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Simulation of demand response on buildings and district heating production

Yuchen Ju[1,2*], Joakim Lindholm[1], Moritz Verbeck[3,4], Juha Jokisalo[1,2], Risto Kosonen[1,2,5], Philipp Janßenc[3,4], Yantong Li[6], Hans Schäfers[3,4], Natasa Nord[6]
[1]Department of Mechanical Engineering, Aalto University, Espoo, Finland
[2] FinEst Centre for Smart Cities, TalTech, Tallinn, Estonia
[3]Department of Environmental Engineering, Hamburg University of Applied Sciences, Hamburg, Germany
[4]Competence Center for Renewable Energy and Energy Efficiency (CC4E), Hamburg, Germany
[5]College of Urban Construction, Nanjing Tech University, Nanjing, China
[6]Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
* *corresponding author: yuchen.ju@aalto.fi*

Abstract

Demand response (DR) has effectively maximized renewable energies integrated into energy supply systems. This paper investigated DR benefits on three building types and the district heating (DH) production of a community consisted by these buildings in German conditions. Firstly, the buildings and the DH production were simulated without DR by tools IDA-ICE and HGSO, separately. Secondly, the three buildings were simulated by a rule-based DR control. After that, the tool HGSO calculated the total production costs and CO_2 emissions based on the power demand with DR. The results show 2.8%-4.8% heating cost savings by DR for different building types. For DH producers, DR application reduces the total DH demand and CO_2 emissions by 3.8% and 32.3 %, respectively.

Introduction

The European Commission aims to reduce 40% greenhouse gas emissions from 1990 levels by 2030 and to realize carbon neutrality by 2050 (European Commission 2018a; European Commission 2020). Half of the total EU energy consumption was from heating and cooling in buildings and industry (European Commission 2018b). In addition, in 2018, 75% of the heating and cooling energy was still generated by fossil fuels, while only 19% of energy was generated from renewable energies (European Commission 2018b). All these figures reflect that there is an immense potential of increasing the renewable energy share, especially in DH systems, to reduce CO_2 emissions.

There are various techniques of DR to improve the energy flexibility of buildings and their clusters based on dynamic electricity or DH prices. Massive building structures are treated as short-term thermal energy storage (TES). During low energy prices periods, the indoor air temperature could be increased, and heat is charged in the structures. This part of the heat is discharged during high price periods to maintain the indoor air temperature at an acceptable level. Therefore, there are studied mainly for residential buildings with different levels of thermal insulation and the impacts of charging and discharging heat were evaluated (Le Dréau and Heiselberg 2016; Johra, Heiselberg, and Le Dréau 2019). In addition, three flexibility factors have been defined to quantify the characteristics of building thermal mass by the DR control for residential buildings: available storage capacity, storage efficiency and power shifting capability (Reynders, Diriken, and Saelens 2017).

The cost-saving potential from DR control at the building level is another aspect which has been investigated to encourage prosumers to actively control their energy demand and increase monetary benefits. For district heated buildings, it has been analyzed in various studies (Wu et al. 2020; Vand et al. 2020; Ala-Kotila, Vainio, and Heinonen 2020).

Besides the building-level analysis, more scholars began to analyze DR benefits for energy systems. The optimization of energy supply units with renewable energies has been examined (Tereshchenko and Nord 2016). Moreover, a short-term TES, such as a water tank, has been integrated to effectively decrease the demand for peak power and make system operation more flexible. To quantify the flexible operation, temporal flexibility, power flexibility and energy flexibility were defined and mainly adopted in the analysis of CHP systems (Stinner, Huchtemann, and Müller 2016).

Although DR effects on buildings or their clusters and energy systems have comprehensively addressed cost, time, power and energy aspects, they are examined separately. There are only few studies which analyzed DR effects simultaneously and together on buildings and their DH systems. Kontu et al. (2018) investigated ways in which different DR control strategies affected three different size DH systems. Hourly heat power data with different building types were measured to establish the consumption profiles of the DH systems so that the control strategies were designed to optimize the operation of the DH systems without the building level being linked to the analysis performed. Moreover, the study did not conclude the results of CO_2 emissions reductions of the DH systems. Dominković et al. (2018) analyzed the DR benefits of DH production costs. They also discussed the impact of thermal mass storage in buildings on DH production. The paper focused on production cost savings while the results did not involve energy cost savings at the building level.

The novelty of this study is that the DR control impacts on buildings and DH production were analyzed in tandem and considered the interaction between them. This paper examined DR benefits for both building owners and energy producers. Firstly, the building-level DR control was applied in three building types (apartment building, cultural center and office building) in German conditions. After that, a DH network for a community of 22 buildings consisting of these three building types was established for the production-level simulation. Finally, the results show the DR impacts on cost savings for building owners and the producer, and CO_2 emissions reduction.

Methodology

Description of simulation process

Figure 1 describes the whole simulation process. Firstly, three building types, apartment building (AB), cultural center (CC) and office building (OB), were simulated without DR separately by the dynamic building simulation tool IDA ICE. Secondly, a DH network consisting of these three building types was established with a similar annual heat demand to an actual DH network in Hamburg. Thirdly, the total production costs and CO_2 emissions of the DH network without DR were calculated by the dynamic production optimization tool, heat generation schedule optimizer (HGSO) (Tillmann 2017). After that, DH prices for consumers were calculated according to the hourly production costs without DR. Then, the three example buildings were simulated by a rule-based DR control based on these DH prices, and the procedure for calculating the total production costs and CO_2 emissions with DR was repeated by HGSO.

Building-level simulation

Figure 2 describes the building-level simulation process of a rule-based DR control. The Behrang-Sirén method (Alimohammadisagvand, Jokisalo, and Sirén 2018; Vand et al. 2020) changed hourly DH prices and the moving future 24-hour prices into control signals. The moving future 24-hour price is the DH price for the subsequent 24 hours. The outdoor 24-hour moving average temperature is the average outdoor temperature of the past 24 hours. The minimum indoor air temperature setpoint (20 °C) was chosen based on the thermal environmental category II of standard EN 16798-1(2019). The maximum acceptable indoor temperature setpoint (23 °C) was set similar to Suhonen et al. (2020). The setpoint smoothing technique was applied for preventing the sharp increase of power load (Suhonen et al. 2020; Ju et al. 2021).

Table 1 shows the parameters of the three example buildings. The apartment building was built during the 1930s. The cultural center and office building were built in the early 1980s and have been renovated recently. Internal heat gains of occupants were set based on an activity level of 1.2 MET with a clothing of 0.75 ±0.25 clo for sedentary activity and normal clothing (CEN 2007). The heating energy demand for domestic hot water (DHW) was set at 17, 4 and 6 kWh/m^2, respectively (Loga and Imkeller-Benjes 1997). Design heating power represents the heating power demand of water radiators and ventilation in each building type at the design outdoor temperature of -12 °C.

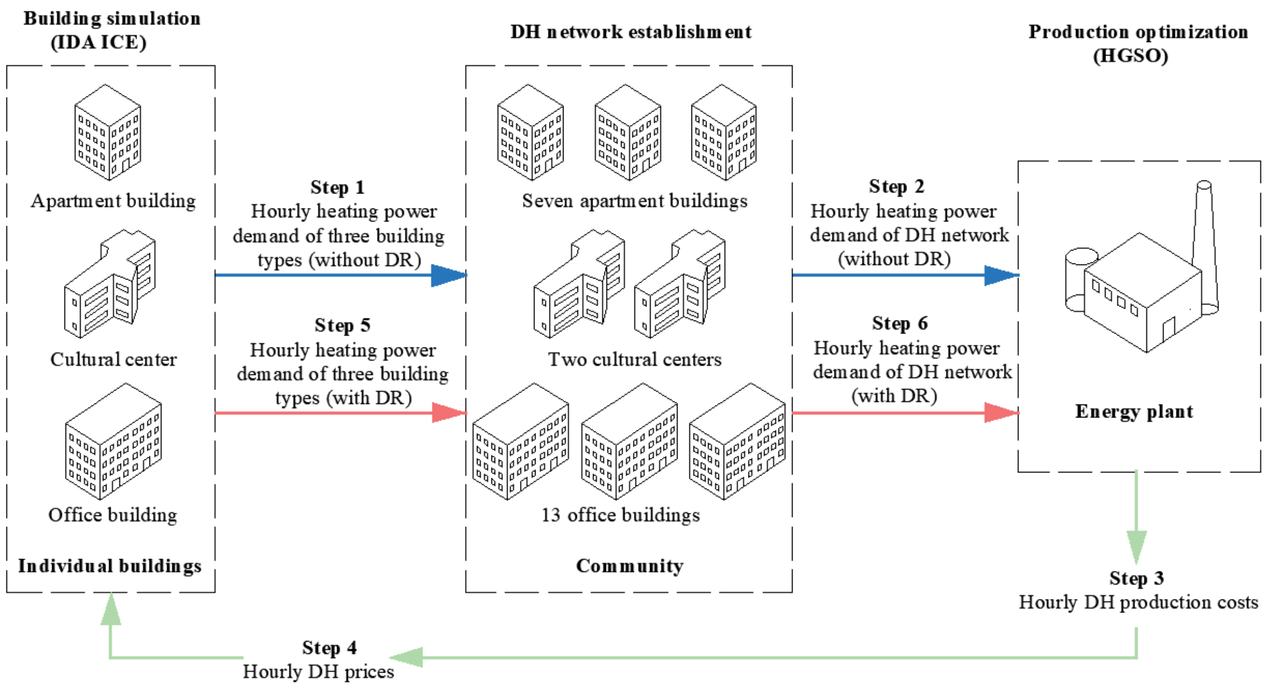

Figure 1: Description of the whole simulation process.

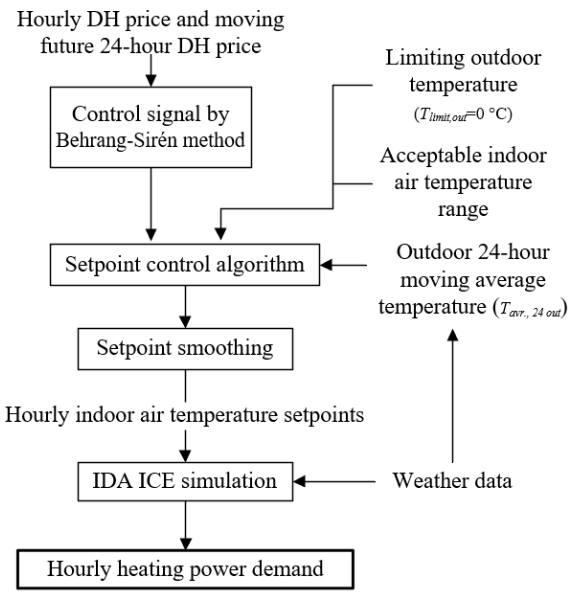

Figure 2: Flow chart of building-level simulation process with DR control.

Table 1: Building model parameters.

Parameters		**Apartment building**	**Cultural center**	**Office building**
Heated net floor area (m^2)		4885	3937	2383
Number of floors		4	3	4
Envelope area (m^2)		4780	6921	3855
Window/envelope area		7.6%	8.8%	9.5%
U-value ($W/m^2 \cdot K$)	External walls	1.7	0.2	0.2
	Roof	1.4	0.19	0.19
	Ground slab	1.0	0.28	0.28
	Windows	3.0	3.0	3.0
Air leakage rate, n_{50} (1/h)		7.0	3.0	4.5
Usage time		Continuous	8 am–9 pm (every day)	8 am–4 pm (working days)
Annual internal heat gains of equipment ($kWh/m^2 \cdot a$)		11	9	2

Production-level simulation

The production-level simulation aims to gain comparable results of DR impacts on DH generation costs and CO_2 emissions. Based on the procedure of the production-level simulation depicted in Figure 1, firstly, the hourly heat demand of three example buildings without DR for the whole year was calculated by IDA-ICE. After that, a DH network was established with a close annual heat demand as an actual DH network in Hamburg. The average yearly heat demand for 2017 and 2018 from all substations of a local DH system was adopted for this study. For the actual community, the existing building stock includes 22 apartment buildings (yearly heat demand of 3444 MWh), five office buildings (yearly heat demand of 3735 MWh) and two cultural centers (yearly heat demand of 721 MWh). Therefore, the established community consists of seven apartment buildings, 13 office buildings and two cultural centers according to the simulated yearly heat demand without DR of each building type. The deviation of the actual average yearly heat demand and that of the established DH network is 0.19%. Finally, the total production costs and CO_2 emissions for the established DH network and DH prices without DR were calculated by the dynamic optimization tool HGSO. The HGSO tool can optimize and output the most economical heat generation schedule of production units under technical and economic limitations (Tillmann 2017). The optimization schedule of the tool was shown in Figure 3 below.

In this paper, the calculation of DH prices includes three steps, as shown in Figure 1: (1) The input data (hourly heating power demand of DH network without DR) was processed. (2) The dynamic optimization tool HGSO calculated the hourly heat production costs. (3) These hourly heat production costs were normalized to fit the real DH price of 91.2 €/MWh of the actual DH network in Hamburg provided by Vattenfall Wärme Hamburg GmbH (2019). Since these prices were calculated based on operational expenditure, capital expenditure was not considered in this study.

Table 2 lists production combinations. The COP of the heat pump was 4. The solar thermal unit supplied the generated energy to the system directly. For every hour, the heat demand had to be covered by a combination of units and a heat store. There was a hot water tank in the system with a heat capacity of 1.4 MWh. All the units were able to charge the water tank. It could be operated temporarily to balance over- or underproduction. The storage tank must be filled to 50% by the generation units at the end of the considered period (24 hours, Figure 3). Depending on the market electricity price, HGSO optimized the most economical way to generate the demanded heat. It resulted in an hourly schedule of the unit and storage operations. For high electricity price periods, the heat generated from CHP units was maximized to cover the heat demand and the extra generated electricity was sold for high profits. The CHP unit is fed with bio-methane. German legislation for renewable energy stipulates revenues for electricity from renewable sources fed into the grid (Blazejczak et al. 2014). Thus, the producer gains profits granted governmental subsidy.

Table 2: Heat generation units and their maximum powers.

Generation unit	**Heat/electricity power (MW)**
CHP	+0.737 / +0.527

Generation unit	Heat/electricity power (MW)
Gas boiler 1	+1.950 / 0
Gas boiler 2	+1.100 / 0
Heat pump	+1.320 / -0.330
Solar thermal (ST)	+0.483 / 0
Total heat power	5.590

Figure 3 shows the operation schedule of the units and the heat storage system. The optimization considered market electricity price, limitations (minimum runtime/downtime of production units and minimum generation) and the threshold value (depending on the current electricity price and the average price of the previous month). Based on the market electricity price, electricity generated by CHP units could be consumed by the heat pump. Firstly, heat demand was covered by the solar thermal and heat storage units. Secondly, the operation order of the CHP and heat pump depended mainly on production costs. If the heat pump production profit was higher than that of the CHP, the heat pump would generate initially to cover the remaining heat demand. Otherwise, the CHP unit would be operated first. The boilers were never generated to cover heat demand unless the heat pump or CHP could not cover it in this step. The reason is that either the CHP or the heat pump generates heat with lower costs. After that, if CHP had been chosen in the latter step and it could not cover all the demand, the heat pump would be generated for the additional demand during low electricity price periods. When the market electricity price was high, the boiler would cover the additional heat demand.

DH prices

Table 3 describes the DH prices for the rule-based DR control. The data on heat demand of the established community and electricity was input as hourly steps. And all relevant heat demands, prices, costs and emissions were calculated for every hour. Then, the optimization tool HGSO minimized the production cost for 24 hours and output the hourly production cost, $C_{prod.}(t)$. After that, on the consumer side, an hourly DH price was created as shown in Eqs. (1)-(4). These hourly heat production costs were normalized to fit the real DH price (p_{real}) of 91.2 €/MWh.

$$p_{prod.}(t) = \frac{C_{prod.}(t)}{Q(t)} \quad (1)$$

$$R = \left|\min[p_{prod.}(t)]\right| + \left|\max[p_{prod.}(t)]\right| \quad (2)$$

$$F = \frac{p_{real}}{R} \quad (3)$$

$$p_{DH}(t) = F \cdot (p_{prod.}(t) + \left|\frac{\sum_{t=1}^{8760} p_{prod.}(t)}{8760}\right|) + p_{real} \quad (4)$$

where $p_{prod.}(t)$ is the specific production price per hour, €/MWh; $C_{prod.}(t)$ is the production cost per hour, €; and $Q(t)$ is the hourly heat demand of the DH network, MWh; R is the total price range of specific production price in the simulated year, €/MWh; F is the price normalization factor; p_{real} is the real DH price, €/MWh; and $p_{DH}(t)$ is the hourly specific normalized DH price, €/MWh.

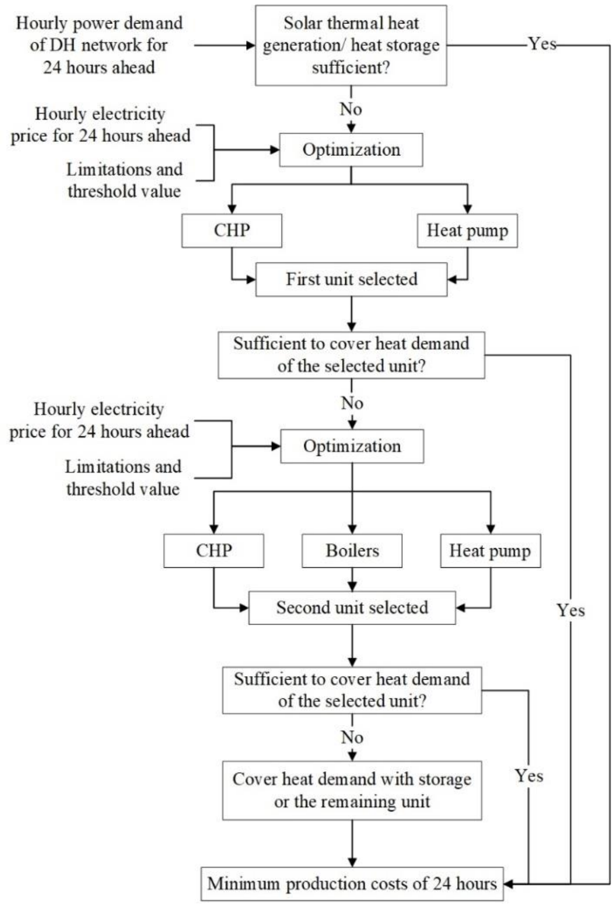

Figure 3: Operation schedule of units and the heat storage system.

Table 3: Description of DH prices.

Maximum (€/MWh)	Minimum (€/MWh)	Average (€/MWh)	Standard deviation (€/MWh)
99.9	8.6	91.2	5.2

Building-level rule-based demand response control

It was assumed that the moving future 24-hour price of DH was known in this study. Control signals (CS) for DR were calculated using the Behrang-Sirén method (Alimohammadisagvand, Jokisalo, and Sirén 2018; Vand et al. 2020). The price trend was defined as decreasing, increasing and flat with values of -1, +1 and 0. The marginal 75 €/MWh was chosen based on Martin's research (2017). The control signal was calculated as shown below:

$$\textit{If} \begin{cases} HEP < HEP_{avr.}^{+1,+24} - \textit{marginal value} \\ \textit{or} \\ HEP_{avr.}^{+6,+12} > HEP_{avr.}^{+6,+24} + \textit{marginal value} \end{cases}, \textit{Then } CS{=}{+}1 \quad (5)$$

$$\textit{Elseif } HEP > HEP_{avr.}^{+1,+24}, \textit{Then } CS{=}{-}1$$

$$\textit{Else } CS{=}0$$

$$\textit{End If}$$

where *HEP* is the hourly district heat energy price, €/MWh; $HEP^{+1+24}_{avr.}$ is the future average DH price from hour 1 to 24, €/MWh; $HEP^{+6+12}_{avr.}$ is the future average DH price from hours 6 to 12, €/MWh; and $HEP^{+6+24}_{avr.}$ is the future average DH price from hours 6 to 24, €/MWh.

The rule-based DR control algorithm is described in Figure 4. The aim is to use the thermal mass of the building structures as a short-term energy storage by adjusting the indoor air temperature. The hourly target indoor air temperature was controlled by the space heating system. $T_{SH,\ min}$, $T_{SH,\ norm}$ and $T_{SH,\ max}$ are the minimum indoor air temperature setpoint (20 °C), the normal indoor air temperature setpoint (21 °C), and the maximum indoor air temperature setpoint (23 °C), respectively. Limiting outdoor temperature ($T_{limit,\ out}$) was set as 0 °C to avoid overheating based on Martin's research (2017). Setpoint smoothing technique of these setpoints was applied for minimizing rebound effects (Suhonen et al. 2020; Ju et al. 2021).

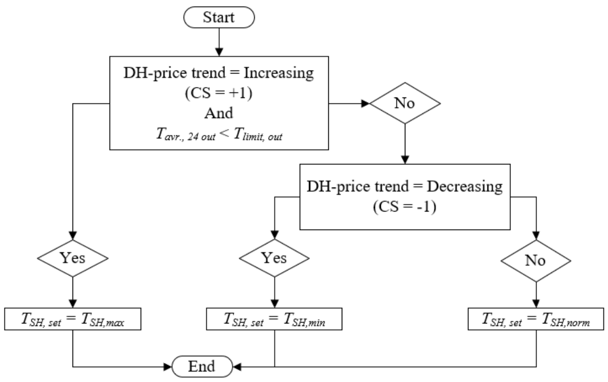

Figure 4: Control algorithm for space heating.

Results

DR benefits for building owners

Table 4 lists simulation results for the three building types with and without DR. The total DH consumption consists of heat consumption of space heating, ventilation and DHW. The differences show the reduction of annual DH consumption and energy costs compared with the reference cases without DR. In the apartment building, the application of DR decreases 2.8% of consumption and energy costs. For the cultural center cases, there are about 1% higher savings than those of the apartment building. In the office building, the energy and cost savings are the highest among the three building types.

DR benefits for district heating production

Table 5 shows annual production results with and without DR control. Positive values of the generation cost are the payment by the heat producer for energy generation while negative values represent that the heat producer earns profits from generation units which produce and sell electrical energy. The differences describe the change by DR. By DR, the DH producer earn an additional 5.9% profits. The results also reflect that the application of DR control decreases the total DH consumption by 3.8% and has the greatest reduction of CO_2 emissions, at 32.3%.

Table 4: Simulation results of three building types without and with DR.

Scenario	DH consumption		DH energy costs	
	Total (MWh)	Difference (%)	Total (€)	Difference (%)
AB without DR	480.2	--	44 115	--
AB with DR	466.8	-2.8	42 858	-2.8
CC without DR	457.4	--	42 087	--
CC with DR	438.9	-4.0	40 371	-4.1
OB without DR	280.3	--	25 937	--
OB with DR	267.0	-4.7	24 686	-4.8

Table 5: Annual production results without and with DR.

Scenario	Total DH consumption (MWh)	CO_2 emission (ton)	Total generation cost (€/year)
Without DR	7919.2	133.0	-83 801
With DR	7615.7	90.0	-88 718
Difference	303.5 3.8%	43.0 32.3%	4917 5.9%

Conclusion

The aim of this study is to identify the economic and environmental effects of the application of DR on both buildings and DH production. It was executed in the form of a co-simulation combined building simulation by IDA ICE and the optimization tool HGSO for energy production and price signal calculation. The results about the benefits of DR were shown below:

For building owners, DR application cuts heat energy costs. Cost-savings are from 2.8%–4.8% for different building types. The cost-saving rate of the simulated office building is the highest among the three building type cases. For the DH producers, the large-scale DR application increases 5.9% of generation profits and decreases the total DH demand and CO_2 emissions by 3.8% and 32.3%, separately.

The building-level results are relevant to the certain building types in this study with similar climate conditions and price characteristics of the studied DH production scenario. However, the DR control algorithm employed in this study is general, which could be adopted in any building type in different climate conditions and with different prices. In addition, although the production-level simulation results are typical of the studied DH production scenario, the methodology of DH production analysis is applicable for all production combinations.

Building-level results indicate that DR control for space heating could effectively save DH energy costs, which could be an incentive for building owners to take action towards becoming more environmentally friendly. The large-scale application of DR could become economically and ecologically profitable for DH producers. The all reflect the benefits of DR utilization in DH systems.

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