Work report

Economically optimal coordinated expansion of district heating: a case study with an optimized strategy

*Raul Fernandez-Lacruz[1] & Peter Lohmander[2]

[1]Department of Forest Biomaterials and Technology
[2]Department of Forest Economics
Swedish University of Agricultural Sciences
SE-901 83 Umeå, Sweden

*Corresponding author: Raul.Fernandez@slu.se

This report is based on the undergraduate thesis "Economically optimal coordinated expansion of district heating, CHP and bioenergy in a region" in the Forest Engineering (MSc.) programme (5-year full time studies) from the School of Agricultural Engineering, Polytechnic University of Valencia, Spain. The work was carried on during an Erasmus traineeship (January-September 2010) at the Department of Forest Economics, Swedish University of Agricultural Sciences in Umeå.
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Abstract

District heating (DH), mostly in combination with the production of power, via combined heat and power (CHP), has been growing hugely in Sweden. The expansion of DH is, still, an on-going process, and it's expected to continue in this direction in the future. Since the 80's, renewable energy sources, such as wood fuels, have been replacing oil and coal in DH. Wood fuels represented 56% of the total input into DH in Sweden (equivalent to 28 TWh). An operations research model, based on dynamic programming and a geographical information system (GIS) was applied to optimize the expansion of a DH net in a municipality in northern Sweden. The problem was investigated from three points of view: the energy company, the customers and the whole society. Optimized expansion strategies were developed for each case. The model results were compared to the real expansion in the study site and showed that investments in DH, under considered conditions, and powered by wood fuels, were profitable, especially if switching from oil boilers to DH. Results highlighted the significance of DH and CHP as efficient and sustainable systems for energy supply. Similar sustainable and economically rational systems can be developed in many parts of the World.

Keywords: bioenergy; wood fuels; dynamic programming; applied operations research; geographical information systems.

Introduction

During the latest five decades, the use of district heating (DH) has been growing hugely in Sweden, becoming the most common system for space heating and domestic hot water in cities [1]. It represents an efficient, clean, and environment-friendly technology, in continuous expansion [2] and available in 270 of the 290 municipalities comprising Sweden [3]. In the early 50's, oil and coal were the main fuel inputs in the heating plants, but fossil fuels have been almost been replaced by biomass nowadays, amongst other sources [4], of which forest wood fuels are one of the main inputs [5] [6]. It is important to be aware of the fact that it is economically rational to use forest fuels in DH partly because of the Swedish carbon tax. In case fossil fuels such as coal and oil are combusted, the CO_2 tax must be paid. Burning of renewable fuels such as tops and branches, round wood, sawdust, etc., is exempted from this tax. Such CO_2 taxes do not exist in many parts of the world and therefore, forest resources are often not used for energy production as intensively as in Sweden [7] [8]. The general structure of a DH is based on a central heating plant, where water is heated up by means of a boiler. The hot water is distributed to the final users through a net of pipelines and heat exchangers. In combined heat and power plants (CHP), both heat and electricity are produced. Investments in DH and CHP are considered to be capital intensive projects, and they require a long-term perspective analysis, since the facilities and the pipelines are designed to last for many decades. Several studies have focussed in the development of models to determine the optimal location of the production facilities, since location is one of the main aspects affecting the operational costs of the whole system [33]. The same study has showed that the main factors determining these costs are the fuel supply chain (transport distances) and the spatial distribution of the heat demand, which will affect the length of pipeline and heat losses from the production source to the final users.

The aim of our work was to design an optimized strategy for planning the expansion of the DH distribution net (DHDN) in a city where the expansion of the net had already occurred. Results would show to and from which neighbourhoods of the city the net should be connected, and when such connections should occur.

Materials and methods

Study design

The study presented in this paper was performed as outlined below:

1) The real expansion of the DHDN in a case study area was investigated, including a visit to the CHP plant;
2) A geographical information system (GIS)-based model of the study site was designed;
3) Parallel to this work, a software based on dynamic programming was developed and adapted to solve the specific type of spatial problem raised in the study;
4) The input data to use in DHINV was calculated with the GIS-based model and other empirical sources from the visit to the case site and literature research;
5) The output results from DHINV were interpreted and translated to the GIS-based model, displaying the optimized expansion plan and the net present value of the investment in DH.

Study site

A study visit to the CHP plant in the case study city (Lycksele) and an interview with the managers of the plant was done in April 2010 (Fig. 1 and Table 1). Lycksele is located northern Sweden (64º35'20''N, 18º40'40''E, 223 m above sea level) and the climate in the area is characterized by long winters and short summers [9]. Forests cover 72% of the municipality, and population was 8597 inhabitants in 2009 [10]. Before DH was established, the massive combustion of firewood and oil into individual heating units, together with a phenomenon of thermal inversion during the winter, caused big problems in public health [11]. As a response to

this situation, the municipality started to implement DH at the beginning of the 70's, within the public housing, the local businesses and industry. In 2000, a new CHP plant was put into operation, to be completely powered by wood fuels [12] [13].
The large-scale expansion of the net started in 1998, and the connection of the neighbourhoods was planned in a sequence of 10 years (1998-2009), dividing the town into 16 areas, to organize the building operations in space and time. Since then, the number of customers increased a lot, especially amongst the private house owners. In 2009, the total number of subscribers was 1300, of which 900 were small houses. The total length of the net reached 80 107 meters (m) the same year [14]. National subsidy programs and the municipality supported the conversion in small houses. The connection cost was the greatest barrier to attach more houses to the net, especially for those which previously were heated with electricity. An average connection cost of 100 000 SEK was indicated in this case, including the cost of attaching the house to the street pipeline and the installation of the domestic heating system and radiators. In case the building had already a domestic hot water system, the average connection cost in small houses was 38 000 SEK according to Skellefteå Kraft [15]. This cost would depend on the type and size of building considered.

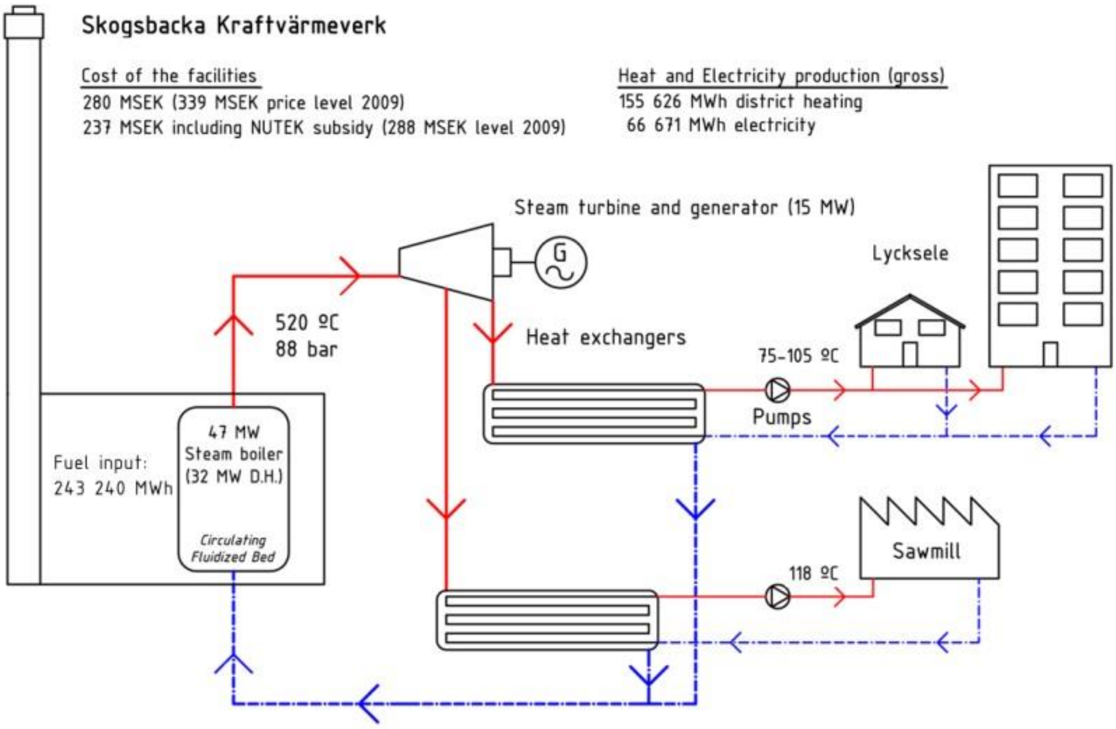

Figure 1. DH system in Lycksele [14] [16].

Table 1. Features of the CHP plant (*Skogsbacka Kraftvärmeverk).*

Combustion technology	Circulating Fluidized Bed (CFB)
Contractor	Foster Wheeler Energia Oy (Finland)
Total cost of the facilities	280.0 MSEK (339 MSEK ≈ 36 million €, year 2009)
Cost of the facilities including subsidy	237.4 MSEK (288 MSEK ≈ 31 million €, year 2009
Installed effect	47 MW steam boiler (32 MW for DH) 15 MW steam turbine (for electricity production)
Gross production 2009 (excl. heat loses and own consumption)	155 626 MWh DH 66 671 MWh electricity 3 745 MWh district cooling
Steam temperature	520 ºC
Pressure in the boiler	88 bar
Boiler room height	35 m
Furnace height	63 m

Accumulator tank volume	7 200 m^3 (dual)
Area of facilities incl. storage area	17 ha (estimation)
Fuel mix	50% GROT (“tops and branches”) 20% Roundwood 20% By-products (bark and sawdust) 10% Peat

Dynamic programming

An operations research software, “DHINV” [17], based on dynamic programming, was programmed in parallel to this work and and applied to optimize the DHDN expansion in the case study. The operational principle of dynamic programming is to work backwards, from the end of the problem (the horizon) towards the beginning. In this particular case, the problem was treated from the latest year of the expansion towards the start. The time period to investigate was 25 years (t_{max}), and it was split into shorter time intervals called stages, in this problem, years (t). For every stage, there were an associated number of states (i). The state index showed which areas were connected (denoted as “1”) and which were still not connected (denoted as “0”). The entering partial states represented the state index. In the problem, to say that at stage $t=1$ the state was $i=1$, would be equivalent to say the entering partial states equalled *00000000*, meaning that no area was connected at that particular stage. This was the entering condition in the model, assuming that nothing had been built before, and considering 8 possible areas. The total number of possible states for every stage (i_{max}) was calculated as 2^{kmax}, in the model, $i_{max}=2^8=256$. For each combination of stage and state, there was an optimal decision: the decision at stage t described how we should move from current state, i, to future state, j, at the next stage, $t+1$. In other words, it showed the state at which we should end up next period, pointing out which area should be attached during that particular stage, and from which area it should be connected. Bellman’s Principle of Optimality was of special relevance in the resolution of the dynamic problem: “given the current state, the optimal decision for each of the remaining stages must not depend on previously reached states or previously chosen decisions” [18]. For optimal decision, it was considered the decision maximizing the expected present value of the investment at that particular stage. The software would point out the optimal decisions, regardless of what we did previously: we looked for the optimal decision at every possible combination of stage and state. Constrains were also included, like the maximum number of neighbourhoods attachable per year (one). Table 2 summarizes the input dataset required by DHINV. More details about the software, examples, the source code, and the program itself can be downloaded from the website [17].

Table 2. Input dataset in the software DHINV.

Data	Description	Value
k	Number (identifier) of the area (neighbourhood)	[1, 8]
k_{max}	Total number of areas	8
t	Number of the stage (year)	[1, 25]
t_{max}	Total number of stages (years)	25
i	Current state	[1, 256]
i_{max}	Total number of states	256
j	Future state	[1, 256]
$z(k)$	Number of units (small houses, apartments, etc.) within an area	[10, 222]
$c(k)$	Cost of connection from the area to source	SEK
$cc(k(1, ..., k_{max})$	Cost of connection between each area	SEK
$d(k)$	Distance from the area to source	km
$dd(k(1, ..., k_{max})$	Distance between each area	km
concos	Individual cost of connection of one unit	SEK
p	Yearly profit per additional unit connected within an area	SEK/year/unit
rate	Rate of interest in the capital market	%

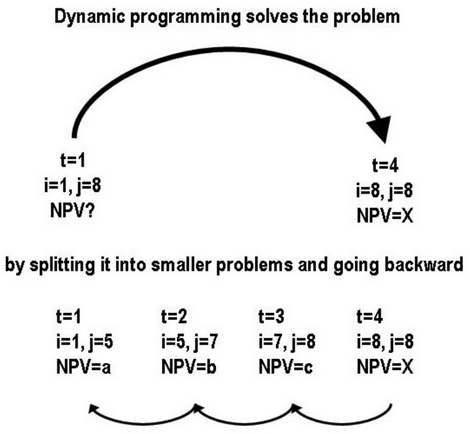

Figure 2. Working principle of dynamic programming (NPV=Net Present Value).

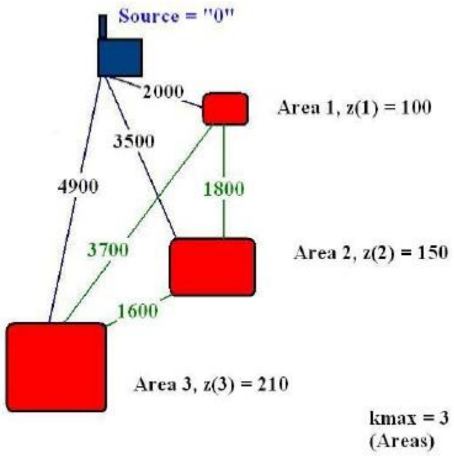

Figure 3. Definition of the spatial problem [17]

Geographical information system (GIS) model

A geographical model of Lycksele was created in ArcGIS®9.2. to organize the spatial information and provide the software DHINV with an input dataset. The GIS allowed high accuracy in length measurements and easy detection of errors. In a first layer, the boundaries of every area (neighbourhood) in the expansion strategy were represented. A similar division as done in Lycksele for the period 1998-2009 was followed, with some adjustments, though. The resulting number of areas at each side of the river was 8 (k_{max}). The different sides of the river were handled separately, which reduced the size of the state space. As a result, the solution of the optimization problem could be obtained much faster and with more limited computer resources. The calculation of units (small houses, apartment blocks, schools, etc.) to be potentially attached to the net, within each area, $z(k)$, was done by counting the units connected in the real development, using the information from the study visit. In the areas with no data available, the figure was estimated by calculating an average degree of connection in Lycksele amongst the total number of units within each area (59%). The number of units expected to be attached within each area was, on the east side, $z(1)=47$, $z(2)=86$, $z(3)=96$, $z(4)=60$, $z(5)=33$, $z(6)=22$, $z(7)=113$, $z(8)=15$, and on the west side, $z(9)=54$, $z(10)=72$, $z(11)=10$, $z(12)=135$, $z(13)=222$, $z(14)=68$, $z(15)=21$, $z(16)=27$ (Fig. 4).

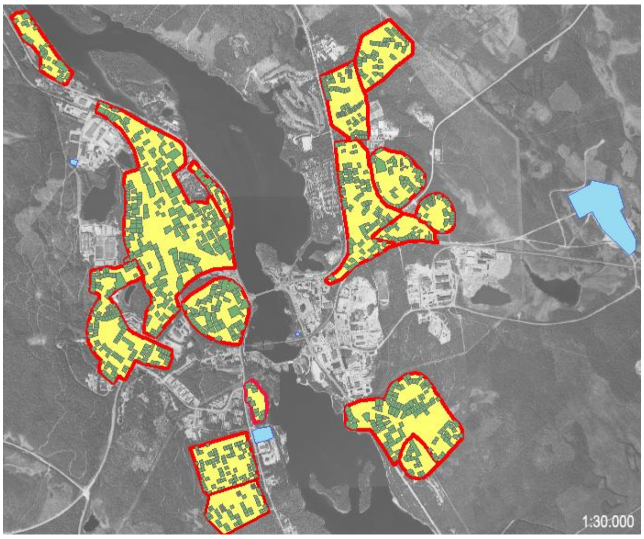

Figure 4. Division in areas, *k*, (red), and expected number of units, *z(k)*, (green) to connect within each area. The polygons in blue represent the existing CHP plant (right part of the figure) and several smaller heating facilities. © Lantmäteriet, i2014/764.

The model considered the construction of one unique production facility, assuming it wouldn't be necessary to build additional production units as the net expands. Often, with economies of scale, the most cost-efficient solution is to have a unique central production unit [19]. It was also decided to build up the net, first, on the east side. After some areas on this side had been connected, the expansion would continue towards the west, and a pipeline over the river would connect both shores (Fig. 5, pipeline in dark-blue colour). Another limitation in the model was to consider only combinations within areas contained in the same side of the river. Both constraints were necessary because of the software design. Existing roads were followed when laying down the pipelines (cost-effective solution), and in most cases, the marked paths were similar to reality. Fig. 5 showed the possible combinations of connections overlapped (in yellow) from each area (in black) to the CHP plant (in orange), although the geographical model considered 8 combinations on each shore, 16 in total. In Fig. 6, combinations within each area are also overlapped, but the model considered 64 possibilities on each side, 128 in total. The length of the pipelines, $d(k)$ and $dd(k(1, ..., k_{max})$were measured in the GIS, and a lineal cost of 2000 SEK per meter of pipeline [15] applied to calculate the input data $c(k)$ and $cc(k(1, ..., k_{max})$. It was assumed that this lineal cost included all associated expenses, e.g. projecting, digging, etc. Note that the model handled the currency in Swedish crowns (SEK), but it doesn't matter the used currency as long as it's the same in all calculations.

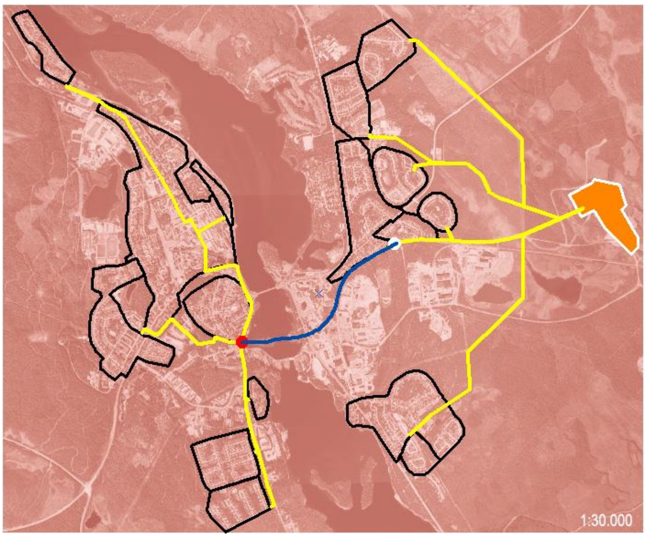

Figure 5. Model of pipelines from each area to the source, *d(k)*. © Lantmäteriet, i2014/764.

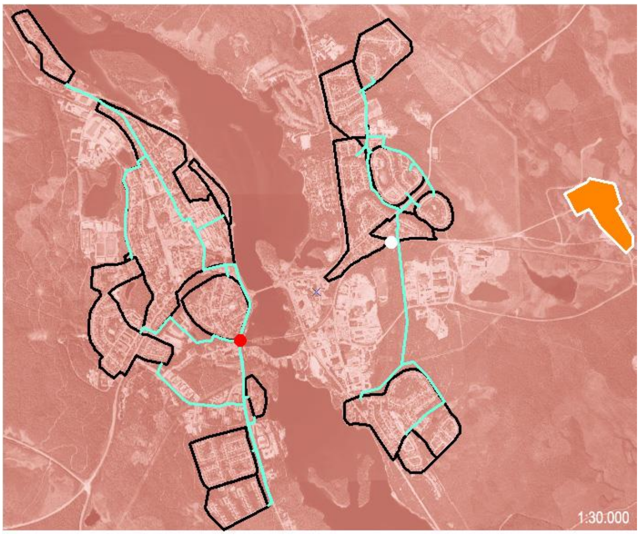

Figure 6. Model of pipelines within each area, *dd(k(1, …, a-1, a)*. © Lantmäteriet, i2014/764.

Yearly economic profit per unit

Given a certain area, *k*, the marginal yearly profit per additional unit connected, *p*, (SEK/year/unit), was calculated as the average yearly consumption of DH per unit (MWh/year/unit) multiplied by the marginal profit per sold megawatt hour (SEK/MWh). Three analysis cases were considered when doing this calculation: the energy company, the customer and the whole society's point of view. Figures referred, when possible, to year 2009 and northern Sweden. The model considered a homogeneous and average consumption of 88 MWh/year/unit, calculated by dividing the yearly sales of DH (115 000 MWh/year) by the total number of subscribers attached to the net in reality (1300 subscribers). Figures were taken as an average, since heating consumption would depend on the size of the building. It was also assumed that one subscriber would be equivalent to one unit (not necessarily true).

Table 3. Yearly economic profit (improvement) per unit.

Case		***p* (SEK/year/unit)**	**concos**
a	**Company point of view**	34 673	0 SEK
b	**Costumer point of view**		
b.1	From electricity	11 251	100 000 SEK
b.2	From electricity (+subsidy)	13 502	70 000 SEK
b.3	From oil	24 749	38 000 SEK
c	**Whole society's point of view**		
c.1	From electricity	45 924	100 000 SEK
c.2	From oil	59 422	38 000 SEK
c.3	50% electricity, 50% oil	52 673	69 000 SEK

Marginal profit from the energy company's point of view

For this analysis case, the marginal profit, *p*, was calculated as the difference between the marginal revenue from every sold MWh of DH (discarding revenues from electricity) and the costs of wood fuels, labour, and operation & maintenance of the CHP plant. Capital costs of building the CHP plant were excluded, since the temporal extent of the analysis was constrained to the moment the plant had been built up and DH net started to expand. In year 2009, the average consumer price of DH in Lycksele, for small multi-dwelling buildings, was 631 SEK/MWh (excluding 25% VAT) [20]. The marginal costs of wood fuels were considered to be the prices paid to private forest owners by Skellefteå Kraft [21], 150 SEK/ton for GROT (tops and branches) and 275 SEK/ton for roundwood. Average values of 50% moisture content for GROT (2,5 MWh/fresh ton) and 25% moisture content for roundwood (3,9 MWh/fresh ton) were considered [22], and a transportation cost, 58 SEK/MWh, was included [23]. The cost of by-products and peat was 178 SEK/MWh, and 169 SEK/MWh, respectively [24]. The fuel-mix in the real CHP plant was 50% GROT, 20% roundwood, 20% by-products (mostly sawdust and bark), and 10% peat [14]. In Equation 1, *y(x)* denotes the average cost of labour (SEK), as a function of the total DH production, *x* [25]. The marginal cost of labour was calculated as the derivative of the cost of labour, *C(x)*, with respect to DH production, *x*, as described in Eq. 2. The resulting expression was used to perform the calculation, entering a DH production of 155 626 MWh [26]. The marginal cost of labour decreases as production increases, because of the logarithmic factor.

$$y(x) = 86{,}96 - 5{,}875 \cdot \ln(x) \qquad (1)$$

$$\frac{C(x)}{x} = y(x) \qquad (2)$$

$$C(x) = y(x) \cdot x = ((86{,}96 - 5{,}875 \cdot \ln(x)) \cdot x$$

$$\frac{\partial C(x)}{\partial x} = 86{,}96 - 5{,}875 \cdot \ln(x) - 5{,}875 = 81{,}09 - 5{,}875 \cdot \ln(x)$$

The marginal operation and maintenance costs (O&M) of the CHP plant and the DHDN were calculated according to the guidelines from Energimyndigheten [25]. O&M costs of the plant were considered to be 6,8 MSEK/year (2% of the replacement value of the plant, in this case, the investment cost, 339 MSEK, considering an average producer price index increment of 21%, from year 1998 to 2009 [27]. O&M costs of the DHDN were 1,6 MSEK/year, representing 1% of the replacement value of the net in the real development, assumed to be the cost of the investment (considering a length of 80 km and a linear cost of 2 000 SEK/m). The marginal values were calculated dividing the total O&M costs by the yearly sales, 115 000 MWh/year.

Table 4. Marginal profit, revenue and cost from the energy company point of view.

Marginal profit	**392 SEK/MWh**
Marginal revenue	**631 SEK/MWh**
Marginal cost	**239 SEK/MWh**
Marginal cost of fuel	*155 SEK/MWh*
Marginal cost of labour	*11 SEK/MWh*
Marginal cost of O&M	*73 SEK/MWh*

Marginal profit from the customer's point of view

For this analysis case, the marginal profit, *p*, was considered to be the amount of money the costumer "would save" per consumed MWh, if switching to DH from electricity, oil or pellets. It was calculated as the difference between the marginal costs of the current heating alternative minus the marginal cost of changing to DH (including the marginal cost per consumed MWh of DH). A huge variation amongst prices of oil, electricity and pellets was found, so the calculation figures should be taken as a reference in the area, within domestic sector, including taxes, and excluding fixed fees or delivery expenses. In case of pellets, the option to change was uneconomical, due to the comparatively-low prices. However, this alternative was excluded from the analysis. The connection costs, *concos*, referred in this analysis as capital or investment costs, were dependent on the current heating alternative: 100 000 SEK if switching from electricity, or 38 000 SEK if switching from oil. The analysis also considered a subsidy of 30 000 SEK per house. The yearly capital costs were calculated assuming discounting with 5% rate of interest and 20 years depreciation time. The used rate of interest should be regarded as the real rate of interest, since there was no-inflation assumption in the costs and prices in the analysis. If, for instance, inflation was 2%, the present value calculation would be consistent with 7% rate of interest. The 20 years depreciation time is the standard assumption in yearly reports of industrial companies [19]. The annuity was calculated with discounting in continuous time, as described in Eq. 3, where *A* denotes annuity, *C* investment cost, *d* denotes one period discounting factor, and *r* denotes rate of interest (%) in continuous time. The marginal capital cost was calculated dividing the annuity by the average yearly consumption of DH per unit (88 MWh/year/unit).

$$A = C \cdot \left(\frac{1-d}{1-d^{n+1}} \right) \quad \text{and} \quad d = e^{-r} \qquad (3)$$

Table 5. Marginal profit from the costumer's point of view (profit equals to savings).

Marginal profit, switching from electricity		**127 SEK/MWh**
Marginal cost of electricity		**1000 SEK/MWh**
Marginal cost of switching to DH from electricity		**873 SEK/MWh**
Marginal cost of DH	*788 SEK/MWh*	
Marginal capital cost	*85 SEK/MWh*	*concos=100 000 SEK*
Marginal profit, switching from electricity, including a subsidy		**153 SEK/MWh**
Marginal cost of electricity		**1000 SEK/MWh**
Marginal cost of switching to DH from electricity (+subsidy)		**847 SEK/MWh**
Marginal cost of DH	*788 SEK/MWh*	
Marginal capital cost	*59 SEK/MWh*	*concos=70 000 SEK*
Marginal profit, switching from oil		**280 SEK/MWh**
Marginal cost of oil		**1100 SEK/MWh**
Marginal cost of switching to DH from oil		**820 SEK/MWh**
Marginal cost of DH	*788 SEK/MWh*	
Marginal capital cost	*32 SEK/MWh*	*concos=38 000 SEK*
Marginal profit, switching from pellets		**-320 SEK/MWh**
Marginal cost pellets		**500 SEK/MWh**
Marginal cost of switching to DH from pellets		**820 SEK/MWh**
Marginal cost of DH	*788 SEK/MWh*	
Marginal capital cost	*32 SEK/MWh*	*concos=38 000 SEK*

Marginal profit from the whole society's point of view

In this analysis case, it was showed "how much society would gain" if changing to DH fuelled by renewable biomass resources, instead of using electricity or oil for heating. The marginal profit from the company point of view and the marginal profit from the costumer point of view (for the different sub-cases) were summarized, and no subsidies were considered.

Table 6. Marginal profit from the whole society's point of view.

100% of society changing from electricity		
Marginal profit	519 SEK/MWh	concos=100 000 SEK
100% of society changing from oil		
Marginal profit	672 SEK/MWh	concos=38 000 SEK
50% of society changing from electricity and 50% from oil		
Marginal profit	595 SEK/MWh	concos=69 000 SEK

Since there was no link between the dynamic model of the software DHINV and the GIS-model, the calculated input data from previous steps was introduced manually in the dynamic model, for each side of Lycksele and for each analysis case (a, b.1, b.2, b.3, c.1, c.2 and c.3). The output results from the dynamic model were also manually-transferred to the GIS (Fig. 7).

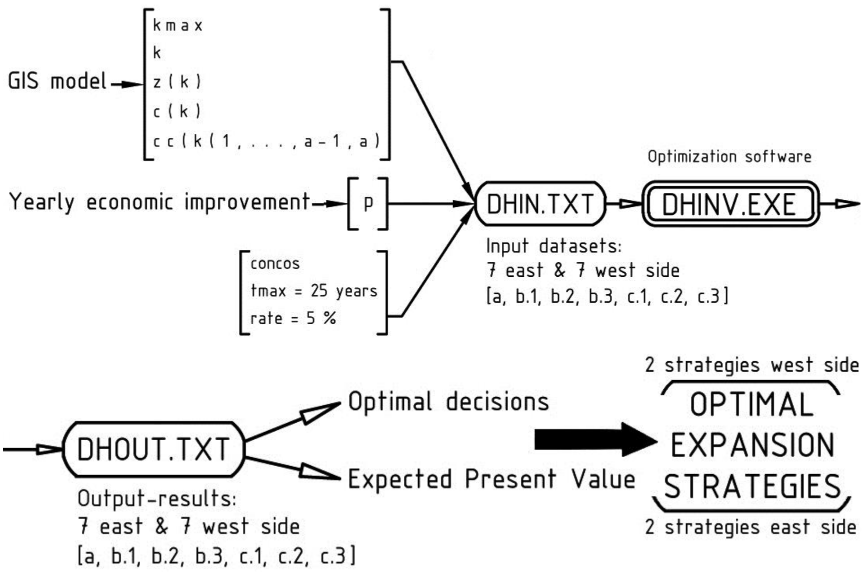

Figure 7. Workflow in the resolution of the optimization problem.

Results

DHINV gave as output (for each side of Lycksele and each analysis case), a table with the structure of Table 7, where *t* denotes the stage (year), *i(t)* denotes the entering state at period *t*, *i(t+1)* denotes the optimal state to go to in next period, *E(PV)* denotes the optimal expected present value, *DEC* shows the optimal area *k* to connect at period *t*, *CVIA* shows the optimal area *k* from which it should be connected, and the entering partial states show the "state of connection" on that particular stage *t* (1=connected / 0=not connected). In the simulation, the total number of combinations of possible entering states was 256, calculated as $2^{k,}$, 2 possibilities (1=connected / 0=not connected), and *k=8* areas on each side. Tables 8 and 9 showed the expected present value E(PV) the first year of the expansion of the net, for each side of Lycksele and analysis case. The variation in the E(PV) along the investigated 25-year period was represented in Figures 8 and 9.

Table 7. Output from DHINV for the analysis case "a", and east side of Lycksele.

t	i(t)	E(PV)	i(t+1)	DEC	CVIA	Entering Partial States
1	1	173 184 992	33	3	0	0 0 0 0 0 0 0 0
2	33	176 474 480	35	7	3	0 0 1 0 0 0 0 0
3	35	176 799 568	99	2	3	0 0 1 0 0 0 1 0
4	99	170 957 216	115	4	2	0 1 1 0 0 0 1 0
5	115	162 893 392	243	1	2	0 1 1 1 0 0 1 0
6	243	153 616 144	251	5	3	1 1 1 1 0 0 1 0
7	251	143 616 496	255	6	3	1 1 1 1 1 0 1 0
8	255	132 987 856	256	8	7	1 1 1 1 1 1 1 0
9	256	122 513 240	256			1 1 1 1 1 1 1 1
10	256	112 078 040	256			1 1 1 1 1 1 1 1
11	256	102 151 768	256			1 1 1 1 1 1 1 1
12	256	92 709 608	256			1 1 1 1 1 1 1 1
13	256	83 727 944	256			1 1 1 1 1 1 1 1
14	256	75 184 320	256			1 1 1 1 1 1 1 1
15	256	67 057 376	256			1 1 1 1 1 1 1 1
16	256	59 326 788	256			1 1 1 1 1 1 1 1
17	256	51 973 224	256			1 1 1 1 1 1 1 1
18	256	44 978 300	256			1 1 1 1 1 1 1 1
19	256	38 324 520	256			1 1 1 1 1 1 1 1
20	256	31 995 250	256			1 1 1 1 1 1 1 1
21	256	25 974 662	256			1 1 1 1 1 1 1 1
22	256	20 247 702	256			1 1 1 1 1 1 1 1

23	256	14 800 048	256	1 1 1 1 1 1 1 1
24	256	9 618 080	256	1 1 1 1 1 1 1 1
25	256	4 688 839	256	1 1 1 1 1 1 1 1

Results for the east side (from area k=1 to area k=8)

Table 8. Expected Present Value, E(PV), year 1 (t=1), and optimal decisions, DEC(CVIA), east side.

Analysis case	E(PV) MSEK	Optimal decisions DEC(CVIA)
a	173.2	3(0),7(3),2(3),4(2),1(2),5(3),6(3),8(7)
b.1	10.4	3(0),2(3),7(3),4(2),1(2),5(3),6(3),8(7)
b.2	34.3	3(0),7(3),2(3),4(2),1(2),5(3),6(3),8(7)
b.3	106.0	3(0),7(3),2(3),4(2),1(2),5(3),6(3),8(7)
c.1	191.7	3(0),7(3),2(3),4(2),1(2),5(3),6(3),8(7)
c.2	287.3	3(0),7(3),2(3),4(2),1(2),5(3),6(3),8(7)
c.3	239.5	3(0),7(3),2(3),4(2),1(2),5(3),6(3),8(7)

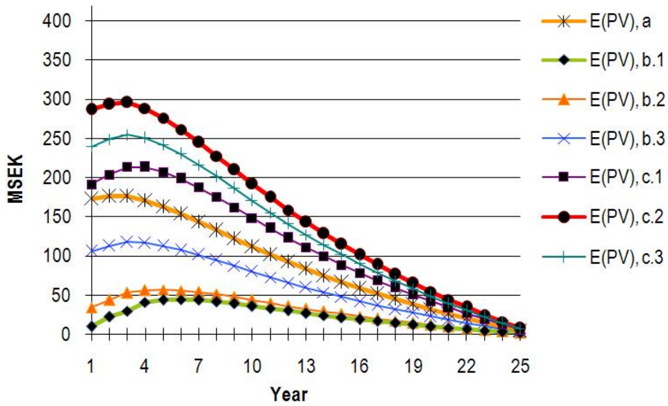

Figure 8. Expected Present Value, E(PV), along the investigated 25-year period, east side.

Results for the west side (from area k=9 to area k=16)

Table 9. Expected Present Value, E(PV), year 1 (t=1), and optimal decisions, DEC(CVIA), west side.

Analysis case	E(PV) MSEK	Optimal decisions DEC(CVIA)
a	234.5	13(0),12(13),14(13),10(14),9(10),16(13),15(13),11(10)
b.1	17.0	13(0),12(13),14(13),10(14),9(10),16(13),15(13)
b.2	48.5	13(0),12(13),14(13),10(14),9(10),16(13),15(13),11(10)
b.3	144.5	13(0),12(13),14(13),10(14),9(10),16(13),15(13),11(10)
c.1	260.0	13(0),12(13),14(13),10(14),9(10),16(13),15(13),11(10)
c.2	387.9	13(0),12(13),14(13),10(14),9(10),16(13),15(13),11(10)
c.3	324.0	13(0),12(13),14(13),10(14),9(10),16(13),15(13),11(10)

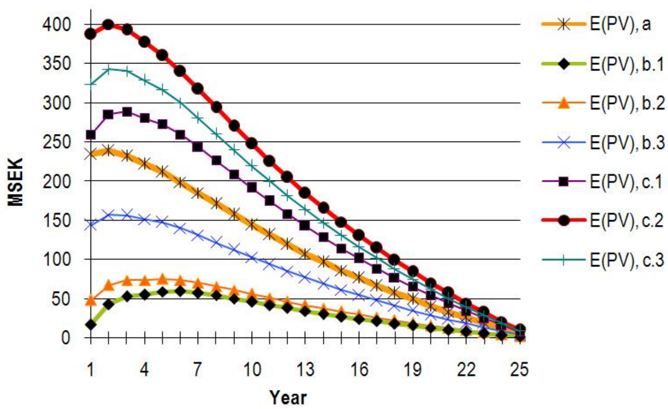

Figure 9. Expected Present Value, E(PV), along the investigated 25-year period, west side.

Optimal expansion strategies

The optimal decisions obtained from the software (decisions which would maximize the net present value of the investment), were translated to the GIS-model, representing the optimal way to expand the DHDN in the case study. Except for the analysis case b.1, the strategies to follow were the same in all analysis cases and side (2 expansion strategies on each side of the city). In the main layout map, the number in the centre of each area showed the order (year) it should be attached to the net.

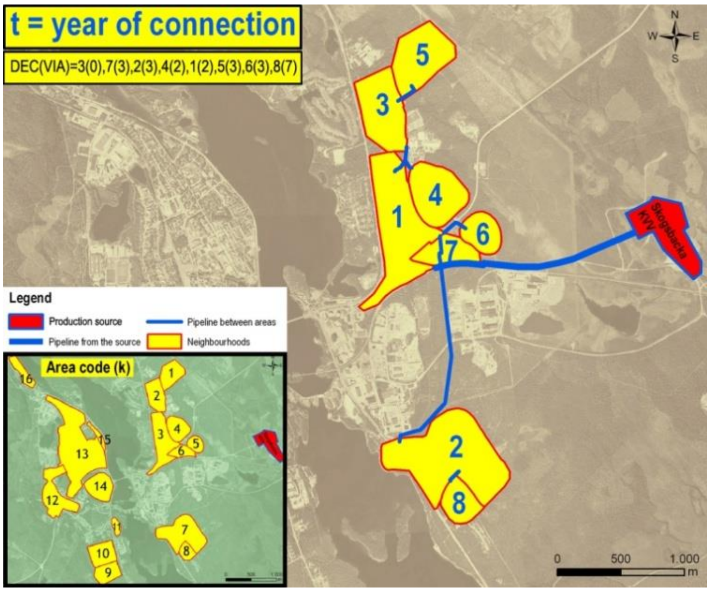

Figure 10. Optimal expansion strategy, OPT1, east side, common to analysis cases a, b.2, b.3, c.1, c.2, c.3. © Lantmäteriet, i2014/764.

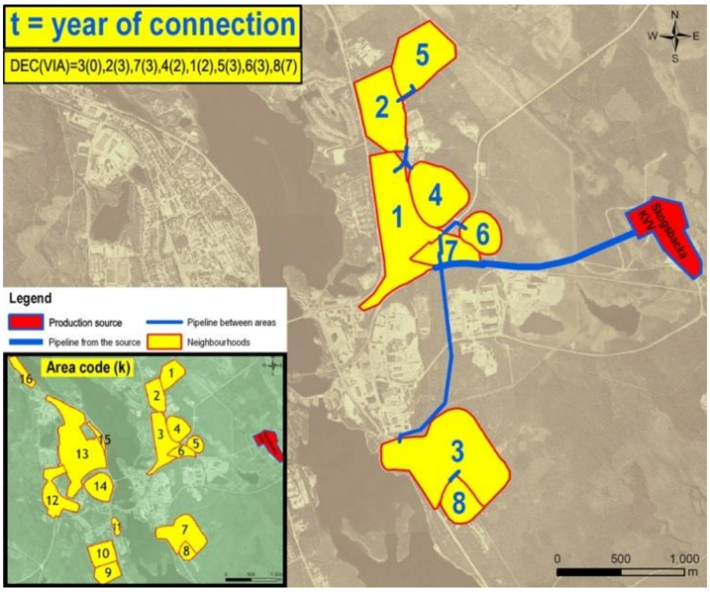

Figure 11. Optimal expansion strategy OPT2, east side, analysis case b.1. © Lantmäteriet, i2014/764.

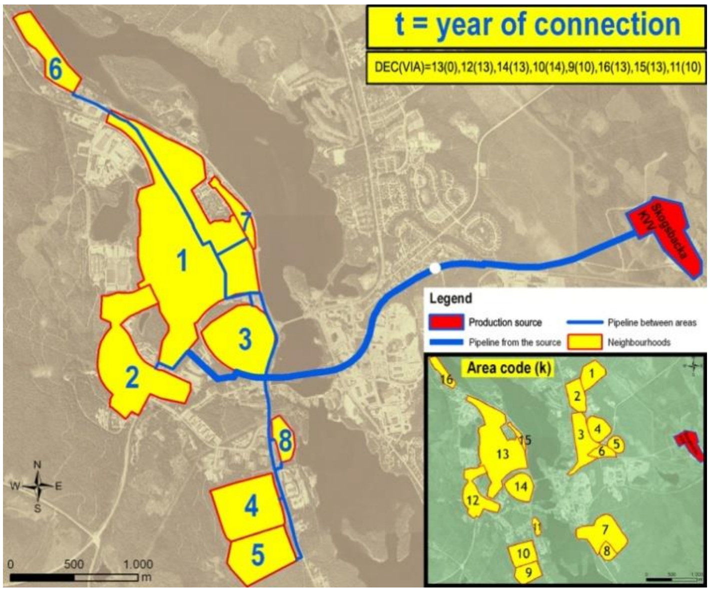

Figure 12. Optimal expansion strategy OPT3, west side, common to analysis cases a, b.2, b.3, c.1, c.2, c.3. © Lantmäteriet, i2014/764.

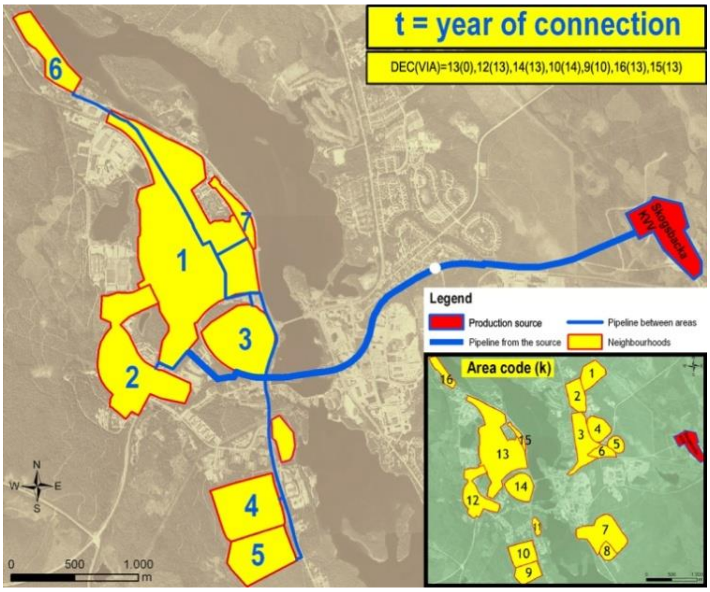

Figure 13. Optimal expansion strategy OPT4, west side, analysis case b.1. © Lantmäteriet, i2014/764.

Discussion

The optimization problem considered that he expansion of the DHDN started from an initial state of non-connected areas (at stage *t=1*, the entering state was *i(1)=1*, and entering partial states=00000000). The general decreasing tendency in the E(PV) as moving further in time (Fig. 8 and Fig. 9) was due to two reasons. First, the influence of the discounting rate in future revenues, second, there were less years ahead of the investment, and therefore, fewer revenues to come. This had the greatest effect, meaning that it would be better to make decisions as soon as possible and don't wait for long (otherwise, we wouldn't make all the profit we could have made). For these reasons, before all areas in the city were attached to the net, the E(PV) showed a decreasing tendency (e.g. after year 2, or year 4). Although it may seem that the E(PV) reached zero in the graphs, it didn't't: the investment was only investigated along a 25-year horizon, but it was expected to continue further in time. The graphs also showed that during the first years, the E(PV) increased until it reached higher levels. The initial growth tendency occurred because the expansion started from the lowest possible state, *i(t)=1*, and it improved very much the first years. If, for instance, the expansion had started from a higher state (imagine a couple of areas connected), the initial increase would have been less pronounced. The E(PV) was only dependent on where we were (current stage and state), and optimal decisions ahead. One could also affirm that past decisions were responsible for the current entering state. But the calculations only considered the entering state, no matter how we got to it. Therefore, the values of E(PV) at $t=1$ and the other stages dependent on following the optimized plan. If something would happen (e.g. a delay in the building operations), the program would tell what to do and where to go, depending on the new entering state: there would always be an optimal solution for every entering stage and state.

Company's point of view

Considering the eastern and western areas together, the E(PV) from the company point of view was 408 MSEK. If the cost of the production source was also considered, 339 MSEK (288 MSEK if a national subsidy included), it turned out a net present value of 69 MSEK (or 120 MSEK if subsidy included). This revealed the total investment was less attractive for the company, and the subsidy probably helped to stimulate their decision. Another point of discussion was to consider all revenues were coming from DH sales. Sales of electricity should have also been included in the models, since the production source was a CHP plant. If so, the net present value was expected to be greater, and therefore, one could affirm that simulation results were placed on the side of safety. On the other hand, the input cost of wood fuel was relatively low, compared to the average woodchip prices paid by heating plants: 181 SEK/MWh [24]. The calculation didn't include the cost for comminution of the logging residues and roundwood, and this was one of the reasons. Alternative methods would of course be possible to use to derive these parameters, but this simple approach was selected because of the lack of detailed empirical data.

Customer's point of view

The worst scenario from this point of view was found in case the customer would switch to DH from electricity (analysis case b.1), as showed in Fig. 8 and Fig. 9. The expansion strategies for this sub-case also differed from the rest (Fig. 11 and Fig. 13), explained by the large expenses of attaching the houses to the net. The inclusion of the public subsidies (analysis case b.2) had positive effects: the expansion strategies were modified, compared to b.1, and E(PV) increased over the total cost of the subsidy (considering a subsidy of 30 000 SEK per unit, 472 units on the east and 609 units on the west side). In case the customers would change from oil boilers (analysis case b.3), the E(PV) was even higher, especially on the west side of the city. This result was explained by the high prices of oil and the low connection expenses for houses having already a water heating system. Although this analysis case considered 3 sub-cases (b.1, b.2 and b.3), the proportions in the users changing from each of the old heating systems could have been modified. The model expected a number of subscribers similar to the real development, but the degree of connection could be different. Although the costs of connection were assumed as constant, those expenses could be very variable.

Whole society's point of view

For both sides of the case study area, results showed the investment in DH, powered by wood fuels, was positive for the whole society, especially when customers were switching from heating systems based on fossil sources (analysis case c.2). The resulting E(PV) represented the sum of the E(PV) from the company and the customers point of view, but results are greater than the arithmetic sum, since in analysis cases c.1 and c.2, the connection costs were shared by the whole society and not only by the customers. The expected demand should be treated as a factor of risk and uncertainty, especially for such a capital intensive project. Without houses willing to attach to the net, it would have been uncertain for the company to perform such investment, especially during the first stages of the expansion, in areas with no existing demand. This is also a reason to analyse profitability in a long time perspective, since the investment is expected to have a long duration in time.

Optimal expansion strategies and real expansion in Lycksele

The optimized expansion strategy differed from the real expansion in Lycksele, already from the starting point: in the real development, DH began with small production facilities, and production capacity was increased as the net expanded, upgrading the existing facilities. In reality, the investment in the new CHP plant and large-scale expansion of the net was planned with a consolidated demand. The model considered one unique production source, starting from a situation of non-connected areas, and the optimal solution showed that expansion should be completed in a period of 8 years (at a rate of 1 area per year), for each side of the town. Although eastern and western areas were handled separately (partly because the model limitations), it didn't mean western areas should wait for eastern areas to finish. With enough resources (e.g. labour, materials, machines, etc.), both sides of the town could be managed simultaneously. One of the advantages of dynamic programming was the capacity to upgrade the strategies in case the entering conditions for a particular year had changed or some unexpected event occurred.

In the strategies OPT1 and OPT3 (Fig. 10 and Fig. 12), it was clearly showed the first areas to connect should be those with more units, regardless the longer distances to the production source. Regarding the connection within areas, the optimum was to establish the connection between the closest areas. The sub-case b.1 gave different expansion strategies, OPT2 and OPT4 (Fig. 11 and Fig.13), because the connection costs were dominating over future revenues. On the west side, the software revealed it was optimal to leave area $k=11$ unconnected, because of the few expected units to attach. Compared with the real development, the patterns of expansion differed in many points, since they were probably affected by other criteria, like the proximity to the old production facilities, the hospital and the industry, excluded in the model.

Conclusions

Results showed that investments in DH are feasible and positive from all points of views, especially if the whole society would switch to DH, powered by wood fuels, from alternative systems based on fossil sources. This work presented a first approach to the optimization of DHDN expansion, and therefore, it should be taken as a starting point. The optimization software could be upgraded with further development, making possible to handle at the same time whole city areas, and considering multiple production facilities. One of the major contributions of this work was the development and the test of an innovative methodology that may be useful to decision makers to plan DH expansion. Although the model was applied to a particular location in Sweden, the input parameters could be adjusted to any other local conditions and applied in other regions of the World. It is obvious that every technology and model should adapt to the particular country's conditions. Simulation results could be very much improved with detailed empirical information about the case study area. Higher economic profitability, efficiency, safety, and positive environmental impact of DH systems and CHP, should be expected where these systems are implemented. The methodology presented could be of also of application to develop systems based on tri-generation (CCHP, combined cooling, heat and power). In addition to the improvement of air quality in the urban environment, the global impact of using DH and CHP technologies, fuelled by renewable biomass resources, is of special relevance to the carbon cycle and global warming, since most of CO_2 emissions from renewable biomass resources are considered carbon neutral. The use of forest biomass in a sustainable and rational way provides multiple economic and environmental benefits.

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Kraft, for their invitation to perform a study visit to *Skogsbacka Kraftvärmeverk* in Lycksele (northern Sweden).

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APPENDIX 1. DHINV Dynamic Optimization (program code).

This software code was developed and programmed by Peter Lohmander *(Lohmander*, *2010)*. The software, descriptions and examples can be downloaded and executed from **http://www.lohmander.com/Program/Program.htm**

```
REM
REM DHInv22
REM Peter Lohmander
REM 2010_08_11_1437
CLS

OPEN "DHOut.txt" FOR OUTPUT AS #1
OPEN "DHIN.txt" FOR INPUT AS #2

DIM W(256, 26), M(8, 256), z(8), c(8, 256)
DIM cc(8, 8), MEX(10)
DIM jopt(256, 26), cvia(8, 256)

INPUT #2, Info$
INPUT #2, Less, a$
INPUT #2, kmax, a$
INPUT #2, tmax, a$
INPUT #2, rate, a$
INPUT #2, p, a$
INPUT #2, concos, a$

imax = 2 ^ kmax
jmax = imax

FOR k = 1 TO kmax
INPUT #2, z(k), a$
NEXT k

REM
REM ***** Connection Costs via the Primary Source *****
REM
FOR k = 1 TO kmax
INPUT #2, c(k, 1), a$
c(k, 1) = c(k, 1) + concos * z(k)
NEXT k


REM
REM ***** Costs of connecting one area via another area *****
REM
FOR k = 1 TO kmax
FOR M = 1 TO kmax
INPUT #2, cc(k, M), a$
NEXT M
NEXT k

FOR k1 = 1 TO kmax
 FOR k2 = 1 TO kmax
  IF k2 = k1 THEN GOTO 444
  cc(k1, k2) = cc(k1, k2) + concos * z(k1)
444 REM
 NEXT k2
NEXT k1


PRINT #1, ""
PRINT #1, "OPTIMAL RESULTS FROM DHINV"
PRINT #1, "Software by "
PRINT #1, "Peter Lohmander 2010"
REM PRINT #1, ""
REM PRINT #1, "tmax = ", tmax, " kmax = ", kmax, " imax = jmax = "; imax

REM
REM ***** Terminal conditions *****
REM
FOR i = 1 TO imax
 W(i, (tmax + 1)) = 0
```

```
NEXT i


REM
REM ***** Calculation of the membership function *****
REM
 mnum = 0
 FOR k = kmax TO 1 STEP -1
  value = 0
  mnum = mnum + 1
  mm = 2 ^ (mnum - 1)
  count = 0
   FOR i = 1 TO imax
    count = count + 1
    M(k, i) = value
    change = 0
    IF count = mm THEN change = 1
    IF change = 1 THEN count = 0
    chdown = 0
    IF value = 1 THEN chdown = 1
    chup = 0
    IF value = 0 THEN chup = 1
    IF (change = 1 AND chdown = 1) THEN value = 0
    IF (change = 1 AND chup = 1) THEN value = 1
 NEXT i
NEXT k


REM
REM ***** Calculation of State Dependent Partial *****
REM ***** Investment Cost Functions            *****
REM
FOR i = 2 TO imax
 FOR k = 1 TO kmax
  IF M(k, i) = 1 THEN c(k, i) = 0
  IF M(k, i) = 1 THEN GOTO 222
  c(k, i) = c(k, 1)
   FOR kconect = 1 TO kmax
    IF M(kconect, i) = 0 THEN GOTO 333
    IF kconect = k THEN GOTO 333
    clok = cc(k, kconect)
    IF clok < c(k, i) THEN cvia(k, i) = kconect
    IF clok < c(k, i) THEN c(k, i) = clok
333 REM
    NEXT kconect
222 REM
 NEXT k
NEXT i


REM
REM ***** Dynamic Programming via Backward Recursion *****
REM
FOR t = tmax TO 1 STEP -1
    d = EXP(-rate * t)
 FOR i = 1 TO imax
    optF = -999999
    optJ = 0
     FOR j = 1 TO jmax
      neginv = 0
      numinv = 0
      FOR k = 1 TO kmax
       IF (M(k, j) - M(k, i)) = 1 THEN numinv = numinv + 1
       IF (M(k, j) - M(k, i)) < 0 THEN neginv = neginv + 1
     NEXT k
   IF neginv > 0 THEN GOTO 100
   IF numinv > 1 THEN GOTO 100
    net = 0
    FOR k = 1 TO kmax
     net = net + p * M(k, i) * z(k)
    NEXT k
    FOR k = 1 TO kmax
     IF (M(k, j) - M(k, i)) = 1 THEN net = net - c(k, i)
    NEXT k
   F = d * net + W(j, (t + 1))
   IF F > optF THEN optJ = j
   IF F > optF THEN optF = F
```

```
100 REM
   NEXT j
  W(i, t) = optF
REM PRINT #1, "t = "; t; " i = "; i; " optF = "; optF; " optJ = "; optJ jopt(i, t) =
optJ
 NEXT i
NEXT t



PRINT #1, ""
PRINT #1, "OPTIMAL TIME AND STATE DEPENDENT DECISIONS AND EXPECTED PRESENT VALUES"
instate = 1
FOR t = 1 TO tmax
PRINT #1, ""
PRINT #1, " t = ";
PRINT #1, USING "###"; t

PRINT #1, " i(t)  E(PV)      i(t+1)  DEC  CVIA  Entering Partial States"
PRINT #1, " -------------------------------------------------------"
FOR i = 1 TO imax

IF (i < instate OR i > instate) AND (Less = 1) THEN GOTO 888


 FOR k = 1 TO kmax
 MEX(k) = M(k, i)
 NEXT k

PRINT #1, USING "####"; i;

PRINT #1, USING "##########."; W(i, t);


invnumb = 0
FOR k = 1 TO kmax
IF (M(k, jopt(i, t)) - M(k, i)) > 0 THEN invnumb = k
NEXT k
PRINT #1, USING "####"; jopt(i, t);
PRINT #1, "  ";

IF invnumb > 0 THEN PRINT #1, USING "###"; invnumb;
IF invnumb = 0 THEN PRINT #1, "     ";

IF invnumb > 0 THEN PRINT #1, USING "#####"; cvia(invnumb, i);
IF invnumb = 0 THEN PRINT #1, "     ";

PRINT #1, "  ";
FOR k = 1 TO kmax
PRINT #1, USING "##"; MEX(k);
NEXT k
PRINT #1, ""

888 REM

NEXT i
instate = jopt(instate, t)

NEXT t

CLOSE #1
CLOSE #2

END
```

APPENDIX 2. DHINV Dynamic Optimization (application data).

Input file, **DHIN.txt**, for the analyses on the eastern side of Lycksele (western side not shown)

```
"DHIN East side Lycksele"
1          "Less"
8          "kmax"
25         "tmax"
.05
              "ra
           te"
           "p"
           "conco
           s"
47         "z1"
86         "z2"
96         "z3"
60         "z4"
33         "z5"
22         "z6"
113        "z7"
15         "z8"
4935519    "c1"
4317912    "c2"
3458145    "c3"
3449263    "c4"
2676765    "c5"
2659252    "c6"
5425920    "c7"
5645343    "c8"
0          "cc11"
396686    "cc12"
1568176   "cc13"
1489182   "cc14"
2986410   "cc15"
2854888   "cc16"
6542767   "cc17"
7511298   "cc18"
396686    "cc21"
0          "cc22"
458821    "cc23"
379360    "cc24"
1876521   "cc25"
1745000   "cc26"
5432828   "cc27"
6401347   "cc28"
1568176   "cc31"
458821    "cc32"
0          "cc33"
429970    "cc34"
440425    "cc35"
0          "cc36"
3687886   "cc37"
4656418   "cc38"
1489182   "cc41"
379360    "cc42"
429970    "cc43"
0          "cc44"
838898    "cc45"
499434    "cc46"
4181768   "cc47"
5150304   "cc48"
2986410   "cc51"
1876521   "cc52"
440425    "cc53"
838898    "cc54"
0          "cc55"
515273    "cc56"
4198047   "cc57"
5166569   "cc58"

2854888   "cc61"
1745000   "cc62"
```

```
0          "cc63"
499434    "cc64"
515273    "cc65"
0          "cc66"
3179065   "cc67"
4147598   "cc68"
6542767   "cc71"
5432828   "cc72"
3687886   "cc73"
4181768   "cc74"
4198047   "cc75"
3179065   "cc76"
0          "cc77"
219275    "cc78"
7511298   "cc81"
6401347   "cc82"
4656418   "cc83"
5150304   "cc84"
5166569   "cc85"
4147598   "cc86"
219275    "cc87"
0          "cc88"
```

Note that when inserting the input data from the western side of Lycksele (from k=9 to k=16) in the optimization software, it will be necessary to do next equivalence, since the software can handle up to 8 areas (k_{max}=8)

Table 1. Code of each area (neighborhood) and equivalence in the program.

Area	**Equivalence**
k=9	k=1
k=10	k=2
k=11	k=3
k=12	k=4
k=13	k=5
k=14	k=6
k=15	k=7
k=16	k=8

Table 2. Code of the connection cost of each area (neighborhood) and equivalence in the program.

Connection cost	**Equivalence**
cc91	cc11
cc92	cc12
cc93	cc13
cc94	cc14
cc95	cc15
cc96	cc16
cc97	cc17
cc98	cc18

APPENDIX 3. Calculations.

<u>Number of units, z(k)</u>

Degree of connection to the District Heating Distribution Net (DHDN) (derived from satellite pictures and maps from the DHDN).

Table 1. Amount of units within each area.

	Attached	Total	Attached/Total
z(2)	86	120	0,72
z(3)	96	197	0,49
z(6)	22	42	0,52
z(7)	113	197	0,57
z(8)	15	29	0,52
z(10)	72	140	0,51
z(11)	10	19	0,53
z(12)	135	142	0,95
z(13)	222	291	0,76
z(14)	68	109	0,62
z(15)	21	58	0,36
z(16)	27	50	0,54
AVERAGE DEGREE OF CONECTION			**0,59**

Table 2. Assumption of connected units in the "empty" areas.

	Attached (estimation)	Total (theoretical)	Connected/Total
z(1)	47	80	0,59
z(4)	60	101	0,59
z(5)	33	55	0,59
z(9)	54	91	0,59

<u>Cost of connection from the area to the source, c(k)</u>

Lineal cost of pipeline: 2000 SEK / m

Table 3. Cost of connection from the area to the source, c(k)

k	*Distance code*	Distance (m)	*code*	Cost (SEK)
1	*d1*	2468	***c1***	4935519
2	*d2*	2159	***c2***	4317912
3	*d3*	1729	***c3***	3458145
4	*d4*	1725	***c4***	3449263
5	*d5*	1338	***c5***	2676765
6	*d6*	1330	***c6***	2659252
7	*d7*	2713	***c7***	5425920
8	*d8*	2823	***c8***	5645343
9	*d9*	3233	***c9***	6466316
10	*d10*	2737	***c10***	5474708
11	*d11*	2275	***c11***	4550235
12	*d12*	2831	***c12***	5661966
13	*d13*	2474	***c13***	4948036
14	*d14*	1981	***c14***	3962557
15	*d16*	3351	***c15***	6701218
16	d16	4897	***c16***	9794137

Note: From ***k(9)*** to ***k(16)***, the distance from the area to the source was calculated as the distance from the area to the white color node (Figure 5), assuming the connection from Skogsbacka to the white node has already been done in the past to connect the areas on the right side of the river.

Cost of connection between each area, *cc(k(1, ..., k_{max})*

Lineal cost of pipeline: 2000 SEK / m

Table 4. Cost of connection between each area to the source

k	***Distance code***	**Distance (meters)**	***Cost code***	**Cost (SEK)**
1				
	dd11	0	***cc11***	0
	dd12	198	***cc12***	396686
	dd13	784	***cc13***	1568176
	dd14	745	***cc14***	1489182
	dd15	1493	***cc15***	2986410
	dd16	1427	***cc16***	2854888
	dd17	3271	***cc17***	6542767
	dd18	3756	***cc18***	7511298
2				
	dd21	198	***cc21***	396686
	dd22	0	***cc22***	0
	dd23	229	***cc23***	458821
	dd24	190	***cc24***	379360
	dd25	938	***cc25***	1876521
	dd26	873	***cc26***	1745000
	dd27	2716	***cc27***	5432828
	dd28	3201	***cc28***	6401347
3				
	dd31	784	***cc31***	1568176
	dd32	229	***cc32***	458821
	dd33	0	***cc33***	0
	dd34	215	***cc34***	429970
	dd35	220	***cc35***	440425
	dd36	0	***cc36***	0
	dd37	1844	***cc37***	3687886
	dd38	2328	***cc38***	4656418
4				
	dd41	745	***cc41***	1489182
	dd42	190	***cc42***	379360
	dd43	215	***cc43***	429970
	dd44	0	***cc44***	0
	dd45	419	***cc45***	838898
	dd46	250	***cc46***	499434
	dd47	2091	***cc47***	4181768
	dd48	2575	***cc48***	5150304
5				
	dd51	1493	***cc51***	2986410
	dd52	938	***cc52***	1876521
	dd53	220	***cc53***	440425
	dd54	419	***cc54***	838898
	dd55	0	***cc55***	0
	dd56	258	***cc56***	515273
	dd57	2099	***cc57***	4198047
	dd58	2583	***cc58***	5166569
6				
	dd61	1427	***cc61***	2854888
	dd62	873	***cc62***	1745000
	dd63	0	***cc63***	0
	dd64	250	***cc64***	499434
	dd65	258	***cc65***	515273
	dd66	0	***cc66***	0

	dd67	1590	***cc67***	3179065
	dd68	2074	***cc68***	4147598
7				
	dd71	3271	***cc71***	6542767
	dd72	2716	***cc72***	5432828
	dd73	1844	***cc73***	3687886
	dd74	2091	***cc74***	4181768
	dd75	2099	***cc75***	4198047
	dd76	1590	***cc76***	3179065
	dd77	0	***cc77***	0
	dd78	110	***cc78***	219275
8				
	dd81	3756	***cc81***	7511298
	dd82	3201	***cc82***	6401347
	dd83	2328	***cc83***	4656418
	dd84	2575	***cc84***	5150304
	dd85	2583	***cc85***	5166569
	dd86	2074	***cc86***	4147598
	dd87	110	***cc87***	219275
	dd88	0	***cc88***	0
9				
	dd99	0	***cc99***	0
	dd910	566	***cc910***	1132696
	dd911	852	***cc911***	1703412
	dd912	1900	***cc912***	3799783
	dd913	2229	***cc913***	4458989
	dd914	1737	***cc914***	3473511
	dd915	3106	***cc915***	6212165
	dd916	4653	***cc916***	9305073
10				
	dd109	566	***cc109***	1132696
	dd1010	0	***cc1010***	0
	dd1011	356	***cc1011***	711803
	dd1012	1404	***cc1012***	2808177
	dd1013	1734	***cc1013***	3467358
	dd1014	1241	***cc1014***	2481903
	dd1015	2610	***cc1015***	5220543
	dd1016	4157	***cc1016***	8313466
11				
	dd119	852	***cc119***	1703412
	dd1110	356	***cc1110***	711803
	dd1111	0	***cc1111***	0
	dd1112	1067	***cc1112***	2133369
	dd1113	1271	***cc1113***	2542907
	dd1114	779	***cc1114***	1557429
	dd1115	2148	***cc1115***	4296084
	dd1116	3694	***cc1116***	7388993
12				
	dd129	1900	***cc129***	3799783
	dd1210	1404	***cc1210***	2808177
	dd1211	1067	***cc1211***	2133369
	dd1212	0	***cc1212***	0
	dd1213	52	***cc1213***	103208
	dd1214	862	***cc1214***	1723982
	dd1215	2704	***cc1215***	5407810
	dd1216	2030	***cc1216***	4059456
13				
	dd139	2229	***cc139***	4458989

	dd1310	1734	***cc1310***	3467358
	dd1311	1271	***cc1311***	2542907
	dd1312	52	***cc1312***	103208
	dd1313	0	***cc1313***	0
	dd1314	101	***cc1314***	202100
	dd1315	0	***cc1315***	0
	dd1316	337	***cc1316***	674467
14				
	dd149	1737	***cc149***	3473511
	dd1410	1241	***cc1410***	2481903
	dd1411	779	***cc1411***	1557429
	dd1412	862	***cc1412***	1723982
	dd1413	101	***cc1413***	202100
	dd1414	0	***cc1414***	0
	dd1415	923	***cc1415***	1846163
	dd1416	2470	***cc1416***	4939071
15				
	dd159	3106	***cc159***	6212165
	dd1510	2610	***cc1510***	5220543
	dd1511	2148	***cc1511***	4296084
	dd1512	2704	***cc1512***	5407810
	dd1513	0	***cc1513***	0
	dd1514	923	***cc1514***	1846163
	dd1515	0	***cc1515***	0
	dd1516	2095	***cc1516***	4190557
16				
	dd169	4653	***cc169***	9305073
	dd1610	4157	***cc1610***	8313466
	dd1611	3694	***cc1611***	7388993
	dd1612	2030	***cc1612***	4059456
	dd1613	337	***cc1613***	674467
	dd1614	2470	***cc1614***	4939071
	dd1615	2095	***cc1615***	4190557
	dd1616	0	***cc1616***	0

Marginal Profit (MP) from the energy company point of view

Marginal Costs (MC)

Marginal Cost of Fuel

Table 5. Marginal Cost of Fuel.

	MWh/Ton [1)]	**SEK/Ton** [2)]	**SEK/MWh**	**Fuel mix** [7)]
GROT	2,48	150	60,5	50 %
Roundwood	3,9	275	70,5	20 %
By-products			178 [3)]	20 %
Peat [5)]			168,5 [4)]	10 %
Transportation [6)]			58,2	
TOTAL	**155 SEK/MWh**			

[1)] Energy value for GROT, 50% moisture content, report "INFO från projektet 125" *(Dag Fjeld et.al, 2007)*. Estimation of energy value for roundwood, assuming 25% moisture content (MC). Stemwood 0% MC=5.4 MWh/ton; 50% MC=2.4 MWh. Original figures from the Swedish Forest Agency *(Skogsstyrelsen, 2009).*

[2)] Prices obtained from "Prislista Energisortiment" *(Skellefteå Kraft, 2009).*

[3) 4)] Prices obtained from "Prisblad för biobränsle,torv m.m. Nr 4/2009" (*Swedish Energy Agency, 2009).*

[5)] Assumption: 50% milled peat, 50% peat in block. The price includes sulphur emission tax.

[6)] It was the transportation price of GROT, with a 20 Tons truck. The original source was "INFO från projektet 125", *(Dag Fjeld et. al, 2007),* although in the model, it has been assumed the same value for all fuels.

7) *(Kjell-Olov personal communication, 2010).*

Marginal Cost of Capital (Skogsbacka KVV)

Table 6. Investment cost Skogsbacka Kraftvärmeverk (Lycksele Energi, 2000).

	(December 1998)	2009
Investment ***(C)***	280 MSEK	339,2 MSEK
Subsidy (NUTEK)	42,6 MSEK	51,6 MSEK
Investment ***(Cnetto)***	237,4 MSEK	287,6 MSEK

Table 7. Producer Price Index (SCB, 2010).

PPI (December 1998)	90,7
PPI (average 2009)	115
Increase (December 1998-average 2009)	0,21 (21%)

Table 8. Calculation of the cost of capital per year.

Rate of interest	**5 %**
Period	**20 years**
Discount factor, continuous compounding **k=e^(-r)**	0,951229425
(1-k)/(1-k^(n+1))	0,075024469
C *· [(1-k)/(1-k^(n+1))]*	**25,4 MSEK/year (no subsidy)**
Cnetto *· [(1-k)/(1-k^(n+1))]*	**21,6 MSEK/year (with subsidy)**

Table 9. Calculation of the MC of capital.

Sales of district heating (2009) [1)]	115.000 MWh
MC (no subsidy)	**221,3 SEK/MWh**
MC (with subsidy)	**187,6 SEK/MWh**

1) Personal estimation from a graph from the study visit

Marginal Cost of Capital (District Heating Distribution Net)

Table 10. Investment cost District Heating Distribution Net.

Total length (2009) [1)]	80197 m
Lineal cost [1)]	2000 SEK/m
TOTAL (C)	**160,2 MSEK**

1) *Jan-Erik Lindholm personal communication, 2010*

Table 11. Calculation of the cost of capital per year.

Rate of interest	**5 %**
Period	**20 years**
Discount factor, continuous compounding **k=e^(-r)**	0,951229425
(1-k)/(1-k^(n+1))	0,075024469
C · [(1-k)/(1-k^(n+1))]	**12 MSEK/year**

Table 12. Calculation of the MC of Capital

Sales of district heating (2009)	115.000 MWh
MC of Capital DHDN	**104,5 SEK/MWh**

Marginal Cost of personal

Table 13. Calculation of the Marginal Cost of Personal

Production of District Heating	155.626 MWh
Total cost of personal [1)]	*y=86,96 - 5,875· LN(x)*
Marginal Cost of personal	*y=81,09 - 5,875· LN(x)*
Marginal Cost of personal	**10,8 SEK/MWh**

[1)] The source, *“Värme i Sverige: En uppföljning av värmemarknaderna” (Energimyndigheten, 1999),* indicated to use the value of district heating production.

Marginal Cost of Operation and Maintenance (O+M)

Table 14. Calculation of the Marginal Cost of Operation and Maintenance (O+M) at Skogsbacka KVV

Cost of the investment	339,2 MSEK
2% Cost of the investment [1)]	*6,8 MSEK*
Sales of district heating	115.000 MWh/year
MC of O+M at Skogsbacka KVV	**59 SEK/MWh**

[1)] Although the source, *“Värme i Sverige: En uppföljning av värmemarknaderna” (Energimyndigheten, 1999)* referred to ”replacement value”, the calculations assumed the cost of investment.

Table 15. Calculation of the Marginal Cost of Operation and Maintenance (O+M) for the district heating net

Cost of the investment	160,2 MSEK
1% Cost of the investment [1)]	1,6 MSEK
Sales of district heating	115.000 MWh/year
MC of O+M at Skogsbacka KVV	**13,9 SEK/MWh**

[1)] Although the source, *“Värme i Sverige: En uppföljning av värmemarknaderna” (Energimyndigheten, 1999)* referred to ”replacement value”, the calculations assumed the cost of investment

Table 16. Total Marginal Cost of Operation and Maintenance (O+M)

Total MC of Operation and Maintenance	**72,9 SEK/MWh**

Total Marginal Cost

Table 17. Total Marginal Cost from the company point of view

Total MC (without subsidy)	**564,6 SEK/MWh**
Total MC (with subsidy)	**530,9 SEK/MWh**

Marginal Revenues (MR)

Table 18. Marginal Revenues from the company point of view

District heating domestic price [1)]	788,4 SEK/MWh
District heating domestic price (excl. VAT)	**591,3 SEK/MWh**

[1)] Average district heating consumer price in Lycksele (small and multi-dwelling buildings). “Priser fjärrvärme 08-09” *(Svensk Fjärrvärme, 2010).*

Marginal Profit (MP)= Marginal cost (MC) – Marginal Revenues (MR)

Table 19. Marginal Profit from the company point of view

MP (without subsidy)	**26,7 SEK/MWh**
MP (with subsidy)	**60,4 SEK/MWh**

Marginal Profit (MP) from the costumer point of view

Marginal cost (MC)

Marginal Cost of Fuel

Table 20. Marginal Cost of Fuel [1)]

	SEK/MWh
Gasoil (Eo1)	**1100**
Pellets	**500**
District heating	**788**
Electricity	**1000**

[1)] The values were personal estimations for year 2009, within domestic sector (all taxes included). The original information was obtained from a comparative graph between different energy sources, found in Skellefteå Kraft website.

Marginal Cost of Capital (if upgrading to district heating from electricity)

Table 21. Average yearly consumption of district heating per unit within each area in Lycksele

Total sales of district heating	**115.000 MWh**
Number of costumers [1)]	**1300 costumers**
Average yearly consumption [2)]	**88,5 MWh/year/unit**

[1)] The number of customers in year 2009 (Jan-Erik Lindholm personal communication, 2010)
[2)] In the calculation, it has been assumed: costumers=units within an area. The total yearly sales were estimated from a presentation during the study visit (Skellefteå Kraft, 2010).

Table 22. Investment cost if the costumer would upgrade from elecitricty

Investment cost **(C)** [1)]	100.000 SEK/unit
Investment cost **(Csubsidty)** [2)]	70.000 SEK/unit

[1)] Average consumer connection cost, for small houses (Skellefteå Kraft, 2010)
[2)] Assuming the costumer would obtain the maximum subsidy, 30.000 SEK/unit (Boverket, 2006)

Table 23. Calculation of the cost of capital per year in case the costumer would upgrade from electricity

Rate of interest	**5 %**
Period	**20 years**
Average yearly consumption per unit	**88,5 MWh/year/unit**
Discount factor, continuous compounding k=e^(-r)	0,951229425
(1-k)/(1-k^(n+1))	0,075024469
C· [(1-k)/(1-k^(n+1))]	**7502,4 SEK/year/unit**
Marginal Cost of Capital	**84,8 SEK/MWh**
Csubsidy· [(1-k)/(1-k^(n+1))]	**5251,7 SEK/year/unit**
Marginal Cost of Capital (with subsidy)	**59,4 SEK/MWh**

Marginal Cost of Capital (if upgrading to district heating from oil or pellets)

Table 24. Investment cost in case the costumer would upgrade from oil or pellets

Investment cost (C) [1)]	38.000 SEK/unit

[1)] Average consumer connection cost, for small houses (Skellefteå Kraft, 2010)

Table 25. Calculation of the cost of capital per year

Rate of interest	**5 %**
Period	**20 years**
Average yearly consumption per unit	**88,5 MWh/year/unit**
Discount factor, continuous compounding k=e^(-r)	0,951229425
(1-k)/(1-k^(n+1))	0,075024469
C· [(1-k)/(1-k^(n+1))]	**2850,9 SEK/year/unit**
Marginal Cost of Capital	**32,2 SEK/MWh**

Total Marginal Cost

Table 26. Total Marginal Cost from the costumer point of view

MC if upgrading from electricity	**872,8 SEK/MWh**
MC if upgrading from electricity (with subsidy)	**847,4 SEK/MWh**
MC if upgrading from oil / pellets	**820,2 SEK/MWh**

Marginal Profit ("Savings") : Marginal cost fuel – Marginal cost if the costumer would change to district heating

Table 27. Marginal Profit from the costumer point of view

MP if upgrading from electricity	**127,2 SEK/MWh**
MP if upgrading from electricity (with subsidy)	**152,6 SEK/MWh**
MP if upgrading from oil	**279,8 SEK/MWh**
MP if upgrading from pellets	**-320,2 SEK/MWh**

Marginal Profit (MP) from society point of view

(MP from the energy company and costumer point of view summarized, without subsidy)

a) In case society will upgrade to district heating from electricity

Table 28. Marginal profit from society point of view (upgrading from electricity)

Marginal profit	**153,9 SEK/MWh**
Cost of connection (concos)	100 000 SEK

b) In case society will upgrade to district heating from oil

Table 29. Marginal profit from society point of view (upgrading from oil)

Marginal profit	**306,5 SEK/MWh**
Cost of connection (concos)	38 000 SEK

c) In case 50% of society will upgrade from oil and 50% of society will upgrade from electricity

Table 30: Marginal profit from society point of view (upgrading from oil and electricity)

Marginal profit	**230,2 SEK/MWh**
Cost of connection (concos)	69 000 SEK