ABSTRACT
Combined heat and power (CHP) plants enable an efficient use of low-grade energy carriers, such as domestic waste and biomass, for co-generation of district heating (DH) and electricity. Expected future building energy-efficiency improvements reduce the demand for space heating and may limit the possibilities to co-generate electricity. The use of DH for new applications, such as household appliances, can improve conditions for co-generation of electricity. This paper investigates the future potential to increase DH demand and co-generation of electricity due to large-scale implementation of household appliances that use DH instead of electricity. The analysis is applied to the DH system in Uppsala, Sweden. Results show that co-generation of electricity and total fuel use increase with implementation of household appliances connected to a building hot water circuit (HWC). The impact on CO2 emissions depends on DH fuel mix and electricity assessment approach.

1. INTRODUCTION
In 2008, the EU member states agreed to increase the share of renewable energy to at least 20 % of the energy use in the year 2020. Also, both the European CO2 emissions and the primary energy use are to be reduced by 20 % until 2020. (1) If these goals are to be reached significant changes are needed in all energy sectors. Within European buildings the potential for energy savings is large, both in existing buildings and in new buildings. The EU recast of the energy performance in buildings directive states that all new buildings are to be nearly zero-energy buildings in 2020. (2)

Several European countries use district heating (DH) to supply heat to households for space heating (SH) and domestic hot water (DHW). The centralised heat production in DH systems can be adjusted to local conditions due to its flexibility regarding fuels and large-scale heat production advantages, such as higher efficiency and improved flue gas cleaning. DH also enables the use of low grade energy carriers, such as domestic waste and industrial waste heat. In several DH systems efficient utilisation of fuels is possible in CHP plants, where electricity is co-generated with the heat produced to supply heating demands in buildings. But as the heat demand in buildings depends on the outdoor temperature and therefore varies significantly between seasons, electricity generation capacity in CHP plants is often not fully utilised throughout the year. Thus, a more levelled annual heat demand can be expected to enable increased utilisation of CHP plants and thereby the share of co-generated electricity in the system. The DH demand can be levelled out by decreasing the SH peak demand and increasing the share of the not outdoor temperature dependent heat demand.

Here, heat demands from the use of household appliances (washing machines, tumble dryers, dish washers and refrigerators) that use DH for heating instead of electricity are investigated using time use data (TUD) and the MODEST energy system optimisation tool. The appliances are supplied through a separate hot water circuit (HWC) from the DH heat exchanger in the building. The heat demand changes are scaled up to investigate the impact that a large-scale implementation of HWC-connected appliances would have on local DH system operation. A case study of the Swedish DH system in Uppsala is presented, where both large-scale implementation of HWC household appliances and building energy efficiency improvements are included in scenarios for the years 2020 and 2030. The scenarios for energy efficiency were presented in (3). The parameters of interest are co-generated electricity in CHP plants and CO2 emissions.

This paper is structured as follows. In Section 2 the optimisation modelling tool is presented along with the
specific model used in the study. In Section 3 the studied scenarios are described and in Section 4 the optimisation results. Section 5 includes a discussion of the results and in Section 6 the conclusions from the study are presented.

2. METHODOLOGY

In order to investigate the effects of possible future changes in DH system operation conditions and to estimate co-generation potentials, energy system modelling is a valuable tool. An energy system optimisation model enables the investigation of energy systems under optimal operational conditions. This means that the system can be studied when isolated from unpredictable factors that impact the DH system operation. This section includes a description of the optimisation method and the necessary input data.

2.1 The MODEST optimisation tool

The energy system modelling tool used in this study is MODEST, which is an acronym for Model for Optimisation of Dynamic Energy Systems with Time dependent components and boundary conditions. MODEST uses linear programming to optimise the energy flows of a system to minimise system cost, while satisfying one or more energy demands.

MODEST models are based on a set of nodes interconnected with energy flows. Each flow can be associated to a cost, for example fuel costs or energy taxes. A characteristic for MODEST is the flexible time-division that enables the capturing of peak demands and offers great adaptability to different types of systems and analytical focuses. MODEST has been used for several different applications and has been described in detail in (4, 5).

2.2 MODEST model of the Uppsala DH system

A detailed model is used to describe the DH system in Uppsala, Sweden. The model is described in detail and validated in (3). Figure 1 shows an aggregated picture of the Uppsala DH system model. The column to the left represents the fuels used in the system. The two columns in the middle represent the different energy conversion units and the distribution networks. To the far right the energy demands and electricity market are shown. The interconnections between the components represent the energy flows (fuels, heat or steam, electricity and district cooling).

Fig. 1: Aggregated view of the MODEST model of the Uppsala DH system.

The Uppsala DH system is characterised by a relatively large share of CHP production in a peat-fuelled CHP plant (Boland+Husbyborg in Fig. 1) and in an electricity-generating turbine connected to the waste incineration plant (Block 5). The peat-fuelled CHP plant has a lower heat output limit of about 110 MW. The consequence of this is that a reduced heat demand might lead to significantly shortened utilisation time of the CHP plant, which also means that other heat production units are...
used to replace the CHP plant when the heat demand is not sufficiently high to enable CHP production.

The large share of fossil peat in the fuel mix for the CHP plant and the peat fuelled hot water boiler along with the electric heat pump facility and the distribution network for district cooling (Fig. 1) are also important characteristics for the Uppsala DH system.

2.3 CO₂ emissions

CO₂ emissions are calculated from the use of fuels for heat and electricity production. Indirect emissions caused by changes in electricity use are taken into account, as well as indirect emission reductions due to electricity generation in the DH system and electricity savings due to converted household appliances. The latter are due to conversion from electric household appliances.

The fuels used for heat and electricity production are assigned emission factors. Electricity use and production are assessed by using two different electricity-on-the-margin approaches. This concept is described and discussed in (6). As a worst case approach the electricity used is assumed to stem from ineffective European coal fired condensing (CC) power plants. A long-term perspective is also used, based on the assumption that natural gas combined cycle (NGCC) power plants have replaced coal condensing power plants in the future European electricity generation mix. Produced electricity is assumed to displace CC and NGCC, respectively. Table 1 shows the emissions factors used in the calculations.

### TABLE 1: EMISSIONS FACTORS

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emission factor [kg CO₂/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>waste</td>
<td>90</td>
</tr>
<tr>
<td>peat</td>
<td>370</td>
</tr>
<tr>
<td>oil</td>
<td>270</td>
</tr>
<tr>
<td>electricity (CC)</td>
<td>950</td>
</tr>
<tr>
<td>electricity (NGCC)</td>
<td>400</td>
</tr>
</tbody>
</table>

2.4 Electricity price

For the optimisations performed here an electricity price profile is used that mirrors the electricity price variations in Sweden during the years 2006 until 2010. This electricity price profile is presented in more detail in (3).

3. HEAT DEMAND SCENARIOS

This chapter describes the previously studied building energy efficiency scenarios (see Section 3.1) that constitute the base for the HWC appliance scenarios that are presented in Sections 3.2 and 3.3.

### 3.1 Building energy efficiency scenarios

Two building energy efficiency improvement scenarios for the Uppsala DH system in the years 2020 and 2030 were described in (3) and have been used as a scenario base in this work. These scenarios included an annual 1.5% reduction of heat demand due to energy efficiency improvements in the existing multi-family residential apartments in Uppsalan. This was based on a report from the Swedish district heating Association (7). Also, since Uppsala is an expanding region 1000 low-energy apartments annually were assumed to be built within the district heating system until the year 2030. The number of new apartments is in accordance with the Uppsala City comprehensive plan in 2010 (8). A reference scenario was also used representing the Uppsala DH demand in the year 2010. The heat demand in the two building energy efficiency scenarios for 2020 and 2030 were 11% and 23% lower than in the reference scenario, respectively. These differences are also visualised in Figure 3.

An annual 1.5% reduction of the total DH demand until 2030 requires that energy efficiency improvements are applied not only to all multi-family residential buildings but heat demand reductions are needed also for other heat consumers (detached houses, public buildings, industries etc.). The total number of multi-family apartments in Uppsalan were approximately 67,000 in the beginning of 2011, this according to statistics obtained from the City of Uppsala (9).

### 3.2 Time-use data based approximation of HWC appliance heat demand

In this work the 2020 and 2030 scenarios are extended to also include large-scale implementation of HWC household appliances that use district heating instead of electricity. The considered appliances are washers, dryers, dish-washers and absorption cooling refrigerators. The hourly demands for district heating for these different appliances were approximated using time-use data (TUD) and technical data for each appliance. Table 2 shows the technical data for the different applications. These data were obtained from a report published by the Swedish district heating association in 2004 (10).

TUD is data that maps the activities of a number of people through diaries (11). TUD may differ in for example time resolution, population size and detail of recorded activities. The data set used here originates from a time-use study on 179 Swedish households conducted by Statistics Sweden (SCB) in 1996. The data involves 463 individuals in total and their activities on a 5-min basis for one weekday and one weekend day. (12)

From these data the frequency and time-of-day usage of household appliances in 64 households in multi-family
Building apartments is extracted. Using an extension of the model presented in (13) to convert TUD to energy use profiles, these data were used to model the use of HWC appliances.

**TABLE 2: TECHNICAL DATA FOR HWC APPLIANCES**

<table>
<thead>
<tr>
<th></th>
<th>Washer</th>
<th>Dryer</th>
<th>Dishwasher</th>
<th>Abs. Cooling appl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle time (min)</td>
<td>130</td>
<td>90</td>
<td>160</td>
<td>-</td>
</tr>
<tr>
<td>Demand per cycle (kWh)</td>
<td>0.7</td>
<td>3.45</td>
<td>0.65</td>
<td>-</td>
</tr>
<tr>
<td>Output demand (W)</td>
<td>323</td>
<td>2300</td>
<td>244</td>
<td>131/72*</td>
</tr>
<tr>
<td>Electricity savings per cycle (kWh)</td>
<td>0.45</td>
<td>3.45</td>
<td>0.65</td>
<td>0.49**</td>
</tr>
</tbody>
</table>

* Depending on the season. 131 W during summer and 72 W during winter
** Savings for one 24-hour period

Figure 2 shows the mean heat demand profiles for one week day and one weekend day during winter (diagrams a and b) and the corresponding demand profiles for one weekday and one weekend day during summer (diagrams c and d). The heat demands are based on mean values from the data for the 64 multi-family apartment households. It is clear from Figure 2 that the main part of the heat use in these appliances is in the absorption cooling appliances and the dryers.

The reason for the difference between winter and summer in cooling appliance heat demand is that during winter the cooling appliance (refrigerator) partly supplies the space heating demand in the building that would otherwise have been supplied through the radiators. The increase in district heat demand during winter is equal to the previously wasted heat from a conventional electric cooling appliance (i.e. a refrigerator), which now is covered by DH instead. For summer days, the heat-demand increase is equal to the heat demand in the absorption cooling appliance.

For the 2020 scenario it is assumed that HWC applications are implemented in 57% of the existing buildings in Uppsala and in the 10,000 newly built low-energy apartments. For the 2030 scenario 100% of the existing multi-family residential buildings and all 20,000 newly built apartments are assumed to use HWC household appliances.

![Fig. 2: Mean heat demands due to use of HWC household appliances. Diagram (a) shows the hourly demand for a winter weekday. Diagram (b) shows the demand for a winter weekend day. Diagrams (c) and (d) show the corresponding demands for a summer weekday and a summer weekend day, respectively.](image-url)
3.3 Complete scenarios for 2020 and 2030

The heat demand profiles from Figure 2 were up-scaled and added to the heat demands for the 2020 and 2030 heat demand change scenarios described in Sect. 3.1. Figure 3 shows duration diagrams for the total district heating demand in the studied scenarios. It is clear that the implementation of large amounts of HWC household applications have a relatively small impact on the total DH demand in Uppsala compared to the effects of energy efficiency improvements in the buildings. As expected, the effects of both energy efficiency improvements and implementation of HWC appliances are larger for the 2030 scenario (diagram b) than for the 2020 scenario (diagram a).

The largest heat-demand changes are due to building energy efficiency measures and are seen for the low tempered part of the year to the left in the duration diagrams. However, during low-demand hours in summer (to the right in the diagrams) the demand for DH in household appliances is larger than in winter hours. The total demand is increased during summer compared to the 2010 reference heat demand and decreased during winter. This means that building energy efficiency improvements and implementation of HWC household appliances both contribute to the levelling of the annual heat demand in Uppsala.

Total approximated electricity savings due to conversion from electric appliances in the 2020+HWC scenario was 17 GWh compared to the 2020 scenario without HWC appliances. The corresponding number for the 2030+HWC scenario was 31 GWh.

![Duration diagrams for the total district heating demand in the studied scenarios.](image)

Fig. 3: Total DH demands for the studied scenarios. In (a) the 2020 scenario and the 2020+HWC scenario are shown and in (b) the corresponding 2030 scenarios, both in relation to the 2010 reference scenario.

4. RESULTS

Figures 4 and 5 present the results from the optimisations of heat production for the studied scenarios of the Uppsala DH system. Figure 4 shows the fuels used in the different scenarios while Figures 5 (a) and (b) show the electricity generation in different CHP units and the CO₂ emissions due to the system, respectively.

In Figure 4 the fuels used in the Uppsala system for the different scenarios are shown. The total use of fuels in all scenarios is lower than the fuel use in the reference scenario due to lower heat demand. Also, the implementation of HWC household appliances clearly increases the total use of fuels for both scenarios 2020 and 2030.

The incineration of waste is beneficial for the energy company due to a reception fee received for waste management. This means that the income from incineration of waste is double when it is converted to heat and electricity. Therefore waste incineration is highly prioritised within the system and this explains why the use of waste is constant for all studied scenarios. The share of oil in the fuel mix is generally low and mainly used for back-up heat production. The use of electricity in the heat pumps is also low. This production is slightly higher for the scenarios with implemented HWC appliances compared to the scenarios for 2020 and 2030.
without the HWC appliances. This is explained by the HWC appliance heat demand increase generally being insufficiently large to motivate increased CHP production since the minimum output limit in the CHP plant is not exceeded. The increased demand is therefore supplied by other heat production units, mainly electric heat pumps and the peat fuelled hot-water boiler.

The largest differences in fuel use between the scenarios are seen for the use of peat. This is mainly due to the reduced utilisation time of the peat fuelled CHP plant as a consequence of the reduced heat demand levels. In the reference scenario, the CHP plant is operated from November until March. In the 2020 scenarios the utilisation time is limited to the period from December to February and for the 2030 scenario without HWC appliances the plant is not utilised at all. This explains the lower use of peat for all scenarios compared to the reference scenario.

![Figure 4: Fuels used in the Uppsala DH system for the studied scenarios.](image)

The results for the 2020 and 2030 scenario cases with and without HWC appliances (Figure 4) show that the use of peat is higher for the scenario cases where the HWC appliances are implemented. For the 2030 scenario this is mainly because the increased heat demand in HWC appliances enables the CHP plant to be utilised for one month instead of not being operated at all. For the 2020 scenario the increased use of peat is also explained by an increased electricity co-generation in the CHP plant even though its utilisation time is not changed.

The increased use of the CHP plant for the scenario cases with HWC appliances is also seen in Figure 5 (a) where the electricity generation in the CHP plant and the waste incineration Block 5 turbine is presented. Compared to the reference scenario the electricity generation in the CHP plant will be reduced by about half until 2020. Implementation of HWC household appliances leads to slightly higher electricity generation in the 2020 scenario than if electric appliances are used. For the 2030 scenario the implementation of HWC appliances is crucial since it enables the use of the CHP plant for one month.

In Figure 5 (b) the total CO₂ emissions (fuels and electricity included) for the scenarios are presented. For the worst case electricity assessment approach, with coal fired condensing power generation on the electricity margin, the differences in CO₂ emissions for the different scenarios are relatively small. However, the emissions are slightly reduced as the heat demand is reduced in scenarios 2020 and 2030. Implementation of HWC appliances has a further decreasing effect on the CO₂ emissions for the CC-case. The small differences in CO₂ emissions is due to the fact that the reduced use of highly emitting peat fuel evens out the effects of increased credited emissions due to co-generated electricity that displaces CC electricity on the margin.

For the long-term electricity assessment approach where natural gas combined cycle (NGCC) power plants are assumed to have replaced the CC power plants in Europe the results are somewhat different. The total emissions for the NGCC perspective are generally larger due to the fact that produced electricity is assumed to replace marginal power generation with a lower emission factor than for the CC perspective. The results show that the NGCC emissions are reduced significantly with the reduced heat demand in scenarios 2020 and 2030. However, the implementation of HWC appliances for the scenarios 2020 and 2030 actually increases the CO₂ emissions for both scenarios compared to corresponding scenarios without HWC appliance implementation.

This is even though electricity savings are taken into account due to conversion from electric household appliances. Again, this is explained by the use of highly emitting peat fuel in combination with a lower amount of credited emissions due to displacement of marginal electricity for NGCC compared to CC.

To sum up the results for large-scale implementation of HWC household appliances presented here it is clear that it leads to an increased and annually more levelled total heat demand in the DH system. However, the relative heat demand change due to a large-scale conversion from electric appliances to HWC appliances is small. The co-generation of electricity is increased when HWC appliances are implemented. However the changes in global emissions of CO₂ depend on the electricity assessment approach. The worst-case CC perspective implies lower global emissions when HWC appliances are implemented while the long-term NGCC perspective implies the opposite because carbon-rich peat fuel is used for the heat production.
5. DISCUSSION

When using theoretical models to investigate these types of energy systems and their response to changes in their surroundings, it is important to discuss the validity of assumptions made regarding the system. The results presented here are general in the sense that the changes in total heat demand in a DH system is relatively small even though a large amounts of households convert their electric household appliances to HWC appliances. Also, the difference in CO₂ emissions due to different approaches for electricity assessment is generally valid. However, it is important to note that the specific values for electricity co-generation and CO₂ emissions presented here are valid only for the Uppsala DH system and under the assumption that the heat production side of the system as it is structured and operated today would not be significantly changed until 2030.

There are however plans within the energy company that operates the system today to replace the peat fuelled CHP plant within the considered time period, i.e. until 2030. In the process of replacing the plant the results presented here are useful when considering heat and electricity output dimensioning for the new plant and in the choice of fuels to be used.

The results presented for the 2030+HWC scenario showed that the heat demand here would be sufficient to operate the CHP plant for one month per year. However such a short utilisation time is probably not realistic for the real case, but the results do indicate that large-scale implementation of HWC appliances generally could have a positive effect regarding the conditions to increase CHP production. This compared to the case where HWC appliances are not implemented.

The results for the CO₂ emissions indicate that the emissions caused by use and generation of electricity depend on the choice of electricity assessment approach. It is also clear that even if electricity use is considered to cause large emissions indirectly today this might not be the case in the future. The European power system is dynamic and under transformation. This needs to be taken into account when taking long-term decisions regarding our energy systems.

Washing machines, tumble dryers and dish washers supplied by DH are now installed in a few Swedish residents. But heat-driven absorption cooling refrigerators have to our knowledge not been installed in ordinary households and the technique is still being developed. Absorption cooling advices are also demanding relatively large spaces and might therefore be more suited for commercial applications than for households.

The CO₂ emission results also depend on the fact that the highly emitting peat fuel is used in the CHP plant. If this plant is replaced by a different plant using a fuel with a significantly lower emissions factor the results would also be different for the future scenarios. This would lead to lower local emissions from the fuels used within the system, and indirectly the electricity generated in the system would cause a larger reduction of global emissions. Therefore, the CO₂ emissions from a DH system with more biomass in the CHP fuel mix could be expected to be decreased to a larger extent due to implementation of HWC appliances, than what was the case for the Uppsala DH system.

6. CONCLUSIONS

A projected large-scale implementation of HWC household appliances in the Uppsala DH system for the years 2020 and 2030 leads to a slightly increased and more levelled annual heat demand compared to the corresponding scenarios without HWC appliances. HWC appliance implementation yields a higher fuel use and larger amounts of co-generated electricity in CHP plants.

A large scale implementation of HWC household appliances also lead to somewhat lower CO₂ emissions when CC electricity generation is considered on the
electricity margin. However, the long-term NGCC electricity assessment approach yields opposite results with higher levels of global CO2 emissions for the scenarios with implemented HWC appliances compared to corresponding scenarios without the HWC appliances due to use of highly emitting peat for heat production.

Finally, the relative increase of the total heat demand due to large-scale conversion from electric household appliances to HWC appliances is small. Future changes in DH system heat demands are more likely to be due to building energy efficiency improvements. This should be of interest to DH companies in future development of DH systems.

7. REFERENCES