Characteristics and Challenges in Prosumer-Dominated Thermal Networks

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Abstract. Prosumer-dominated thermal networks interconnect distributed prosumers. These networks form the infrastructure that allows to execute the trading of thermal energy as desired in the context of local energy markets. However, the significantly different behavior of such networks compared to conventional district heating and cooling networks has not yet been comprehensively investigated. This paper provides a compilation of instrinsic characteristics of prosumer-dominated thermal networks and discusses challenges that arise from these characteristics. As a basis for the investigations an underlying reference concept for the considered type of networks is described. Simulative case studies are combined with scientific deduction and literature references to gain new insights on the design and operation of this type of networks. It is found that due to the variability in these networks, the definition of a design case is a challenge for the dimensioning of concrete network implementations. To anticipate the strong coupling between prosumers and the nonlinear network behavior, it is concluded that centralized control combined with a model of the physical network behavior is necessary. The discussion of characteristics and challenges in prosumer-dominated thermal networks indicates open points in this field and thus provides a starting point for consecutive studies.

1. Introduction

Prosumers are entities that can act as consumers or producers to the network and switch between these modes over time. Inspired by microgrids and virtual power plants in the electricity sector, the most exhaustive adaption to the thermal sector are thermal networks that consist only or predominantly of prosumers. Linked to the idea of local multi-energy markets, a prosumer-dominated network allows to physically execute the trade of thermal energy between prosumers. The behavior of such networks however differs a lot from conventional district heating and cooling systems, that were characterized by dominant central generation units. Even though some papers compare different concepts for specific applications, to the best of our knowledge there are no investigations on the general characteristics and challenges of prosumer-dominated thermal networks.

Therefore, this paper aims to give a comprehensive compilation by combining scientific deduction with simulative case studies and references to literature where applicable. For the sake of simplicity, all discussions are performed subject to heating networks, but in principle they can also be transferred to cooling networks as well as to combined heating and cooling networks.

Nomenclature

Symbols

$\dot{Q}$	thermal power flow, transferred heat
$\dot{V}$	volume flow
T	temperature
u	normalized pump speed as control (input) variable of variable speed pumps
κ	normalized flow coefficient as control (input) variable of control valves, proportional to valve opening

Indices

cold	cold subnetwork, return line
hot	hot subnetwork, supply line
in	inflowing (into substation)
out	outflowing (out of substation)
prim	primary side, network side
sec	secondary side, prosumer side

Abbreviations

cons	consumption mode (of prosumer)
prod	production mode (of prosumer)
pros	prosumer

2. Reference Concept and Case Studies

2.1. Reference network concept

Since there is no unified standard network concept for prosumer-dominated networks, a reference architecture is needed as a basis for the investigations and simulation studies. This paper focuses on the network side while the internal prosumer side is considered only by a net heat flow in form of an accordingly heated or cooled fluid flow. Further investigations on different prosumer side configurations in the context of thermal networks are presented in [1]. Figure 1 illustrates a setup with three prosumers using the reference network concept the paper at hand is based on. The used reference concept is a 2-pipe-system with counter-flow plate heat exchangers in the heat transfer stations. Prosumers feed-in from the cold subnetwork (return line) to the warm subnetwork (supply line) and extract in consumption mode vice versa. The network is controlled by distributed actuators in the substations: variable speed pump (production mode), control valve (consumption mode). Radial, meshed and mixed topologies are allowed.

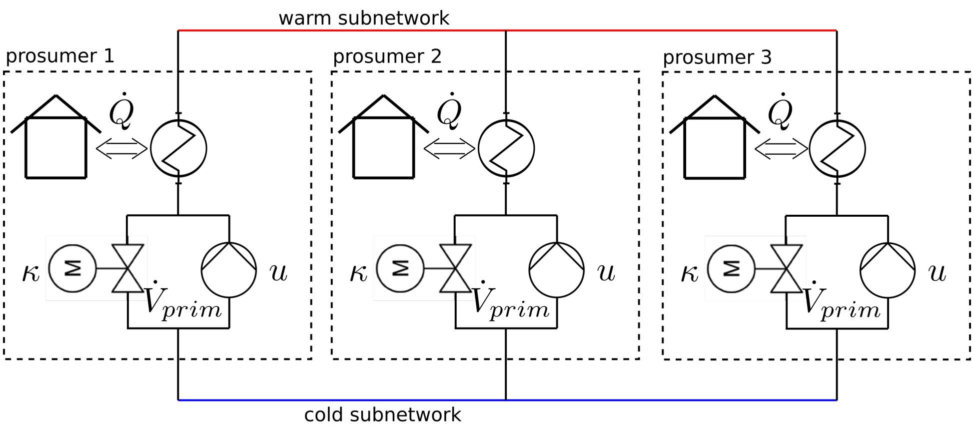

Figure 1. Setup of three prosumers in a radial topology following the reference network concept

This reference network concept is quite generic and applicable for heating, cooling networks or combined heating & cooling networks. It is compatible with recent trends in literature, like decentral booster heat pumps in substations. For this application case the heat exchanger can be substituted by a booster heat pump. The generality of the proposed reference network concept allows the derivation of general statements regarding the operation of prosumer-dominated thermal networks.

2.2. Case studies

In this section, the considered simulation scenarios are explained. The discussion of the results takes place in the following sections. Four scenarios were simulated, all using the setup of figure 1 and parameters (e.g. pipe diameters, pump dimensioning etc.) from the *CoSES* laboratory environment [2]. The scenarios I & II are steady-state scenarios that were simulated with the tool *ProHeatNet_Sim*[1]. With the scenarios III & IV dynamic behavior is investigated using the modelica-based simulation tool *Dymola* together with the library *ProsNet*[2].
In scenario I, prosumer 1 consumes while the prosumers 2 and 3 produce. The pumps of prosumer 1 and 2, both run on 80% speed. Scenario II is the same as scenario 1, but the pump speed of prosumer 2 is reduced to 60%. In scenario III, the thermal network is cold ($30°C$), as prosumers 1 and 2 start to exchange energy with prosumer 2 being the consumer. Scenario IV starts from the steady-state of scenario 1. Then prosumer 2 switches from production to consumption mode and after some time back to production mode.
Table 1 shows the steady-state simulation results of the scenarios I & II. Figure 2 shows for the scenarios III and IV the dynamic simulation results over time.

Table 1. Simulation results of the scenarios I and II (described above). u is the control input for pumps in producers, κ the control input for valves in consumers (100% is max speed / open).

		parameters				simulation results		
scenario		mode	$\dot{V}_{sec}\left[\frac{l}{min}\right]$	$T_{sec,in}\,[°C]$	control	$T_{sec,out}\,[°C]$	$\dot{V}_{prim}\left[\frac{l}{min}\right]$	$\dot{Q}\,[kW]$
I	pros1	cons	8	40	$\kappa = 100\%$	59.8	8.8	-11.1
	pros2	prod	-5	65	$u = \mathbf{80}\%$	42.8	-5.8	7.8
	pros3	prod	-5	65	$u = 80\%$	50.7	-3.0	5.0
II	pros1	cons	8	40	$\kappa = 100\%$	54.2	6.9	-7.9
	pros2	prod	-5	65	$u = \mathbf{60}\%$	63.5	-0.3	0.5
	pros3	prod	-5	65	$u = 80\%$	39.5	-6.6	8.9

3. Characteristics

3.1. Bidirectionality

A central characteristic for prosumer-dominated thermal networks is the bidirectionality of both, energy and mass flows. This bidirectionality occurs within the network as well as between the individual prosumers and the network.

3.2. Temporal and spatial fluctuations of temperatures

Conventional district heating system typically have fixed desired fluid temperatures for the whole warm and cold subnetwork. Prosumer-based thermal networks can consist of different prosumers with various generation technologies and demand profiles. They might exchange heat

[1] `https://github.com/thomaslicklederer/ProHeatNet_Sim`
[2] `https://github.com/ilyaelizarov/ProsNet`

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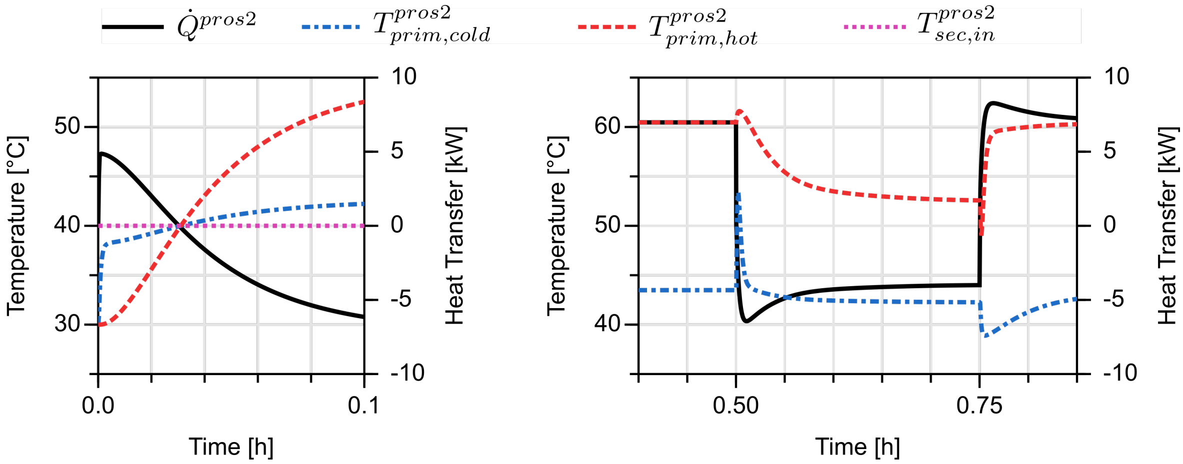

Figure 2. Simulation results of scenario III (left) and scenario IV (right) in form of heat flows (solid) between the network and prosumer 2, together with the corresponding primary side temperatures (hot dashed, cold dash-dotted) and secondary side inlet temperatures (dotted).

on different temperature levels, best fitting to the current requirements and in order to minimize losses. Additionally, the variable mass flow rates through the individual substations influence the local temperature levels. If not inhibited by specific control concepts, the temperature levels can fluctuate not only temporally, but also spatially within in the network.

3.3. Mutual influence of actuators

The distributed pumps and valves control the whole network. They are mutually coupled. Each change on the operation of a pump or valve influences the overall network state including temperatures and energy flows. This can be observed in the simulation results of table 1. When reducing the speed of the pump of prosumer 2 from 80% in scenario I to 60% in scenario II, the volume flow and thereby the heat transfer of prosumer 2 decreases. Without any other changes in the system, prosumer 1 and 3 are also significantly influenced as it can be seen at the changes in their temperatures, volume flows and transferred heat.

3.4. High sensitivity on control inputs

Comparing the simulation results of scenario I and II in table 1 makes clear that the network state shows a very high sensitivity on changes in the control inputs. While the pump of prosumer 2 is only slowed down from 80% to 60% speed, the volume flow trough the substation of prosumer 3 more than doubled and its heat transfer raised from 5 kW to 8.9 kW. This is a nonlinear behavior caused by the mutual influence of the distrubed actuators and the nonlinear relations between pressure differences, volume flows and heat transfer coefficients.

3.5. Pump blocking

Another nonlinear effect is the pump blocking as described in [3]. In the simulation results of scenario II (table 1) the volume flow through the substation of prosumer 2 is almost zero. The pump of prosumer 3 runs on 80% speed and holds the pressure difference between hot and cold subnetwork at a level at which the pump of prosumer 2 is not able to generate significant volume flow. That means pump 2 is effectively blocked by pump 3 and prosumer 2 therefore can not contribute to the network. How and when this effect occurs is depending on the dimensioning of the pumps and the distances and hydraulic resistances in the network.

3.6. Supply frontier and hydraulic network splitting
In a thermal network with multiple feed-in points another effect, similar to pump blocking occurs: the creation of a supply frontier. When there are prosumers in consumption mode topologically between two or more prosumers in production mode, then the producers "compete" for the supply of the consumers. The colliding opposite flows annihilate at a certain point to no flow. This is described as supply frontier by [4]. The supply frontier can shift over time, due to the operation point of the individual pumps and valves. If it does not shift over a longer period of time, the network can cool down locally at the supply frontier. From an hydraulic system perspective, the network is effectively split into two or multiple hydraulic subsystems by the supply frontier.

3.7. Energ flow reversal for network heat-up
In prosumer-dominated networks that are operated with flexible temperatures and a local energy market, the network can (locally) cool out. This can happen e.g. when the network is not used because prosumers operate self supplying over a longer period of time or because previous heat exchange was at a lower supply temperature. The simulation results in figure 2 (left) show the case of prosumer 2 that wants to consume from the cooled out network while prosumer 1 feeds in. It can be seen that the inlet temperature on the prosumer side is higher than the temperature on the network side. Therefore prosumer 2 feeds in heat to the network in the beginning, although it wanted to consume. When the hot subnetwork is heated up to a temperature above the inlet temperature on the prosumer side, prosumer 2 starts to consume, as intended.

3.8. Network behavior during prosumer mode switching
Figure 2 (right) shows the network behavior when prosumer 2 switches its mode. When switching from production to consumption, the local temperature in the cold subnetwork rises significantly. At the same time, the local temperature in the warm subnetwork rises slightly. These observations are caused by the following effects: The mass flow directions are inverted quite fast, while the inlet temperature on the secondary side sinks gradually. That means, in the beginning the network side flow is not significantly cooled by the prosumer side. So the temperature in the cold subnetwork rises. At the same time, warmer water from prosumer 3 (production) is now pushed trough substation 2 where the local temperature in the warm subnetwork rises. After some time, the prosumer side inlet temperature is cold enough to cool the network side flow and the steady-state begins to settle. When switching back from production to consumption mode the opposite effects can be observed. The magnitude of these effects depends on the volume of water in the substations, the rate of temperature change on the secondary side and various other aspects.

4. Challenges
4.1. Challenges in network design
The planning of conventional district heating systems is based on representative design cases. It affects aspects like the topology, design temperatures as well as the dimensioning of pipes and pumps. In prosumer-dominated thermal networks there are no representative design cases due to the high variability in operation. Therefore, new procedures for the network planning are needed. Further, new challenges for the network design come up related to the characteristics discussed in section 3 : mixed topologies (meshed and radial), temperature control, substation dimensioning, pressure difference between the subnetworks etc. For the dimensioning of the pumps and pipes the decisive question is over which distance the supply of other prosumers should be possible. Oversizing the distributed pumps for the supply over long distances is uneconomical and inefficient. Therefore either the whole network must be geographically compact or the energy exchange must be restricted to local groups of prosumers within the network.

4.2. Challenges in network control

The type of networks under consideration is controlled only by distributed actuators in the prosumers' substations. As discussed in section 3 these actuators mutually influence each other and the overall thermohydraulic network state behaves sensitive and nonlinear to changes in the control variables. This is a big challenge for the network control, as prosumers with their substations cannot be controlled independently. Ref. [5] warns that the mutual influence of the actuators can lead to hydraulic oscillations and water hammers. In order to prevent this, ref. [5] proposes to adjust all actuators simultaneously. Further, ref. [6] shows that in order to minimize the pumping power, the control valve of at least one consuming point has to be completely opened, while the other valves are adjusted relatively to it.

The previous points argue for a central network controller for prosumer-dominated thermal networks. Such a central controller must consider power setpoints for the feed in or extraction of each prosumer as well as temperature requirements and other specifications. Also, the central controller must take into account and anticipate described phenomena like pump blocking, the supply frontier or network heat-up. For this, the central control approach must rely on some kind of model of the underlying physical network behavior. In ref. [7] a thermohydraulic model is presented in form of a system of equations that can be the basis for such a central network controller. Further, ref. [7] shows that the complexity of simulating and controlling a prosumer-dominated thermal network increases exponentially with the number of interconnections, which is usually proportional to the number of prosumers in the network.

4.3. Challenges for thermal markets

Related to the characteristics discussed in section 3, the following challenges must be faced by heat markets in the context of prosumer-dominated thermal networks: How to allocate costs for heating up or cooling down the network? How to integrate variable temperatures into the market? How to reflect the restriction of energy exchange only within local groups by the market? What is the general market design and market clearing process? It can be seen that compared to local electricity markets, for the thermal sector the technical implementation & control level strongly influences and limits possible local energy market concepts.

5. Conclusion

Prosumer-dominated thermal networks are the infrastructure that physically allows to exchange thermal energy between prosumers, as this is desired in the context of local energy markets. This paper shows, that the technical execution of the thermal energy trading has several challenges. Previously used procedures for the design of district heating networks cannot be adopted directly. Further research is necessary on how to determine reasonable design cases for such networks with high variability. For the control of prosumer-dominated networks it was deduced that a central controller with an underlying model of the relations and physical network behavior is necessary. Based on the technical insights, challenges are named for heat markets in the context of prosumer-dominated networks. It becomes clear that for the development of local thermal energy market concepts the feedback between the market level and the technical level is an important and limiting factor. As an overarching hypothesis, it is stated that energy exchange between thermal prosumers is technically more reasonable over small distances and is very complex to control with higher numbers of prosumers exchanging energy simultaneously.

Summarized, the higher flexibility of prosumer-dominated thermal networks and their compatibility with the idea of local market is bought with higher complexity in design and operation. The presented compilation of characteristics and challenges is to be extended and provides a basis for consecutive studies in this innovative field of thermal networks.

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