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Development of a framework for the simulation and evaluation of flexible district heating systems

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Abstract

Future district heating networks are characterized by low supply and return temperatures and decentralized feed-in. Major challenges arise from the volatile energy supply due to the increasing share of renewable energies and the not yet utilized system flexibility to compensate for this. This necessitates new strategies for grid design and operation to ensure security of supply at all times. In the collaborative research project "EnEff:Wärme MeFlexWärme", funded by the German Federal Ministry for Economic Affairs and Energy, different departments from the Technical University of Darmstadt as well as the industrial companies Siemens AG and Entega AG collaborate to develop a framework to simulate and evaluate future district heating network systems. The district heating network system of Darmstadt serves as a case study that allows empirical validation of the models developed in the project. In this paper, we present an exemplary physical simulation of the district heating network proving the feasibility of the approach which allows the simulation of different constellations by adapting operation modes to given optimization values (e.g. minimizing heat production costs). The framework is the key element to tackle further questions in "EnEff:Wärme MeFlexWärme", such as an estimation of the network's state based on a few carefully selected sensors in the grid, integration of renewable heat sources and analyzing CO_2-emissions.

Keywords: district heating, simulation, state estimation

1. Introduction

The global demand for heating is increasing in a wide range of sectors while the regulations on greenhouse-emissions and sustainable energy economics get stricter to prevent climate change. In Germany, more than 50 % of the final energy consumption is caused by heating and cooling demands. Space heating alone makes up for around 30 % of that, especially in private households where 90 % of the heat is used for space heating. At the same time, the majority of heat generation is based on fossil fuels with gas as the main energy source, which of course leads to CO_2-emissions [1].

District heating is a proven technology to distribute heat, most often generated in a centralized location, to the consumer. The first commercial district heating systems in Europe were set up in Germany in the 1920s when German engineers identified water as the more efficient heat carrier in comparison to steam that was used until then. It was not until the 1970s that the third generation of district heating networks was introduced, characterized by prefabricated, pre-insulated pipes and compact substations as well as supply temperatures often below 100 °C [2, 3].

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While district heating grids served as distribution networks only with centralized feed-in during this time, their function will have to change in the future. This means a change away from a sole distribution grid towards a flexible network, which compensates between consumers, producers and storage capacities [4].

This enables a wide range of possibilities to incorporate alternative energy sources. Fig. 1 shows an example of how district heating may change in the future. The district heating networks of the future are therefore characterized by decentralized feed-in and low supply and return temperatures to exploit the potentials of sources such as renewable energy sources or waste heat. From that, new requirements for network operation strategies and grid design arise. Major challenges occur from the volatile supply due to the increasing share of renewable energies and the not yet utilized system flexibility to compensate for this.

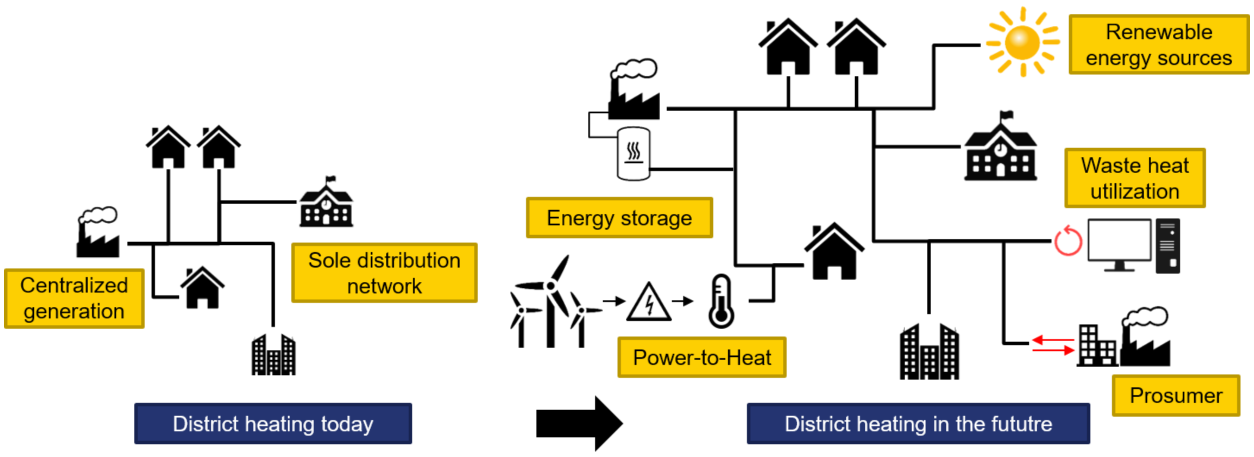

Fig. 1. District heating networks today vs. district heating networks of the future

The collaborative project “EnEff:Wärme MeFlexWärme” addresses these challenges focusing on the three topics network transparency, flexibility control and mathematical optimization [5]. The project is funded by the German Federal Ministry for Economic Affairs and Energy. Here different departments from the Technical University of Darmstadt as well as the industrial companies Siemens AG and Entega AG work together to develop a framework to simulate and evaluate future district heating network systems. Within the project, the district heating network system of Darmstadt serves as a use-case and starting point for the research.

This paper gives an overview of the framework concept and describes the functionality using a simplified example. Thereby the definition of a basic structure and interfaces between the different parts of the framework serves as foundation for the overall development. This includes different types of facilities (buildings, means of supply, etc.) as well as the heating grid itself but also a trading platform to bring together the different interests in heat demand or supply of the facilities. A mathematical model using an object-oriented approach provides the opportunity to execute small-scale tests to check the basic interaction functionality of all components.

2. Framework concept

The software framework developed collaboratively in “EnEff:Wärme MeFlexWärme” aims to model an entire trading day with all relevant data. Fig. 2 shows the layers of the framework: the schedulers on top, the participants in the middle and a physical simulation at the bottom.

The scheduler computes operating schedules for all facilities (e.g. buildings, heating plants). This can be either a market model or a global optimization. The heat market is designed as an open day-ahead market platform where every participant can trade energy. The global optimization serves as a benchmark for the market, so that the performance of the market in terms of both economic and energetic efficiency can be evaluated. The scheduler receives information about heat demand and supply, constructs and solves an optimization problem and returns operating schedules for each facility. It uses information on the network structure to construct physical constraints, so that the optimization returns physically valid operation schedules. The internal network model needs to be simplified for that to guarantee convergence and feasibility.

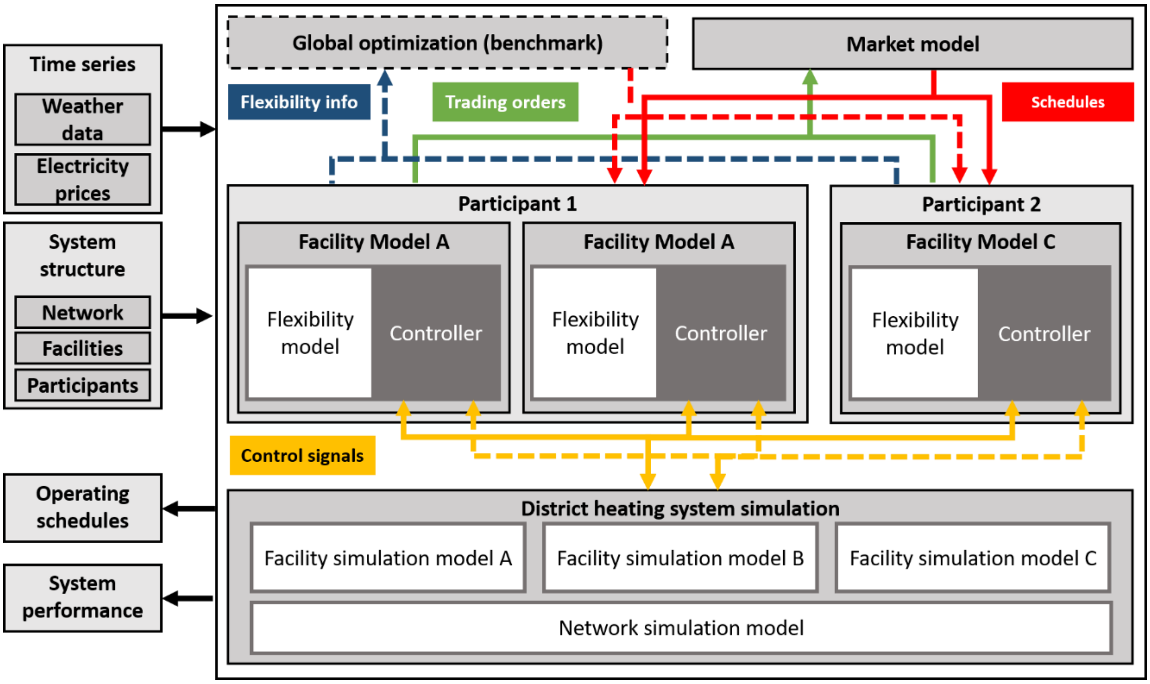

Fig. 2. Schematic diagram of the overall framework concept

In the middle of the framework, there are models of participants and facilities. A participant models economic behavior, while facilities model physical and technical behavior of real-world assets. A participant represents one or multiple facilities at the market and places orders at the heat market to request or offer heat. Facilities contain a flexibility model and a controller. The flexibility model describes the ability to provide heat or a demand for heat. In a simple case e.g. a private household, this can be a fixed heat demand curve. In a more complicated case, e.g. an industrial site, this can be the model of a prosumer who can choose between self-production and the purchase of heat, dependent on heat prices, or which can shift consumption and therefore offer flexibility. These relations are described by a set of mixed-integer linear equations. The flexibility model is either used by the overlying participant to generate orders, or used directly by the global optimization to construct constraints. The controller is used to pilot the facility's simulation model within the simulation and therefore translates a received operating schedule into (simulated) physical behavior.

The bottom part of the framework consists of a physical simulation of the whole district heating system, including detailed models of the facilities and the network. A realistic physical behavior of the network model is key to make reliable statements about the quality of the scheduling process. For this purpose, previously the two modeling languages MATLAB and Modelica have been compared and Modelica was found to be more appropriate to cope with the phenomena that occur within district heating systems; such as bidirectional fluid flows [6]. A Modelica-library was created consisting of models for each component in the network and each possible facility which can be parametrized to fit the respective scenario [7]. This way, it is possible to efficiently simulate the whole system behavior in a time-dependent manner.

An execution of the overall program within the framework is called *Sequential Execution Test* (SET). An SET starts with loading all data that defines a scenario. This includes data such as the structure of the district heating network, heat demand curves and electricity prices. In principle, any data needed can be included, e.g. weather data if a consumer's model scales its heat demand dependent on the ambient conditions.

The framework itself is written in an object-oriented manner. Each relevant object, such as participants, facilities, schedulers and simulation models belong to a class with a defined structure and interfaces, so that they can easily be exchanged. The data about network structure, participants and present facilities is stored in a JSON format. The structures are held flexible, so that the evaluated scenario can be easily altered. This way, it is possible to evaluate possible future developments and their influence on market outcome and function as well as heating system performance by simply exchanging a current network for an extended, future one or by replacing old buildings with energy efficient refurbished ones; by using simple or complex, self-optimizing controllers and so on.

Communication between the Modelica-model and the controllers of the facilities is realized via the FMI-Standard. The Modelica model therefore has in- and outputs, which are connected to the controllers defined in the SET. For each time step, every controller gets the needed state variables from the simulation and creates its control signal, which is fed into the Modelica-model to simulate the next time step [7].

3. Simulation, Results and Discussion

For testing purposes, a small-scale district heating network was modeled using the modeling language Modelica. It consists of the following facilities: inflexible consumer, flexible consumer, prosumer, heat generation plant. The inflexible consumer has to cover its heat demand completely from the district heating network, whereas the flexible consumer has the possibility to cover its heat demand to some extent itself. The prosumer can switch between taking out heat from the grid and feeding heat into the grid. In addition to feeding in heat, the heating plant also serves to maintain the system pressure by means of differential pressure measurement at the furthest point of the network. All facilities are arranged parallel to each other. Fig. 3 shows the test network. The facilities are, from left to right: heat generation plant, two prosumers, two inflexible consumers, two flexible consumers. The solid red line represents the supply line, the solid blue line the return line. The small red rectangles stand for the pipes of the grid connecting the facilities with each other. They contain information on the dimensions as well as material characteristics to take heat and pressure losses into account. For heat loss calculation, they are linked with a temperature boundary representing a constant temperature of the environment (broken red line). To simulate ideal mixing, mixing volumes are connected in between the pipes and the facilities (light blue circles).

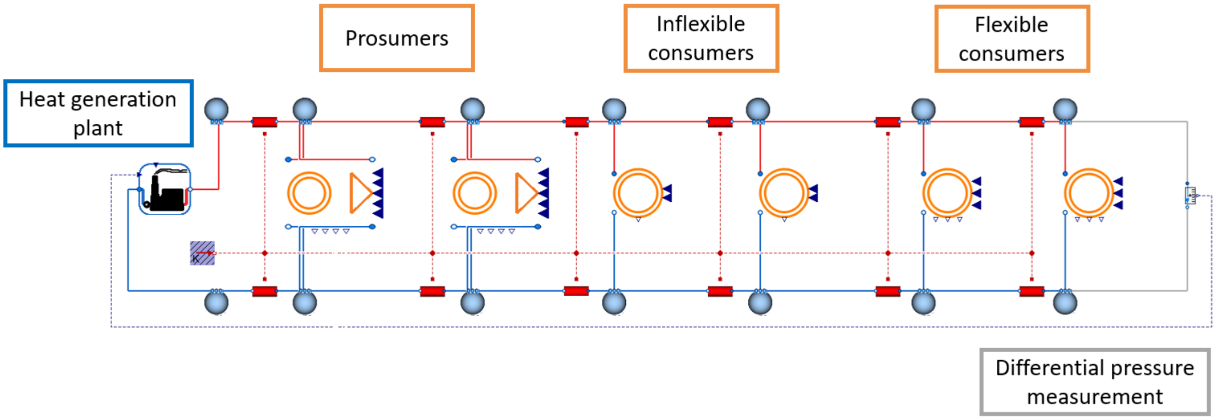

Fig. 3. Schematic diagram of the district heating test network

A simple global optimization was used for this test scenario as scheduler. The global optimization minimizes heat production cost. As physical constraints, it only balances global energy input and output of the system without consideration of any network losses. Furthermore, the heat generation plant and prosumers have limited feed-in power and dedicated constant marginal costs.

Fig. 4 shows the comparison of the computed schedule (left) and system behavior (right) in the physical simulation for one day. The green line shows the feed-in of the heat generation plant, the blue and orange lines show the feed-in of the two prosumers, prosumer0 and prosumer1. The scheduler prioritizes the production on basis of marginal costs, so that prosumer1 is always chosen first to produce and the heat generation plant is chosen last. Besides its role as a heat supplier, the heat generation plant serves as a controller of the network pressure in the simulation, which explains its heavy reaction when another supplier shifts its heat production to another level. Furthermore, the effect of model errors in the scheduler's optimization is visible by comparing the heat generation plant's simulated feed-in, when its heat production should be zero according to the schedule. Due to network losses not considered by the simple optimization model, the heat generation plant needs to deliver a small amount to level the energy balance.

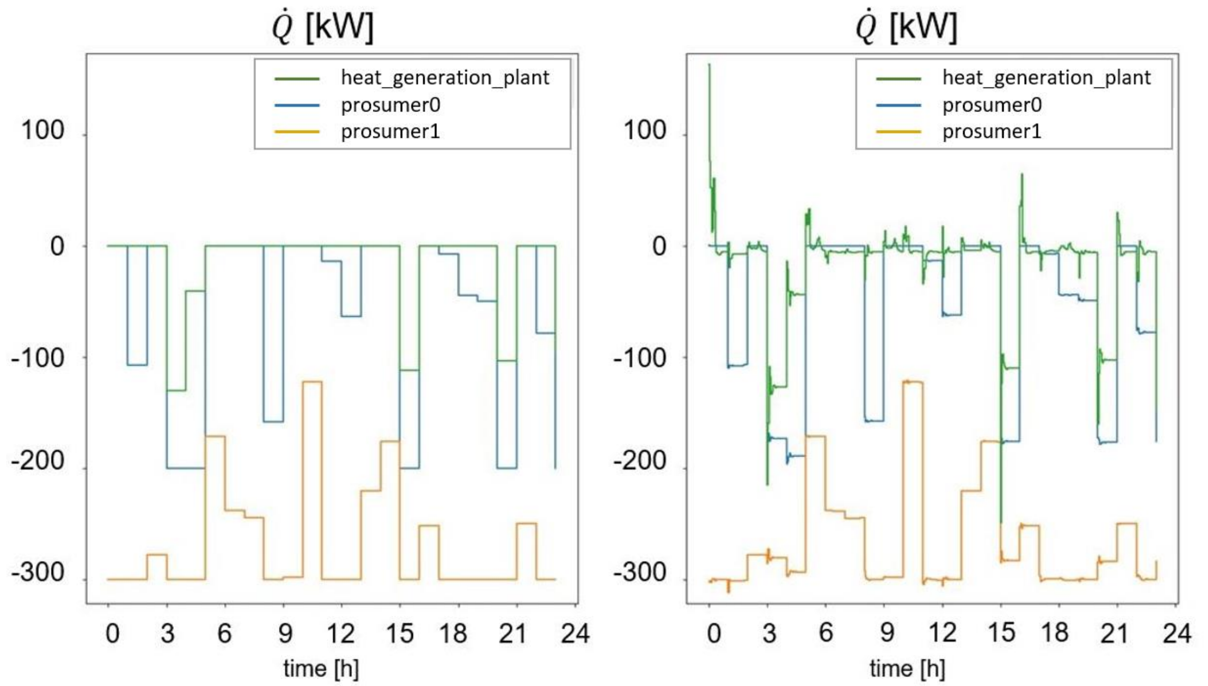

Fig. 4. Comparison of computed schedules (left) and system behaviour in the simulation (right) for one day (24 hours)

4. Conclusion

As part of the project, a basic modelling structure and interfaces were defined and transferred into an overall framework. The functionality was tested using a simplified district heating network. It was shown that at this point the basic functions of the framework are implemented. These are initially the import of grid data and other relevant scenario data such as weather data or energy prices. Based on that a schedule was created via global optimization and passed to the controllers, which set the state variables for the district heating network simulation. The schedule drawn up and the actual operation of the heat-generating facilities coincide quite well. Deviations during load changes can be due to pressure changes in the system and must be adjusted in the further course of the project. Also instead of a global optimization, a market model that has already been developed will be implemented as a next step.

Due to its modular structure, the framework can be used for a variety of network constellations and scenarios. This makes it the key element in the project for defining future district heating networks and potential scenarios for the efficient integration of sustainable energy sources in the heating sector.

In the longer run, the goal is to develop a prospective scenario for the district heating system Darmstadt for the year 2030. Potentials to reduce CO_2-emissions and to increase the share of renewable energies will be concretized and weighed up in terms of costs. In the course of that, the role of thermal energy storages and heat pumps will be evaluated and advantageous concepts of integration will be elaborated. Along with the theoretical work, points of measurement are defined in the real network to acquire validation data for the network simulation model [8]. That way the use-case Darmstadt will help to design operation strategies to achieve the optimal scenario of the above-mentioned. This leads not only to a realistic, physical simulation of the current network, but also allows deriving information for unspecific future network designs.

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