<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Applied Energy*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Lundström, L., Wallin, F. (2016)

Heat demand profiles of energy conservation measures in buildings and their impact on a district heating system.

Applied Energy, 161: 290-299

<http://dx.doi.org/10.1016/j.apenergy.2015.10.024>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:mdh:diva-29430>

Heat demand profiles of energy conservation measures in buildings and their impact on a district heating system

---

Lukas Lundström*, Fredrik Wallin

Mälardalens University, Västerås, Sweden

* Corresponding author. Tel.: +46-70-0866773. *E-mail address:* lukas.lundstrom@mdh.se

Keywords: district heating; energy conservation; weather normalisation; typical meteorological year; building energy simulation; energy system assessment

Abstract

This study highlights the forthcoming problem with diminishing environmental benefits from heat demand reducing energy conservation measures (ECM) of buildings within district heating systems (DHS), as the supply side is becoming “greener” and more primary energy efficient. In this study heat demand profiles and annual electricity-to-heat factors of ECMs in buildings are computed and their impact on system efficiency and greenhouse gas emissions of a Swedish biomass fuelled and combined heat and power utilising DHS are assessed. A weather normalising method for the DHS heat load is developed, combining segmented multivariable linear regressions with typical meteorological year weather data to enable the DHS model and the buildings model to work under the same weather conditions. Improving the buildings’ envelope insulation level and thereby levelling out the DHS heat load curve reduces greenhouse gas emissions and improves primary energy efficiency. Reducing household electricity use proves to be highly beneficial, partly because it increases heat demand, allowing for more cogeneration of electricity. However the other ECMs considered may cause increased greenhouse gas emissions, mainly because of their adverse impact on the cogeneration of electricity. If biomass fuels are considered as residuals, and thus assigned low primary energy factors, primary energy efficiency decreases when implementing ECMs that lower heat demand.

Acronyms

DH	District heating
DHS	District heating system
ECM	Energy conservation measure
TMY	Typical meteorological year
RMSE	Root mean square error
HO	Heat only (boiler)
CHP	Combined heat and power
FGC	Flue gas condensing
EAHP	Exhaust air heat pump
HRV	Heat recovery ventilation
ERV	Energy recovery ventilation
HDD	Heating degree days
PE(F)	Primary energy (factor)

1 Introduction

Energy conservation in the built environment is seen as an important measure towards mitigating climate change, increasing resource utilisation efficiency and thereby increasing energy supply security [1]. Whether to improve the supply side or the demand side is an open issue. Jennings states that from a UK perspective “There is a primary conflict when considering the impact of an energy system retrofit decision in buildings: whether to improve the efficiency of supply side technologies, or whether to invest in demand side technologies with the intention of reducing primary energy requirements, and maintaining the embedded value of the incumbent supply side technologies” [2]. This conflict is even more apparent in countries like Sweden with a high penetration of district heating (DH). Especially, since a majority of these systems have high utilisation of secondary biomass fuels, waste incineration, waste heat sources and cogeneration of electricity. As pointed out by Gustavsson [3,4] these conflicts may be more difficult to manage within district heating systems (DHS) compared to other types of supply side technologies. This due to high capital investment needs and limited possibilities of alternative use.

A driving force for DH is its ability to provide heat in urban areas from centralised production units in a more resource efficient way than would be the case with separate heat production units at each site of heat demand. DH can utilise lower valued energy sources like industrial waste heat, bulky biomass fuel and municipality waste and improve resource utilisation by cogeneration of heat and electricity. DH can therefore play an important role in efforts aiming towards decarbonisation of energy systems (which the Swedish DH sector is a good example of as shown in Fig. 1). DH systems exist in most countries of the Northern hemisphere, but have their stronghold in Nordic countries and countries of the former Soviet Union. For most of these countries DH have a heat market share of over 40 % of the building stock [5]. Today China shows the fastest DH sector growth and there also exist a large potential for DH growth in urban areas of many Central and Western European countries [5,6], while many DH systems of Nordic countries have matured and are addressing new issues when heat demand savings no longer can be met by extending the DH network.

Gustavsson’s article series from 1994 [3,4] is a comprehensive case study of demand side energy conservation in Swedish DH systems and discuss on most topics still of concern today. It was concluded that there was a 30 – 60% energy conservation potential if considering both marginal operating costs as well as avoided future investments in DH production; that energy conservation would alter the shape of the heat load duration curve in a favourable way and therefore lead to higher utilisation rates of supply side investments; that higher share of biomass fuels and cogeneration of heat and electricity would lower fossil CO₂ emissions. In more recent papers [7–13] climate change mitigation, demand side energy conservation measures (ECMs) and their impact on electricity cogeneration has come into focus. Difs et al. [7] study demand side ECMs in the DHS of Linköping, Sweden, and their different impacts, considering both the local impact as well as the global impact (caused by cogenerated electricity being displaced by standalone production). It was shown that even if ECMs reduce the local emissions, the total CO₂ emission reduction could be closely to zero for certain ECMs in the studied DHS. Gustavsson et al. [8] and Truong et al. [9] investigate building ECMs and how these would have an impact on primary energy usage under different DH production configurations, considering the interactions between energy demand of the building and the combined heat and power (CHP) production. It was shown that electricity saving measures in buildings connected to systems with high share of CHP production yields high primary energy savings, mostly due the electricity saving itself but also partly due to increased cogeneration of electricity as saved electricity in buildings partly give place to new heat demand. Heat recovery ventilation had a less favourable impact, partly due to increased electricity demand at the building level. Individual DH

systems differ considerably in fuel mix and production units (see Fig. 2) which makes it difficult to generalise results from case studies. Åberg [10] define four typical DH systems to represent the whole Swedish DH sector. The results show a general reduction of total CO₂ emissions in Swedish DH sector due to demand side ECMs, but also that the reduction potential depends on the production unit configuration of the DHS. Harrestrup and Svendsen [11] show in Danish study that ECMs that decrease the peak load could enable lower supply temperatures in the DHS, which increase possibilities for renewable energy sources. In a later paper by the same authors [12] the DHS of Copenhagen was studied. It was concluded that in order to reach Danish energy targets it would be similar costs to for demand side ECMs as to mitigate supply side to renewable production. It was argued that to implement demand side ECMs in a fast pace could be a better option, this to avoid a future situation with oversized renewable production capacity. Klobut et al. [13] state that in Finland the specific energy consumption of buildings heated by DH has decreased by 50 % in the last 35 years and that this trend is expected to continue in light of energy policies by EU and its member states. It was also concluded that the DH sector of today might be uncompetitive, assuming a future heat market of low heat density, if it does not speed up its development pace.

Fig. 1. The fuel mix of Swedish DH sector 1980-2010 and amount of fuels for cogenerated electricity (black line) for 1990 to 2012 [14,15].

Compared to the case studies and generalisations of papers [3,4,7–13] Eskilstuna DHS is already today in a situation where further implementation of ECMs on the demand side can, depending on the assessment perspective, cause even higher fossil CO₂ emission rates and adversely impact primary energy efficiency. An alternative view is that the Eskilstuna DHS already has reached a point of oversized renewable production capacity, assuming an existing potential of demand side ECMs. From Fig. 2 it is clear that the sector is diverse and that the DHS of Eskilstuna places itself as one of the most green and efficient DHS. As shown in Fig. 1, today's Swedish DH systems have: to a large extent mitigated from fossil fuels; increased the share of CHP production; slowed its expansion, even turned into a decline. Considering targets and visions by EU and its member states [1,13] these trends can be expected to continue and in the future more DHS will likely resemble that of Eskilstuna. In addition this paper contributes with a comprehensive study of eight different ECMs, their energy profiles, interaction between electricity and heat demands and their impact on the studied DHS. Three ECMs affecting both electricity and heat demand are studied in detail: exhaust air heat pump, heat recovery ventilation and household electricity savings. A method to weather normalise the heat load is developed, this method also serve the purpose of connecting the buildings and DHS models making it possible to study ECMs that

depend on other weather variables than outdoor temperature (i.e. ‘thermal solar’, ‘exhaust heat pumps’ and ‘operational optimisation’). Also the common practice of by-passing CHP’s turbine to produce peak heat load is modelled which further highlight the benefit of ECMs that reduce heat demand at cold weather conditions.

A weather normalising method for the DHS heat load is developed with the aim of enabling the DHS and the buildings model to use the same weather dataset. The method builds on the concept of the energy signature method that is used in e.g. [16–19] for both DHS heat load and buildings heat demand. In [16] Heller compares a simple energy signature method, a simulation approach and a degree-day method for heat load modelling and concludes that “For low-energy, solar-optimized building area, the energy–signature method leads to reasonable results and if system-wide load data are available, the energy–signature method can even do better than the degree-day method”. Energy signature methods use linear regression with outdoor temperature and energy consumption data as input variables. While heating degree days methods use just the outdoor temperature to calculate a correction factor. Both methods also need to set a balance temperature – the outdoor temperature above which a building needs no space heating. Energy signature based methods can be used to determine the balance temperature, while degree days based methods usually use an empirically predetermined value. The energy signature method described in the standard EN 15603:2008 to be used for building performance ratings, utilise monthly metering data, outdoor temperature and segmentation into two segments. This paper presents an improved method using daily data, five weather related explanatory variables, segmentation of data on daily basis into four seasonal related segments and weather normalisation by using typical meteorological year (TMY) weather data. The purpose of the developed method is to be able to use the same TMY dataset for both the building simulation as well as for weather normalising the heat load of the DHS model. Adding more explanatory variables, using higher resolution and dividing the data into more segments allows for a better linkage between the building model and the DHS model compared to than would be possible by traditional energy signature with outdoor temperature as only variable. For example, thermal solar panels are strongly dependent on solar radiation and would be poorly modelled using just outdoor temperature. Higher resolution is necessary to account for peak loads, using monthly values would smooth out these peaks.

The following research questions are addressed:

- What impact will various ECMs in buildings have on system efficiency and greenhouse gas emissions of DHSs?
- What are the heat demand profiles and electricity-to-heat factors of common ECMs?
- Could building and DHS models be connected through the use of a common normalised weather file?

As the purpose of this article is to compare marginal impact of ECMs, technical and economic potentials of ECMs are studied. All studied ECMs are currently being implemented in Sweden and can all be considered as feasible measures in isolation. The building model used is based on existing multifamily residential buildings located in the mid-Sweden climate, but most of the studied ECMs would have similar heat demand profiles if implemented on other types of buildings in broadly similar climate conditions.

To differentiate ECMs and their impact on the energy system, daily heat demand profiles and annual electricity-to-heat factors of various typical ECMs are derived by numerical simulation. These are then used to calculate how heat producing units are affected and how this affects cogeneration of electricity. These results are used in turn to analyse impact on primary energy (PE) efficiency and CO₂ emission rate for each ECM. In order to include different assessment

perspectives, the selected CO₂ and PE factors roughly correspond to first and third quartiles of commonly used factors for electricity [20–23]. From these values, results can be linearly interpolated or extrapolated to match the perspective of the readers choosing.

1.1 Eskilstuna case description

Eskilstuna municipality is situated in mid-Sweden and has a population of 100 000 people. Most buildings in the Eskilstuna-Torshälla urban area are connected to the DHS. In 2012 delivered district heat was distributed as follows: 47% to multifamily buildings, 15% to single-family houses, 9% to industry (process & space heating) and 25% to facilities (public & private).

Annual DH production in the area is about 770 GWh and the daily mean peak heat load is about 225 MW at an outdoor temperature of -14°C (long-term average of the coldest three days of the heating season in Eskilstuna). The system is essentially biomass fuelled and cogenerates about 190 GWh of electricity annually. Fig. 7 shows the running order of plants and the heat load duration for a typical year. Fig. 2 shows Eskilstuna in relation to other Swedish DHS. The x-axis shows α_{system} , the ratio between cogenerated electricity and delivered DH, and the y-axis shows fossil CO₂ emissions of delivered DH when accounting for the whole production and allocation of fuels between heat and electricity with the efficiency method [17].

Fig. 2. The 100 largest Swedish DHSs in 2012. Eskilstuna is marked in red. Size of bubbles indicates the size of the system.

2 Methods

A system perspective approach is used to explore the impact of different ECMs. The approach is visualised in Fig. 3 and described in the following points.

a) Heat demand profiles of ECMs: A baseline model of residential buildings is modelled (Section 2.1) under TMY (Section 2.6) weather conditions; models of eight ECMs that affect heat demand are simulated (Section. 2.2); heat demand profiles of the ECMs are then computed (Section 2.3) by subtracting the ECM simulation result from the baseline simulation.

b) Baseline heat load for a TMY: Historical DH production and weather data for 2012-2014 are used to compute regression coefficients which are then applied to TMY weather data to compute a weather normalised baseline heat load (Section 2.4).

c) Electricity prices for a TMY: historical electricity prices and weather data for 2006-2014 are used to compute the

Fig. 3. The workflow starting from gathering of data to be used as input to models that produce results that, in turn, are used as model input and to draw conclusions from.

proportion of time when electricity prices are sufficiently low so that it is cheaper to generate heat with oil boilers than to bypass the CHP turbine (Section 2.5); these results are then applied under TMY weather conditions to get the amount of days when it is expected that oil boilers are cheaper under a typical year.

d) DHS model: cost optimisation (Section 2.5) is performed to compute the running order of plants, using points b) and c) above and Table 3 as input.

e) Impact on DHS: new heat loads are computed by subtracting heat demand profiles (scaled to 10 GWh/y) of ECMs from the baseline heat load; point d) above is then repeated to compute the running order of plants and the impact calculated as the difference from the baseline optimisation.

f) Environmental assessment is conducted by calculating ECM-specific CO₂ and PE factors for the impact on the system computed in point e), using a range of commonly used environmental assessment factors presented in Section 2.7.

2.1 The building model

The model is based on two existing multifamily residential buildings in the Lagersberg district in Eskilstuna, Sweden. The buildings are typical of the early Swedish million homes programme era of the 1960s and 70s. They are connected to the same DH substation, are 4 floors high, consist of 6900 m² heated floor area (using the Swedish A_{temp} definition) and have external walls of aerated concrete. The buildings are part of a larger district renovation project that consists of a total of 23 similar buildings. They have recently been renovated with the goal of reducing the consumption of bought energy by half. The model is based on the buildings referred to as Lagrårdsgatan 10-12 in report [24], which has detailed description of the buildings and the renovation project.

The simulation is performed with the IDA ICE 4.6 software. The baseline model's specific electricity consumption is 26 kWh/m²,y household electricity and 19 kWh/m²,y facility electricity. District heating specific consumption is 30 kWh/m²,y for domestic hot water, 8 kWh/m²,y for heat losses (mainly hot water circulation) and 100 kWh/m²,y for space heating. The buildings model ground area is 1810 m², envelope area is 7360 m², envelope area per volume is 0.38 m²/m³, window/envelope ratio is 13 %, the average U-value is 0.87 W/K,m² and ventilation consist of mechanical exhaust air at 0.39 l/s,m².

Compared to the original buildings the baseline model differs by having only exhaust air where the original buildings had poorly performing exhaust and return with heat recovery ventilation (HRV). The model specific energy consumption matches the average of the whole Lagersberg district, but taking into account that the models has no HRV the model slightly outperforms the real buildings. Heat saving potential for ECMs for the buildings model is estimated as seen in Table 1. Based on measured and verified outcome of the renovation project [24], except for ‘household electricity’ and ‘exhaust air heat pump’ which are estimated as described in section 2.2.4 and 2.2.6.

Table 1. Estimated potentials for annual heat demand savings relative the baseline, for independently simulated ECMs

ECM	Building envelope	Heat recovery ventilation	Household electricity	Domestic hot water	Exhaust air heat pump	Operational optimisation	Thermal solar
Savings (%)	23	28	3	4	25	3	7

2.2 Energy conservation measures (ECMs)

Seven different categories of ECMs are modelled and simulated – all of which, except for the exhaust air heat pump (EAHP), have been applied to the real building renovation case described in Section 2.1.

2.2.1 Building envelope

Building envelope measures include ECMs which reduce the building’s heat loss factor for transmission, such as additional insulation of external walls or attic, improved glazing or reduced thermal bridges. This group of ECMs are modelled here as an improved U-value of the window glazing with no change of the glazing’s g-value.

2.2.2 Heat recovery ventilation

Heat recovery ventilation (HRV) employs a counter-flow heat exchanger between the inbound and outbound air flows and recovers sensible heat. In contrast to HRV an energy recovery ventilation (ERV) system also recovers latent heat in the moist outbound air flow, most commonly utilising a rotary enthalpy wheel. HRV systems require a frost protection mechanism to prevent ice formation in the heat exchanger, while ERV allows much lower exhaust air temperatures without freezing. Parameters that affect the outdoor temperature at which the frost protection starts up are the heat exchanger temperature efficiency, air flow balance, and temperature and moisture content of the indoor air.

HRV is modelled with the heat recovery temperature efficiency set to 80%, frost protection setpoint at 0°C (taking into account the lack of internal moisture gains in the model), supply air flow at 0.35 l/s,m² floor area, exhaust air flow set 5% higher than supply air flow, indoor temperature at 21°C, specific fan power (SFP) at 1.25 kW/m³,s for both fans (doubled electricity consumption for ventilation compared to baseline model), and supply fan motor electricity set to contribute to the heating while exhaust fan motor electricity is wasted.

2.2.3 Operational optimisation

Operational optimisation is a rough grouping of different types of measures. Two schemes that affect the DHS are studied here. The first is simulated as simple lowering of the indoor temperature: the motivation being that a better control scheme gives a more even indoor temperature in different parts of the building, therefore allowing for an overall lower indoor temperature. The second control scheme is simulated as the difference between an ideal space heating controller and a more realistic one which does not adapt as quickly to passive heat gains or rapid temperature changes.

2.2.4 Electricity savings

Fig. 4 shows measured average household electricity demand in 2011 and 2012 for 192 randomly selected apartments.

Fig. 4. Measured diurnal variation of household electricity consumption for 192 households, grouped by time of year.

2.2.5 Domestic hot water

Measures to reduce domestic hot water (DHW) consumption include use of water-efficient showerheads and taps and insulation of DHW recirculation piping. Another such measure is individual metering and charging of DHW instead of including it in the rent or tenant fee. DHW savings are simulated as a uniform decrease over the year, appearing as a straight line when average daily DHW saving is plotted against time as diurnal variations are evened out.

2.2.6 Exhaust air heat pump

The annual electricity-to-heat factor (often referred to as seasonal performance factor) for an EAHP depends on factors such as working mode (space heating or domestic hot water) and connection scheme. The ESBO plant module in IDA ICE is used to model the EAHP, see [25,26] for more details. The EAHP is modelled to deliver heat for both space heating and domestic hot water, dimensioned to take 1/3 of the exhaust air flow and connected to a 1 m³ stratification tank. The EAHP impact on the DH return temperature is not accounted for in this study.

2.2.7 Thermal solar

The thermal solar system is modelled with the ESBO [25] module in IDA ICE to deliver heat for both space heating and domestic hot water, and is dimensioned after domestic hot water consumption during the summer season.

2.3 Heat demand profiles of ECMs

Heat demand profiles for the studied ECMs are acquired by calculating the daily difference between the district heating demand of the baseline model and the model including the ECM, resulting in vectors of 365 daily mean values which are scaled to the annual sum of 1 MWh. Each of these 365 values has a corresponding set of weather variables in the TMY weather data and the TMY heat load of the DHS. Daily average values are selected based on the assumption that the dynamic effect of the buildings' heat storage capacity can be neglected.

2.4 Heat load for a TMY

Weather normalised heat load of the DHS is derived from regression coefficients of weather and heat load data from 2012-2014 which are used with TMY weather data to calculate the weather normalised heat load. Multiple linear regression of the form $Y = \beta_0 + \beta_1 * x_1 + \dots + \beta_p * X_p + \varepsilon$ is used, where Y denotes the response variable (heat

load), β_0 denotes the intercept, $x_1, \dots, x_p$ are explanatory variables with coefficients $\beta_1, \dots, \beta_p$ and ε represents the unexplained part. The regression coefficients β are calculated using the *lm* function in the R statistical programming language.

Fig. 5 illustrates how historical heat loads and weather data (a and b) are segmented by the use of heating degree days (c). Through linear regression (d) and segmentation by TMY weather data (e and f) the regression coefficients are determined (g). Finally, the weather normalised heat load can be calculated (h). Heating degree days (HDD) is used to find change points for the segmentation and is calculated as the mean difference between the assumed balance temperature of 17°C and the hourly outdoor temperature for each hour per day: $HDD = \sum_{h=1}^{24} (T_b - T_o)^+$, where the $^+$ symbol indicates that negative values are set to zero. In the final model the dataset is segmented into four sets: summer, heating, transition and very cold segments. Days with HDD lower than 35°C_h are categorised as summer, days with 35 - 120°C_h are categorised as transition period, 120 - 530°C_h as heating and over 530°C_h as very cold. These boundaries are selected manually by minimising the RMSE.

Fig. 5. The heat load weather normalisation process.

Five explanatory variables are included in the final model: outdoor temperature, global solar radiation, ground temperature, temperature change and wind speed. The purpose is to obtain a good prediction, not to interpret the included explanatory variables. As shown in Table 2, all included variables contribute to a better prediction, even though outdoor temperature is by far the most important variable. The root mean square error (RMSE) is used as a metric of prediction power and is calculated with cross-validation by splitting the data into two datasets by placing the first 15 days of each month in one set and the remaining days in the second set. Heat load is then predicted for one of

Table 2. Root mean square error (RMSE) and normalised RMSE of predicted district heating production on daily basis. Each column show the prediction power of the model if excluding a variable, 'none' denotes the full model with no excluded variables

Excluded variable	none	Wind speed	Temperature change	Ground temperature	Global solar irradiation	Outdoor temperature
RMSE [MW]	4.9	5.3	5.3	5.4	6.7	16.2
Normalised RMSE [%]	2.2%	2.4%	2.4%	2.4%	3.0%	7.2%

Fig. 6. Correlation of DHS model residuals and outdoor temperature when segmenting into two, three or four seasons when all explanatory variables are included into the model. Solid line: local linear regression, dashed line: linear regression.

the datasets and validated against the other dataset, and vice versa. Ground temperature is calculated as the average of the mean annual outdoor temperature and the mean outdoor temperature of the last 30 days. Temperature change is calculated as the difference between the mean temperature of the current date and the day before. Fig. 6 shows the impact of segmentation: adding the transition period (three segments) improves the model substantially (visualised by the much more uniformed residuals), as the change point between heating and summer season is not as sharp for a whole DHS as for a single building. Adding the cold seasons (four segments) has almost no impact on the RMSE but as the accuracy increases at the peak load production (which has a strong influence on environmental and economic assessments) the fourth segments are still added.

2.5 District heating optimisation model

The applied method builds on the method presented in [27]. Production cost of district heating is described by the cost function

$$y = \sum_i^n (x_i \times Cost_i + x_i \times \alpha_i \times (Cost_i - Income_i)) \quad (1)$$

where y is the total cost, x_i is the amount of district heating produced for unit i , $Cost_i$ is the production cost per unit thermal heat (includes fuel cost, environmental taxes and plant efficiency), α_i is the ratio of electricity produced per unit produced heat and $Income_i$ includes revenue from selling electricity.

Fig. 7. Heat load duration of the Eskilstuna DHS model. Daily mean heat and electricity production for a TMY. Flue gas condensing is included in CHP and biomass HO plants.

The cost function (1) is minimised by using the constrained nonlinear multivariable function finder *fmincon*, available in the Matlab Optimization Toolbox. Constrains are set as $\sum_i^n x_i = \text{total heat load}$; $x \in [0, \mathbf{ub}]$, where $\mathbf{ub}$ is the upper bounds vector (maximum capacity for each unit); $x_j \leq \alpha_i \times x_i$ where i is a CHP plant and j is the turbine bypass of that CHP plant; $x_j \leq ub_j/ub_i$, where i is a CHP plant and j is the flue gas condenser of that CHP plant. Table 3 presents the parameters used. The heat storage tank is not included in the optimisation model under the assumption that it will mostly level out diurnal variation, hence daily average values are used. Heat losses in the district heating pipelines (about 12% on yearly basis) are omitted. Depending on marginal heat production cost and the electricity selling price the CHP-plant can produce both heat and electricity or bypass the turbine (thus producing heat only). Based on temperature and electricity price data from 2006 to 2014 there have on average been 21 days per year with average temperatures under the -5°C , where peak heat need to be produced by either by oil boilers or by bypassing the turbine. For 13% of these days electricity prices were high enough so it would be profitable to produce heat via oil boilers rather than bypassing the turbine. This has been included in the model. Fig. 7 shows the heat and electricity

299 production for a typical weather year.

300 Table 3. Parameters used in the Eskilstuna DHS model

Unit	CHP	FGC	Bypass turbine	Biomass HO*	Oil HO
Production cost (SEK/MWh)	250	0	250	220	750
Capacity (MW)	72	24	38	70	No limit
Efficiency	0.9	1	1	1.02	0.8
α -value	0.53	-	-1	-	-

301 * include FGC

302
303 To validate the model, it is run with electricity and weather data of 2012 and compared to the real production mix of
304 that year. As shown in Table 4 the modelled and the actual production match reasonable well. The model generates
305 higher production values for the CHP which to a large part is explained by that the model does not consider downtime
306 which according to the plant manager occurred more frequently during 2012 than normally. This also partly explains
307 the higher electricity production value for the model. Electricity production is also affected by that the model does not
308 consider part load conditions which gives lower α -values compared to the used nominal values.

309 Table 4. The measured and modelled production mix of 2012

Unit	Measured [GWh/y]	Modelled [GWh/y]
CHP incl. FGC	548	577
Bypass turbine	12*	15
Biomass HO incl. FGC	204	193
Oil HO	40	21
Total heat production	804	807
Electricity production	195	215

310 *Estimated from the difference between real and possible electricity production

311

312 2.6 Weather data

313 The typical meteorological year (TMY) weather data used for Eskilstuna, also known as test reference year, were
314 acquired from [28] and are described in [29]. A TMY consists of real observations but with each month originating
315 from a different calendar year. These are selected by comparing the frequency distributions of daily climatic variables
316 during a single month of a candidate year with the corresponding distributions for the same calendar month but based
317 on data from a 30 year period. Historical weather data were acquired from the Swedish Meteorological and
318 Hydrological Institute (SMHI) metrological weather station in Eskilstuna; modelled solar irradiation data were obtained
319 from the SMHI STRÅNG project [30]. The data acquisition and conversion of weather data is processed through this
320 tool [31].

321 2.7 CO₂ and primary energy factors

322 Electricity CO₂ and PE (primary energy) factors are selected that roughly correspond to first and third quartiles of in
323 Sweden commonly used factors, defined as low and high in Table 5. The low values for electricity correspond to yearly
324 average of the historical electricity production mix in the Nordic countries [20,21]. The high values correspond to an
325 expected near future with marginal electricity production covered by natural gas combine power plants [10,20]. This
326 approach gives the possibility to linearly interpolate or extrapolate the results to meet the perspective of the readers'
327 choice. See [23] for more discussion regarding emission factors for Nordic electricity production. For biomass fuels a

328 fossil CO₂ emission factor of 16 kg/MWh is used [21,22], which accounts for emissions from handling and
 329 transportation. The low PE factor for biomass corresponds to case when biomass is considered as a residual product
 330 without any PE value [21], fuel handling and transportation is still accounted for. The high PE factor corresponds to the
 331 case when the biomass is considered to have a full PE value [21]. The oil is composed of a 50% mixture of bio-based
 332 and fossil-based why lower values compared to traditional fossil-based oil are shown in the table.

333 Table 5. Used fossil CO₂ and PE factors

Energy carrier	PE factor (MWh/MWh)		CO ₂ (kg/MWh)	
	Low	High	Low	High
Electricity	1.5	2.5	100	400
Biomass	0.1	1.1	16	16
Oil (bio and fossil)	0.6	1.1	160	160

334 3 Results

335 3.1 Electricity-to-heat factors

336 The annual electricity-to-heat factors in Table 6 describe the connection between annual heat and electricity demands,
 337 e.g. decreasing the 'electricity consumption' by 1 kWh/y would lead to a 0.69 kWh/y increase in heat demand. These
 338 values are obtained by simulation and are valid for buildings and weather conditions similar to those studied in this
 339 paper. At higher outdoor temperatures when no space heating is needed, changes in electricity consumption will not
 340 have any impact heat demand. Therefore annual electricity-to-heat factors will be less than 1 for electricity saving
 341 measures. The factor depends upon the balancing temperature of the building, the local climate, the extent that heat
 342 dissipation from equipment displaces heat demand and at what time the electricity is consumed.

343 Table 6. Annual electricity-to-heat factors

ECM	Electricity consumption	EAHP	HRV
Factor	0.69	3.2	10

344 The results for electricity consumption and 'HRV' are quite straightforward. But for the 'EAHP' the result can vary
 345 substantially depending on connection scheme, working mode, etc. The annual electricity-to-heat factor agrees well
 346 with results in paper [32]. The 'EAHP' connection scheme can also affect the return temperature, which will affect the
 347 DHS, which is not accounted for in this study.

349 3.2 Heat demand profiles of ECMs

350 Fig. 8 shows heat demand profiles of ECMs. The heat demand of the baseline model is added for
 351 comparison. All values are scaled to 1 MWh/y, for comparability reasons. The y-axis shows the change in
 352 heat demand as daily mean power [kW]. In order to obtain a clearer view smoothened trend lines are shown
 353 in Fig. 8, not actual data points. The grey shaded area shows the local confidence interval at a standard error
 354 (SE) of 95% and is a measure of local variation. Subfigure (a) shows the heat demand duration curve (daily
 355 values on the x-axis are arranged in ascending order according to the heat demand of the baseline model).
 356 Subfigures (b and c) show the correlation to outdoor temperature and solar radiation and indicate under
 357 which weather conditions in the ECMs will have an impact. Subfigures (a and b) appears quite similar as
 358 outdoor temperature is the factor having the strongest impact on energy consumption. However the duration

curve also provides information about the number of certain level of savings is obtained (thus the area in-
between the lines, zero and the duration equals energy). For example, the curve of ‘HRV’ suggest it perform
poorly at low temperatures compared to ‘building envelope’ (see Fig. 8b), but it is also clear that the
duration of this occurrence is limited in time (see Fig. 8a). Thereby these hours do not affect energy
consumption considerable, but still affect the peak load. Obviously ‘thermal solar’ correlates strongly to the
level of solar radiation, it also correlates to outdoor temperature as outdoor temperature is a good indicator
of time of the year and thereby the probability of solar radiation. ‘Operational optimisation’ mostly
contribute at mild weather when there are still need for space heating and more overheating issues due to
solar gains and fast outdoor temperature changes. The duration curve illustrates that ‘thermal solar’ does not
contribute at all to reduce peak loads, also ‘operational optimisation’ contribute poorly to reduce peaks. The
‘ERV’ (not included in the figure) is essentially identical to the profile of the ‘building envelope’.

Fig. 8. Heat demand profiles of the baseline building model and the ECMs, scaled to the annual sum of 1 MWh heat. Lines are smoothed by local linear regression and grey shaded areas show local confidence interval at standard error of 95%.

3.3 Impact on the district heating system

Fig. 9b shows the resulting marginal impact of ECMs on the DHS heat producing units and how the electricity balance (production and consumption) is affected. Impact on PE and CO₂, accounting for the impact on the electricity balance, is shown in Fig. 9c. All values are scaled to 1 MWh of change in annual heat demand (1MWh increase for ‘household electricity’ and 1MWh decrease for the other ECMs), this makes it possible to compare the impact from studied ECMs. Resulting values can also be used as factors to estimate the absolute impact from an ECM or a package of ECMs, which the developed interactive tool at <https://reesbe.shinyapps.io/eskilstuna> is an example of.

There is a strong connection between the shape of the heat demand profiles of the ECMs and the impact on the DHS. The heat load strongly correlates to the outdoor temperature, thereby measures such as ‘building envelope’ and ‘HRV’ that reduce heat demand at low outdoor temperatures have more favourable impacts on the DHS. However, the most important parameters for the environmental assessment are to which degree the electricity consumption is affected (i.e. electricity-to-heat factors in Table 6) and which PE and CO₂ factors that are assigned to the electricity and biomass fuels.

387 Improving the building envelope has a positive impact on the DHS independent of the environmental emissions
 388 perspective. This is due to the reduced need for bypassing the DHS turbine in cold weather resulting in an increase in
 389 electricity production which roughly equals the reduction in electricity cogeneration in milder weather. Reducing
 390 household electricity consumption would have the most favourable environmental impact, partly because it would allow
 391 for more electricity cogeneration at the CHP.

392 Fig. 9. Marginal impact of ECMs, scaled to 1 MWh of change in annual heat demand. Positive values indicate a decrease/saving,
 393 negative values indicate an increase, (a) miniatures of Fig. 8a, (b) wider bars show impact on heat producing units; the two narrow
 394 bars show the impact on the electricity cogeneration and consumption and (c) marginal impact on PE and CO₂

397 4 Discussion

398 The Eskilstuna DHS has an exceptionally high share of renewable fuels and electricity cogeneration, and hence a low
 399 fossil CO₂ emission rate. The Eskilstuna case study is therefore not easily generalizable to other current DHSs.
 400 Nevertheless, it is an interesting case as it highlights the forthcoming problem of diminishing environmental benefits
 401 from ECMs. In future, more Nordic DHSs are likely to have similar characteristics as heat demand decreases and DH
 402 production becomes “greener” and more efficient. At some point, benefits from decreasing heat demand due to ECMs
 403 in DH connected buildings will diminish. In Central & Western Europe, China and other countries where DH have
 404 small to medium market shares, this is less of an issue as heat demand savings can be met by expanding the DH

405 networks.

406 Improving buildings envelope and installing heat/energy recovery ventilation level out the DHS heat load duration
407 curve, which will allow reduced future investment in peak load plants and higher utilisation rate of future base load
408 plants.

409 The presented weather normalisation method and heat demand profiles could be used for example a) to predict how
410 future DH heat load would look if an assumed/known package of ECMs were applied to a building stock; b) to design
411 policies and price models to incentivise a desired future DH heat load; c) to take into account expected future climate
412 warming by using climate files similar to those derived for Finland [33]. In paper [34] Finnish heating demand is
413 predicted to decrease by about 3% per decade due to global warming.

414 The energy recovery ventilation (ERV) heat demand profile appears similar to the profile of the ‘building envelope’ in
415 Fig. 8. These measures provide a greater saving in cold weather than heat recovery ventilation (HRV). In years with
416 extreme cold weather the differences between ERV and HRV would be larger, and therefore simulating HRV under
417 TMY weather conditions may lead to misleadingly favourable results. ERV is usually not installed in residential
418 buildings because of problems with moisture accumulation and odour recovery to the supply air stream. However, from
419 an energy system point of view ERV appears to be a better option than HRV.

420 Table 1 gives a rough picture of heat savings potentials for typical Swedish multifamily buildings that are due to
421 renovation. Recovering heat from the ventilation system and improving the building envelope have the largest potential,
422 while other studied ECMs show less potential. But feasibility of ECMs is also dependent on the investment cost. For
423 example operational optimisation can be relative cost-effective and can thereby still be expected to give significant
424 contribution to heat savings when looking on a package of ECMs for a whole stock of buildings.

425 **5 Conclusions**

426 The environmental impact of each ECM in terms of primary energy (PE) and CO₂ emissions is strongly influenced by
427 the choice of assessment perspective. Reducing electricity consumption and improving the building envelopes are the
428 only ECMs that are favourable regardless of the choice of assessment factors. If biomass fuels are not considered a
429 residual and are assigned a PE factor of 1.1 then all studied ECMs do increase primary energy efficiency.

430 Heat demand profiles and annual electricity-to-heat factors vary for ECMs. It is not only the amount of energy that can
431 be saved but also at what time of the year the energy can be saved that matters. Saving heat by increasing electricity
432 consumption does not improve primary energy efficiency or mitigate global warming. ECMs with energy system-
433 favourable heat demand profiles and high annual electricity-to-heat factors should be prioritised.

434 The weather normalisation method presented in Section 2.4 proves useful for getting the heat load of the DHS model
435 and heat demand savings of the building model to work under the same (and typical) weather conditions. The freely
436 available modelled solar hourly irradiation database STRÅNG from SMHI increases the prediction power.

437 **Acknowledgements**

438 The work has been carried out under the auspices of the industrial post-graduate school Reesbe. Financers are
439 Eskilstuna Kommunfastigheter, Eskilstuna Energy & Environment and the Knowledge Foundation (KK-stiftelsen).

440 References

- 441 [1] European Parliament and the Council of the European Union. Energy performance of buildings directive.
442 Directive 2010/31/EU; 2010.
- 443 [2] Jennings M, Fisk D, Shah N. Modelling and optimization of retrofitting residential energy systems at the urban
444 scale. *Energy* 2014;64:220–33. doi:10.1016/j.energy.2013.10.076.
- 445 [3] Gustavsson L. District heating systems and energy conservation—part I. *Energy* 1994;19:81–91.
446 doi:10.1016/0360-5442(94)90107-4.
- 447 [4] Gustavsson L. District heating systems and energy conservation—Part II. *Energy* 1994;19:93–102.
448 doi:10.1016/0360-5442(94)90108-2.
- 449 [5] Frederiksen S, Werner S. District Heating and Cooling. First. Lund: Studentlitteratur; 2013.
- 450 [6] Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, et al. HEAT ROADMAP EUROPE
451 2050. Aalborg; 2013.
- 452 [7] Difs K, Bennstam M, Trygg L, Nordenstam L. Energy conservation measures in buildings heated by district
453 heating – A local energy system perspective. *Energy* 2010;35:3194–203. doi:10.1016/j.energy.2010.04.001.
- 454 [8] Gustavsson L, Dodoo A, Truong NL, Danielski I. Primary energy implications of end-use energy efficiency
455 measures in district heated buildings. *Energy Build* 2011;43:38–48. doi:10.1016/j.enbuild.2010.07.029.
- 456 [9] Truong N Le, Dodoo A, Gustavsson L. Effects of heat and electricity saving measures in district-heated
457 multistory residential buildings. *Appl Energy* 2014;118:57–67. doi:10.1016/j.apenergy.2013.12.009.
- 458 [10] Åberg M. Investigating the impact of heat demand reductions on Swedish district heating production using a set
459 of typical system models. *Appl Energy* 2014;118:246–57. doi:10.1016/j.apenergy.2013.11.077.
- 460 [11] Harrestrup M, Svendsen S. Changes in heat load profile of typical Danish multi-storey buildings when energy-
461 renovated and supplied with low-temperature district heating. *Int J Sustain Energy* 2013;34:232–47.
462 doi:10.1080/14786451.2013.848863.
- 463 [12] Harrestrup M, Svendsen S. Heat planning for fossil-fuel-free district heating areas with extensive end-use heat
464 savings: A case study of the Copenhagen district heating area in Denmark. *Energy Policy* 2014;68:294–305.
465 doi:10.1016/j.enpol.2014.01.031.
- 466 [13] Klobut K, Heikkinen J, Shemeikka J, Laitinen A, Rämä M, Sipilä K. Huippuenergiätehokkaan asuintalon
467 kaukolämpöratkaisut [District heating solution for very-low-energy residential building]. 2009.
- 468 [14] Swedish District Heating Association. Supply energy mix 1980-2012 (Tillförd energi utveckling 1980-2012)
469 n.d. [http://www.svenskfjarrvarme.se/Statistik--Pris/Fjarrvarme/Energitillforsel/Tillford-energi-utveckling-1980-](http://www.svenskfjarrvarme.se/Statistik--Pris/Fjarrvarme/Energitillforsel/Tillford-energi-utveckling-1980-2012)
470 2012 (accessed August 10, 2015).
- 471 [15] Statistics Sweden (SCB). Annual energy statistics (Årlig energistatistik - Bränsleförbrukning för elproduktion i
472 Sverige efter produktionsslag och bränsletyp. År 1990 - 2013) 2014. <http://www.scb.se/en0105> (accessed
473 August 10, 2015).
- 474 [16] Heller AJ. Heat-load modelling for large systems. *Appl Energy* 2002;72:371–87. doi:10.1016/S0306-
475 2619(02)00020-X.
- 476 [17] Aronsson S. Fjärrvärmekunders värme- och effektbehov : analys baserad på mätresultat från femtio byggnader
477 = [Heat load of buildings supplied by district heating] : [an analysis based on measurements in 50 buildings] /
478 av Stefan Aronsson. Göteborg : Chalmers tekniska högsk., 1996 ; (Göteborg : Teknologtr., Chalmers); 1996.

- 479 [18] Andersson S, Sjögren J-U, Östin R, Olofsson T. Building performance based on measured data n.d.
- 480 [19] Vesterberg J, Andersson S, Olofsson T. Robustness of a regression approach, aimed for calibration of whole
481 building energy simulation tools. *Energy Build* 2014;81:430–4. doi:10.1016/j.enbuild.2014.06.035.
- 482 [20] Sjödin J, Grönkvist S. Emissions accounting for use and supply of electricity in the Nordic market. *Energy*
483 *Policy* 2004;32:1555–64. doi:10.1016/S0301-4215(03)00129-0.
- 484 [21] Gode J, Martinsson F, Hagberg L, Palm D. Miljöfaktaboken 2011 - Estimated emission factors for fuels,
485 electricity, heat and transport in Sweden (Uppskattade emissionsfaktorer för bränslen, el, värme och
486 transporter). Stockholm: Värmeforsk; 2011.
- 487 [22] Swedish District Heating Association - Environmental assets 2012 (Svensk Fjärrvärme - Miljövärden 2012)
488 2012. <http://www.svenskfjarrvarme.se/Fjarrvarme/Miljovardering-av-fjarrvarme/Miljovarden-2012/> (accessed
489 December 15, 2013).
- 490 [23] Dotzauer E. Greenhouse gas emissions from power generation and consumption in a nordic perspective. *Energy*
491 *Policy* 2010;38:701–4. doi:10.1016/j.enpol.2009.10.066.
- 492 [24] Levin P, Karlsson C. Rekorderlig Renovering – Demonstrationsprojekt för energieffektivisering i befintliga
493 flerbostadshus – Slutrapport för Lagersbergs renoveringsetapp1 – Kommunfastigheter i Eskilstuna. Stockholm:
494 2015.
- 495 [25] Equa. IDA Early Stage Building Optimization (ESBO). Version 109 2013.
496 <http://www.equaonline.com/esbo/IDAESBOUserguide.pdf> (accessed April 27, 2015).
- 497 [26] Maivel M, Kurnitski J. Heating system return temperature effect on heat pump performance. *Energy Build*
498 2015;94:71–9. doi:10.1016/j.enbuild.2015.02.048.
- 499 [27] Åberg M, Widén J. Development, validation and application of a fixed district heating model structure that
500 requires small amounts of input data. *Energy Convers Manag* 2013;75:74–85.
501 doi:10.1016/j.enconman.2013.05.032.
- 502 [28] Sveby & SMHI. Klimatfiler 81-10 SvebySMHI 2015. [http://www.sveby.org/wp-](http://www.sveby.org/wp-content/uploads/2011/09/Klimatfiler-81-10-Sveby-SMHI.rar)
503 [content/uploads/2011/09/Klimatfiler-81-10-Sveby-SMHI.rar](http://www.sveby.org/wp-content/uploads/2011/09/Klimatfiler-81-10-Sveby-SMHI.rar) (accessed March 6, 2015).
- 504 [29] Levin P, Clarholm A, Andersson C. Nya klimatfiler för energiberäkningar. Stockholm: 2015.
- 505 [30] SMHI. STRÅNG - a mesoscale model for solar radiation n.d. <http://strang.smhi.se> (accessed August 5, 2015).
- 506 [31] Lundström L. RTWC n.d. <https://sites.google.com/site/weatherconverter> (accessed April 27, 2015).
- 507 [32] Mikola A, Köiv T-A. The Efficiency Analysis of the Exhaust Air Heat Pump System. *En-Gineering*
508 2014;6:1037–45. doi:10.4236/eng.2014.613093.
- 509 [33] Jylhä K, Kalamees T, Tietäväinen H, Ruosteenoja K, Jokisalo J, Hyvönen R, et al. Rakennusten
510 energialaskennan testivuosi 2012 ja arviot ilmastomuutoksen vaikutuksista (Test reference year 2012 for
511 building energy demand and impacts of climate change). Helsinki: 2012.
- 512 [34] Jylhä K, Jokisalo J, Ruosteenoja K, Pilli-Sihvola K, Kalamees T, Seitola T, et al. Energy demand for the heating
513 and cooling of residential houses in Finland in a changing climate. *Energy Build* 2015.
514 doi:10.1016/j.enbuild.2015.04.001.