Mutual-benefit of district heating market and network operation for prosumers integration

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ABSTRACT

The integration of prosumers (consumers who can both consume and produce energy) in a current district heating network (DHN) brings new challenges to the market and DHN operation, since they can change the thermal flow in the DHN and increase competition in the district heating market.

In this scope, this work proposes the implementation of a coordination methodology based on a peer-to-peer (P2P) market to enable bilateral energy trades between producers, prosumers and consumers, coupled with the DHN operation.

A Nordic DHN containing prosumers is used to test and validate the proposed methodology. The results point out that the coordination methodology is able to provide compromise solutions between the market negotiation and the DHN operation. An important conclusion is that the coordination methodology encourages prosumer integration in DHN, increasing market competition that may pull down the energy costs for consumers while avoiding DHN's operating and management burdens.

KEYWORDS

District heating network; District heating market; peer-to-peer market; energy exchange; prosumer; thermal flow.

INTRODUCTION

Over the last years, district heating markets have been in a process of deregulation and liberalization, opening the doors to the inclusion of new players in district heating systems. These new players are known as prosumers (consumers that can both consume and produce heating energy), which are supported through the recent technological advances in waste heat recovery. They can actually reuse surplus thermal energy and even inject it into the district heating network (DHN) [1]. This is the case with supermarkets [2], data centers [3], paper mill [1] among other industries [4], [5] equipped with waste heat recovery units, heat pumps and renewable heating plants, which are able to consume and produce heat at different periods of the day, becoming prosumers [6]. End-users as small buildings can also behave as prosumers if equipped with excess heat recovery systems [7].

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The integration of these players in the current DHNs brings new challenges to the market and DHNs operation. More precisely, the prosumer will change DHN's current operating and management practices as it can change the thermal flow in the DHN, simultaneously increasing competition in the district heating market.

At the DHN operating level, several studies have been addressing advantages and problems that prosumers bring to the system. More precisely, prosumers can introduce operational problems related to the bidirectional flow in the DHN, differential pressure and velocity in the pipes, which may require analysing pipes dimensions before introducing prosumers in the DHN [ref4]. At the market level, prosumers will enforce the complete deregulation of the market, adding competitiveness to the system. More precisely, the marginal price of prosumers is often lower than the conventional sources, thereby, improving market performance, i.e., increasing the system's social welfare [8].

There are some studies addressing how prosumers can be integrated into the market, proposing market models and frameworks to allow the exchange of excess heat recovery. Some studies have been addressing the value that one-side and two-side auctions can bring to increase the competitiveness in DHN, yet ignoring prosumers integration and DHN potential operation problems [9]–[11]. The Open District Heating project [12] uses the pool market design based on the uniform system price to encourage industrial excess heat units (prosumers) to exchange in the market. However, the market and system operator roles are performed by the same entity. In contrast, a local thermal energy market is addressed in [13], which accounts for the different roles of producers, consumers, market and system operators, similarly to current electricity markets. The market operator is responsible for establishing the pool market, while the system operator is responsible for operating the DHN, establishing setpoints for producers and prosumers, according to the market results and system operating requirements.

Consumer-centric market models for increasing prosumers proliferation in the district heating are proposed in [14]. It proposes and compares different market designs (namely, pool, peer-to-peer (P2P) and community) for district heating considering the role of the prosumer. The DHN operation is disregarded, yet providing suggestions to include it in the market operation through a product differentiation mechanism.

None of the studies above clearly addresses the interdependencies between the market and DHN operators considering the prosumer integration in the system. To overcome this gap, new models to coordinate the market and DHN problems under prosumers integration are essential. In this scope, this work proposes a coordination methodology able to integrate market solutions in the DHN operation, ensuring a compromising solution to the whole system. This coordinative approach is inspired by the power sector [15]. More precisely, the market framework is built upon the P2P market considering the product differentiation mechanism, i.e., producers and consumers can choose to whom they want to exchange thermal energy. Then, the market solution is validated at the DHN based on a simplified thermal flow algorithm capable of validating the setpoints of producers and consumers at the DHN. In case of occurring DHN operating issues, the trades that create technical issues are updated in the market with a penalty based on the network distance between the peers, through the product differentiation mechanism. This iterative and coordinated process is performed until there are no issues in the DHN operation. The main contributions of the present work are twofold:

- To explore a mutual-benefit approach of the P2P market applied to DHNs, considering DHN operation. It considers the product differentiation mechanism to influence market solutions, following a thermal flow validation of the DHN;
- And to test and validate the proposed approach on a typical Nordic DHN, including multiple producers and prosumers.

The rest of the paper is organized as follows. Section 2 shows the iterative coordination methodology, accounting for the P2P market and DHN operation. Section 3 presents the case study based on a Nordic DHN considering multiple producers, consumers and prosumers. The proposed approach is compared with a benchmark approach. Section 4 gathers the most important conclusions of the present work.

COORDINATING APPROACH FOR THE MARKET AND DHN OPERATION

P2P market considering product differentiation mechanism

The P2P market structure defines bilateral trades between several market participants/players (namely, producers, consumers and prosumers), to increase agents' engagement in the market. The market structure is based on a purely decentralized model, allowing each player to exchange energy with any other player in the market without any supervising entity. The main purpose is to meet the requirements of agents and maximize revenue. The full P2P market design can be changed by applying product differentiation, namely, adding a benefit or penalty to each bilateral trade according to the preferred preference, such as geographical distance or heat losses. More precisely, the product differentiation mechanism allows consumers to set preferences with whom they want to exchange energy based on economic, environmental, technical or even social specificities. For instance, consumers may give priority to trade energy with their neighbours through the geographical distance preference. The full mathematical formulation of the P2P market model considering product differentiation is presented as follows:

$$\min_{D} \sum_{t}^{T} \left[\sum_{n \in \Omega_n} C_{t,n} P_{t,n} + \sum_{n \in \Omega_n} \sum_{m \in \Omega_n} c_{n,m} \, P_{t,n,m} \right] \quad (1)$$

$$P_{t,n} = \sum_{\mathrm{m} \in \Omega_{\mathrm{n}}} P_{t,n,m} \,, \; \forall \; \mathrm{n} \in \Omega_{\mathrm{n}}, \forall \; t \in T \quad (2)$$

$$\underline{P}_{t,n} \le P_{t,n} \le \overline{P}_{t,n}, \forall n \in \Omega_n, \forall \; t \in T \quad (3)$$

$$P_{t,n,m} + P_{t,m,n} = 0, \forall \{n, m\} \in \{\Omega_n\}, \forall \; t \in T \quad (4)$$

$$P_{t,n} \le 0, n \in \Omega_c, \forall t \in T \quad (5)$$

$$P_{t,n} \ge 0, \forall n \in \Omega_p, \forall t \in T \quad (6)$$

where Equation (1) represents the objective function composed by the energy exchange and product differentiation mechanism, respectively. The aim is to maximize social welfare, which can also be represented by minimizing operating costs in the market. Equation (2) states that the total heat traded by an agent n at time step t in the market must be equal to the sum of the heat traded by this agent with all the other agents $m \in \Omega_n$. Equation (3) establishes the upper and lower heat boundaries traded by agent n at time step t. Equation (4) sets the reciprocity of the model, meaning the trade from agent n to agent m is symmetrical to the one of agent m to agent n, for each time step t. Equations (5) and (6) define a negative or positive heat power at each time step t, whether an agent n is a consumer or a producer, respectively.

Note that the prosumer behaves either as a producer or as a consumer in the market, but not at the same time step t. For each time step t, the expected net balance (generation - consumption) of the prosumer n is settled before participating in the market, thereby the prosumer knows if it needs to sell or buy heat in the market.

The product differentiation mechanism, present in the objective function, works as a benefit or penalty linked to a heat trade between two agents. Product differentiation can be addressed by different means, such as geographical distance, heat losses or CO_2 emissions [14]. Within the scope of this work, geographic distance has been adopted as a consumer preference. Thus, a trade between agents *n* and *m* is penalized according to the distance and the higher the distance between them, the higher the penalty will be. The penalty factor $c_{t,n,m}$, often translated as a cost, can be defined as:

$$c_{n,m} = \frac{D_{n,m}}{Total\ Distance}\ \forall\{n,m\} \in \{\Omega_n\} \quad (7)$$

where $D_{n,m}$ is the geographical distance between agents *n* and *m* and $Total\ Distance$ is the total network distance.

District heating network operation and management

This section intends to expose the network operation and management methodology applied throughout this work. In this section, it is presented a nodal method to verify and validate the DHN operation (inspired by the power sector), once the market solution is known, instead of using a conventional optimal thermal control method. Note that this is a simplified method that does not take thermal losses into account. First of all, after the market settlement, it is necessary to determine the heat flowing in each pipeline for each time step ($H_{t,i,j}$). To do so, we assume that the B matrix is defined according to:

$$B_{i,i} = \sum_{i \neq j} \frac{1}{D_{i,j}} \quad , \quad B_{i,j} = -\frac{1}{D_{i,j}}\ (i \neq j), \qquad \forall\{i,j\} \in \Omega_{pip} \quad (8)$$

where B is symmetric and singular. $D_{i,k}$ represents the geographical distance between nodes *i* and *j*. In the next step, a node is selected to be the reference one and its row and column are removed from the B matrix, defining B' matrix. Generally, the node with the highest injected power is selected. In this case of the DHN, the node referring to the combined heat and power (CHP) unit. By inverting B' matrix, the Z matrix is set.

$$Z = (B')^{-1} \quad (9)$$

Then, a row and a column of zeros are added to the Z matrix at the reference node position. After that, the angle of each node is calculated through:

$$\theta_{t,i} = \sum_{n \neq REF} Z_{t,i,n} P_{t,n}\ , \forall\ i \neq REF, \forall t \in T \quad (10)$$

where $P_{t,n}$ represents the total heat traded/scheduled by agent *n* in the market, in time frame t. Whether the node linked to an agent *n* is a heat producer or a consumer, P_n will be positive or negative, respectively. Finally, the heat in a pipeline for each time frame *t* can be determined as:

$$H_{t,i,j} = \frac{\theta_{t,i} - \theta_{t,j}}{D_{i,j}}, \forall\{i,j\} \in \Omega_{pip}, \forall t \in T \quad (11)$$

Therefore, since DHN management is based on the heat transfer laws and in the flow velocity, the volumetric flow rate in a pipe ($Q_{t,i,j}$) is given by:

$$Q_{t,i,j} = \frac{H_{t,i,j}}{C_\rho\, \rho\, \Delta T}, \forall\{i,j\} \in \Omega_{pip}, \forall t \in T \quad (12)$$

where C_ρ is the specific heat capacity of the fluid circulating in the pipes (we assume water in the case of DHN). ρ is the density of the fluid and ΔT is the difference between the supply and return temperatures. Afterwards, it is determined the area of each pipeline $A_{t,i,j}$ in the DHN based on the expected flow of the fluid, represented by the equation (13). If the required/calculated area is lower than the pipelines' area specifications, the market solution is feasible in terms of DHN operation.

$$A_{t,i,j} = \frac{Q_{t,i,j}}{V_{t,i,j}}, \forall\{i,j\} \in \Omega_{pip}, \forall t \in T \quad (13)$$

Iterative coordination approach

The iterative process intends to find a compromising solution between the market optimization and the DHN operation, as depicted in Figure 1. The idea is to solve the market problem and verify its solution in terms of DHN operation feasibility, iteratively.

Step 1: The iterative coordination approach, starts with the market problem without the product differentiation mechanism, i.e., $C_{n,m} = 0$. The outcomes of the market are the bilateral trades ($P_{n,m}^{k*}$), the power setpoint of each player n (P_n^{k*}) and the clearing price for each trade ($\lambda_{n,m}^{k*}$).

Step 2: The market solution is tested and verified on the DHN operating model, checking for feasibility issues. In case the market solution is unfeasible in the DHN operation, all trades ($P_{n,m}^{k*}$) causing the unfeasibility are selected and penalized (Step 3). Otherwise, the market solution is technically feasible and therefore the iterative process is finished (Step 5).

Step 3: In case of DHN unfeasibility, all trades causing the network issue are selected and a penalty is generated in line with the geographical distance between those agents ($C_{n,m}^{k+1}$). In case the number of iterations is lower than 5, the iterative approach continues by calling step 1 to run the P2P market considering new penalties ($C_{n,m}^{k}$). In case the grid congestion remains after 5 iterations, it is assumed that there are convergence issues and, therefore, Step 4 is activated.

Step 4: Once the penalty per transaction is insufficient to modify the market solution and find a compromising solution, it means that load consumption is higher than the DHN distribution capabilities. In this case, the only way to obtain a DHN feasible solution is to enforce load shedding. The consumers that are causing the unfeasibility of the DHN are selected, and their scheduled heating demand in the market from the last iteration is updated by reducing it by 1%. Afterwards, the market (Step 1) is run again with updated heating demand limits. The process is repeated by adding new load curtailment of 1% until the DHN operation is feasible.

Step 5: The market solution is technically feasible, as it can be operated in the DHN, and the heat dispatched by the agent (P_n^{k*}), the bilateral trades ($P_{n,m}^{k*}$) and the market clearing price per bilateral trade ($\lambda_{n,m}^{k*}$) is settled.

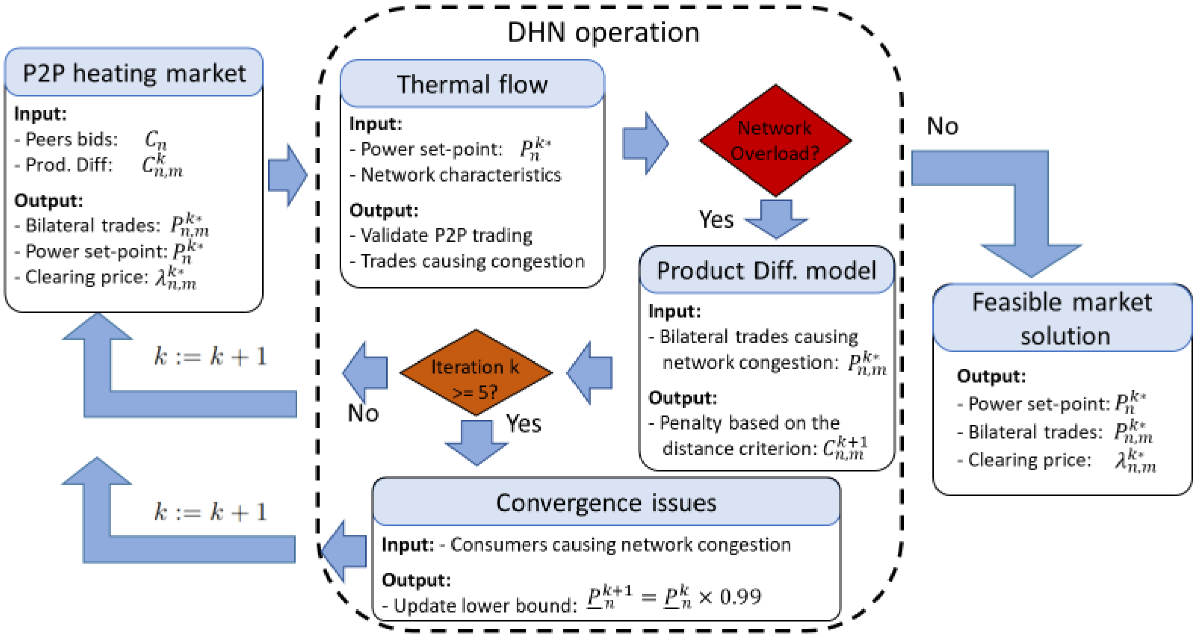

Figure 1. Iterative process flow chart.

CASE STUDY

Data Description

The data used in this work is based on a Nordic DHN test case available in [14], considering minor adjustments. One year generating, consumption and pricing profiles were taken from [14], while nine row houses with the same consumption and pricing patterns were added to this test case. The schematic diagram of the DHN is depicted in Figure 2.

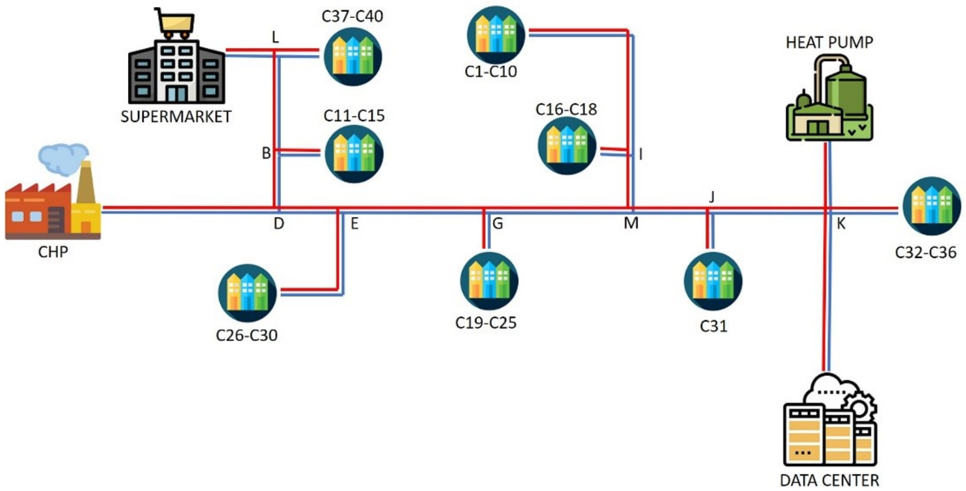

Figure 2. Illustrative district heating network.

Other input data required to run the P2P market model via product differentiation, were retrieved based on the THERMOS project tool [16]. This tool is able to provide the distance (Table 1) between agents and the pipelines' diameter (Table 2) based on the supply and return temperatures, and on the maximum heat flow in the pipelines.

Table 1. Distance between agents.

	Distance (m)			
Agent	CHP	Supermarket	Data Center	Heat Pump
C1-C10	266.24	181.25	206.15	174.96
C11-C15	190.76	20.47	168.58	199.06
C16-C18	228.66	143.67	230.27	137.38
C19-C25	175.25	90.26	158.21	127.01
C26-C30	196.37	111.38	224.52	193.31
C31	259.32	174.33	122.23	94.28
C32-C36	295.01	210.02	102.91	71.71
C37-C40	270.59	75.08	310.09	278.89
Supermarket	201.37	-	240.87	209.67

Table 2. Pipelines' diameter.

From	To	Diameter (mm)
Supermarket	L	32
L	B	25
L	C37-C40	32
B	C11-C15	32
B	D	32
D	E	32
E	C26-C30	25
E	G	32
G	C19-C25	25
G	M	25
I	C1-C10	25
I	C16-C18	20
M	I	32
M	J	32
CHP	D	32
Heat Pump	K	32
Data Center	K	32
K	C32-C36	20
J	C31	20
J	K	32

General Results

To properly validate and compare the performance of the proposed method, we use a benchmark method. The benchmark consists of the market simulation disregarding product differentiation, i.e., the benchmark solution refers to the first step of the proposed method, corresponding to the single P2P market simulation. Afterwards the iterative process starts. Figure 3 shows the number of hours that the DHN is congested for both the benchmark and proposed iterative methods. One can see that, in the worst case of congestion, 38 iterations are necessary to reach a feasible network operation, where no pipelines are congested. When considering the benchmark, there are 166 hours with network burdens in at least one pipeline, since no penalty based on the distance is applied and the market is settled in a standardized way. Once the iterative model is placed and product differentiation is applied (Iteration 1), the number of hours with network congestion drop to just 11, which means that 93,37% of congested hours are solved in a single iteration. In iteration 5, load curtailment is applied and another hour is cleared. After that, the iterative process from Figure 1 continues and the last pipeline to get a feasible result is the one connecting the CHP to node D at hour 5962.

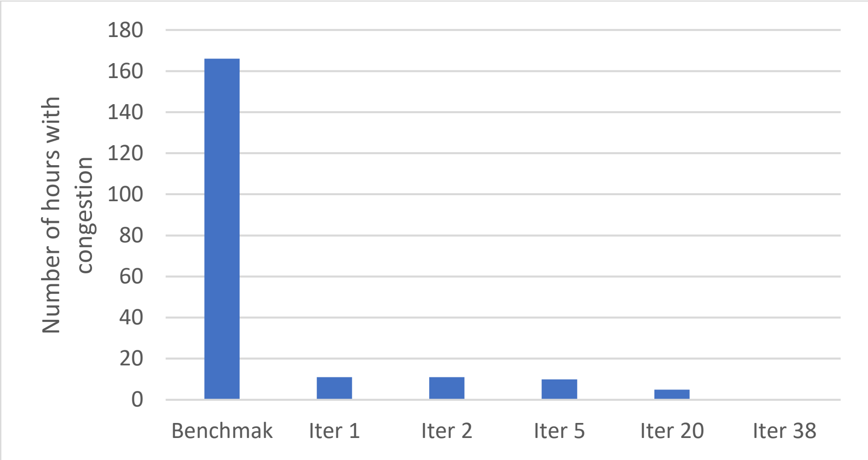

Figure 3. The number of network congested hours for the benchmark and iterative method (over iterations).

Table 3Table 3 gathers the overall revenue and energy dispatch results for both methods, accounting for iterations 1 and 38. Looking at the results from the benchmark and iteration 1, one can see that CHP is the most affected agent in the iterative process since the dispatched heat decreases by about 8%. In regards to other agents, the opposite effect is shown, the dispatched heat increases, as these are the closest peers to the consumers. This is expected since distance preference is used in the product differentiation mechanism. The total load also decreases as expected and the 70% threshold is met in iteration 1 for time frames in which network management is unreliable. From then until iteration 4, there are no substantial differences in results, because the penalty from product differentiation is not enough to achieve feasible results.

From iteration 5 onwards, load shedding is mandatory to tackle the network issues. All agents are getting the same revenue and dispatched heat from iteration 1 to 39, except the CHP, pointing out that the major management burdens are caused by the pipelines used by this agent. A revenue decrease of less than 0.07% is stated when analysing the load revenue after the first iteration, enhancing the good performance of the method while accomplishing network feasibility.

Table 3. Total revenue and heat dispatched for each agent type.

	Benchmark		Iteration 1		Iteration 38	
Agent	Revenue (€)	Dispatched Heat (kWh)	Revenue (€)	Dispatched Heat (kWh)	Revenue (€)	Dispatched Heat (kWh)
CHP	162024	341473	156784	315461	156277	314912
Supermarket	5672	40272	5704	40515	5704	40515
Data Center	92644	462071	95714	472327	95714	472327
Heat Pump	7495	16229	8402	18334	8402	18334
Load	455555	860045	448446	846637	448156	846088

Individual Hour Assessment

By analysing an individual hour like 2613, one can understand what is happening in each iteration and the effects of the iterative process on the market. The benchmark presents overload in 4 pipelines across the network. Looking at Figure 4, it can be seen that 3 of these lines manage to solve network congestion after the first iteration. After iteration 4, the pipeline CHP-D is still congested. From there on, the load shedding process starts and all heat consumers supplied by the CHP curtail the load to release congestion level in the pipeline CHP-D. The CHP, as a major heat producer, is supplying almost all consumers (except C32 to C36, the farthest ones), which forces a load decrease in all downstream pipelines, justifying the decrease in the level of load of pipelines that do not have any congestion problem. When network management is finished (Iteration 28), the market is settled and the iterative process is completed for this hour.

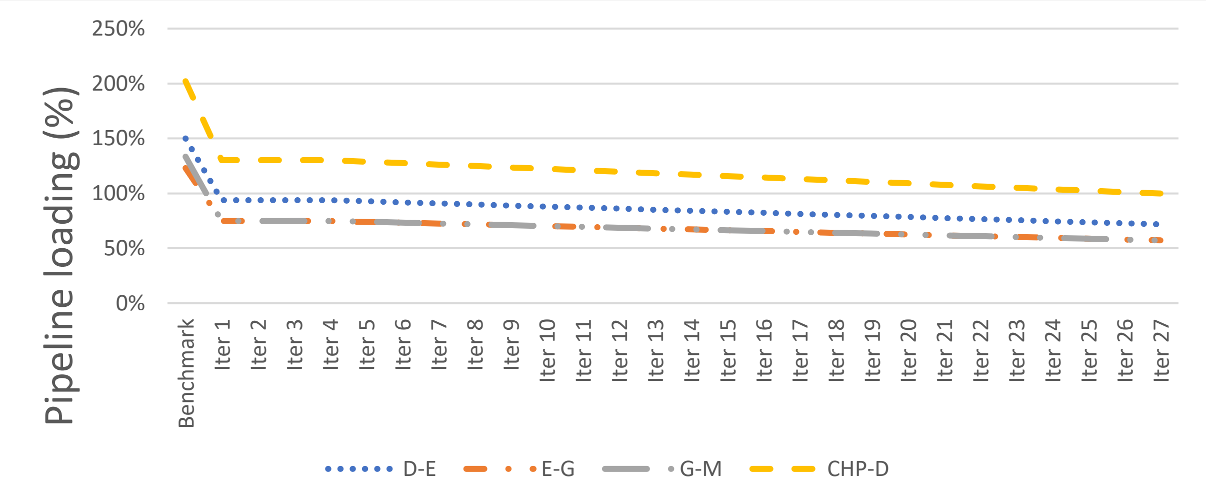

Figure 4. Level of congestion in several pipelines at hour 2613.

Congested pipelines diameter increase

A potential solution to solve congestion in pipelines is to increase its diameter instead of constraining the market, as we proposed in this study, although it is a very expensive solution. Thus, we have increased the diameter of the congested pipes (CHP-D, D-E , E-G to 40 mm from 32 mm, and G-M to 32 mm from 25 mm) to test whether this solution is sufficient to solve all the aforementioned congestion problems.

Table 4. Revenue and dispatched heat by agent following diameter increase.

	Benchmark		Iteration 1	
Agent	Revenue (€)	Dispatched Heat (kWh)	Revenue (€)	Dispatched Heat (kWh)
CHP	162024	341473	161718	340242
Supermarket	5672	40272	5672	40272
Data Center	92644	462071	92735	462375
Heat Pump	7495	16229	7556	16364
Load	455555	860045	455136	859252

As expected, the problem reaches convergence faster, requiring only an iteration. The benchmark results are the same, as the network constraints have not yet been applied. When considering the entire year, only 6 hours have a network overload. The distance penalty is enough to manage the network congestion, therefore, the problem is solved in a single iteration.

When considering the yearly revenue from the heat consumers, there is a decrease of about 0.09%, while for the initial diameters there is a decrease of 1.62% in load revenue from the first iteration until the iterative method converges. Furthermore, this solution achieves a higher load demand (1.53%) than the initial one. This kind of trade-off solution must be addressed by network operators.

CONCLUSION

Given the evolution witnessed in recent years of district heating, this work also aims to contribute to this, presenting a methodology to face the inconveniences that a decentralized market may bring to the DHN operation. Through penalties on the trades that are causing congestion in the pipelines (product differentiation mechanism), a market dispatch reallocation can be performed in order to validate the market and to assist the DHN operator.

The overall results indicate that the implemented solution is effective in finding and dealing with heat flow in the network. Only in 1.8% of the hours, network troubles are found and only in 0.12% of the hours, these problems are not fixed after applying product differentiation. These burdens are kept until iteration 5, meaning that there is only a partial load shedding in 11 hours of the entire year, which causes a minor impact on the earned revenue. Note that the proposed iterative method makes strategic decisions, cutting only the loads causing the flow congestion. DHN with an improved pipeline diameter is also analyzed to test the performance of the algorithm. An important conclusion is that the proposed iterative approach can be of great interest for district heating market and network operators, as it is able to provide a trade-off solution between the market and network operation.

Future work will focus on improving the developed method, considering a more complex and accurate DHN operating model. Other features will also be implemented, for instance, using CO_2 signals or global heat losses as preferences in product differentiation. In addition, the proposed method will be tested and validated in a larger case study, aiming to assess the method's flexibility and scalability.

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NOMENCLATURE

Sets and indexes

t	Time period index
n	Agents index
m	Agents index
Ω_n	Set of agents *n*
Ω_m	Set of agents *m*
Ω_c	Set of consumers
Ω_p	Set of producers
Ω_{pip}	Set of pipelines

Parameters

$C_{t,n}$	Agent *n* bid in time frame *t*
$c_{n,m}$	Penalty between trade *n,m*
$\underline{P}_{t,n}$	Heat power lower bound of agent *n* in time frame *t*
$\overline{P}_{t,n}$	Heat power upper bound of agent *n* in time frame *t*
$D_{n,m}$	Geographical distance between agents *n* and *m*
$B_{i,j}$	Element of matrix B representing the nodes *i* and *j*
C_ρ	Specific heat capacity of water
ρ	Density of water
ΔT	Difference between supply and return temperatures
$V_{t,i,j}$	Water velocity in pipeline *i,j* in time frame *t*

Variables

$P_{t,n}$	Agent *n* heat power in time frame *t*
$P_{t,n,m}$	Heat power trade between agents *n* and *m* in time frame *t*
$\lambda^{k*}_{n,m}$	Market clearing price for trade *n,m*
$\theta_{t,i}$	Angle of node *i* in time frame *t*
$H_{t,i,j}$	Heat in the pipeline *i,j* in time frame *t*
$Q_{t,i,j}$	Volumetric flow rate
$A_{t,i,j}$	Required are for the pipeline *i,j* in time frame *t*

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