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# Demand response in the German district heating system

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**Abstract**. The renewable energy share in energy supply systems is increasing for carbon neutrality. The realization of carbon neutrality can be supported by demand response (DR) strategies. This paper analyzed the DR control benefits of a German district heating (DH) system. For the first step, in German conditions, three building types were simulated by IDA-ICE software with and without a rule-based DR control. Secondly, a community was established based on the heat demand of the simulated buildings. This paper selected two different production scenarios. One scenario consisted by a biofuel CHP and gas boilers and the other one included a heat pump, an electric heater, and a solar thermal storage. After that, the production of the two scenarios with and without DR was optimized by the HGSO tool and it calculated the total production costs and $CO_2$ emissions. It indicates that building owners and DH producers all earn benefits from the application of demand response. The maximum heating cost saving by DR is 4.9% for building owners. In the optimized two production scenarios, DH producers gain higher financial benefits and there are less $CO_2$ emissions. The maximum total generation cost and $CO_2$ emission savings are 12.6% and 8.6%, respectively.

## 1. Introduction

The European Commission released, by 2030, to decrease 40% emissions of greenhouse gas compared with 1990 levels and by 2050, to achieve carbon neutrality [1, 2]. Heating and cooling contributed for 50% of the total EU energy consumption in buildings and industry sectors [3]. Furthermore, in 2018, fossil fuels covered 75% of heating and cooling energy generation. However, renewable energies accounted for only 19% of total energy production [3]. All these figures reflect that there is a huge opportunity to integrate more renewable energy share, particularly into DH systems, to reduce $CO_2$ emissions.

DR techniques considering price incentives have been applied for buildings and their clusters [4, 5]. Massive building structures have been used as short-term thermal energy storage (TES). Heat stored inside the building thermal mass can be used to increase the indoor air temperature during low energy price period. To maintain acceptable indoor air temperatures, the stored heat is discharged during high price periods. As a result, this DR effects have been evaluated primarily for residential buildings considering varying thermal insulation [6, 7]. Another aspect is the investigation of the cost savings of building-level DR control which encourages prosumers to actively take part in to control the energy demand for monetary benefits. There are also various studies for district heated buildings [8, 9, 10].

Aside from building-level investigation, researchers analyzed the benefits of DR for energy systems. The use of renewable energies to optimize energy supply units has been evaluated [11]. Furthermore, energy systems integrated short-term TES for the purpose of effectively peak power demand decrease and being more flexible system to adjust to more renewable energy proportion [12].

However, the DR effects on building level or system level have been examined separately. Only a few studies have considered buildings and their DH production DR impacts at the same time. Kontu et al. [13] analyzed different DR control strategy effects on three different size DH systems. For determining the DH systems consumption characteristics and develop control algorithms to maximize their performance, they measured hourly heating power data from a variety of building types. Furthermore, the results of DH system $CO_2$ emissions reductions were not included in their research. Dominković et al. [14] studied DH production cost savings by DR and proposed building thermal mass short-term storage effects on the DH production. Production cost savings were presented while the building-level energy cost saving results were not included in this study.

The novelty of this study is that we examined effects for building owners and DH production by DR control concurrently with considering their interaction. First, the building-level DR control based on dynamic DH prices was implemented in three building types in German conditions, separately. They were apartment building (AB), cultural center (CC), and office building (OB). Following that, for the production-level simulation, a DH network was established including a community (22 buildings in total) comprised of these three building types. This paper chose two production scenarios. One scenario included biofuel CHP and gas boilers, while the other included units mainly consuming electricity (a heat pump, an electric heater, and a solar thermal storage). Finally, the results demonstrate the building owners and the DH producer DR application cost savings, as well as $CO_2$ emissions reduction of the DH production.

## 2. Methodology

### *2.1. Description of simulation process*

As shown in Figure 1, for the first step, we used the tool IDA ICE, which is a software for dynamic building simulation, to separately simulate the hourly DH power of these three buildings. Following that, a DH community with these three building types was built with totally 22 buildings. Its annual heat demand was comparable to that of a Hamburg actual DH community. Thirdly, we chose two production scenarios to supply heat to the community. The dynamic production optimization tool, named heat generation schedule optimizer (HGSO), was employed to find cost optimal solutions. Therefore, it calculated the total production costs and $CO_2$ emissions of these two scenarios. According to the optimized hourly production costs, hourly dynamic DH prices were calculated for building-level DR. A rule-based DR control was used in these three example buildings so that we gained the hourly heating power data both for the buildings and the community. The tool HGSO repeated the optimization procedure. Finally, after the DR application, the results of production costs and $CO_2$ emissions were proposed and analyzed in a later section.

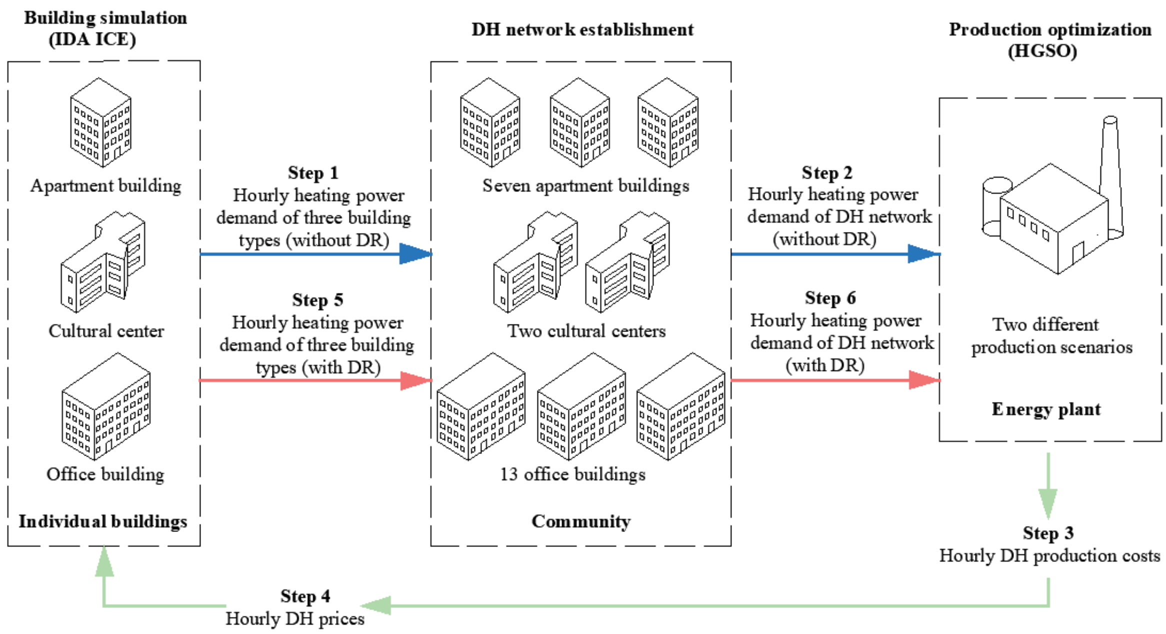


**Figure 1.** Description of the whole simulation process.

### 2.2. Building-level simulation

A rule-based DR control was used in this study for building-level simulation as shown in Figure 2. Control signals were calculated based on hourly DH prices and the moving future 24-hour prices by the Behrang-Sirén method [9, 15]. The moving future 24-hour price represents the DH price for the subsequent 24 hours. The average outdoor temperature of the past 24 hours was named as the outdoor 24-hour moving average temperature ($T_{avr.,24\ out}$). 20 °C was set as the minimum indoor air temperature setpoint based on the standard EN 16798-1 [16]. Considering the study of Suhonen et al., the maximum acceptable indoor temperature setpoint was 23 °C [17]. To prevent the sharp increase in heating power load, we employed setpoint smoothing technique [17, 18].

The properties of the three example buildings were shown in Table 1. In the 1930s, the apartment building was constructed while in the early 1980s, the other two buildings were built and they had renovation recently. Occupants internal heat gains were set considering an activity level of 1.2 MET with a clothing of 0.75 ±0.25 clo which was chosen for sedentary activity and normal clothing [19]. For the apartment building, the cultural center and the office building, the domestic hot water (DHW) consumption values were 17, 4 and 6 kWh/m$^2$, respectively [20].

### 2.3. Production-level simulation

According to Figure 1, firstly, IDA-ICE calculated the hourly heating power demand for the whole year of the three example buildings based on the weather condition in Hamburg, Germany. Following that, we established a community which had a similar annual heat demand of the actual community in Hamburg. This study used the average yearly heat demand data from all substations of a local DH network. The existing building stock in the actual community consists of 22 apartment buildings (annual heat demand of 3444 MWh), five office buildings (annual heat demand of 3735 MWh), and two cultural centers (yearly heat demand of 721 MWh). Therefore, based on the simulated yearly heat demand of the three building types, the established community consists of seven apartment buildings, 13 office buildings, and two cultural centers. The average annual heat demand of the established and the actual communities differed by 0.19%. We chose two production scenarios to supply heat to the community. Finally, the dynamic optimization tool HGSO output the total costs and $CO_2$ emissions for these two production scenarios. According to the optimized hourly production costs, hourly dynamic DH prices were calculated for building-level DR. A rule-based DR control was used in the three example buildings so that we gained the hourly heating power data both for the buildings and the community. The tool HGSO repeated the optimization procedure.

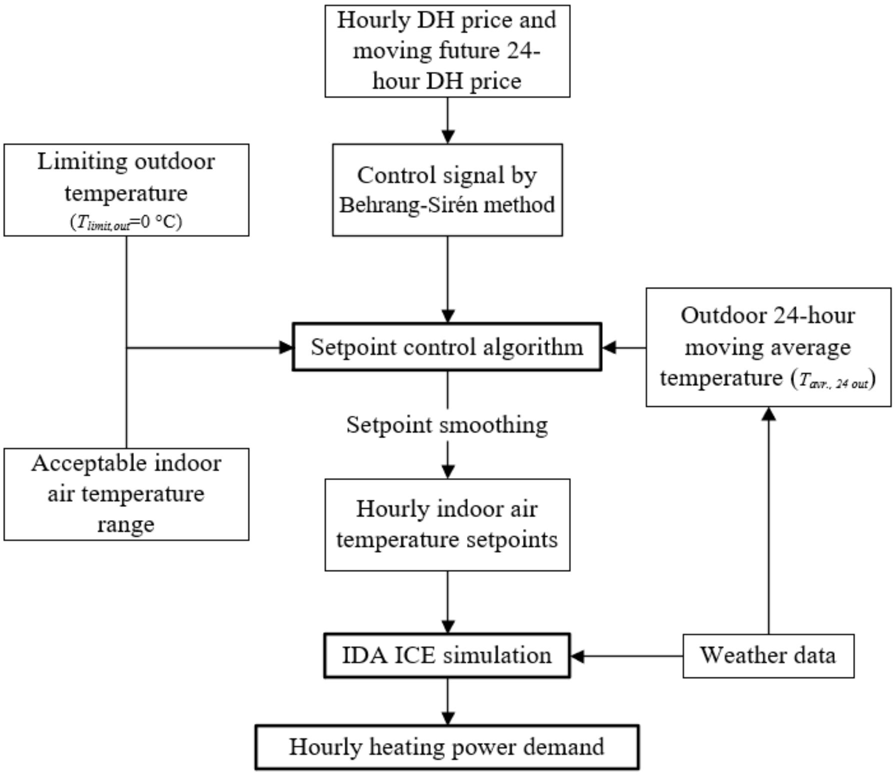


**Figure 2**. Building-level simulation process for DR control.

**Table 1**. Properties of example buildings.

| 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 of external walls (W/m$^2$·K) | 1.7 | 0.2 | 0.2 |
| U-value of roof (W/m$^2$·K) | 1.4 | 0.19 | 0.19 |
| U-value of ground slab (W/m$^2$·K) | 1.0 | 0.28 | 0.28 |
| U-value of windows (W/m$^2$·K) | 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$^2$·a) | 11 | 9 | 2 |

In this paper, there are three steps for the calculation of DH prices: (1) The input data (hourly heating power demand of the DH network without DR) was processed. (2) The hourly heat production costs were calculated by the HGSO tool. (3) These hourly heat production costs were normalized to adjust to the real DH price of 91.2 €/MWh of the actual DH network in Hamburg offered by Vattenfall Wärme Hamburg GmbH [21]. In this study, capital expenditure was ignored because the production costs were calculated mainly considering operational expenditure.

Table 2 lists production combinations. Scenario 1 represents the actual generation unit mix of the Hamburg DH system. The CHP unit used bio-methane. The producer gains profits granted governmental subsidy since German legislation for renewable energy stipulates revenues for electricity from renewable sources fed into the grid [22].

In scenario 2, it was assumed that all of the generation units could deliver the requisite temperature since it was the third-generation local district heating network in Hamburg and ran below 100 °C [23]. Therefore, in this study, the discussion of various heat pump scenarios about the influence of COP values on DR was not taken into account, and we disregarded the impacts of heat pump COP values on supply temperatures. The heat pump COP was set as 4. The solar thermal unit generated energy was directly supplied to the system.

In addition, each scenario included a 1.4 MWh heat capacity hot water tank. The community heat demand had to be supplied via the production units and the tank for each hour. The water tank could be charged by all the units. It could be operated temporarily to balance over- or underproduction. The generation units must fill the storage tank to 50% capacity by the end of the optimization period (24 hours). Therefore, HGSO optimized the cost optimal approach to generate the required heat considering the market electricity price of 24 hours. Finally, the unit and storage operations were output as an hourly schedule. Taking the scenario1 as an example, during periods of high electricity prices, the CHP generated heat was maximized for the heat demand supply, and based on the marker electricity price, the excess electricity was sold to make a profit.

**Table 2.** Heat generation units and their maximum powers.

| Generation unit | Scenario 1<br>Heat/electricity power (MW) | Scenario 2<br>Heat/electricity power (MW) |
|---|---|---|
| CHP | +0.737 / +0.527 | -- |
| Gas boiler 1 | +1.950 / 0 | -- |
| Gas boiler 2 | +1.100 / 0 | -- |
| Gas boiler 3 | +1.100 / 0 | -- |
| Heat pump (HP) | -- | +2.000 / -0.500 |
| Electric heater (EH) | -- | +3.550 / -3.740 |
| Solar thermal (ST) | -- | +0.483 / 0 |
| Total heat power | 4.887 | 6.033 |

### 2.4. *Description of studied building cases*

As shown in Figure 3, first, we simulated each building without DR. Based on the two different DH prices, we calculated the annual DH energy costs. Following that, IDA ICE was employed to simulate three buildings using these DH prices with DR. In scenario 1, for example, we labelled the apartment building cases with DR as AB with DR Scen1. Similarly, the apartment building cases without DR was named as AB without DR Scen1. Thus, we simulated a total of 12 cases.

## 3. DH prices

Table 3 describes the DH prices for the rule-based DR control. The established community heat demand and electricity consumption were input in hourly steps. And all related heat demands, prices, costs and emissions were calculated for every hour. The production cost optimal solution for 24 hours was optimized by the HGSO tool and it output the hourly production cost, $C_{prod.}(t)$. After that, on the consumer side, an hourly DH price was calculated by Eqs. (1)-(4). The hourly heat production costs were normalized to adjust to the real DH price ($p_{real}$) of 91.2 €/MWh.

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

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

$$F = \frac{p_{real}}{R} \tag{3}$$

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

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.

Because of normalization, the average prices are the same. Due to a bigger standard deviation than scenario 2, in scenario 1, the DH price is more unstable. The maximum and minimum values for the DH price in scenario 2 are greater.

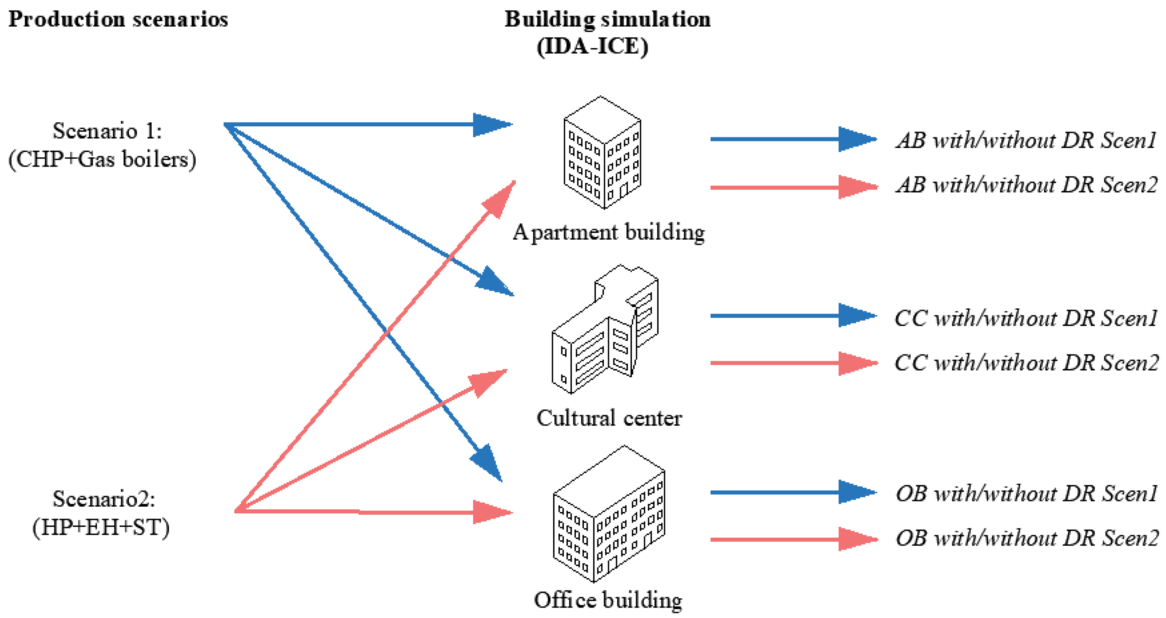


**Figure 3.** Description of studied building cases.

**Table 3**. Description of DH prices.

| Scenario | Maximum (€/MWh) | Minimum (€/MWh) | Average (€/MWh) | Standard deviation (€/MWh) |
|---|---|---|---|---|
| 1 | 98.8 | 7.52 | 91.2 | 8.5 |
| 2 | 138.5 | 47.3 | 91.2 | 4.5 |

## 4. Building-level rule-based demand response control

It was assumed that the moving future 24-hour price of DH was known in this study. We employed the Behrang-Sirén method for DR control signals (CS) calculation [9, 15]. The CS values were set as -1,

+1 and 0 reflecting the price trend of decreasing, increasing and flat. We chose the marginal value 75 €/MWh considering Martin's study [24]. As shown in Eq. (5), the control signal was created:

$$\begin{aligned}&If \left\{\begin{matrix} HEP < HEP_{avr.}^{+1,+24} - marginal\ value \\ or \\ HEP_{avr.}^{+6,+12} > HEP_{avr.}^{+6,+24} + marginal\ value \end{matrix}\right\}, Then\ CS{=}{+}1 \\ &Elseif\ \ HEP > HEP_{avr.}^{+1,+24}, Then\ CS{=}{-}1 \\ &Else\ CS{=}0 \\ &End\ If\end{aligned} \tag{5}$$

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

Figure 4 shows the rule-based DR control stragety according to the two dynamic DH prices. Through changing of indoor air temperature setpoints, our goal is to take advantage of the thermal mass structures in the builidngs for short-term storage. In the three example buildings, the space heating systems controlled the hourly target indoor air temperatures. $T_{SH,\ min}$, $T_{SH,\ norm}$ and $T_{SH,\ max}$ are the minimum indoor air temperature setpoint (20 ºC), the normal indoor air temperature setpoint (21 ºC), and the maximum indoor air temperature setpoint (23 ºC). Limiting outdoor temperature ($T_{limit,\ out}$) was set as 0 ºC to avoid overheating based on Martin's research [24]. These setpoints were smoothed by setpoint smoothing technique for minimizing rebound effects [17, 18].

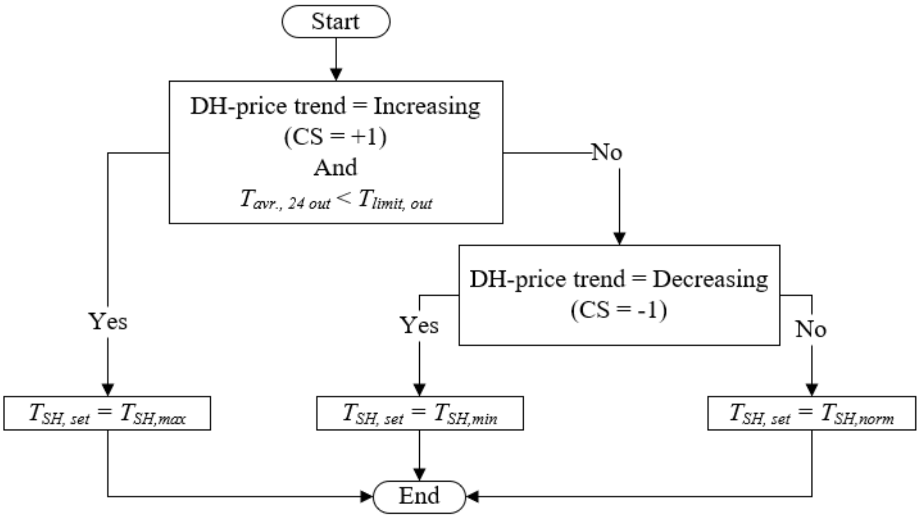


**Figure 4.** Control algorithm for space heating.

## 5. Results

### *5.1. DR benefits for building owners*

Table 4 lists the three building types of DH consumption and energy costs with and without DR under two different production scenarios, separately. The total DH consumption consists the space heating, ventilation and DHW heat consumption. Compared with the reference cases, the differences are annual DH consumption and energy costs reduction. For every building type, cases with DR based on the production mix of scenario 1 have higher DH consumption and cost savings. DR cuts a maximum of 2.8% of DH consumption, which leads to a 2.9% of energy costs in the apartment building. Consumption and energy cost savings for the cultural center scenarios are around 1% greater than for the apartment building cases. Among the three building types, the office building saves the most.

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

| Scenario | DH consumption | | | DH energy costs | | |
|---|---|---|---|---|---|---|
| | Total (MWh) | Difference MWh | Difference % | Total (€) | Difference € | Difference % |
| AB without DR. Scen1 | 480.2 | -- | -- | 44 756 | -- | -- |
| AB without DR. Scen2 | 480.2 | -- | -- | 43 764 | -- | -- |
| AB with DR. Scen1 | 466.6 | -13.6 | -2.8 | 43 455 | -1301 | -2.9 |
| AB with DR. Scen2 | 467.2 | -13.0 | -2.7 | 42 561 | -1204 | -2.8 |
| CC without DR. Scen1 | 457.4 | -- | -- | 42 816 | -- | -- |
| CC without DR. Scen2 | 457.4 | -- | -- | 41 742 | -- | -- |
| CC with DR. Scen1 | 438.9 | -18.5 | -4.0 | 41 070 | -1746 | -4.1 |
| CC with DR. Scen2 | 440.8 | -16.6 | -3.6 | 40 216 | -1526 | -3.7 |
| OB without DR. Scen1 | 280.3 | -- | -- | 26 438 | -- | -- |
| OB without DR. Scen2 | 280.3 | -- | -- | 25 688 | -- | -- |
| OB with DR. Scen1 | 266.9 | -13.3 | -4.8 | 25 152 | -1286 | -4.9 |
| OB with DR. Scen2 | 268.0 | -12.3 | -4.4 | 24 546 | -1142 | -4.4 |

### *5.2. DR benefits for district heating production*

Table 5 shows the results of annual production with and without DR. Positive values of the total generation cost represent payments made by the heat producer for energy generation, whereas negative values represent profits made by the heat producer from generation units that produce and sell electrical energy. For example, -46 057 €/year means that the producer gains 46 057€ during the one-year generation in scenario 1 without DR because of the government subsidy for bio-methane usage and selling extra generated electricity to the market. Since the heat pump and electrical heater consumed electricity from the market, the generation costs in scenario 2 are positive. The differences are the changes caused by DR.

In scenario 1, through DR application, the lower DH consumption reduces the demand for fuels. The DR action cuts 6.9% of $CO_2$ emissions and earns 12.6% profits for producers. In addition, the $CO_2$ emissions as well as absolute $CO_2$ emission savings by DR are significantly higher with scenario 2 because of the production mix. In scenario 2, the application of DR makes the DH system consume less electricity to generate heat which further decreases total $CO_2$ emissions. It results in an 8.6% of emissions reduction, and a decrease of 12.3% of the total generation costs.

**Table 5.** Annual production results without and with DR.

| Scenario | Total DH consumption (MWh) | $CO_2$ emission (ton) | Total generation cost (€/year) |
|---|---|---|---|
| Scenario 1 without DR | 7919.0 | 748.7 | -46 057 |
| Scenario 1 with DR | 7612.7 | 697.1 | -51 846 |
| Difference | 306.3 (3.9%) | 51.6 (6.9%) | 5789 (12.6%) |
| Scenario 2 without DR | 7919.2 | 1264.1 | 108 171 |
| Scenario 2 with DR | 7635.8 | 1155.3 | 94 866 |
| Difference | 283.4 (3.6 %) | 108.9 (8.6 %) | 13 305 (12.3 %) |

## 6. Conclusions

Our goal is to investigate the way in which DR impacts on buildings and DH generation are related to economic and environmental factors. For the building owners, DR utilization cuts costs by 2.8%–4.9% depending on different building types. The office building has the highest cost-saving potential compared with the apartment building and the cultural center. Moreover, the DH producers earn about 12% of generation profits from this large-scale DR application. It decreases the $CO_2$ emissions by 6.9% and 8.6% with different production mixes.

The reduction of total generation cost by DR will lead to the change of dynamic DH prices. Therefore, an adjustment of the prices are required in further studies. Besides, part of the production savings need to be shared with consumers. Parameters could be developed for prosumer accebility determination of DR.

Although the building-level results are applicable to specific building types with similar price characteristics and weather conditions in this study, the DR control is general, which could be applied for any building type with different climate conditions and energy prices. Furthermore, the production optimizaiton results are typical of the investigated generation combinations. However, the DH production analysis approach could be applied for all production mixes.

## 7. Acknowledgement

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