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Intelligent heat networks: First results of an energy-information-cost-model

Klaus Lichtenegger[a,*], David Wöss[b], Christian Halmdienst[c], Ernst Höftberger[a], Christoph Schmidl[a,d], Tobias Pröll[b]

[a] Bioenergy 2020+ GmbH, Gewerbepark Haag 3, 3250 Wieselburg-Land, Austria
[b] Institute of Chemical and Energy Engineering, University of Natural Resources and Life Sciences, Vienna, Peter-Jordan-Straße 82, 1190 Vienna, Austria
[c] Pink GmbH – Energie- und Speichertechnik, Bahnhofstrasse 22, 8665 Langenwang, Austria
[d] Fachhochschule Wiener Neustadt, Campus Wieselburg, Zeiselgraben 4, 3250 Wieselburg, Austria

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ABSTRACT

Integrating additional renewable heat sources into district heating networks can have several beneficial effects, but it also requires more sophisticated control strategies than supply by only one central plant. In this article, we study the integration of *prosumers* (i.e. buildings which have both the capacity to produce and the need to consume energy, here heat) into heat distribution grids.

This study is performed with a simplified model, based on energy and information flows. The prosumers can act autonomously, based on a price communicated by the central heat plant. This price is determined based on the benefit for the network by additional heat feed-in and is regularly updated. This leads to an interlocking of a physical/technical and an economic feedback loop. The control parameters are optimized by using a stochastic optimization algorithm, based on simulation runs for one typical week in winter, spring and summer.

We compare the results with standard setups (heat network with only consumers, central heat generation and additional heat-producing building disconnected from the grid) and obtain an improvement concerning fuel consumption in most and concerning emissions in many situations. While economic benefits are achieved in most scenarios, it is a non-trivial task to construct a market model that distributes these benefits in a fair way between the central heat plant and the prosumers.

1. Introduction

In recent years, approximately 48% of the primary energy consumed in Europe has been used for heating purposes [1]. While the heating sector is still dominated by stoves and boilers for single buildings, district heating has gained significant importance, constituting about 13% of the European heat market for buildings [2]. District heating is particularly well-suited for densely populated regions, mainly urban and suburban areas. As advocated in [2,3], raising the share of district heating based on renewable heat sources or waste heat could constitute a practical and comparatively cheap way to reduce primary energy consumption and carbon dioxide emissions.

Classical district heating networks are based on a single producer and many consumers. More complex heat networks may contain several distributed producers, but still, in classical setups, there is a clear distinction between large heat producers and (usually comparatively small) consumers.

This might be about to change. Even in regions with well-established district heating grids, buildings with (renewable) heat-producing capacity which are not connected to the grid are quite common:

- During sunny days, in particular in summer, single-house solar thermal devices often produce far more heat than required by the building itself. (In Central Europe, solar thermal devices for single houses are usually designed such that, on average, the heat demand of the building can be covered from mid-spring to mid-fall. During summer the heat production significantly exceeds the heat demand. This is even more true for certain public buildings, e.g. schools, which have little to no heat

* Corresponding author.
E-mail addresses: klaus.lichtenegger@bioenergy2020.eu (K. Lichtenegger), david.woess@boku.ac.at (D. Wöss).

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demand during summer vacations.) Excess heat could be fed into a heat network.

- In warmer winter periods and during transition time (i.e. spring and fall), biomass boilers typically operate only in partial load mode or are repeatedly switched on and off. Both result in lower efficiency and typically (often significantly) higher emissions of air pollutants, e.g. CO, particulate matter and volatile organic compounds [4,5].[1]
  The use of a heat storage tank, which is almost standard by now, can improve this situation, but offers no complete remedy. While integration of heat storage devices usually improves the efficiency of a heat distribution system (e.g. by allowing solar energy to be stored, which otherwise would be lost, or by permitting favourable operating conditions for boilers), one inevitably also introduces additional heat losses whenever latent heat storage is used. (Other ways of heat storage, like phase change materials or sorption, do not have this disadvantage, but are significantly more expensive [6].)
  Thus, even when a storage tank is present, the integration into a heat grid, as discussed in this article, can still improve the efficiency of the system and help to reduce emissions.
- While large industrial heat producers are typically integrated in heat networks, small- and medium-scale producers often hesitate to participate in such projects. In many cases, this can be attributed to a lack of reliable and sufficiently flexible business models.

Such buildings could well be used for enhancing and stabilizing the grid. In certain situations, these heat producers may also be interested in receiving heat from an external source. For such participants in the network, the term "prosumer" as a merge of producer and consumer has been coined. Originally, this concept has been studied in the context of "smart" electrical power networks, but to an increasing extent it is also discussed for intelligent heat networks [7–9].

Inclusion of a large number of small- and medium-scale prosumers in a heat network may be beneficial. This can become relevant in particular in two situations:

- In summer, heat plants usually operate in a quite inefficient way. They still have to provide heat for preparation of domestic hot water, but since the mass flows in the heat network are much lower than in the heating season, losses in the network are dramatic, up to 90%, as indicated from analysing consumption and production data of several Austrian heat grids [10]. Here, decentralized sources (in particular solar thermal devices) and storage tanks might permit switching off the main plant for extended periods of time.
- In cold periods, most heat plants have to use peak-load boilers in order to provide additional heat. Even when the base load boilers operate on biomass, the peak load boilers usually burn natural gas or fuel oil. This is more expensive and increases the carbon footprint. Sometimes, old biomass boilers with lower efficiency and higher emissions (see [11] or p. 26 of [12] for an overview of the technological development) are kept for use as peak load boilers. Doing so usually results in higher air pollution. Incorporating many small-scale biomass boilers (which could operate in full load mode for long periods of time) could significantly reduce the operation time of such peak load boilers.

In addition, inclusion of prosumers might be the best way to enhance an existing grid which has been pushed to its technical or economic limits:

- When an existing heat network reaches its capacity limit, cost-intense measures (upgrading the boiler and/or the pipe system) are usually required. Decentralized heat feed-in can be an effective measure to expand the capacity of such a grid.
- Depopulation (in particular of rural areas) and emigration as well as higher building standards (better insulation) can lead to a severe decrease of heat demand in a heating network—to the point where the operation of a heat plant is no longer profitable. A solutions could be the substitution of the central plant with several smaller decentralized heat sources.
- In general, for large networks with distances up to a few kilometres between heat production and consumption sites, heat losses are often dramatic. Covering the heat demand of remote consumers by local production, effectively disconnecting a branch from the grid, can reduce these losses (though for later reconnection, one faces the problem of a cooled forward flow).

Integration of decentralized heat sources and prosumers can effectively split a network into several smaller ones which operate autonomously most of the time and rely on the connections between them only in exceptional situations (like the failure of an important heat source in one of the sub-grids).

While the purely technical challenges for inclusion of small-scale prosumers are moderate [8,13], establishing an adequate control strategy and a viable economic model constitute major challenges. This has been an active area of research during the last few years, and several strategies have been proposed.

In particular, strategies based on mixed-integer linear programming (MILP) have become very popular for superordinate control of energy grids, see e.g. [14–19], and the references given therein. See also [20–22] for information about an advanced software tool for managing distributed energy resources, which relies on this approach.

These concepts are certainly promising and have already proven their worth, but they also exhibit certain limitations. The restriction to linear systems is an obstacle that can, at least partially, be overcome by use of piecewise linear functions. The main problem with these and similarly all centralized approaches is the fact that the complexity of the optimization problem tends to grow exponentially with the number of prosumers.

This calls for a parallel development of strategies for decentralized decisions which are better suited for scaling up to networks with a large number of potential prosumers. For single prosumers a predictive control strategy, possibly formulated as a MILP problem, can improve the performance, also discussed in Section 6. For a complex system, a combination of central and decentralized control instances might turn out to be required [23].

In this article, we study the inclusion of such heat prosumers into heat distribution grids, examining a control strategy, which is based on a communicated price and is expected to exhibit excellent scaling properties. Such a prosumer scenario is compared to traditional setups (heat network with only consumers, central heat generation and additional heat-producing building disconnected from the grid).

2. An energy-information-cost model

District heating networks with several interacting producers are highly complex systems. As a consequence, simulation studies typically simplify several aspects of the system in order to study single aspects in detail. Often, calculations are performed in a (quasi-)static mode, thus neglecting (most notably) dead times, i.e. retardation effects due to finite flow velocity, the heat storage capacity of the network itself and dynamic feedback effects.

The design tool *Simplex*, developed by one of the authors, which has repeatedly and successfully been used for design and analysis of Austrian heat grids, is based on quasi-static calculations.

[1] Note that for a fair assessment, one has to evaluate the mass of pollutant based on the amount of heat provided, e.g. by giving mg of pollutant per MJ of heat.