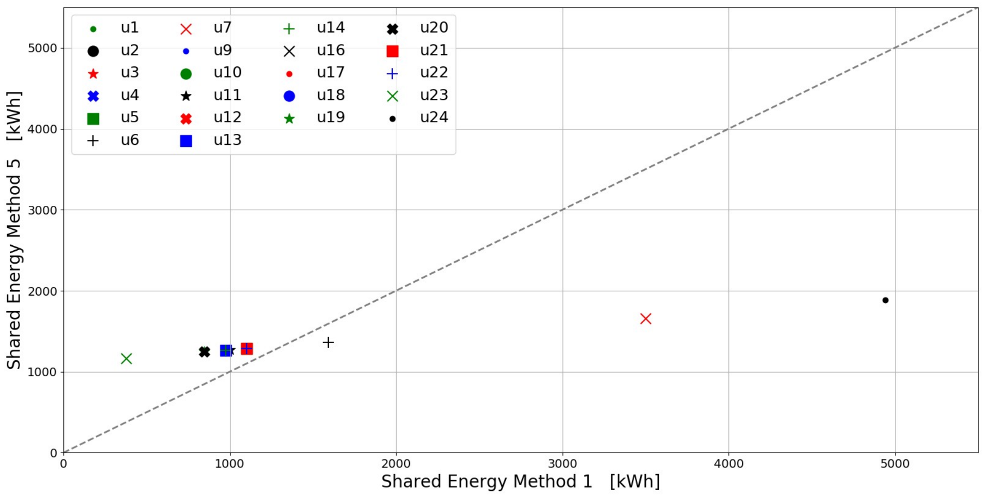


Figure 15. Comparison between the shared energy assigned via M1 and M5 [21] for a typical winter day.

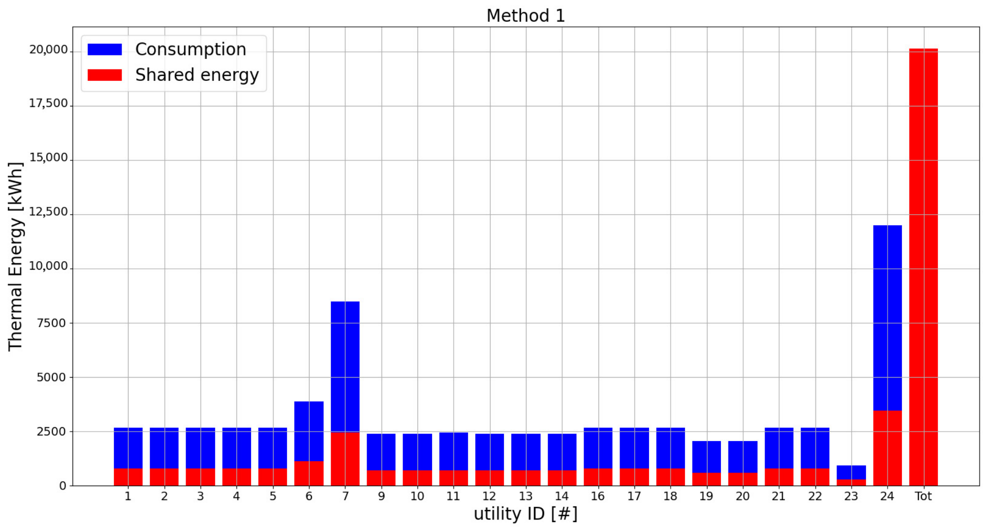


Figure 16. Shared thermal energy allocation according to method 1 [21] for a typical middle season and/or summer day.

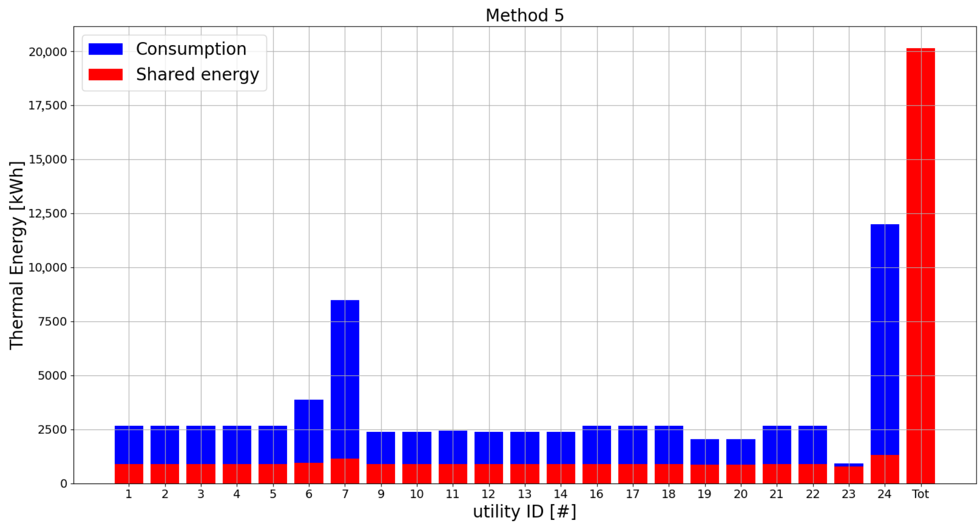


Figure 17. Shared thermal energy allocation according to method 5 [21] for a typical middle season and/or summer day.

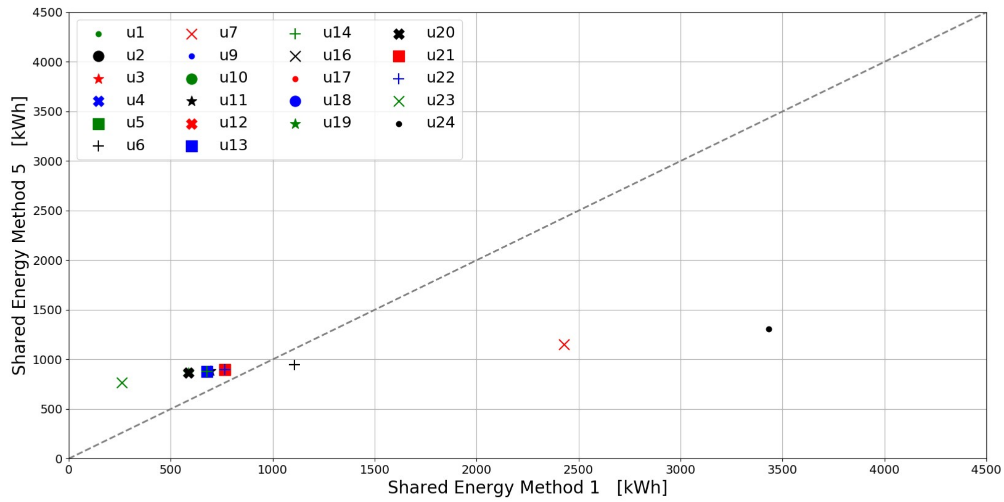


Figure 18. Comparison between the shared energy assigned via M1 and M5 [21] for a typical middle season and/or summer day.

It is important to notice that the shared energy allocation methods adopted in [21] do not consider any physical connections in the model, since they are developed in the framework of the electric energy community. Indeed, only energy consumption and production data are necessary to apply the sharing algorithm and assign a certain amount of shared energy to each user. This approach is robust, effective, and easy to apply for third-party-involved technicians who might not know anything about the network. Furthermore, if the network topology changes or if new prosumers arise, the sharing algorithms can be applied as they are (with updated energy data). Nevertheless, an interesting comparison can be conducted with respect to what is discussed in Section 3. On the basis of the authors' knowledge, this study, for the first time in the literature, highlights that in a thermal community based on a SDHN an evaluation of the allocation of the shared energy can be performed not only by using calculation algorithms adopted in the electrical energy communities but also by following the flows across the network (flows approach).

In this regard, even if a ring type DHN is not so easy, the flows approach always allows the identification of the feed-in points and the corresponding withdrawal points. It follows, as presented in the previous paragraph, that the shared energy would interest only a few users—those placed near the smart user/users. It might be thought that only the users that physically share the energy of the prosumers could access the benefits provided by the regulations envisaged or hypothesized in the literature. Nevertheless, the sharing of energy among some users of an SDHN can increase the efficiency of the whole network, reducing fossil fuel consumption and minimizing electrical consumption for the pumping station and thermal dissipations. These advantages can be maximized only if the SDHN operates at the hydraulic equilibrium point and this means that the users that do not physically use the shared energy must operate at appropriate consumption levels.

It follows that, on one hand, the flow approach for the allocation of the shared energy might be too restrictive, but the current algorithms, on the other hand, risk ignoring the reality of energy flows in the network, leading to unfair energy allocation. Therefore, the correct solution will probably include a mix of the two approaches, as will be analyzed and studied by the authors in the future.

5. Concluding Remarks

This study investigated a Thermal Energy Community realized via a Smart District Heating Network. The SDHN was realized and optimized using IHENA 9.3, developed by the University of Bologna, and it is characterized by a production plant and three smart users. The novelty of this study is the comparison between the allocation of shared energy via two different methodological approaches. On one hand, due to the network characteristics and topology, the shared energy was been allocated considering real feed-in points and corresponding withdrawn points (flows approach). On the other hand, some of the typical algorithms developed for the electrical framework of energy communities were applied for the same case study. A comparison of the results shows that neither of the two approaches completely considers all the aspects of this complex system and that a mix of the two approaches is probably the right way to allocate the shared energy in a SDHN that operates as a thermal community. These studies will be developed in future papers.

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References

1. Ruiz-Cortés, M.; Romero-Cadaval, E.; Roncero-Clemente, C.; Barrero-González, F.; González-Romera, E. Comprehensive Study of the Benefits of Integrating a Sharing Energy Strategy between Prosumers. In Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pp. 3609–3614.
2. Lowitzsch, J.; Hoicka, C.E.; van Tulder, F.J. Renewable Energy Communities under the 2019 European Clean Energy Package—Governance Model for the Energy Clusters of the Future? *Renew. Sustain. Energy Rev.* **2020**, *122*, 109489. [CrossRef]
3. Tostado-Véliz, M.; Jordehi, A.R.; Icaza, D.; Mansouri, S.A.; Jurado, F. Optimal Participation of Prosumers in Energy Communities through a Novel Stochastic-Robust Day-Ahead Scheduling Model. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108854. [CrossRef]
4. Tushar, W.; Yuen, C.; Saha, T.K.; Morstyn, T.; Chapman, A.C.; Alam, M.J.E.; Hanif, S.; Poor, H.V. Peer-to-Peer Energy Systems for Connected Communities: A Review of Recent Advances and Emerging Challenges. *Appl. Energy* **2021**, *282*, 116131. [CrossRef]
5. Butenko, A. Sharing Energy: Dealing with Regulatory Disconnection in Dutch Energy Law. *Eur. J. Risk Regul.* **2016**, *537*, 701–716. [CrossRef]
6. Gielen, D.; Boshell, F.; Saygin, D.; Bazilian, M.D.; Wagner, N.; Gorini, R. The role of renewable energy in the global energy transformation. *Energy Strategy Rev.* **2019**, *24*, 38–50. [CrossRef]

7. Volpato, G.; Carraro, G.; Cont, M.; Danieli, P.; Rech, S.; Lazzaretto, A. General Guidelines for the Optimal Economic Aggregation of Prosumers in Energy Communities. *Energy* **2022**, *258*, 124800. [CrossRef]
8. Brisbois, M.C. Shifting political power in an era of electricity decentralization: Rescaling, reorganization and battles for influence. *Environ. Innov. Soc. Transit.* **2020**, *36*, 49–69. [CrossRef]
9. Mucha-Kuś, K.; Sołtysik, M.; Zamasz, K.; Szczepańska-Woszczyna, K. Coopetitive Nature of Energy Communities—The Energy Transition Context. *Energies* **2021**, *14*, 931. [CrossRef]
10. Bauwens, T.; Schraven, D.; Drewing, E.; Radtke, J.; Holstenkamp, L.; Gotchev, B.; Yildiz, Ö. Conceptualizing community in energy systems: A systematic review of 183 definitions. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111999. [CrossRef]
11. Esposito, P.; Marrasso, E.; Martone, C.; Pallotta, G.; Roselli, C.; Sasso, M.; Tufo, M. A roadmap for the implementation of a renewable energy community. *Heliyon* **2024**, *7*, e28269. [CrossRef]
12. Mariuzzo, I.; Fioriti, D.; Guerrazzi, E.; Thomopulos, D.; Raugi, M. Multi-objective planning method for renewable energy communities with economic, environmental and social goals. *Int. J. Electr. Power Energy Syst.* **2023**, *153*, 109331. [CrossRef]
13. Gjorgievski, V.Z.; Cundeva, S.; Georghiou, G.E. Social arrangements, technical designs and impacts of energy communities: A review. *Renew. Energy* **2021**, *169*, 1138–1156. [CrossRef]
14. Hewitt, R.J.; Bradley, N.; Compagnucci, A.B.; Barlagne, C.; Ceglarz, A.; Cremades, R.; McKeen, M.; Otto, I.M.; Slee, B. Social Innovation in Community Energy in Europe: A Review of the Evidence. *Front. Energy Res.* **2019**, *7*, 31. [CrossRef]
15. Vicente, S.B.; Cordero, D.M.; Estopiñán, A.L.; Lamadrid, Á.Z.; Hernandez-Callejo, L. Technical evaluation of European and North American sustainable benchmark scenarios based on renewable Local energy Communities penetration. *Sustain. Energy Technol. Assess.* **2023**, *60*, 103556.
16. Reis, I.F.G.; Gonçalves, I.; Lopes, M.A.R. Henggeler Antunes. Business models for energy communities: A review of key issues and trends. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111013. [CrossRef]
17. López, I.; Goitia-Zabaleta, N.; Milo, A.; Gómez-Cornejo, J.; Aranzabal, I.; Gaztañaga, H.; Fernandez, E. European energy communities: Characteristics, trends, business models and legal framework. *Renew. Sustain. Energy Rev.* **2024**, *197*, 114403. [CrossRef]
18. Gianaroli, F.; Preziosi, M.; Ricci, M.; Sdringola, P.; Ancona, M.A.; Melino, F. Exploring the academic landscape of energy communities in Europe: A systematic literature review. *J. Clean. Prod.* **2024**, *451*, 141932. [CrossRef]
19. European Commission. Clean Energy for All European Package. 2016. Available online: https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en (accessed on 24 April 2024).
20. European Commission. The European Green Deal. 2019. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en (accessed on 24 April 2024).
21. Official Journal of the European Union. *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast)*; L 328/82, 21 December 2018; Official Journal of the European Union: Luxembourg, 2018.
22. Huang, Z.; Zhu, T.; Gu, Y.; Irwin, D.; Mishra, A.; Shenoy, P. Minimizing Electricity Costs by Sharing Energy in Sustainable Microgrids. In Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings, Association for Computing Machinery, New York, NY, USA, 16 October 2018; pp. 120–129.
23. Lin, C.-C.; Wu, Y.-F.; Liu, W.-Y. Optimal Sharing Energy of a Complex of Houses through Energy Trading in the Internet of Energy. *Energy* **2021**, *220*, 119613. [CrossRef]
24. Italian Law 28 February 2020, No. 8. Conversion into law, with amendments, of Decree-Law No. 162 of 30 December 2019, containing urgent provisions on the extension of legislative terms, the organization of public administrations, and technological innovation. Official Journal General Series No. 51 of 29.02.2020—Ordinary Suppl. No. 10. Available online: https://www.gazzettaufficiale.it/eli/id/2020/02/29/20G00021/sg (accessed on 24 April 2024).
25. Gianaroli, F.; Ricci, M.; Sdringola, P.; Ancona, M.A.; Branchini, L.; Melino, F. Development of dynamic sharing keys: Algorithms supporting management of renewable energy community and collective self consumption. *Energy Build.* **2024**, *311*, 114158. [CrossRef]
26. Fouladvand, J. Why and how can agent-based modelling be applied to community energy systems? A systematic and critical review. *Energy Res. Soc. Sci.* **2024**, *114*, 103572. [CrossRef]
27. Fouladvand; Ghorbani, A.; Mouter, N.; Herder, P. Analysing community-based initiatives for heating and cooling: A systematic and critical review. *Energy Res. Soc. Sci.* **2022**, *88*, 102507. [CrossRef]
28. Papatsounis, A.G.; Botsaris, P.N.; Katsavounis, S. Thermal/Cooling Energy on Local Energy Communities: A Critical Review. *Energies* **2022**, *15*, 1117. [CrossRef]
29. Okur, Ö.; Fiori, F.; Fouladvand, J. Adoption of renewable heating systems and thermal energy communities in the Netherlands: An empirical study. *Energy Reports* **2024**, *11*, 3815–3823. [CrossRef]
30. González, A.; Arranz-Piera, P.; Olives, B.; Ivancic, A.; Pagà, C.; Cortina, M. Thermal energy community-based multi-dimensional business model framework and critical success factors investigation in the mediterranean region of the EU. *Technol. Soc.* **2023**, *75*, 102328. [CrossRef]
31. Official Journal of the European Union. *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955 (Recast)*; L 231/1, 20 September 2023; Official Journal of the European Union: Luxembourg, 2023.

32. Ancona, M.A.; Branchini, L.; Di Pietra, B.; Melino, F.; Puglisi, G.; Zanghirella, F. Utilities substations in smart district heating networks. *Energy Procedia* **2015**, *81*, 597–605. [CrossRef]
33. Lennermo, G.; Lauenburg, P.; Werner, S. Control of decentralised solar district heating. *Sol. Energy* **2019**, *179*, 307–315. [CrossRef]
34. Heymann, M.; Rühling, K.; Felsmann, C. Integration of Solar Thermal Systems into District Heating—DH System Simulation. *Energy Procedia* **2017**, *116*, 394–402. [CrossRef]
35. Todini, E. Towards Realistic Extended Period Simulations (EPS) in Looped Pipe Networks. In Proceedings of the Water Distribution Systems Analysis Symposium, ASCE, Cincinnati, OH, USA, 27–30 August 2006; pp. 1–16.
36. Alleori, R.; Ancona, M.A.; Branchini, L.; Melino, F.; Ottaviano, S. Performance assessment of smart district heating networks: The influence of distributed cogeneration on the network primary energy consumption. In Proceedings of the ASME Turbo Expo 2024, Turbomachinery Technical Conference and Exposition, GT2024, London, UK, 24–28 June 2024.
37. Ancona, M.A.; Branchini, L.; De Pascale, A.; Melino, F. Smart District Heating: Distributed Generation Systems' Effects on the Network. *Energy Procedia* **2015**, *75*, 1208–1214. [CrossRef]