Modelling Contracting and Consumer Behavior for Energy System Optimization in the Residential Sector

Masterarbeit

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Overview

Bidirectional low-temperature district heating and cooling of the 5th generation (5GDHC) belong to the latest trends within the heat transition. In these networks, distributed heat pumps and compression chillers are used to obtain the demanded temperature levels locally, whereas the network's temperature remains at a level of 5-40°C [1]. Therefore, 5GDHC networks are characterized by a high efficiency and low heat losses as well as high shares of renewable energy sources [2].

The submitted thesis focuses on the assessment of business models from both a provider and consumer perspective using a currently planned and constructed residential district in Hassel, Germany, as a case study.

Methods

This work extents classical optimization-based energy system models to account for individual consumer behavior and the contractually governed interaction between consumers and energy providers. For this purpose, different contract structures with respect to costs and profits of consumers and energy providers, as well as their deviation from an overall social welfare optimum, are investigated. Furthermore, the submitted work also considers legal regulations and federal funding options such as price ceiling, CO_2 taxation and subsidization of investments into climate-friendly technologies, which are frequently analyzed in the literature [3-5]. In contrast to the state-of-the-art approaches, however, it analyses their impact on individual decision-making, total system costs and resulting CO_2 emissions for both, central-planner and multi-agent optimization models.

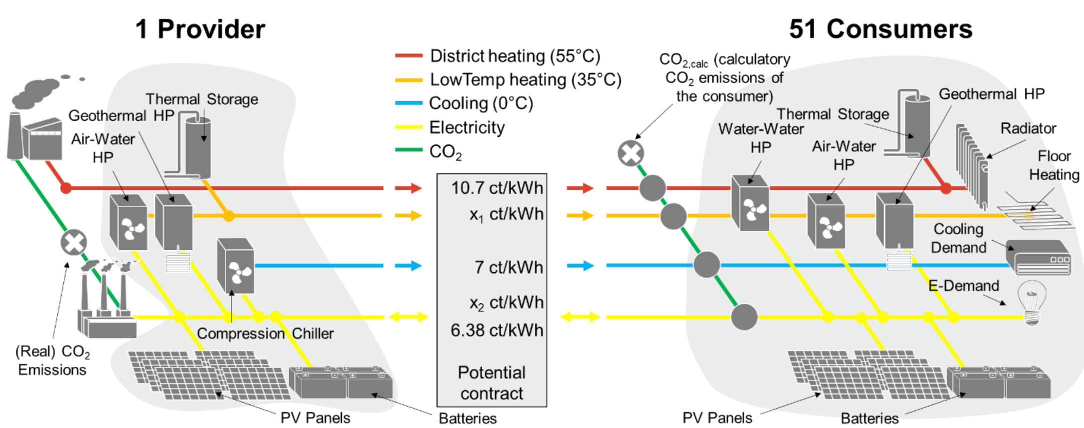

Figure 1. Decomposition of the optimization model into a provider and 51 consumer models interacting by a fixed contract.

In particular, an energy system optimization model for the whole district is formulated and subsequently split into several consumer models and a provider model to avoid solving a computationally intractable bilevel model [6] based on a Stackelberg pricing game. At the interface between the energy provider and the consumers, an energy contract, i.e. a set of concise energy prices, is assumed as depicted in Figure 1.

For these predefined energy prices, the consumer models are run yielding their energy demands depending on the assumed price constellation. Then both, the prices and the demands, are fed into the energy provider model. The procedure is illustrated in a simplified manner in Figure 2.

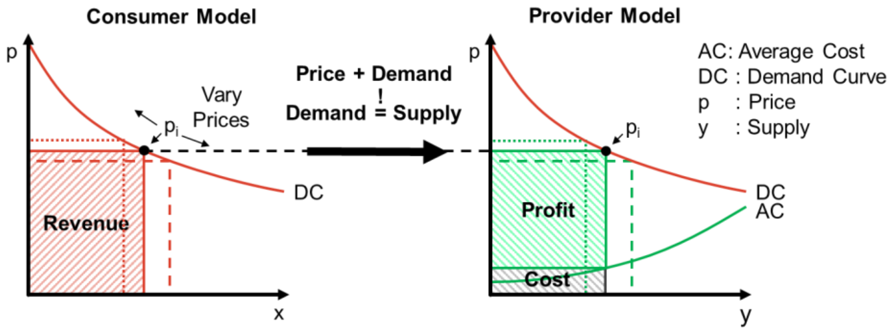

Figure 2. Hierarchical cost and profit calculation for the energy consumers and the provider given predefined energy prices between them.

This analysis is performed for 1681 different price constellations applied to 51 different consumers and 1 provider. Afterwards, the sum of costs and profits for the consumers and the provider based on the contracting model are benchmarked against the central planner model of the whole district, which defines the social-welfare optimum and is solved using cutting-edge time series aggregation techniques to maintain computational feasibility [7].

In a second step, different regulation schemes are imposed on the consumers and the district system operator. These regulations consist of subsidies for energy efficient technologies such as heat pumps on the one hand and carbon taxes on the other hand, that apply to either the consumers, the energy provider or both of them. Then, the sensitivities for different price constellations between energy consumers and the energy provider are re-run and the impact of the regulations on the individual behavior of the market participants as well as on the central-planner model is investigated.

Results

The results comprise approximately 400.000 single (sub-)system optimizations and show a distinctly sensitive reaction of consumers on changing prices or regulation schemes if they have a large number of system options such as, e.g., installing photovoltaic panels on their own. Interestingly, the demand for different energy sources such as low-temperature heat and electricity can suddenly change for slight price changes if the consumers are incentivized to move to an economically more convenient alternative. This behavior is illustrated in Figure 3 for three different buildings within the district, which shows the cash flow from the respective consumer to the provider for low-temperature heat (LTH) depending on the price constellation for electricity and low-temperature heat.

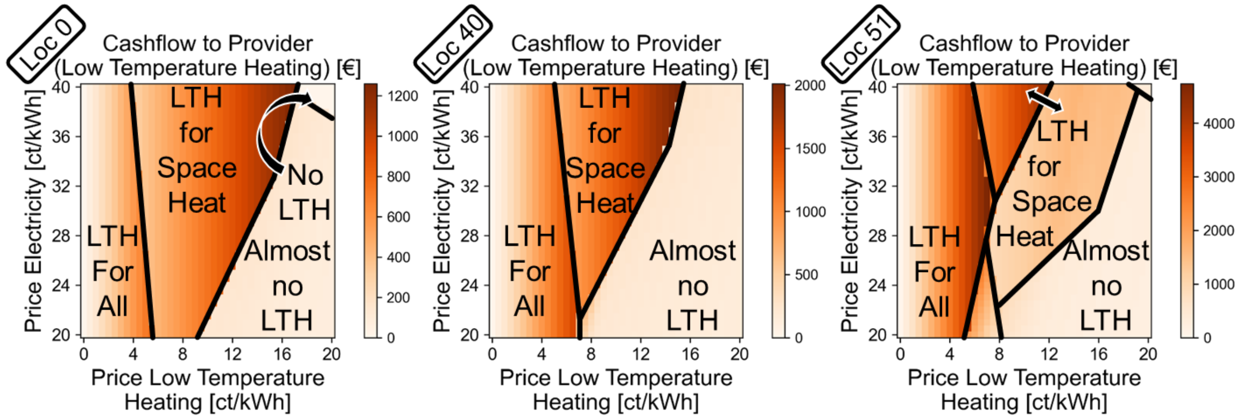

Figure 3. The cash flow from the buildings at location 0, 40 and 51 to the energy provider for low-temperature heat depending on the price constellation for electricity and low-temperature heat.

This, in turn, leads to sudden tipping points in energy demands, which can lead to strong deviations from a social-welfare optimum of up to 14% of total annualized costs within the inspected area. This means that non-aligned incentives can result in a system layout and energy consumption behavior that is 14% more expensive than predicted by a central-planner model as depicted in Figure 4. In particular, this applies when the consumers import high-temperature heat from outside the district instead of using the 5GDHC grid due to too high prices for low-temperature heat.

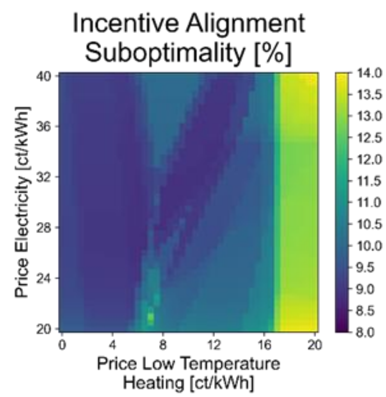

Figure 4. The additional costs compared to the social-welfare optimum in percent.

For the regulations, a similar impact can be observed. Here, poorly defined regulations can have little impact on the overall behavior. Especially CO_2 taxation alone was not very effective and drove costs without setting the incentives to invest into carbon neutral technologies. In contrast to that, carrot-and-stick combinations of subsidies for carbon neutral technologies and CO_2 taxes on the other hand prove to be very effective with respect to multiple criteria, among which are CO_2 reduction as depicted in Figure 5, little impact onto the overall social welfare and system costs as well as the individual costs of the system stakeholders.

Conclusions

The results imply that in district systems, contractually governed constant energy prices can set wrong incentives for energy consumers and providers. Furthermore, these contracts always lead to more or less suboptimal deviations from the macro-economic optimum and similar phenomena can be observed for additional regulations.

In this context, CO_2 taxes for the energy consumers and subsidies for climate-friendly technologies have been proven a preferable regulation scheme, whereby, however, a price ceiling for the provider's energy prices should be introduced in order to avoid a shift of the energy consumers towards less climate-friendly supply options. This implies that well-designed and financially balanced regulation schemes should include subsidization on the one, but taxation of deviating behavior or price ceiling on the other hand. Lastly, this work illustrates that, at times of rising energy prices, more efficient, but slightly more expensive technologies should be favored in the medium term.

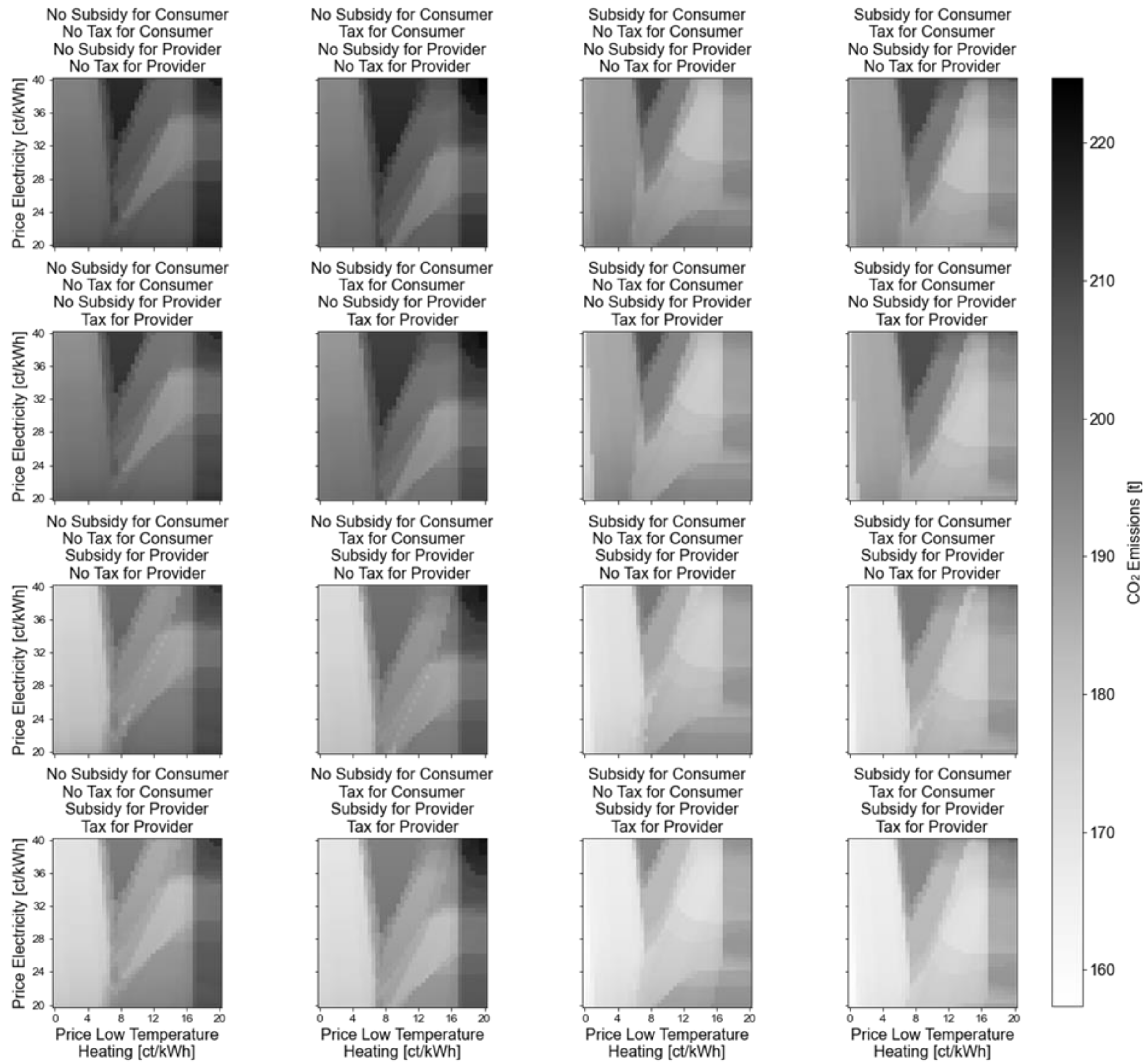

Figure 5. The CO_2 emissions depending on CO_2 tax and subsidies for climate-friendly technologies.

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