Valuation of the System Advantages of Lower District Heating Temperatures

BSc.Eng. Project

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Abstract

In this thesis, a comparative evaluation among conventional, low temperature and ultra low temperature district heating systems is elaborated to quantify the system advantages and disadvantages when proceeding a transition into lower temperature DH. The quantified performance across DH, LTDH, ULTDH covers distribution grid heat loss, cogeneration electricity efficiency, heat pump COP, flue gas condensation as well as additional heating of domestic hot water under ULTDH and extra network costs due to lower temperature difference. A MS Excel based model is developed to conduct calculations with embedded data covering financial, environmental, energy and socio-economic aspects, which could also be used as a generic tool for project evaluation.

According to base load evaluation on 14 DH technologies, heat pump production unit has the best synergy with lower temperature. Besides, it sees a slightly lower levelized costs for biomass/waste based boiler and CHP, under LTDH and ULTDH. However, with regard to fossil fuel based utility plant, no noticeable distinction is observed. As for 6 additional DHW heating concepts, MBST concept (i.e.Heat pump, secondary tank) is the most preferable solution with relatively low levelized heat cost based on real DHW demand of a standard low-energy house.

An undergoing project in Nivå by Sweco is introduced to be a case study. The evaluation results over 20-year period indicate both LTDH and ULTDH have a positive impact on local community and socio-economic compared with DH while LTDH is more beneficial. However, DH company benefits from LTDH rather than ULTDH, in reverse, DH consumers prefer ULTDH with lower costs. All these characteristics make it feasible to re-allocate the benefits to create incentives for all stakeholders to prefer lower temperature district heating. In addition, sensitivity analysis is conducted on heat price, MBST investment and fixed O&M costs, electricity generation externality as well as electricity price.

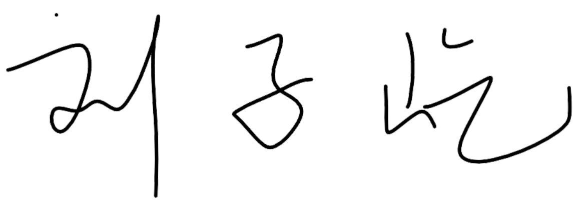
Preface

This bachelor thesis was prepared at the department of Mechanical Engineering at the Technical University of Denmark in fulfillment of the requirements for acquiring a Bachelor of Science degree in Engineering.

Most of all, I would like to express my gratitude to my supervisor Brian Elmegaard and Torben Schmidt Ommen at the Section of Thermal Energy, who gave me patient guides and generous help to finish the project together with Johnny Iversen from Sweco A/S who proposed this topic and also provided essential data&resources and demonstration projects. In addition, the excellent study environment including well-performed facilities in Lyngby campus contributes a positive impact on my outcomes as well.

Thanks to the close relationship between DTU and Shanghai Jiao Tong University, I am so lucky to have the opportunity to spend one amazing year in Denmark. Last but not the least,I am sincerely grateful for the support of my parents, not only financially but also spiritually, also the accompany and encourage from my friends, without which I would never achieve this.

Kongens Lyngby, June, 2018



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Nomenclature

Abbreviations

4GDH 4th Generation District Heating

CHP Combined heat and power (Cogeneration)

COP Coefficient of performance

DCW Domestic cold water

DH District heating

DHW Domestic hot water

FGC Flue gas condensation

HE Heat exchanger

HHV High heat value

HP Heat pump

IRR Internal rate of return

LCOE Levelized cost of energy

LHV Low heat value

LTDH Low temperature district heating

NPV Net present value

RES Renewable energy sources

SH Space heating

ULTDH Ultra low temperature district heating

General Symbols

η Efficiency

p	pressure, bar
r	DH temperature coefficient for efficiency
T	temperature, °C

Subscripts

cond	condensor
elec	electricity
F	forward
R	return
sink	sink reservoir
source	source reservoir
total	total utilization

CHAPTER 1

Introduction

District heating has been a critical factor for improving energy efficiency and decreasing negative environmental impact over decades in Denmark, combined with cogeneration. Till 2017, district heating constitutes 64.4% of the total Danish households heating, not only for space heating, but also for domestic hot water supply [Ass]. Meanwhile, there is still a potential increase in total DH capacities in the near future [Ageb]. However, conventional high temperature DH is facing challenges from local cost-effective alternative technologies mainly because of network costs and distribution heat loss[Omm+17]. Besides, it's recognized that DH should transform into lower temperature district heating to form better synergy effect with future sustainable energy system[Lun+14].

1.1 Current district heating systems in Denmark

After 1973 oil crisis, Denmark was determined to realize energy transition for more self-efficiency. Thus long-term and massive investments had flowed into district heating to get rid of oil-dominated heating situations, with strong support of municipalities. As far, there are 6 large central DH area (approximately 60 PJ heat production per year) and 400 smaller decentralized DH areas (app. 75 PJ per year)[Ageb]. Figure 1.1 showcases a typical district heating system involving power plants, transmission networks, substations, distribution networks and end consumers. Basically, this large scale DH is built in heat-intensive cities, such as Copenhagen, Aarhus. Heat was transported through high temperature and pressure transmission lines over long distance, generally from central heat generation units to distribution networks, then distribution lines with lower temperature and pressure supply heat to consumers. In comparison, for small scale DH in minor cities, town or even villages, there are most often no need for transmission lines, with heat distributing to consumers directly.

In 2015, 127.6 PJ DH heat is generated using 85.3 PJ fuel in sum, and 67.4% of total district heating is produced from CHP, which means saving about 25% of fuel consumption than generating heat and power separately. But the ratio of CHP is 1.4 percent lower than that of 2014 due to increasing heat-only units (Figure 1.2a). Compared with 1990 scenario, the percentage of coal consumption has decreased dramatically, with a incrementally increase in renewable energy utilization such as

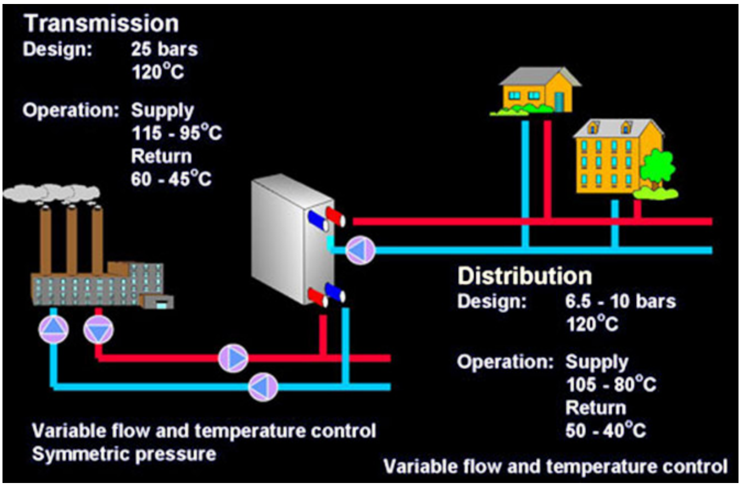
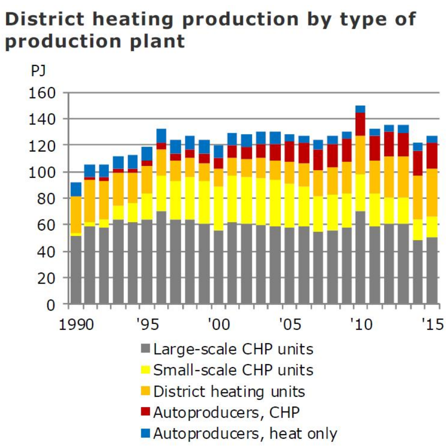


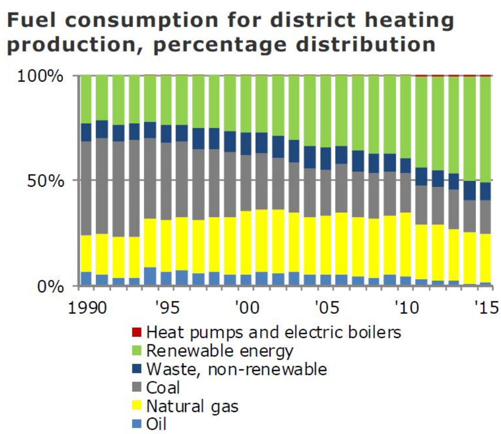
Figure 1.1: Large Danish heat transmission and distribution system[Dis]

biomass and solar.(Figure 1.2b). At the meantime, solar district heating is growing rapidly with an average growth rate at 29% from 2006 to 2016 [Pla]. Therefore, with using less fossil fuel and more clean energy, district heating has been playing an essential role to reduce CO_2 emission and alleviate environmental pollution.

As to the relationship among all the stakeholders in the DH system nearly all the DH



(a) Type of production plants



(b) Type of fuel consumption

Figure 1.2: District heating production in 2015[Agec]

companies' ownership is the consumer, in the shape of direct consumer cooperatives or indirect municipally owned companies. So after a financial statement audit, all the profits of DH companies must be allocated back to consumers at the end of the year or contribute to a lower heat price for next year. In addition, DH companies are voluntarily benchmarked with each other by branch organization and state regulatory authority on a annual basis, to ensure operation efficiency and customer benefits. On the other hand, DH production is based on the real heat demand with the help of the measurement facilities on consumer side. Consequently, consumers have more incentives to save heat in favor of less costs. Meanwhile, consumers have the obligation to connect to the public heat supply and remain connected, which means the consumers need to pay the connection fee or a fixed annual fee whether using heating or not. This requirement by the municipalities contributes to the DH's stability in a long term.[Dis][Odg]

With regard to financial aspects, the consistent national policy and municipal endorsement provide the fundamental guarantee for the DH companies to obtain low interest rate loans, which is critical because of much more expensive infrastructure costs in DH than individual heating alternatives. In addition, the taxes on fuel and subsidies also have important impacts on the production costs. It has seems a significant rise in biomass use, mainly resulting from heat tax exemption and additional subsidies on electricity selling. Conversely, high taxes on fossil fuels decrease the competitiveness of conventional power plants. [Ana] From consumer's perspective, the heating costs are usually made up of per installation fix costs and a variable part related to the heat consumption. On account of non-profit principle, the heating price is dependent on DH company costs, including production (72%), distribution (23%), and administration (5%). Meanwhile the depreciation of assets and financial costs including loan interest, taxes, subsidies, VAT shoule be considered to sustain the DH companies' development.[Agee] The average heating bill per household in 2015 was 1,475 EUR, equal to 2.6% household income or so. 66.7% DH consumers paid less than that with individual natural gas boiler.[Odg]

1.2 Lower temperature district heating in the future

Heat Roadmap Europe 2050 [Con+13] emphasizes the importance of district heating in future energy systems, however, current DH must go through a transition into lower temperature DH to better interact with low-energy building and low-temperature renewable energy. The concept of 4th Generation District Heating were brought up under the background to suggest how to meet and overcome the challenges from new buildings with reduced heat demand, smart energy systems with 100% RES [Lun+14]. 4GDH defines the heat carrier water's temperature should decrease from current 80-100 °C to 30-70 °C. The system advantages of lower DH temperature are indicated as followed.

- Lower grid losses. The difference between average pipe water and ground temperature decreases resulting in less distribution heat loss, in the meantime, the reduced peak flow rate in new building's distribution networks make it feasible to use smaller-dimension twin pipes, which have better heat insulation than two single pipes.
- Higher efficiency of CHP and large-scale heat pumps as well as better use of surplus heat in plants with gas condensation. Specifically, despite of heat source, the lower the required DH supply temperature, the higher the heat efficiency of electrical heat pump is. Lower return temperature helps the condensation, especially for high moisture biomass/waste plants.
- More efficient integration of low temperature renewable and recycled heat, e.g. solar, geothermal, excess heat. As for solar heating, seasonal storage is needed to mitigate the mismatch between solar radiation and heat demand. The available geothermal temperature varies to the depth, mostly 30-70 °C, which will be much easier to contribute under lower DH supply temperature. Additionally, heat pump is mostly used in geothermal plants and the COP will increase as well alongwith reduced auxiliary steam/electricity demand. Similarly, there is higher possibility to utilize industrial and commercial excess heat usually ranging from 30-50 °with auxiliary thermal storage facilities.
- Potential expansion of district heating. On the one hand, because of the benefits mentioned above, it's feasible to connect more building with current grid. On the other hand, it's possible to use existing conventional DH return pipe as lower temperature DH supply pipe to reach more consumers with less investments. In this case, a mixing shunt is used to regulate the flow rate of return and supply water in DH to reach a certain temperature in order for lower temperature DH.

1.2.1 Low temperature district heating (LTDH)

According to [Ols+14] by Danish energy agency, LTDH operate at 50-70 °C for supply with 25-35 °C for return, and LTDH has been proved as a commercialized solutions to meet end-user both SH and DHW demand under central-northern European climate. LTDH could be applied to both new and existing building to perform renovation as Figure 1.3 indicates four types of projects. Especially, LTDH is suited for new building with low space heating demand using under-floor heating or low temperature radiators. What's more, the required radiator size is almost the same between new building LTDH and old building DH.

Nevertheless, special installations are needed on consumer side under LTDH. First, the specific DHW distribute pipes should guarantee the water content in each DHW supply line and secondary side heat exchanger under 3 liters to get rid of legionella risks according to Germany guidelines (DVGW, W551). Then two LTDH substation solutions are recommended for singel family houses, specifically Instantaneous

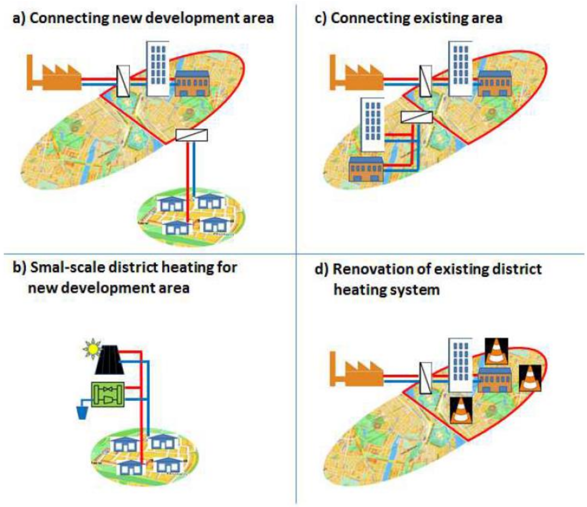
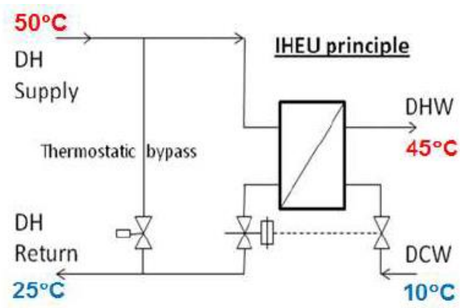


Figure 1.3: Four types of LTDH applications [Ols+14]

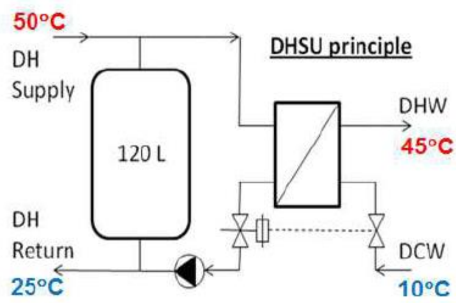
heat exchanger unit (IHEU) and District heating storage unit (DHSU) as Figure 1.4 shows. The common parts are high efficiency heat exchanger and accurate control valves. Extra storage tank and pump are required for DHSU. In addition, higher flow rate are required under LTDH to meet the same heat demand as before, along with the increasing total substation pressure loss . It's recommended to kept below 0.3 bar with special piping design and high-quality component. Moreover, DHW pipes should connect each tap and source of DHW individually without circulation. For multi-story building, a decentralized substation for each flat is suggested to eliminate DHW circulation, which avoids the high temperature requirement. In general, compared LTDH with DH on consumer side, the investment costs is a little higher on account of larger service lines from main distribution grids to houses, different domestic substations.

1.2.2 Ultra low temperature district heating (ULTDH)

A minimal supply temperature at 40 °C and return temperature around 20-22 °C is indicated in [Lun+14] to fulfill the heat comfort demand, where the average temperature in floor/wall heating is only a little higher than the room temperature. Hence, this kind of district heating with supply temperature below 45 °C is defined as ULTDH. However, the ultra temperature can not meet that the waiting time for 40-45 °C hot tap water after tapping should be 10 seconds suggested by Danish standard (DS439). As a consequence, additional energy source is necessary for hot water preparation either on primary side to DH water or on secondary side to tap water directly.



(a)



(b)

Figure 1.4: Diagram of Instantaneous heat exchanger (Left) unit and District heating storage unit(Right)[Ols+14]

Referred from previous research outcomes at DTU Thermal Section, several solutions are proposed, generally classified into two types, heat pump and electric heater. Another classification is based on the linking between SH and DHW, into totally and partially decouple.

- Electric heater

  Three electric heater DHW concepts are analysis in [Zvi+12]. Figure 1.5a shows the electric heater heat the primary side water from 40 to 53 °C, which is stored in the stratified accumulator tank. DCW is heated through the micro plate heat exchanger instantaneously from 10 °C to 45°C. As for Figure 1.5b, domestic cold water is preheated by DH network to 35 °C first and then heated up to 55 °C by electric heater inside storage tank. Another alternative (Figure 1.5c) is the totally decouple case, which means the DCW is directly heated to DHW. The total DHW heat demand is produced by electric heating.

- Microbooster heat pump

  In the same paper as above, three promising microbooster heat pump DHW concepts are analyzed and compared with electric heater solutions. The main difference between Figure 1.6a and Figure 1.6b is the heat source for heat pump, respectively DH supply water and return water from HE . Similarly with the fist concept for electric heating Figure 1.5a, the benefit of storage tank on primary side is to reduce heat pump capacity and DH flow so that to lower investment costs. With regard to Figure 1.6c, the heat pump is used to heat DCW directly with secondary DHW tank. But the DCW is preheated by DH supply water to 37.5 °C before entering the heat pump condenser. In the meantime, the risk of bacteria formation increases in the DHW tank, which means higher temperature

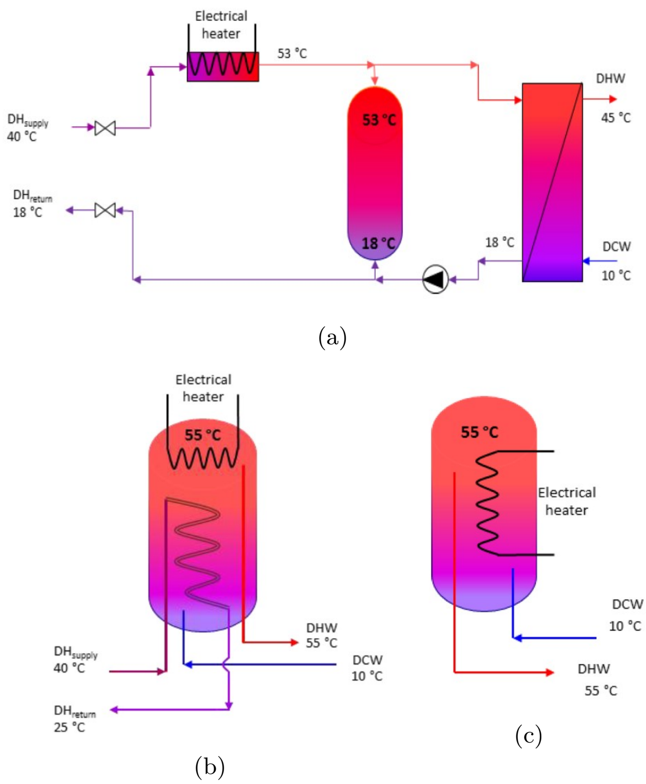


Figure 1.5: Diagram of electric heater DHW concepts for ULTDH [Zvi+12]

at around 60 °C is sometimes required. Based on the calculation results, the first concept is preferred with the highest COP at 5.3, compared with 3.5, 5.0 separately for the rest of two.

Electric heater has the advantages of lower investment costs than heat pump, however, much more electricity consumption compensate the benefits. Nevertheless, if the electricity price goes down in the future due to the massive use of renewable energy such as wind power and solar, with low negative externality as well, the electric heating might become attractive, especially for the second concept (Figure 1.5b). Currently, ULTDH is till under demonstration stage, but it's believed to be a promising alternative in 4GDH.

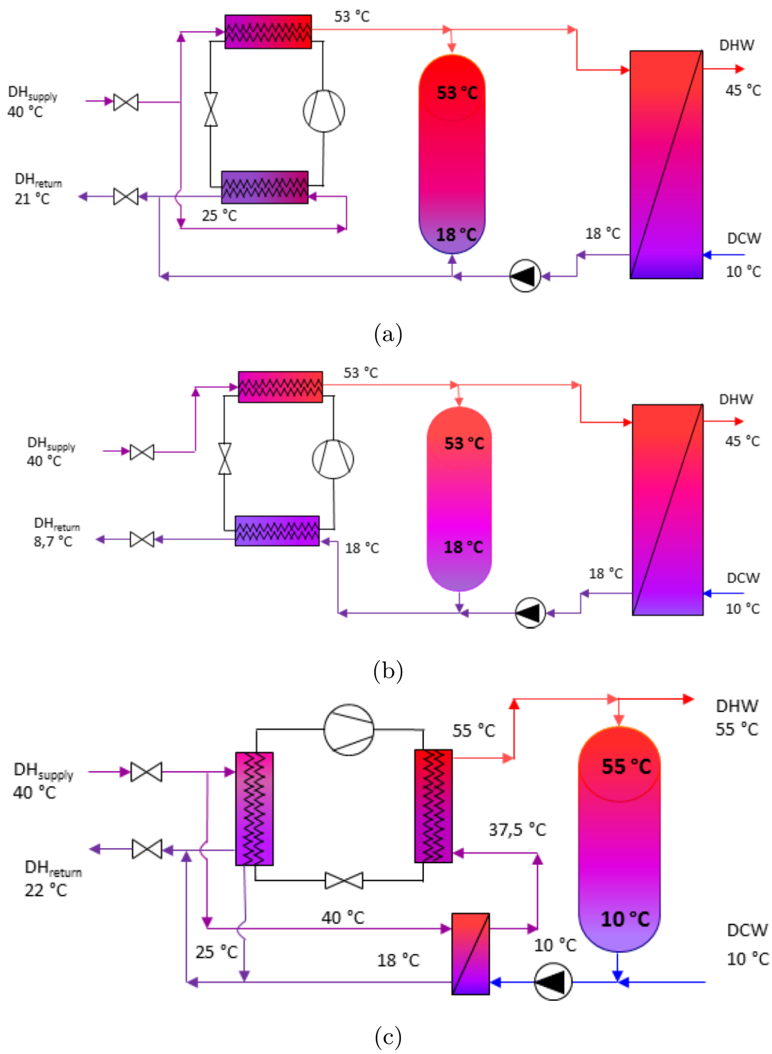


Figure 1.6: Diagram of microbooster heat pump DHW concepts for ULTDH [Zvi+12]

1.3 Valuation of district heating system

In Denmark, the municipalities take charge of the heating planning and heat supply expansion regulated by heating supply law. Specifically, all project proposal related to new DH unit/networks or major changes to existing grids must be approved by the City Council. It's mandatory to cover socio-economic, user-economic, company-financial and environmental analyses in the proposal. In addition, Danish Energy Agency provides the reference database to perform the evaluation, including production technology, fuel & emission price, energy transport, interest rates, etc.[Agee]

Socio-economic cost-benefit analysis is one of main criteria for heating project, which is performed exclude the taxes and subsidies but include the emission externality costs. Only the proposal with optimal benefits to society compared with several alternatives is prioritized. According the guidance methodology by Danish Energy Agency(DEA) [Ageh], it should be evaluated over the entire predicted technical time or with the residual value and re-investments considered over a 20-year depreciation period. The future energy price, emission costs, technology performance as well as other changes are also suggested by DEA, which could also been adjusted based on specific project context.

District Heating Assessment Tool was a MS Excel based model developed by Rambøll Energy for the Danish Energy Agency, aiming at calculate the economic feasibility to renovate a area from individual heating into district heating [Eneb]. After inputting the central parameters by users, the major output results are NPV value for local society, DH consumers, DH company and socio-economic with Levelized Cost of Energy value used. Here local scociety indicates the involved entities, namely DH consumers and company. In general, this tool could provide an comprehensive assessment of the district heating potential for a concerned area. However, additionally detailed analysis is recommended before undertaking investments.

In summary, both LTDH and ULTDH will cause additional investments on consumers sides in comparison to conventional DH, along with the benefits for DH networks and production units by lower temperature. Therefore, how to balance and allocate the system advantages is a meaningful topic to increase the incentives for all the stakeholders of district heating, which will definitely accelerate the transition into lower temperature district heating. Moreover, how to quantify mentioned advantages is the basis to carry out the evaluation.

In this thesis, section 2 clarifies the methods used to perform the comparative evaluation among DH, LTDH and ULTDH including quantifying the system advantages and disadvantages of lower temperature. A MS Excel based model is developed to conduct calculations covering financial, environmental, energy, socio-economic aspects. Section 3 first illustrates the concerned technologies' performance under 3 DH temperature scenarios. Then the valuation results for a specific project in Nivå are demonstrated, followed by sensitivity analysis to test the robustness. Section 4 concludes the major project outcomes as well as project limitations and potential improvements.

CHAPTER 2

Methods

2.1 Scope definition

Sweco is Europe's leading architecture and engineering consultancy, with abundant project experience concerning district heating [Swe]. In collaboration with Sweco Danmark A/S, several definitions based on facts under Danish context are set at the initial stage to indicate the project scope.

2.1.1 House classification

The project is mainly concerned single-family houses dividing into existing house (Fulfilling Building regulation 2010) and new-built house (Fulfilling Building regulation 2015)(Table 2.1). Service line capacity is calculated by dividing annual heat demand by 1850 hours, that's a empirical value for Danish climate. This value also implies the full load hours of a individual heating technology outside the DH area. In comparison, the new-built house's heat demand is about 55% less than the old house owing to better heat insulation, but additional ventilation unit is necessary to guarantee indoor air quality.

Table 2.1: Single-family house classification

	Standard area (m^2)	Habitants	Annual heat demand (MWh)	Share of SH	Share of DHW	Estimated service pipe capacity (kw)
Existing house	130-160	4	app. 18	70-75%	25-30%	9.73
New-built house	130-160	4	app. 8	55-60%	40-45%	4.32

2.1.2 DH scale classification

Table 2.2 defines two types' project scale based on the amount of potential DH consumers (houses) in Danish context. However, it's not feasible to perform a radical change on the existing central DH grid in major cities in the near future. So the small scale project is more concerned when performing lower temperature DH evaluation.

Table 2.2: DH scale classification

	Small scale	Large scale
Houses amounts	150-250	about 2000
Location	Very common, a typical community	Only in major cities, e.g. Copenhagen, Aarhus, Aalborg
Common & promising technology	Heat only boiler (natural gas, biomass), heat pump, solar panel	CHP (biomass, municipal waste, natural gas), central heat pump
Networks	Distribution single lines +service lines to houses +domestic substations	Transmission lines+substation +distribution lines+ domestic substations
Relationship with DH grid	Decentralized or totally out of grids	Central distict heating grid
Ownership	Production unit and networks belong to same company (most often)	DH networks company will buy heat from central production units owned by large energy companies. Usually, transmission is unbundled owned by municipalities.

2.1.3 Temperature scenario classification

Table 2.3 specifies three temperature scenarios used in this project neglecting the seasonal effect. The temperature is acted on both transmission and distribution lines in this project.

Table 2.3: Temperature scenario classification

Temperature scenarios	Forward temperature (°C)	Return temperature (°C)	Temperature difference (°C)	SH distribution methods	DHW preparation
DH	80	40	40	Radiator/Floor	Storage tank/heat exchanger
LTDH	60	30	30	Radiator/Floor	Heat exchanger
ULTDH	45	25	20	floor heating	Booster

2.1.4 Model application scope

The background setting of the valuation model is to project district heating to a certain amount of houses with the same heat demand in new DH area. The goal is to meet the total heat demand of end-consumers that is identical across temperature scenario, including the space heating and domestic hot water. Because some heating technologies' performance and cost differ from different capacity scale, two possible scenarios are discussed here:

- Stand-alone new district heating area

  This scenario is suitable for a total new district heating area, therefore new heat production facilities are invested nearby to supply heat to this area only. Usually, the small-scale projects, e.g. minor cities,towns and even villages, do not need for transmission networks under this context.

- Connecting to existing district heating networks

  This scenario is set for the projected area with district heating network around to invest new capacities on relatively larger scale production units. Additionally, the new capacities are treated as isolated thereby all the influence by lower DH temperature is only acted on concerned capacities as well. Because all the financial costs are unitized , it's feasible to perform this scenario.

Therefore, it's necessary to define the project scale at the beginning in the input sheet. Additionally, the construction time of power plants and district heating networks is neglected in this model.

2.2 Quantify the system advantages and disadvantages of lower temperature

This part is to distinguish the system performance quantitatively across temperature scenarios to decide the central parameters assumed in the evaluation model. With regard to production technology performance, DH temperature coefficient- **r** is introduced, taking DH case as reference. Moreover, "r" is classify into r_{heat} and r_{elec}, representing the relative change to heat efficiency and electricity efficiency respectively under different DH temperature scenario. Based on an intensive literature review and analysis, the recommended value related to the concerned technologies is embedded in the valuation model.

2.2.1 Distribution grid heat loss

[Elm+16] studied the distribution heat loss under several configurations in a low-energy house of 159 m^2 with an annual consumption of 4.01 MWh for SH and 3.2 MWh for DHW. And this is exactly within the scope. Additionally, total length of forward and return pipes in distribution networks is assumed as 3.6 km with a heat loss coefficient at 65 W/km/K. Table 2.4 shows the simulation results with Dynamic Network Analysis (DNA). As for ULTDH configurations, different factors including refrigerants, water tank position and preheat temperature affects the total efficiency marginally. Giving that a generic principle, an average efficiency 89% is adapted, namely total 11% heat loss in ULTDH distribution networks, which is 21.4% less than LTDH, 42.1% less than DH. The value is consistent with Sweco's demonstration results as well. So heat loss values for DH, LTDH, ULTDH are set at 19%, 14%, 11% respectively. The heat loss on transmission networks is negligible (1% or so) compared to distribution loss, so the same value is set for all.

Table 2.4: Heat loss of 7 DH configurations

Heat efficiency	SH	DHW	Total	
DH 80/40	82%	81%	81%	
LTDH 60/30	86%	86%	86%	
ULTDH 45/25+ electric heating	89%	89%	89%	Average: 89%
45/25+R134+ secondary tank	90%	89%	92%	
45/25+R744+ secondary tank	90%	89%	88%	
45/25, R134a+ secondary tank+ preheat	90%	89%	89%	
45/25+R134a+ primary tank	90%	89%	87%	

2.2.2 Cogeneration electricity efficiency

The steam process in a CHP could be classified into three generic types:

- Condensation: all stream flows through the steam turbine into a condenser, then cooled by water at ambient temperature. Only electricity is produced.
- Back-pressure: The difference from condensation is that the steam the condenser is utilized to heat the return stream from DH grid or an industrial heating network. Thus both electricity and heat are produced with an nearly constant ratio. In addition, sometimes the steam could bypass the turbine to produce heat only to serve peak demand. Back-pressure CHP units are widespread used in Eastern Denmark, the Nordpool DK2 area.[OME16]
- Extraction: The difference from condensation is that stream could be extracted from the turbine to produce heat, which means a flexible electricity-heat ratio could be achieved.

[OME16] simulated the typical CHP-plant technologies' performance with the changed DH temperatures in EES. At the beginning, a linear relationship is introduced between $T_{DH,F} = 40-110$ and $T_{DH,R} = 20-55$ and those two variables here represents the temperature at the utility plant side. The results indicates that the lower temperature contribute a significant increase to electricity efficiency of both Extraction and Back-pressure unit (Figure 2.1), mostly due to the forward temperature decrease according to [OME14]. However, the impact for the total energy utilization is minor, which means the heat efficiency will decrease correspondingly due to energy balance principle. In 2017, average day-ahead electricity price in DK2 area is 32 EUR/MWh[Poo], which is relatively low due to large renewable energy share. Therefore, it's not absolutely economic to have more electricity production.

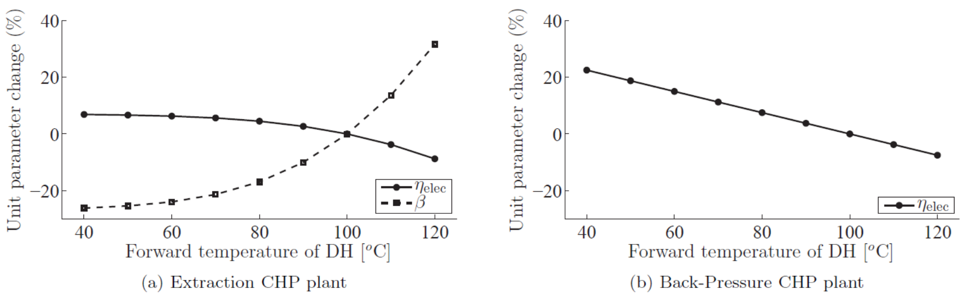


Figure 2.1: CHP Performance versus DH temperature [OME16]

The default value for $r_{heat,chp}$ and $r_{elec,chp}$ are set as Table 2.5 according to results of the plant operating at 100% load with full heat production, i.e. back pressure in [OME16].

Table 2.5: DH temperature coefficient for CHP electricity and heat efficiency

	DH 80/40	LTDH 60/30	ULTDH 45/25
η_{elec}	31.8%	34.0%	36.3%
η_{heat}	60.2%	58.0%	55.7%
$r_{heat,chp}$	1.00	1.07	1.14
$r_{elec,chp}$	1.00	0.96	0.92

2.2.3 Heat pump COP

Figure 2.2 demonstrates a typical single stage heat pump system used in DH to heat DH stream from return temperature to forward temperature. As the reservoir heat capacity is finite, the temperature of inlet and outlet stream has a significant influence on HP performance.[OME14]

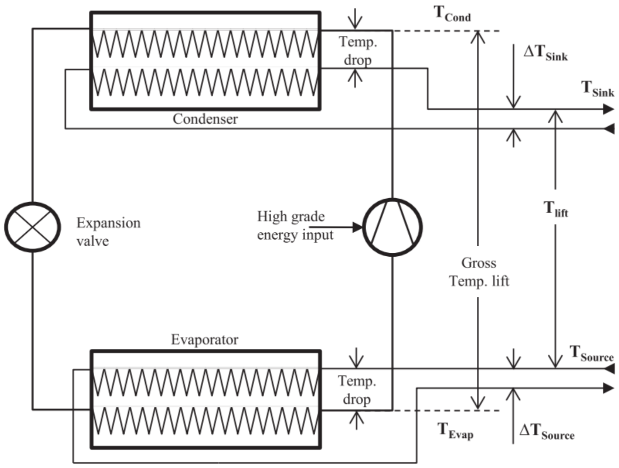


Figure 2.2: Diagram of heat pump for DH [OME14]

Furthermore, [OME16] analyzed this HP configuration under different DH temperature and the boundary conditions are set as Table 2.6. It sees a remarkably increase in COP with the decrease of DH temperature(Table 2.7). Accordingly, the parameter $r_{heat,hp}$ is suggested to differ the COP.

Table 2.6: Operation parameters for heat pump

	Value	Unit	Designation
Type	R134a		Working fluid
Efficiency	0.8		Compressor isentropic efficiency
	0.95		Electric motor efficiency
Temperature	20	°C	Temperature of heat source
	10	K	Temperature variation of heat source
	5	K	Evaporator superheat
	5	K	Minimum pinch point in heat exchangers

Table 2.7: DH temperature coefficient for heat pump COP [OME16]

	DH 80/40	LTDH 60/30	ULTDH 45/25
COP	3.70	4.66	5.92
$r_{heat,hp}$	1.00	1.26	1.60

2.2.4 Flue gas condensation

The flue gas condensation system is installed to recover part pf the latent heat of water vapours in the flue gas leaving the boiler. This system is very important to increase the efficiency of heating plants, especially when high moisture fuel is used, e.g. waste-to-energy facilities, biomass fired facilities. Figure 2.3 denotes a common FGC system, where the heat is first recovered by direct heat exchange with DH water and then by the assistance of heat pumps. In some case, a combustion air humidification is used to add water moisture to the combustion air thereby increase the heat output in FGC. Basically, The lower the DH return temperature, the more heat recovery happens in the first stage.

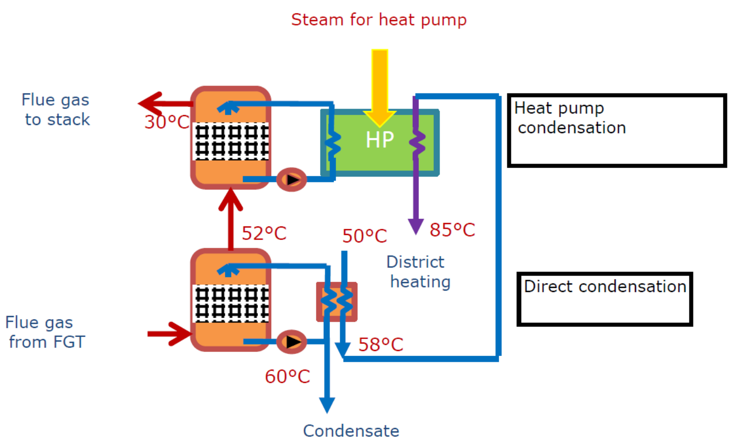


Figure 2.3: Diagram of a flue gas condensation system with $T_R = 50°C$ [Agef]

In [Agef], a total efficiency based on high heating value is introduced to describe a given plant' performance with FGC. It's found that the HHV-based total efficiency is nearly the same despite of the fuel type at a certain DH return temperature (Figure 2.4).

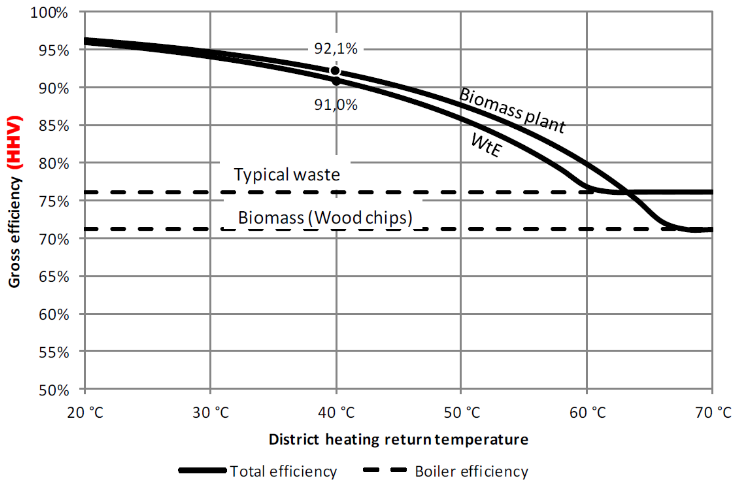


Figure 2.4: HHV-based total efficiency for Waste-to-energy (WtE) and biomass plants versus DH return temperature (Dashed line represents the efficiency of a specific fuel boiler without FGC [Agef]

Here only direct condensation by DH water is considered. Furthermore, the results could be used to calculate the LHV-based efficiency for specific fuel, which is commonly used in Europe. Because potential heat from condensation is excluded in LHV, the total efficiency could be larger than 100%. During 2014 to 2015, the wood-chip used in existing DH boiler in Denmark has an average moisture content at 40%. Selected fuel's LHV-based total efficiency are calculated and listed in Table 2.8. The increased efficiency is mainly originated from the increase in heat efficiency, thereby r_{heat} value is corrected to concerned biomass/waste based CHP/Boiler. The influence of FGC on low moisture fuel based configuration such as natural is relatively marginal ([Sal08]) thus it's neglected in this project.

Table 2.8: LHV-based total efficiency versus DH returen temperature for specific fuel configuration

Fuel	LHV	HHV	DH-40°C	LTDH-30°C	ULTDH-25°C
WtE configuration HHV efficiency			91.0%	94.1%	95.0%
Mixed waste 10.6 GJ/t (31% moisture)	10.6	12.2	104.7%	108.3%	109.3%
Biomass configuration HHV efficiency			92.1%	94.7%	95.7%
Wood chips (40% moisture)	10.3	12.0	107.3%	110.3%	111.5%
Wood pellets (5% moisture)	17.7	19.0	98.9%	101.7%	102.7%
Straw (11% moisture)	15.0	16.4	100.7%	103.5%	104.6%

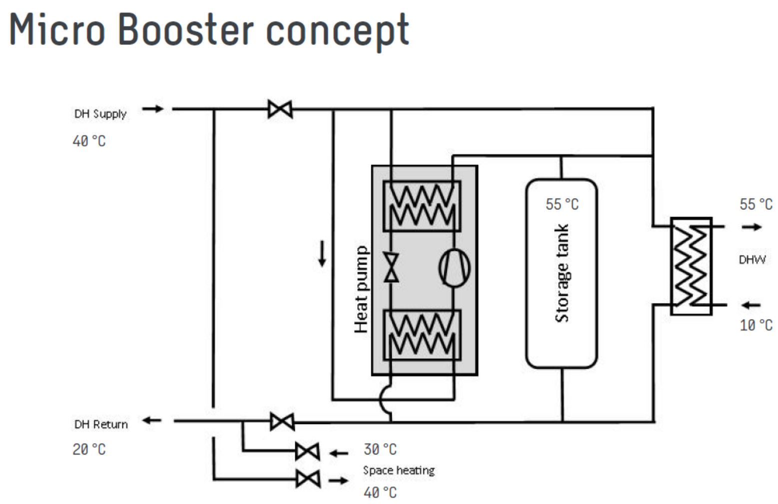
In summary, Table 2.9 gives an overview on DH temperature coefficient for efficiency of all concerned DH production technologies in this project, which is embedded as default value in the model, i.e. ”Central parameters” sheet. In the valuation model, both r_{heat} and r_{elec} are assigned to each heating technology, even though some technologies do not produce electricity in which case the value of r_{elec} should be ”1” for all temperature scenarios.

Table 2.9: Overview on embedded DH temperature coefficient for efficiency

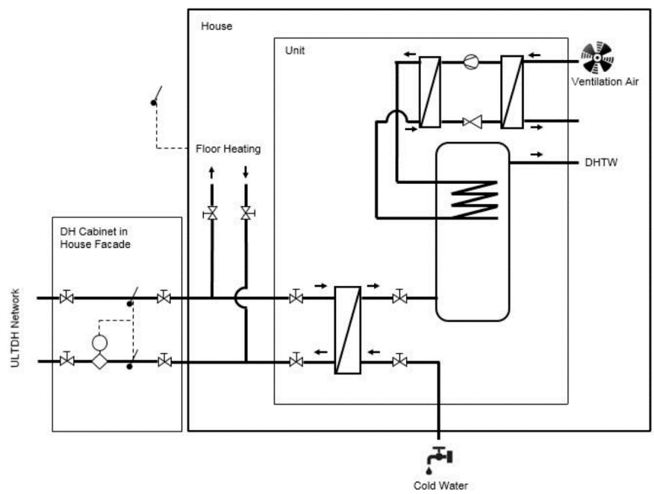
Technology	r_{heat}			r_{elec}		
	DH 80/40	LTDH 60/30	ULTDH 45/25	DH 80/40	LTDH 60/30	ULTDH 45/25
Solar	1.00	1.00	1.00	1.00	1.00	1.00
Med. CHP - wood chips	1.00	1.00	0.97	1.00	1.07	1.14
Med. CHP - straw	1.00	1.00	0.98	1.00	1.07	1.14
Med. CHP - natural gas SC	1.00	0.96	0.92	1.00	1.07	1.14
Med. CHP - waste	1.00	1.00	0.98	1.00	1.07	1.14
Wood chips boiler	1.00	1.03	1.04	1.00	1.00	1.00
Wood pellet boiler	1.00	1.03	1.04	1.00	1.00	1.00
Straw boiler	1.00	1.03	1.04	1.00	1.00	1.00
Med. boiler - waste	1.00	1.03	1.04	1.00	1.00	1.00
Oil boiler	1.00	1.00	1.00	1.00	1.00	1.00
Gas boiler	1.00	1.00	1.00	1.00	1.00	1.00
Coal boiler	1.00	1.00	1.00	1.00	1.00	1.00
Electric boilers	1.00	1.00	1.00	1.00	1.00	1.00
Heat Pump	1.00	1.26	1.60	1.00	1.00	1.00

2.2.5 Additional DHW preparation costs for ULTDH

Based on Sweco’s demonstration experience in last seven years, three DHW preparation concepts with heat pump for ULTDH are considered in this projects, namely Ventilation heat pump only (VHPO), Micro booster with primary side tank (MBPT), Micro booster with secondary side tank (MBST). Figure 2.5a shows that MBPT is comprised of water to water heat pump, storage tank and pump, with expensive investments costs around 30,000 DKK that’s twice of conventional domestic substation. A demonstration project in Deding by Sweco used MBPT to renovate 25 family houses into ULTDH from May, 2015. The operation results verified the annual heat loss reduced by 40% than before, varying between a minimal 9% reduction in April to a maximal 63% reduction in November. VHPO is to use existing ventilation heat pump (around 25,000 DKK) in the new-built house to heat DCW to required temperature directly. This solution will cause relatively high electricity consumption and enormous demand reduction for DH. Additionally domestic substation for SH is still needed in this case, at about 15,000 DKK. MBST is a combination of ventilation unit and DH networks, where DCW is preheated by DH first then transfers heat with heat pump condenser. The total costs is app. 40,000 DKK, which is almost the same with VHPO. Because ventilation unit is a necessary facility in low-energy building and DHW preparation only spares little heat capacity (less than 0.5 kw), its investment and fix O&M costs are excluded when doing economic cost calculations for concepts MBST and VHPO to keep consistent scope with others.



(a) Microbooster with primary side tank



(b) Microbooster with secondary side tank

Figure 2.5: DHW preparation concepts with heat pump [Ive17]

Besides heat pump solutions, 6 concepts in total are included in this project, together with three electric heater concepts illustrated in Figure 1.5, named as Electric heater with primary side tank (EHPT), Electric heater within secondary side tank (EHST), Electric heater only unit (EHOU) separately. Table 2.10 displays the technology and cost specifications with conventional domestic substation data in comparison listed at the end. Technical life time is assumed as 20 years for all concepts. Investments cost and O&M cost are Sweco's empirical value including domestic substation costs for SH as well, since those concepts are very new thus no historical operation data is available. [Zvi+12] simulates 6 concepts through a numerical model implemented in Engineering Equation Solver (EES) to obtain the heat pump COP and DH consumption for DHW in each concept, thus related results are listed in Column "Heat Efficiency" and "Share from DHW demand". Meanwhile, corresponding fuel costs, i.e. electricity consumption could be calculated under specific project setting.

Table 2.10: Technology and cost specifications of six DHW preparation concepts for ULTDH

Technology	Share from DHW demand	Investment EUR/unit	Fixed O&M EUR/unit/year	Var. O&M EUR/MWh	Heat efficiency	Life-time year
Electric heater, primary tank	37.50%	3200	174	0	100%	20
Electric heater, secondary tank	43.75%	3000	174	0	100%	20
Electric heater, only	100.00%	2800	174	0	100%	20
Heat pump, primary tank	7.81%	3800	278	0	530%	20
Heat pump, secondary tank	38.89%	2000	200	0	500%	20
Heat pump, only	100.00%	2000	200	0	330%	20
Domestic substation for DH and LTDH	-	2000	150	0	-	25

2.2.6 Extra network costs due to lower temperature difference

Lower temperature difference means lower heat transfer per meter thus larger service pipes or pumping pressure are needed to meet the heat demand. This disadvantages of lower DH temperature are reflected on DH networks investment costs, specifically service line costs per unit and single line cost per meter (Table 2.11). For other specific costs (per MW) such as heat exchanger, pumping station and O&M costs, it's assumed identical across DH temperature [Ageg]. Here single line represents the main distribution grids, service line is to connect end-consumers (houses) with the main distribution networks, which has a average length of 15 meters.

Table 2.11: Distribution network pipe investment costs

Distribution network pipe investment costs New developed residential area	DH	LTDH	ULTDH
Technical life time (years)	40	40	40
service line, 0 - 20 kW (EUR/unit)	2925	3200	3200
service line, 20 - 50 kW (EUR/unit)	3375	3375	3375
service line, 50-100 kW (EUR/unit)	3775	3850	3850
single line, 0-50 kW (EUR/m)	180	180	180
single line, 50-250 kW (EUR/m)	234.5	234.5	234.5
single line, 100-250 kW (EUR/m)	250	250	250
single line, 250 kW - 1 MW (EUR/m)	320	370	370
single line, 1 MW - 5 MW (EUR/m)	455	540	540
single line, 5 MW - 25 MW (EUR/m)	900	955	955

2.3 Valuation model illustration

2.3.1 Overview of the valuation model

The spreadsheet model built in this project is aimed to perform an comparable assessment of the district heating project across three temperature scenarios, e.g. DH, LTDH, ULTDH. Specifically, economic, energy and environmental evaluations are conducted to indicate the advantages and disadvantages across different scenarios. Moreover, the model could be utilized to determine strategy to affect preference for all the stakeholders, e.g. DH company, customers and local community by adjusting subsidy and price parameters.

This flow chat (Figure 2.6) demonstrates the model layout and interaction between the sheets, where the arrows indicate the calculation procedure. In total, there are 16 sheets with no hidden data and VBA code, including 1 introduction, 1 input, 1 Central parameters sheet, 2 output ,3 data sheets, 8 calculation sheets. Different colors are used to classify the sheets:

- Green: important user interface sheets, input & output
- Yellow: crucial parameters to distinguish the performance versus temperature, including heat loss percentage and DH temperature coefficient.
- Blue: 3 data sheets, basis for evaluation, i.e. Heating technology sheet (DH & Additional DHW heating), Heat transport sheet (Transmission & Distribution & Domestic substation), Price & Emission sheet (Fuel price, Emission factors, Emission prices, Emission taxes, Price adjustment).

- Pink: calculation sheets, the intent from light to dark implies the processes, which are production & technology evaluation, then project evaluation, finally comparative evaluation.

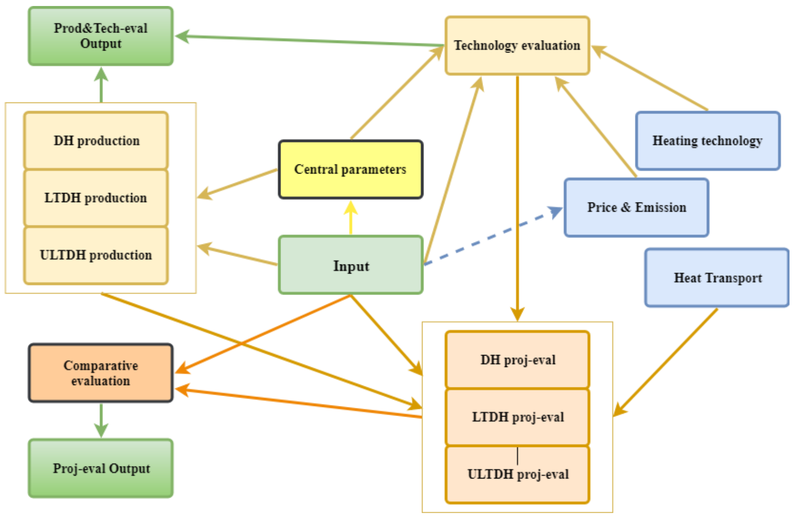


Figure 2.6: Diagram of evaluation model

The basic DH system evaluation method is referred from District Heating Assessment Tool (DHAT) from Danish Energy Agency developed by Rambøll Energy [Agea], including LCOE calculation, feasibility study and socio-economic analysis. In addition to central parameters mentioned in last section, other embedded technical data and cost estimates are based on prerequisites from the Danish Energy Agency to the extent possible for 2020 Scenario, specifically Technology Data for Energy Plants[Agef] and Energy Transport [Ageg] and data in Levelized Cost of Energy Calculator[Aged]. When insufficient, some official databases such as Energinet, International Energy Agency, and empirical data from Sweco are used as supplement. As a whole, the model is designed to be a generic comparative evaluation tool with the consideration of user-friendly principle. The user is free to modify the embedded data according to specific context and project.

2.3.2 Specification of the valuation procedures

First of all, in input sheet, some parameters need to be inserted to define a specific project, e.g. house amount, annual SH/DHW demand, DH production technologies & plants heat capacity, DHW preparation technology for ULTDH & percentage of total installations, distribution line length. In addition, other economic variables should be specified such as discount rate, loan interest rate, heat price, fuel taxation & subsidy level, VAT as well as Net tax factor, calculation rate, distortion loss, net price index used for socio-economic assessments. Because the DH pricing model varies from place to place, only variable costs (EUR/MWh) are considered here to be the total revenue for DH company. Table 2.12 shows the constant variable used in this project.

Table 2.12: Overview of input parameters (set at constant)

Input for project evaluation	
Expected development of heat demand per year	0.00%
Fixed O&M costs of the DH network (pct of of assets)	0.75%
Beginnning year of calculations	2020
Evaluation time periods	20
Input for Economic Calculations (LCOE)	
Discount rate	4.0%
full load hours	5000
Input for Socio Economic Calculations	
Net tax factor	1.17
Calculation rate	4.0%
Distortion loss	20.0%
Input for financial projection	
Long-term loan	4.0%
Short-term loan (debt)	7.0%
Short-term loan (profit)	4.0%
Input for taxation	
VAT	25.0%
Net price index	0.7%
Danish fuel taxation for emission (2017 level)	Euro/MWh
Natural gas	32.45
Coal	34.61
Fueloil	9.25
Oil	47.59
Straw	1.12
Wood chips	0.24
Wood pellets	1.47
Energy crops	0.00
Local biomass	0.00
Electricity	109.33
Municipal waste	95.40
Solar	0.00

According to the input parameters, the model will perform the evaluation automatically, mainly divided into 5 main procedures.

1. Technology evaluation

   Based on inlaid Heating technology data, Price&Emission, Central parameters, a maximal 20 district heating technologies and 10 additional DHW heating technologies could be evaluated to compare. The influence of lower temperature are quantified by assigning corresponding DH temperature coefficient for efficiency into each scenario, which finally inflect on the final LOCE costs (per MWh heat). Following is the main formula to calculate total LOCE with externalities.

   - Levelized cost of heat production = Capital Cost + Fix O&M + Variable O&M + Fuel costs + Emission costs - Electricity revenue

   For district heating technologies, LCOE is calculated under 5000 full load hours per year (Base load scenario). However, for additional heating unit, the heat production per year is based on real project demand. These assumptions will only influence investment and fix O&M cost levelization in technology evaluation to indicate the specific technology performance, but not on proceeding project evaluation. Meanwhile, the investment cost is regarded as a long-term loan for life time period, thereby to calculate capital cost. 6 kinds of emissions are covered, i.e. CO_2, CH_4, N_2O, SO_2, NO_x, $PM2.5$. The first three contributes to climate change, and the rest are treated as air pollutant. The influence of emissions is measured with projected socio-economic costs. However, the emission tax for each fuel is the real cost paid by heat producer. In addition to LCOE, other economic indicators are obtained as well:

   - Marginal cost (without externalities) = Variable O&M + Fuel costs − Electricity revenue
   - Private marginal cost = Variable O&M + Fuel costs + Emission tax − Electricity revenue

     Private marginal cost is the parameter used to calculate production costs in project evaluation.

2. Production calculation

   From projected heating technologies and heat demand, a simple excel simulation is performed on a hourly basis considering fluctuating SH demand and average DHW demand for one year. The production priority of the DH technology follows the order decided by the users, from Solar, base, then intermediate to peak. Thereby, users need to define heat capacity for each technology in the input sheet. If solar heating is concerned in the project, the parameters for auxiliary pit storage unit is needed to define first, then with inlaid hourly maximal solar production percentage under Danish solar radiation, corresponding operation status is determined, i.e. storage level, curtailed heat, heat supply to DH.

For DH and LTDH scenarios, total heat demand including SH and DHW is supplied by district heating facilities. The SH demand for ULTDH is met by district heating as well. However, a certain percentage of DHW heat demand in ULTDH is met by additional heating technology on consumer side. The production simulation of additional heating is based on the percentage of total installations for each technology inputted by users, since usually there should only be one heating facility in a single family house. By defining full load hours, a minimal heat capacity requirement for each technology could be suggested in project evaluation based on peak heat demand. In brief, the production calculation is performed in three separated sheets for specific DH temperature scenario.

3. Project evaluation

   Similarly, the project evaluation is performed in three separated sheets for a 20 years' time period, focusing on economic costs as well as parts of social-economic evaluation under Danish standards. Figure 2.7 demonstrates the detailed evaluation methods. The evaluation considers a stable heat demand development rate over the time period. Based on initial production simulation outcomes, the technology mix for district heating exclude solar is assumed at constant to calculate the heat production each year. Since there is no variable cost for solar and solar production is hard to control as well, so all the solar heat production will be consumed at priority.

   Different from DHAT, this model integrates a overall assessment of DH network without the requirement of a detailed DH network analysis. Generally the networks costs are divided into investment costs of service line, single line, heat exchanger and pumping station as well as O&M costs. Users only need to choose main distribution networks scale and insert value for main distribution line to calculate single line costs. House amount denotes the number of units for service line while peak heat demand is used to determine the capacity of heat exchanger and pumping station. All the data is referred from Technology Data for Energy Transport by Danish Energy Agency [Ageg]

   A direct DH substation is assumed to install in each family house and the costs are allocated to consumers themselves. Unlike DH&LTDH, the domestic substation costs are included in the additional DHW heating preparation costs for ULTDH. In addition, consumers need to pay the fuel costs (electricity) for heating as well. Usually no taxation is applied on the additional heat production. In reverse, emission tax is added to DH production.

   In this part, the residual value at the end of valuation period is subtracted from the investment cost. VAT (The Value Added Tax) is also added on the total costs of each item, which is 25% in Denmark. Furthermore, future cash

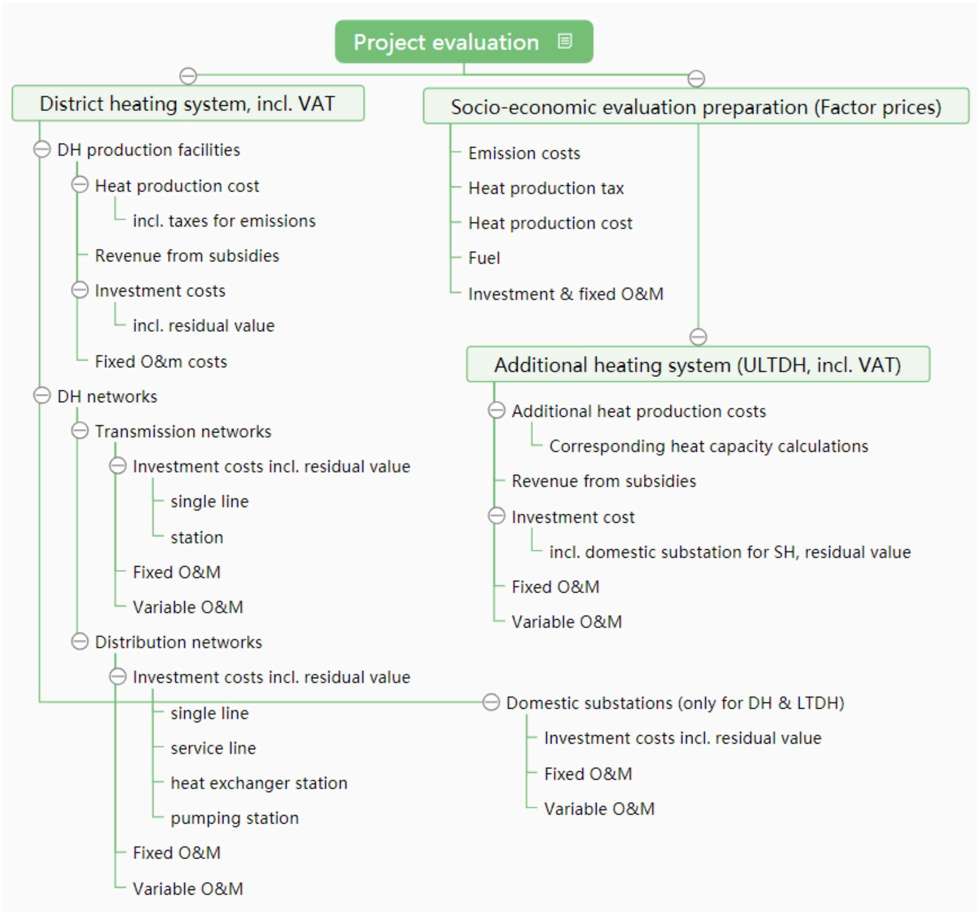


Figure 2.7: Diagram of project evaluation methods

flows are discounted at the discount rate, 4% recommended for energy project in Denmark, which means the total costs are summed by the present value (beginning year) for each years' costs.

At the end, a basis for socio-economic evaluation is conducted, the results of which are used in later comparative evaluation procedure. What's more, fuel consumption is calculated for subsequent energy evaluation.

4. Comparative evaluation

   This specific sheet comprises four parts: Cost evaluation (w/o externalities), Emission Evaluation and Social Economic Evaluation and Energy Evaluation.

DH (Conventional district heating) scenario is taken as the reference case. The main results are relative value of LTDH and ULTDH to DH, e.g.

- NPV and IRR for costs of local community, DH company and consumers
- NPV for socio-economic
- Climate externalities and air pollution influence

Moreover, crucial energy indicators are calculate by following formulas:

- System heat efficiency = Total heat demand on consumer side ÷ Total fuel consumption

  Where the solar heat efficiency is assumed as 1 and all the values are based on results for the beginning year only.
- Utilization factor = Actual DH heat production ÷ Maximum possible DH heat production

  The maximum possible heat production is regarded as the full capacity production for 8760 hours per year. This factor covers all DH production units' over the time period except solar. To some degree, a lower utilization factor reflects the waste of plants' heat capacity so that a higher unitized investment costs and fixed O&M per MWh heat are obtained. In another word, if the heating price keeps constant, DH company will have a lower profit rate given a higher total production cost per MWh heat.
- Solar curtailment Ratio = Curtailed solar production ÷ Total solar production

  This ratio is used to suggest the potential to optimize the solar utilization by adjusting heat storage parameters.

5. Output- results visualization

   The critical evaluation results are classified into production & technology evaluation output based on first two procedures and project evaluation output from procedure 3&4. In the Prod&Tech-eval Output sheet, the first part is the overview of three temperature scenarios' heating projection, i.e. heating technology capacity, production and percentage of total as well as production curves and duration curves on a hourly basis for the beginning year. The second parts compare the economic indicators among different heating technologies and highlights the differences under lower DH temperature scenarios. The Proj-eval Output sheet has a similar structure with Comparative evaluation sheet, where the first part demonstrates energy indicators across DH temperature followed by visualized comparison on cost & emission indicators. In general ,the output could help the user better compare and understand the advantages and disadvantages of different DH temperature systems, also giving insights to decide pricing and subsidy strategy in "Input" sheet.

2.4 Specific case introduction

A undergoing project at Niverød Bakke in Nivå, Fredensborg Municipality by Sweco is introduced as the fundamental setting. Additionally, it is thought to demonstrate latest technology with respect to LTDH and ULTDH in this project. Therefore, the boundary parameters should be identical with real project value to the extent possible. 105 new house is planned with an avearage area of 150 m^2 Figure 2.8. All houses are built according to BR15 standard. The total heat demand is estimated as 825 MWh/year, or that is to say an average heat demand at 7.857 MWh/year/house is applied. A percentage of 45% is assumed for DHW share, corresponding to 55% for SH.

Figure 2.8: Overview of projected 105 houses. Source: Projektforslag i henhold til Varmeforsyningsloven by Sweco

This building block is projected to connect with existing DH production units. The investigation on Nivå area shows the production of district heating is a combination of Helsingør cogeneration plant (HØK) and the waste incineration plant in Hørsholm (Norfors)as well as various peak and reservoirs plants. The CHP plant in Helsingør is currently undergoing conversion from natural gas to wood chips fired. It is expected to be operational from 2019. The evaluation period is from 2020 to 2040. Therefore, the heat production technology mix in this case is assumed as follows:

- Base load: Wood chips based CHP (40%), Waste based boiler (20%), Biomass boiler (10%), Heat pump (5%)

- Peak load: Gas boiler (25%)

In summary, Table 2.13 showcases the main input parameters inserted in the valuation model. The upper part represents the setting for all scenarios. The transmission networks scale is estimated based on the total population of 7,821 in Nivå in 2014 [Sta]. The required distribution network scale is dependent on the total peak demand of 105 houses. However, transmission networks costs are excluded in this project scope, since it is connected with existing DH grids. The main distribution line is set at 1200 meters, expected to be installed in unpaved areas. Based on the Nivå district heating tariffs for 2016, the heat price consist of fixed costs (space tax and metering tax) and variable costs (flow tax and energy tax) and depreciation. The average consumption cost is suggested as 1800 DKK/MWh (240 EUR/MWh) by Sweco, disregarding initial connection fee. According to the constant DH technology mix, corresponding required heat capacity is set as the lower part shows. Besides, it's expected to apply new product - redesigned ventilation unit, i.e. MBST concept as domestic installations for all.

Table 2.13: Central input parameters for case analysis

Number of houses	105
SH demand (MWh/year/house)	4.32
DHW demand (MWh/year/house)	3.54
The need for transmission systems?	Yes
Connecting transmission networks scale (Estimate)	20 - 50 MW
Connecting main distribution networks scale (Estimate)	250 kW -1 MW
Transmission single lines length (twin pipes) (m)	-
Distribution single lines length (twin pipes) (m)	1200
Heat price (EUR/MWh)	240.00
Use Danish taxation level?	Yes
Perform production tax exemption for ULTDH additional DHW preparation ?	Yes
No subsidy payments set for all	

DH Technology	pct of total	DH	LTDH	ULTDH
Med. CHP - wood chips	40%	0.0495	0.0466	0.0372
Med. boiler - waste	20%	0.0249	0.0233	0.0195
Wood chips boiler	10%	0.0142	0.0134	0.0120
Heat Pump	5%	0.0082	0.0078	0.0069
Gas boiler	25%	0.1760	0.1658	0.1530
Additional heating technology				pct of total installations
Heat pump, secondary tank				100%

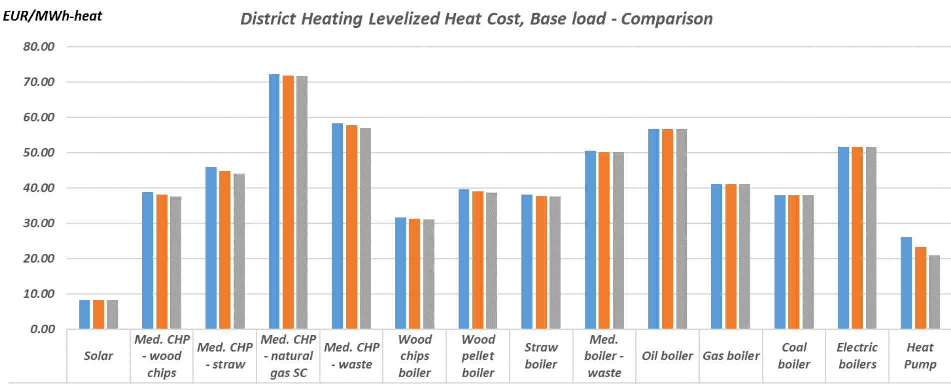
CHAPTER 3

Results & Discussion

3.1 Technology performance across 3 DH temperature scenarios

3.1.1 DH production technologies

Figure 3.1 give a comparative overview of all concerned technologies across different DH temperature. Obviously, heat pump has a significant decrease in LCOE with lower DH temperature. For biomass/waste based boiler and CHP, it sees a slightly lower levelized costs under LTDH and ULTDH. However, for fossil fuel based utility plant, no noticeable distinction is observed. In addition, Figure 3.1 is also a good reference to suggest which technologies are competitive under Danish context. Figure 3.2, Figure 3.3, Figure 3.3 demonstrate the LCOE breakdown for DH, LTDH, ULTDH respectively.



	Solar	Med. CHP - wood chips	Med. CHP - straw	Med. CHP - natural gas SC	Med. CHP - waste	Wood chips boiler	Wood pellet boiler	Straw boiler	Med. boiler - waste	Oil boiler	Gas boiler	Coal boiler	Electric boilers	Heat Pump
DH	8.26	38.74	45.79	72.12	58.33	31.61	39.59	38.07	50.43	56.57	41.13	37.89	51.63	26.13
LTDH	8.26	38.00	44.82	71.91	57.68	31.19	38.95	37.64	50.20	56.57	41.13	37.89	51.63	23.22
ULTDH	8.26	37.47	44.04	71.68	57.00	31.03	38.71	37.48	50.14	56.57	41.13	37.89	51.63	20.85

Figure 3.1: District Heating Levelized Heat Cost, Base load - Comparison

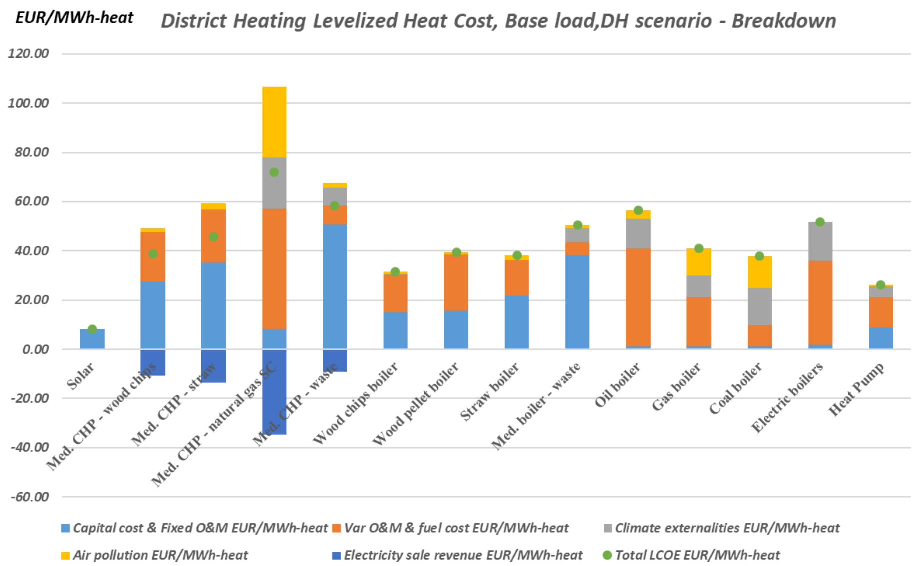


Figure 3.2: District Heating Levelized Heat Cost, Base load, DH scenario - Breakdown

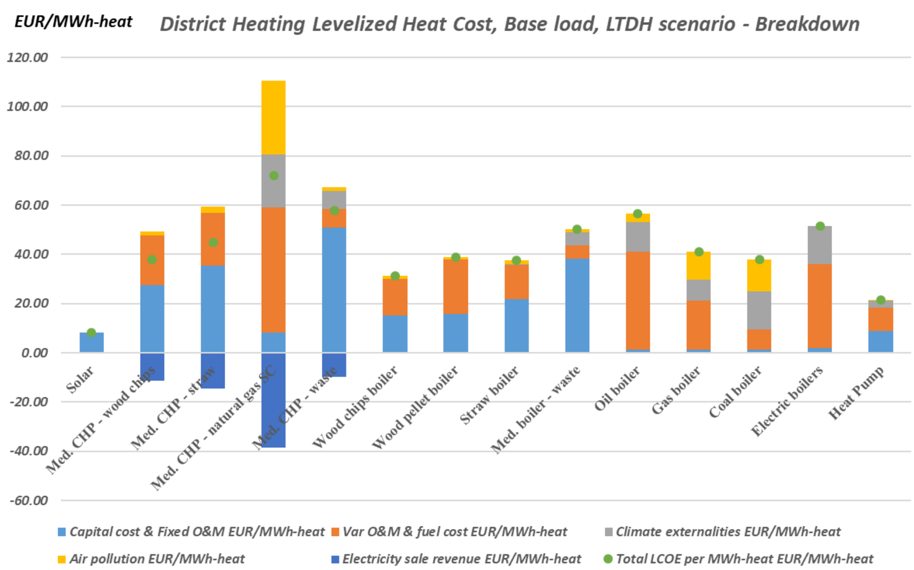


Figure 3.3: District Heating Levelized Heat Cost, Base load, LTDH scenario - Breakdown

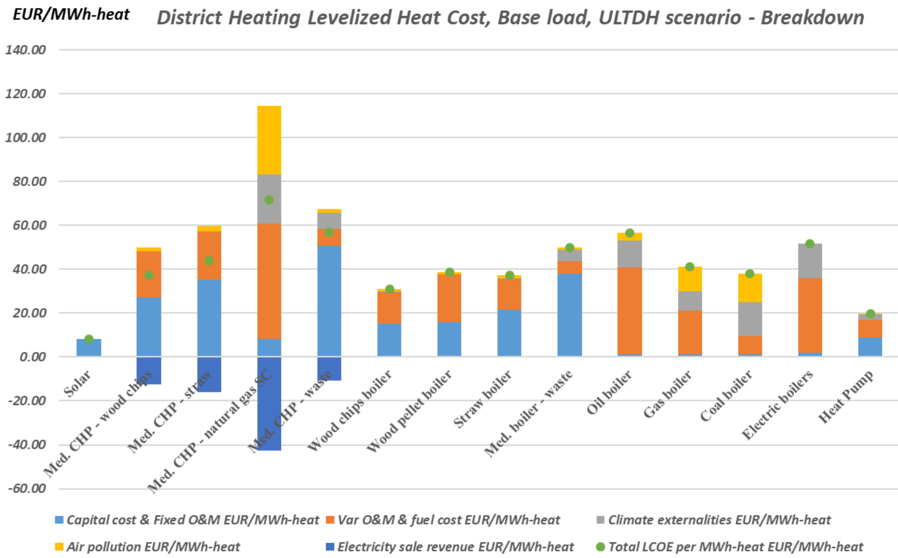


Figure 3.4: District Heating Levelized Heat Cost, Base load, ULTDH scenario - Breakdown

For better comparison, Figure 3.5 is derived to show the reduced levelized heat cost compared to DH scenario. For biomass/waste fired CHP, the increase of electricity revenue compensate the increase in variable O&M & fuel cost, thus a positive impact is obtained with lower DH temperature. This is mainly due to a remarkable increase of heat recovery in flue gas condensation system with lower DH temperature, which alleviates the negative influence on heat efficiency resulting from higher electricity efficiency. What's more, the lower the DH temperature is, the lower LCOE it has. Similarly, better performance of FGC contribute cost savings in wood-chips, wood-pellets, straw and waste boiler. However, for natural gas based CHP, FGC has lower impact on low moisture fuel, besides fossil fuels have much larger environmental negative externalities, which results in a negligible impact on total LCOE. With regard to heat pump, the saving in variable costs constitutes over half of the total saving ,along with a positive impact on the environment. It could also be concluded the heat pump unit has the best synergy with lower temperature DH among these 14 DH heating technologies.

Figure 3.6 and Figure 3.7 show the socio-economic marginal cost and private marginal cost. According to Figure 3.8, fuel taxes has a significant influence on certain technologies, especially for municipal waste, electricity and natural gas based utilities, which further enlarger the benefits (positive value) or extra costs (negative value)of lower temperature DH compared to conventional one.

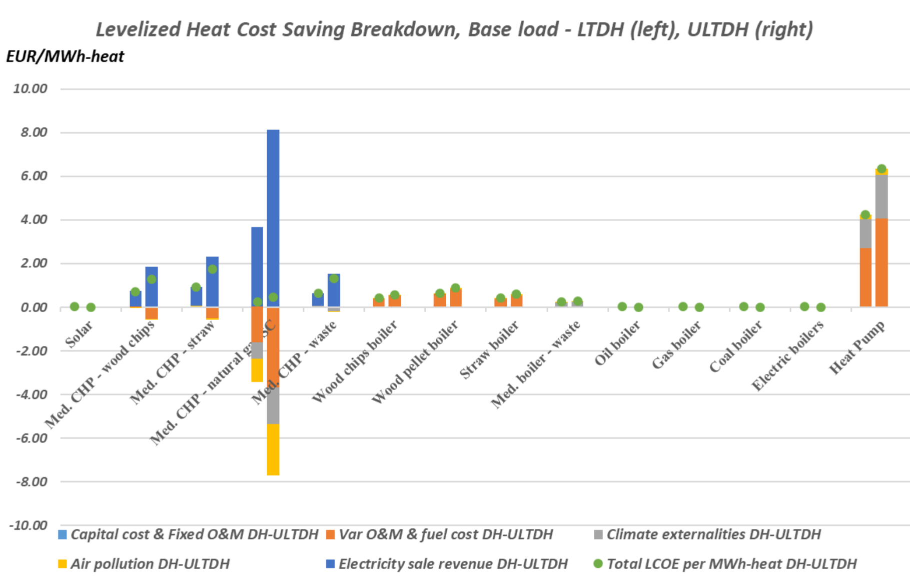


Figure 3.5: Levelized Heat Cost Saving Breakdown, Base load - LTDH (left), ULTDH (right)

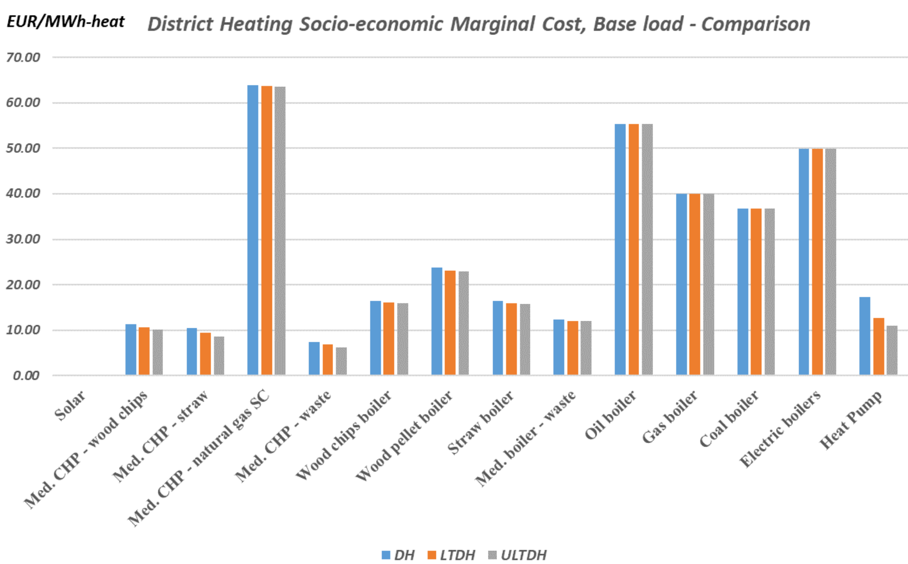


Figure 3.6: District Heating Socio-economic Marginal Cost, Base load - Comparison

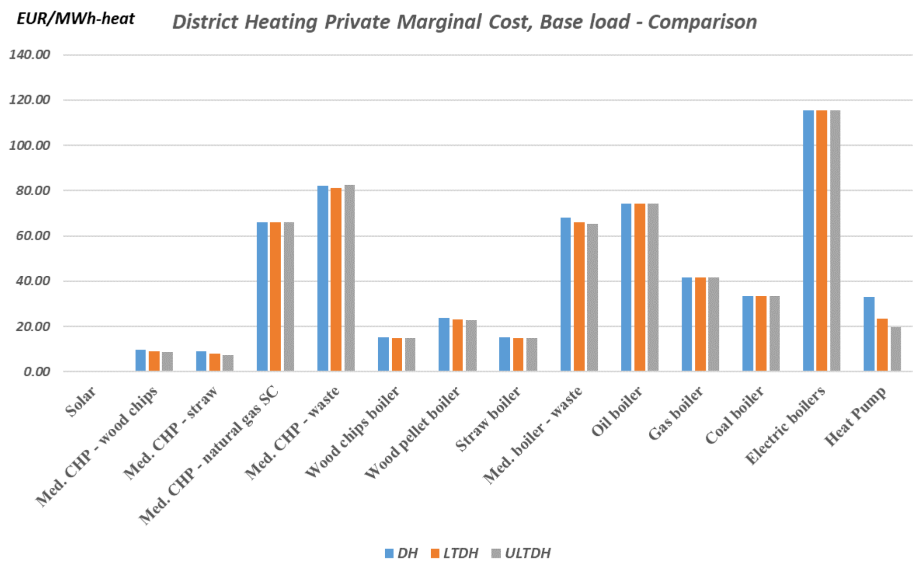


Figure 3.7: District Heating Private Marginal Cost, Base load - Comparison

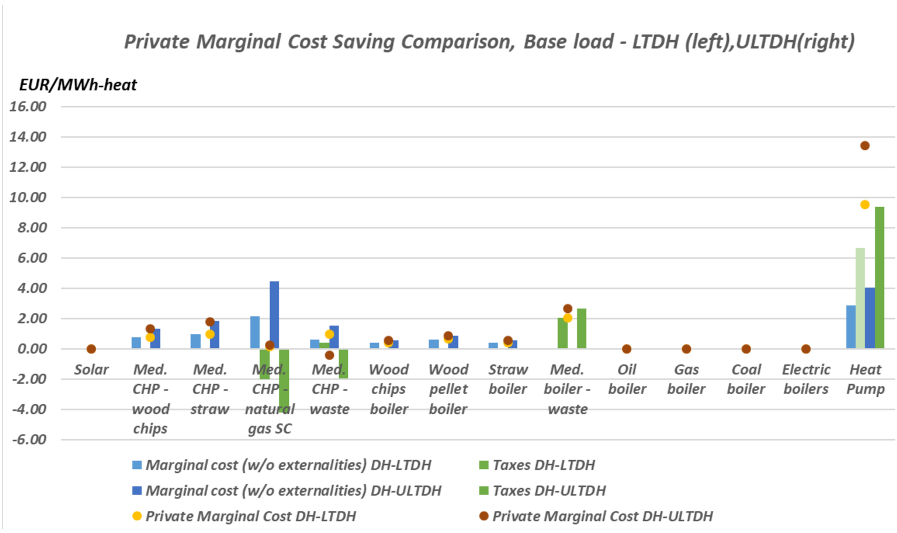


Figure 3.8: Private Marginal Cost Saving Comparison, Base load - LTDH (left), ULTDH (right)

In summary, the results in this part are conducted on base load assumption, 5000 full load hours one year. However, in actual production, the investment costs and fixed O&M costs should be levelized by real operation hours.

3.1.2 Additional DHW heating technologies

Figure 3.9 and Figure 3.10 indicate the different performance of 6 additional DHW heating concepts based on real DHW demand of a standard low-energy house. Obviously, heat pump with primary tank has the highest LCOE, nearly five times than others, mainly due to a high initial investment cost and low share from DHW (i.e. low heat production). Clearly, the marginal costs of electric heater concepts are over three times than that of any heat pump concept, which finally cause a relatively higher LCOE. So two heat pump concepts using ventilation unit shows off good advantages. Nevertheless, heat pump only concept would make DH demand increase by over 1/3 which is not beneficial for DH company. In conclusion, MBST concept (i.e. Heat pump, secondary tank) is the preferable solution for additional DHW heating in ULTDH. Considering that electricity price is expected to decrease due to more and more cost-effective renewable energy utilization, the electric heater concepts might be competitive in the future, especially EHST (i.e. Electric heater, secondary tank).

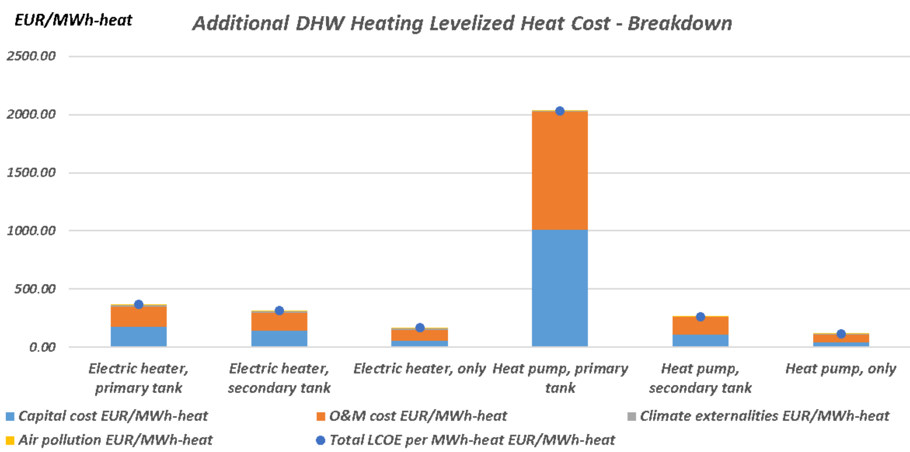


Figure 3.9: Additional DHW Heating Levelized Heat Cost - Breakdown

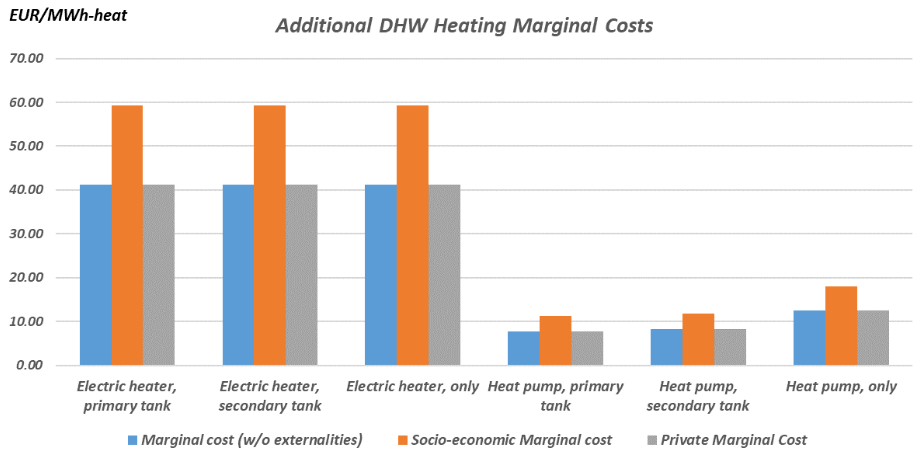


Figure 3.10: Additional DHW Heating Marginal Costs

3.2 Valuation results on the specific project in Nivå

3.2.1 District heating production & energy evaluation

Figure 3.11 and Figure 3.12 demonstrate the heat production curves and duration curves of all concerned units in the beginning year for ULTDH cenario. For DH and LTDH, it could be available in the Appendix (Figure 1,Figure 2,Figure 3,Figure 4).

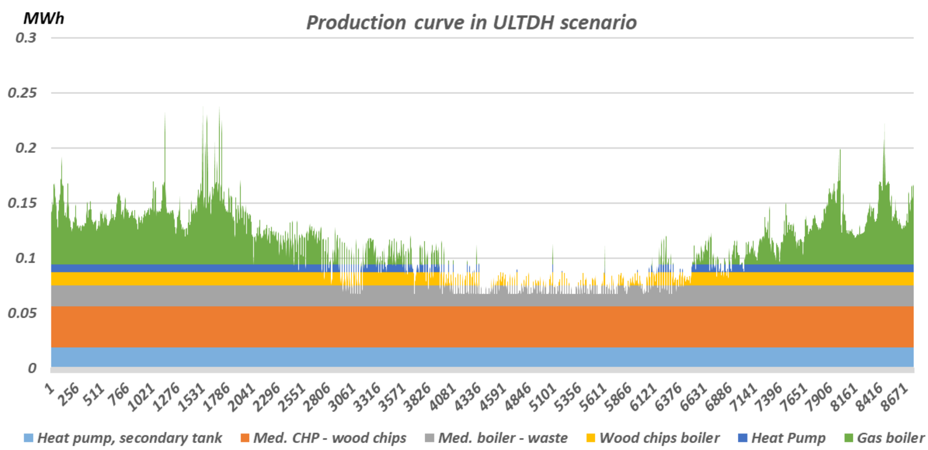


Figure 3.11: Production curve in ULTDH scenario

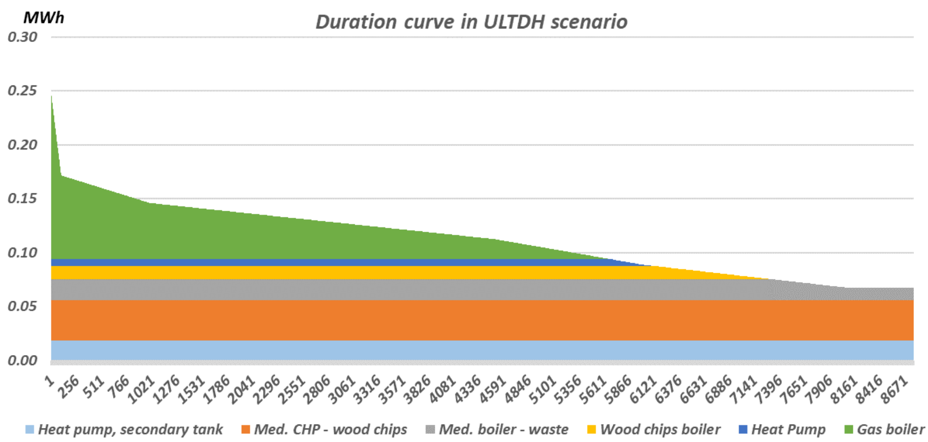


Figure 3.12: Duration curve in ULTDH scenario

As Figure 3.13 denotes, LTDH has an undisputed advantage in energy performance compared with DH. It could save 78 MWh fuel consumption (app. 7%) over one year along with the increasing heat efficiency from 74.9% to 80.6%. As for ULTDH, the total heat efficiency rises dramatically to 96.4 %. One reason is still the technology performance improvement under lower temperature, another reason is the use of heat pump on consumer side for DHW. However, the total utilization factor decrease, which means the new invested heat capacity in production units have an average lower full load hours than DH and LTDH. The major reason is that although additional DHW heating results in a reduced heat supply demand for production units in ULTDH, the peak DH demand do not decrease to the same extent due to stable DHW demand assumptions. Furthermore, the peak demand determines the needed heat capacities, in another word, extra capacities must be invested to serve peak load hours. Specifically, all units of ULTDH except Base1-Med. CHP -wood chips has a lower utilization factors than DH and LTDH as Table 3.1 shows.

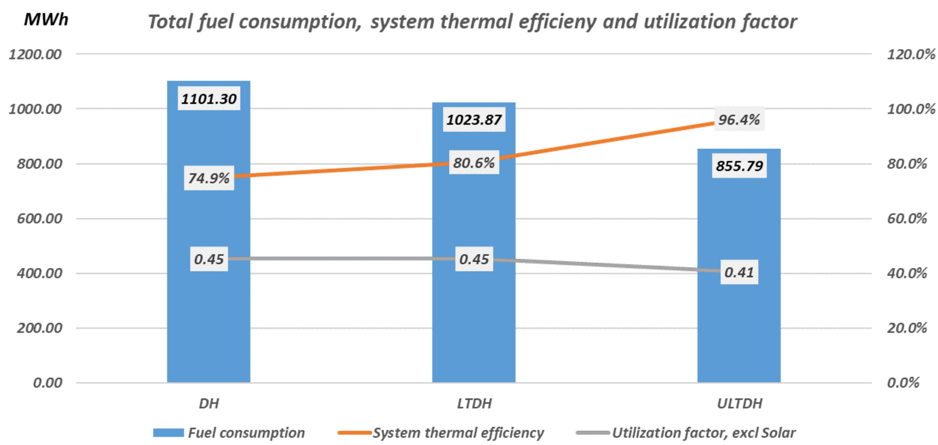


Figure 3.13: Energy evaluation results

Table 3.1: Utilization factors of all production units

Utilization factor	DH	LTDH	ULTDH
Med. CHP - wood chips	1.00	1.00	1.00
Med. boiler - waste	1.00	1.00	0.95
Wood chips boiler	0.86	0.87	0.77
Heat Pump	0.75	0.75	0.67
Gas boiler	0.18	0.18	0.15
Total	0.45	0.45	0.41

However, in the actual production units, heat accumulation is always installed to optimize production activities according to fluctuating heat demand and electricity price. Unfortunately, current excel simulation model do not consider heat storage and optimize the production according to prices since electricity price is assumed on a annual basis. Therefore, the drawbacks of more fluctuating heat demand in ULTDH could expect to be overcome in the real production.

3.2.2 Project economic evaluation

As Figure 3.14 indicates, both LTDH and ULTDH have a positive impact on local community and socio-economic compared with DH while LTDH is more beneficial. However, DH company benefits from LTDH rather than ULTDH, in reverse, DH consumers prefer ULTDH. Moreover, the benefits that consumers obtain from ULTDH is larger than the extra costs for DH company, which finally contribute a positive NPV value for local community. Compared to LTDH, the socio-economic NPV is much lower in ULTDH, only 0.005 mio.EUR, the main reason of which is the increased investment & fixed O&M costs although the fuel and emission costs are lower in this scenario. As for LTDH, DH company obtains extra 0.06 mio.EUR benefits than DH scenario while DH consumers get nothing. This special characteristic makes it feasible to allocate some profits from DH company to consumers, e.g. lower the heat price to create incentives for consumers to prefer LTDH as well. On the other hand, to increase heat price or add subsidy payments to certain production units in ULTDH could also be reasonable strategies. Taking heat price as a financial measure, when heat price increase to 270 EUR/MWh, both company and consumers will prefer ULTDH than DH while a decreased price to 238 EUR/MWh makes both choose LTDH as well, according to Table 3.2.

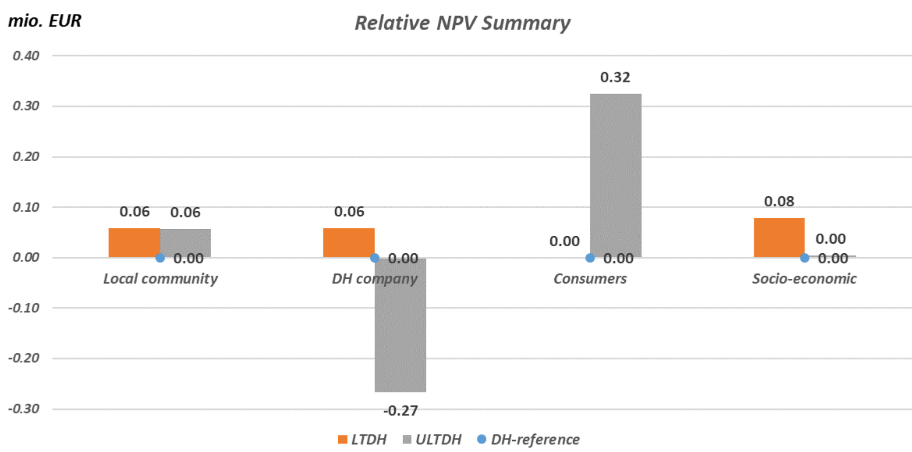


Figure 3.14: Relative NPV Summary

Table 3.2: Adjust heat price to create incentives for DH company and consumers

DH-ULTDH EUR/MWh	NPV-company mio.EUR	NPV-consumers mio.EUR	DH-LTDH EUR/MWh	NPV-company mio.EUR	NPV-consumers mio.EUR
240	-0.27	0.32	232	-0.04	0.10
250	-0.17	0.23	234	-0.01	0.07
260	-0.07	0.13	236	0.01	0.05
270	0.03	0.03	238	0.03	0.02
280	0.13	-0.07	240	0.06	0.00

Specifically, Figure 3.15, Figure 3.16, Figure 3.17 illustrate the yearly costs for local community, DH company, DH consumers separately during the evaluation period.

For DH company, the pay-pack period is 6.18, 6.05, 7.11 years respectively in DH, LTDH, ULTDH. As for ULTDH consumers, the cash flow is defined as the costs savings compared with DH, thereby the pay-back period is calculated as 1.57 years.

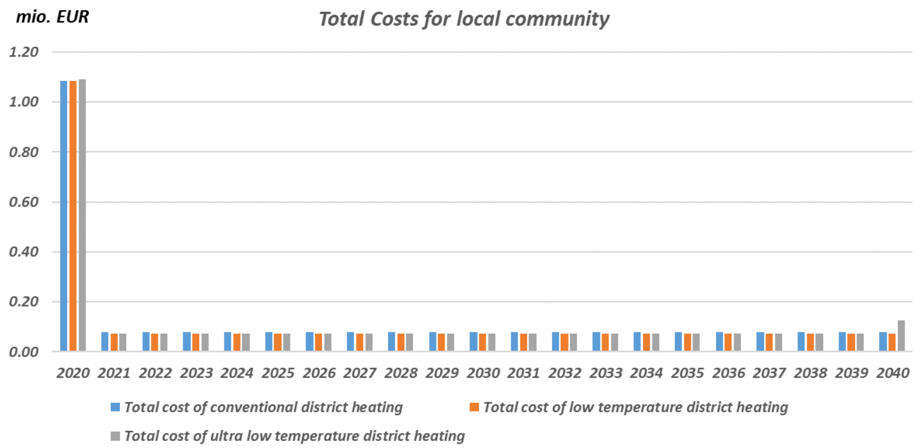


Figure 3.15: Total Costs for local community

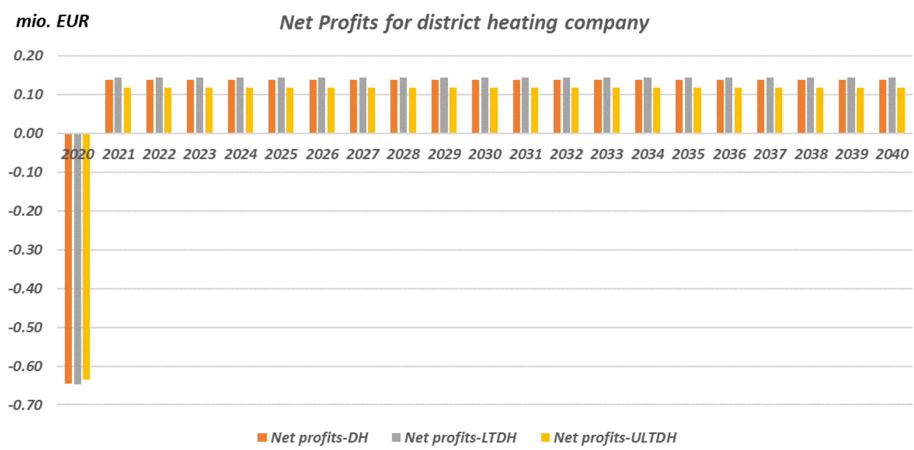


Figure 3.16: Net Profits for district heating company

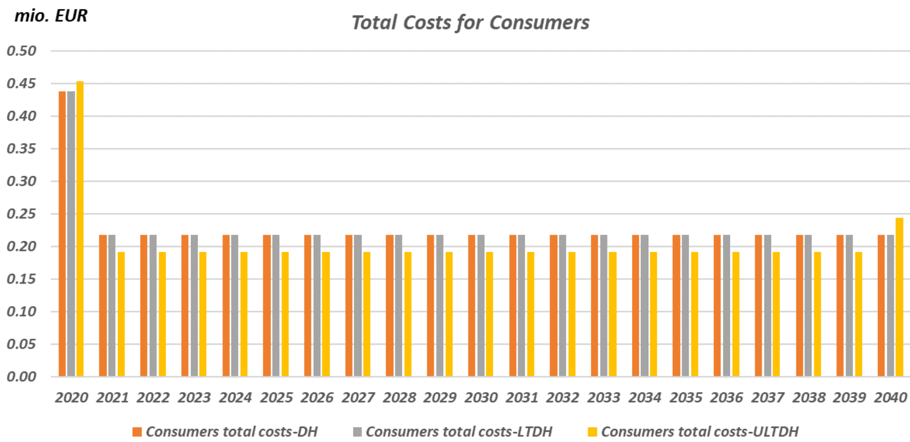


Figure 3.17: Total Costs for Consumers

What's more, Figure 3.18, Figure 3.19, Figure 3.20 demonstrate the NPV breakdown to indicate critical influential factors. LTDH has a larger DH networks costs than DH due to decreased temperature different between supply and return flow. However, both LTDH and ULTDH has a significant saving on DH production costs, which also compensate the disadvantage of lower temperature systems. With regard to DH company in ULTDH, it sees a huge decrease in heat selling revenue due to existing domestic heating units, despite that there is still noticeable savings in production, investment and fixed O&M costs as well as distribution networks costs due to decreased heat load. In the meantime, a lower utilization factor implies a higher investment and fixed O&M cost per MWh heat production. Specifically, the average cost per MWh consumer district heating consumption for DH company is 94.84, 91.49, 98.30 EUR separately.

From Figure 3.20, it could be observed that consumers receive a huge benefits from domestic heating to prepare domestic hot tap water, mainly due a very high heating price under current setting, alongwith additional extra investment and heat production costs. More discussions will be illustrated in sensitivity analysis since all the data about microbooster concepts is empirical and not verified. According to Figure 3.21, ULTDH has a obvious benefit to decrease air pollution, but due to substantial electricity consumption on consumer side, a higher climate change impact is observed.

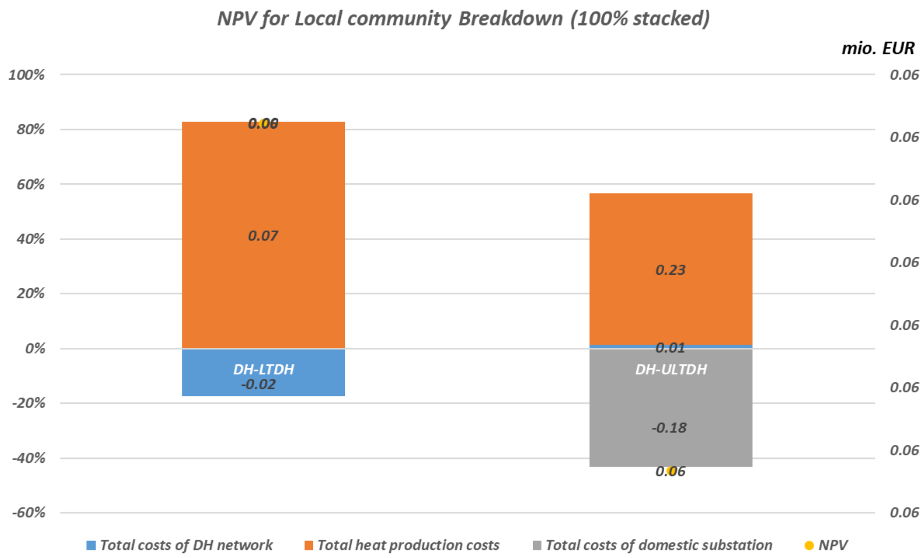


Figure 3.18: NPV for Local community Breakdown (100% stacked)

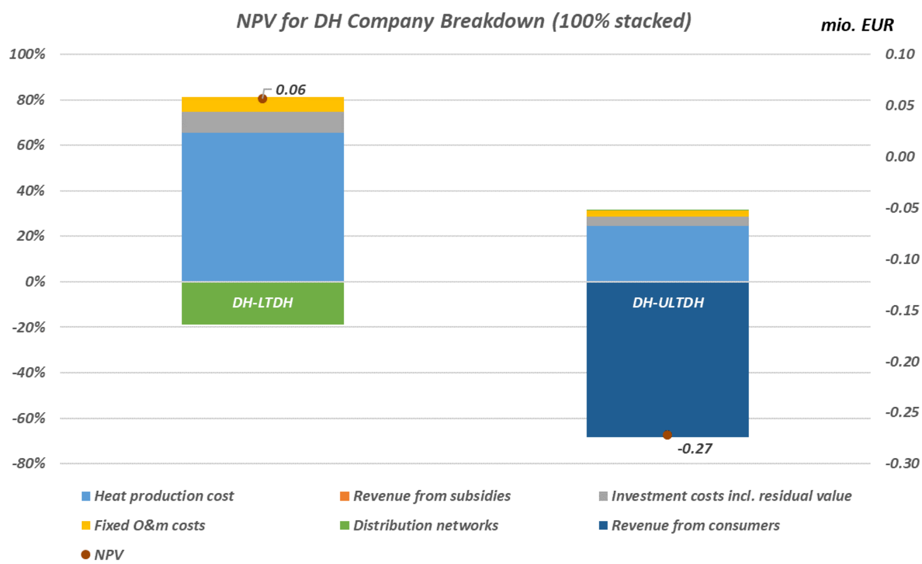


Figure 3.19: NPV for DH Company Breakdown (100% stacked)

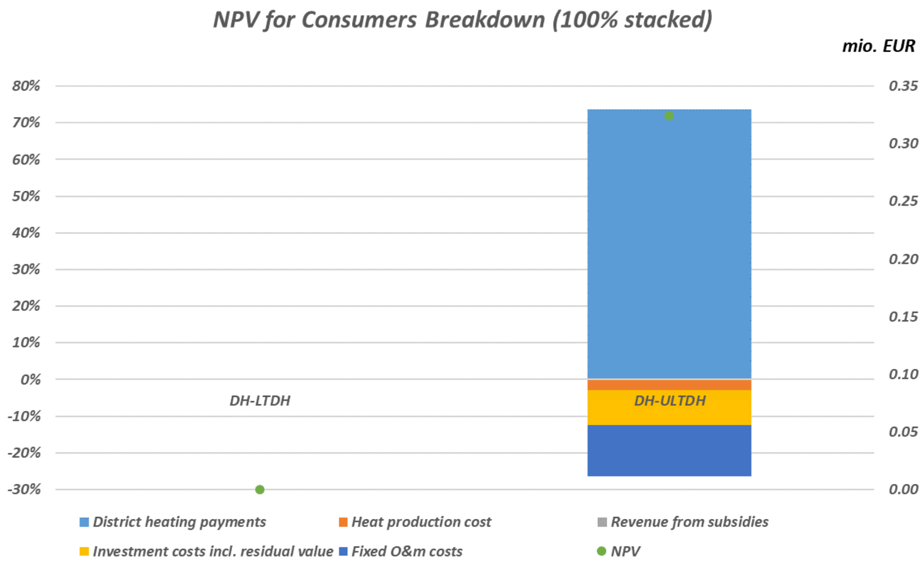


Figure 3.20: NPV for Consumers Breakdown (100% stacked)

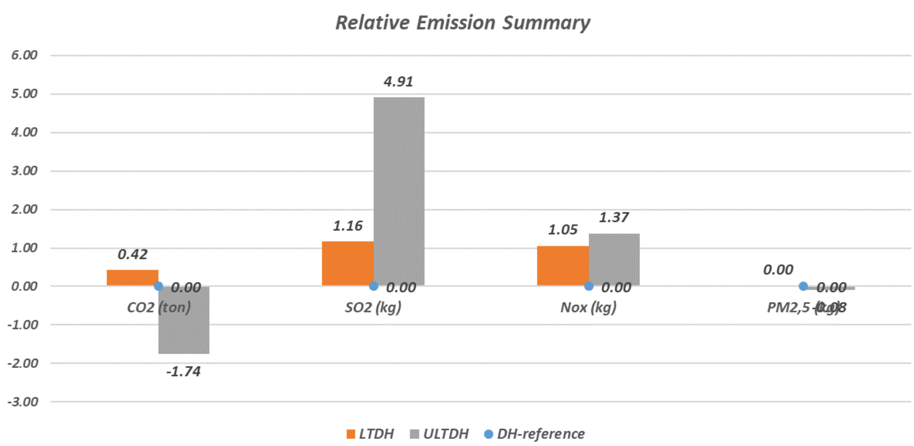


Figure 3.21: Relative Emission Summary

3.3 Sensitivity and uncertainty analysis

3.3.1 Heat price

When changing the heat price, the relative NPV value for local community and socio-economic will keep constant. By varying from 0 to 300 EUR/MWh, Figure 3.22 shows the influence on relative NPV value to company and consumers. When heat price ranges from 90 to 110 EUR/MWh, both company and consumers have incentives to choose ULTDH than DH. But DH company will operate in debt under this condition. Figure 3.22 shows the corresponding pay-back period. When heat price reaches 80 EUR/MWh, ULTDH consumers starts receiving benefits from additional domestic heating. In comparison, only when heat price is over 140 EUR/MWh (150 for ULTDH), DH company could recover the costs of initial investment in 20 years.

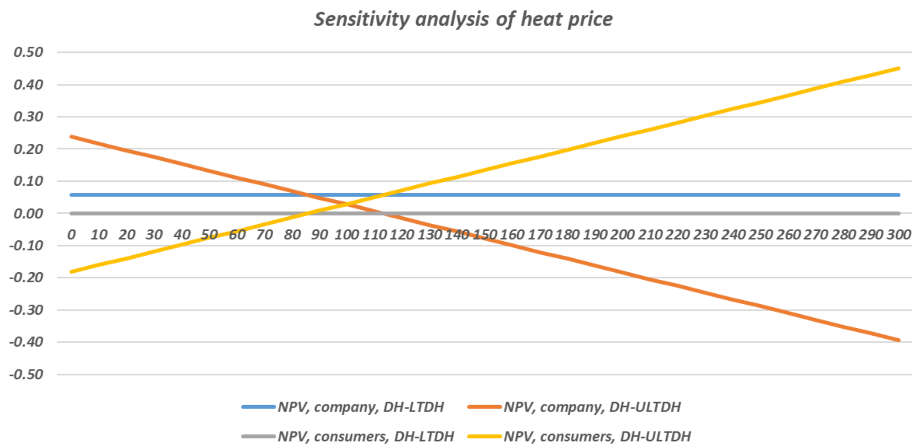


Figure 3.22: Sensitivity analysis of heat price

3.3.2 Microbooster investment and fixed O&M costs

Currently, the investment cost for heat pump concepts using ventilation unit is assumed as the same as conventional domestic substation while the O&M costs for MBST concept is set at 50 EUR higher than conventional domestic substation per unit per year. A two-variable scenario analysis is conducted to observe the change of relative consumer NPV by varying investment cost from 2000 to 3500 EUR and fixed O&M cost from 150 to 300 EUR. Table 3.4 denotes if the costs increase to some degree, consumers will not prefer ULTDH anymore. Moreover, it could be derived that these two types of costs have equal impact on consumers, specifically when MBST investment cost or fixed O&M cost is 2 times than that of conventional one, relative

Table 3.3: Pay-back period versus DH heat price

Payback period	DH company			Consumers
Heat price EUR/MWh	DH years	LTDH years	ULTDH years	ULTDH years
0-70	0.00	0.00	0.00	0.00
80	0.00	0.00	0.00	14.52
90	0.00	0.00	0.00	9.51
100	0.00	0.00	0.00	7.18
110	0.00	0.00	0.00	5.63
120	0.00	0.00	0.00	4.68
130	0.00	0.00	0.00	4.09
140	19.19	17.30	0.00	3.52
150	15.52	14.42	17.47	3.17
160	13.34	12.43	15.17	2.80
170	11.52	11.10	13.22	2.56
180	10.31	9.67	11.57	2.36
190	9.28	8.72	10.47	2.19
200	8.38	8.15	9.51	2.04
210	7.61	7.41	8.67	1.87
220	7.15	6.77	8.17	1.76
230	6.54	6.39	7.50	1.66
240	6.18	6.05	7.11	1.57
250	5.69	5.58	6.56	1.49
260	5.41	5.31	6.25	1.42
270	5.15	5.06	5.79	1.35
280	4.78	4.70	5.54	1.29
290	4.57	4.50	5.31	1.24
300	4.38	4.32	5.10	1.19

consumer NPV is both observed at 0.13. This phenomenon is also suitable for 50% higher scenario.

Table 3.4: Sensitivity analysis on microbooster costs

Fixed O&M /Investment	150	175	200	225	250	275	300
2000	0.42	0.37	0.32	0.28	0.23	0.18	0.13
2500	0.35	0.30	0.25	0.20	0.16	0.11	0.06
3000	0.28	0.23	0.18	0.13	0.09	0.04	-0.01
3500	0.21	0.16	0.11	0.06	0.01	-0.03	-0.08
4000	0.13	0.09	0.04	-0.01	-0.06	-0.11	-0.15
4500	0.06	0.01	-0.03	-0.08	-0.13	-0.18	-0.23
5000	-0.01	-0.06	-0.11	-0.15	-0.20	-0.25	-0.30
5500	-0.08	-0.13	-0.18	-0.22	-0.27	-0.32	-0.37
6000	-0.15	-0.20	-0.25	-0.30	-0.34	-0.39	-0.44

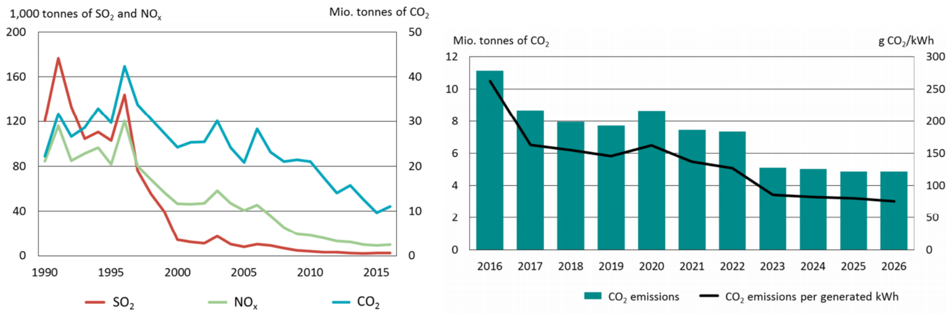
3.3.3 Electricity generation externality

Currently the embedded data for electricity generation externality as Table 3.5 shows is referred to [Enea] (2016 level). And it's assumed to be constant during the valuation period. This parameter is concerned with electricity driven units, i.e heat pump, electric heater. Besides, Figure 3.23a illustrate the trend of emissions from 1990 to 2015. For SO_2 and NOx, it has already reached a very low level nowadays and it's expected to remain stable. However, with respect to CO_2 emissions, a further 56 % reduction in CO2 emissions is projected to be achieved by 2026 Figure 3.23b.

Table 3.5: Electricity environmental externality data for 2016

Gross power generation	30199	GWh		
Emission to air from electricity and CHP generation		Unit	Average	Unit
C02	11118114	tons	102267.13	g/GJ
SO2	2410	tons	22.17	g/GJ
Nox	9819	tons	90.32	g/GJ
CH4	4904	tons	45.11	g/GJ
N2O	191	tons	1.76	g/GJ
PM2.5	329	tons	3.03	g/GJ

Therefore, a sensitivity analysis is conducted varying CO_2 emission per GJ electricity from 0 to 200 kg Figure 3.24. To socio-economic in ULTDH, it shows an incremental benefits with the decrease of CO_2 emission. When it reduces to app. 50 kg/GJ, ULTDH achieve the same climate change impact with DH. In converse, the lower electricity externality insults a larger reduction of CO_2 emission for DH than LTDH.



(a) Electricity generation emission in Denmark

(b) CO_2 emission projection from 2016 to 2026

Figure 3.23: Electricity generation externality in Denmark

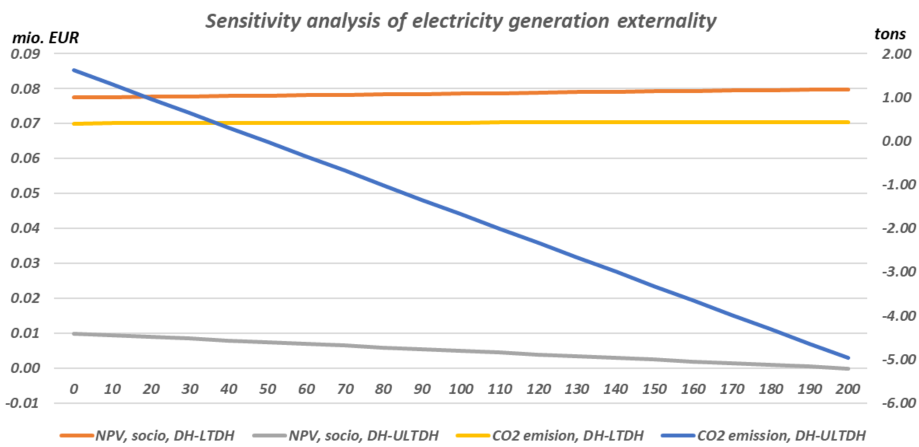


Figure 3.24: Sensitivity analysis of electricity generation externality

3.3.4 Electricity price

In current valuation period, there is a average discounted electricity price at 32.38 EUR/MWh for DH company, while 1.25 times for consumers. Table 3.6 shows the results by varying electricity price by ±20%, ±40%. ULTDH becomes more beneficial for local community than LTDH with lower electricity price due to increasing consumers surplus. In reverse, ULTDH will have equal costs on socio-economic with DH if the price increases by 20%. The higher the electricity price, the more benefits LTDH obtain mainly due to rising revenue from electricity selling of CHP units. In the future, it's expected to have a lower electricity price with the expansion of wind turbines and solar panels, accompanying with a lower environmental externatilies. Thereby, ULTDH is promising to be more competitive.

Table 3.6: Sensitivity analysis of electricity price

NPV	Local community		DH company		DH consumers		Socio-economic	
Electricity price change	DH-LTDH	DH-ULTDH	DH-LTDH	DH-ULTDH	DH-LTDH	DH-ULTDH	DH-LTDH	DH-ULTDH
-40%	0.056	0.067	0.056	-0.265	0.000	0.332	0.077	0.015
-20%	0.057	0.062	0.057	-0.266	0.000	0.328	0.078	0.010
0%	0.058	0.057	0.058	-0.267	0.000	0.324	0.079	0.005
20%	0.059	0.052	0.059	-0.268	0.000	0.320	0.079	0.000
40%	0.060	0.047	0.060	-0.269	0.000	0.317	0.080	-0.006

3.3.5 Taxation scenario

The parts is to analysis the influence of current taxation setting. When eliminating the fuel emission tax and VAT, Figure 3.25 illustrates that LTDH still has a slightly more benefits than DH both for local community and socio-economic, instead ULTDH is not preferable than DH mainly due to a much higher costs for DH company.

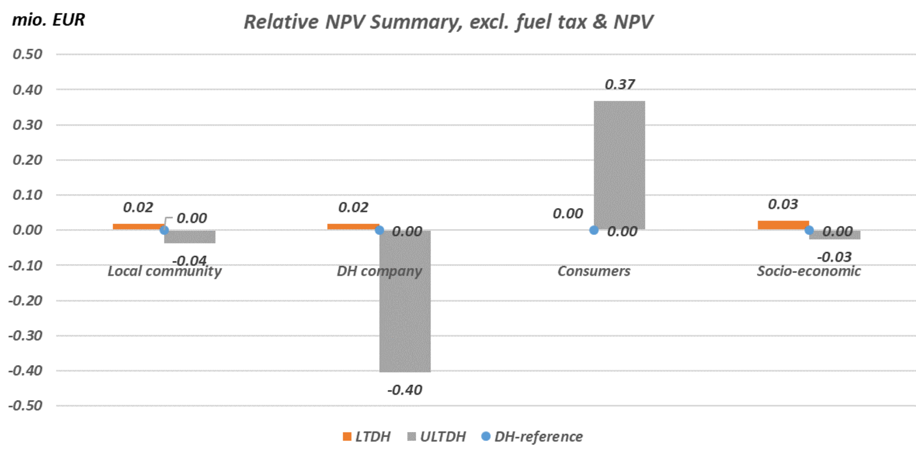


Figure 3.25: Sensitivity analysis of microbooster investment costs

CHAPTER 4

Conclusion

Conclusion

As the basis of specific project evaluation, this thesis first quantifies the advantages and disadvantage of lower temperature district heating from 6 aspects, specifically:

1. Distribution grid heat loss: the heat loss percentage for DH, LTDH, ULTDH are simulated at 19%, 14%, 11% respectively.
2. Cogeneration electricity and heat efficiency: the relative increase than η_{elec} under conventional DH is observed at 7% for LTDH and 14% for ULTDH, at a cost of decreased η_{heat} by 4%, 8% separately.
3. Heat pump COP: Taking DH as reference, COP increases by 47% under LTDH and 82% under ULTDH.
4. Flue gas condensation: for biomass/waste-based configurations, the η_{heat} rises by 3% and 4% for LTDH, ULTDH in comparison to DH.
5. Additional DHW preparation costs for ULTDH: 6 concepts are introduced, the most preferable one, microbooster secondary tank, has the same investment costs with conventional domestic substation with 50 EUR higher fixed O&M costs per unit per year. This concept will contribute 38.89% of DHW demand by simulation.
6. Extra network costs: the service line cost per single family house (0-20kw) is 275 EUR higher in lower temperature DH.

The results above are integrated into the comparative valuation model. Based on LCOE calculations for 14 concerned DH heating technologies, it is concluded that heat pump unit has the best synergy with lower temperature DH with 4.5 EUR, 6.35 EUR LCOE saving per MWh heat production under LTDH, ULTDH separately. In addition, lower DH temperature contribute levelized heat cost savings in biomass/waste-fired plant utilities around 0-2 EUR/MWh.

The case study indicates both LTDH and ULTDH are beneficial for local community and socio-economic compared with DH while LTDH is more preferable. However, DH company benefits 0.06 mio.EUR from LTDH, instead extra 0.27 mio.EUR costs under ULTDH. On the other hand, DH consumers prefer ULTDH with cost savings by 0.32 mio.EUR than LTDH with no surplus. For DH company, the pay-pack period is 6.18, 6.05, 7.11 years respectively in DH, LTDH, ULTDH. While taking heat price as a financial measure and set at 240 EUR/MWh in DH, a improved price to 270 EUR/MWh will create incentives for both company and consumers to prefer ULTDH than DH. On the contrary, a decreased price to 238 EUR/MWh makes both choose LTDH rather than DH as well.

With regard to energy evaluation, the heat efficiency rises from 74.9% in DH to 80.6% in LTDH and 96.4 % in ULTDH. However, the total utilization factor decreases to 0.41 in ULTDH, compared with 0.45 in DH and LTDH, the reason of which is the extra capacity investment due to much more fluctuating heat demand. As a results, the average cost for DH company is 98.3 EUR per MWh consumer heat consumption in ULTDH, while it is 3.5 EUR lower in DH, 6.8 EUR lower in LTDH.

Based on sensitivity analysis, both company and consumers have incentives to choose ULTDH than DH when heat price ranges from 90 to 110 EUR/MWh. But DH company will operate in debt under this condition. When average CO_2 emission for electricity generation reduces to app. 50 kg/GJ, ULTDH has the same climate change impact with DH. As to electricity price, ULTDH will not beneficial for socio-economic than DH if the price increases by 20%. In reverse, he higher the electricity price, the more benefits LTDH will obtain.

Limitations

- DH Production simulation

  As mentioned before, current valuation model perform a simple production simulation from base technology, then intermediate to peak. However, this approach could not optimize the production with the fluctuation of electricity and fuel price as well as the utilization of accumulator. Potential improvements could be achieved using extra programming methods.

- Inlaid data

  The accuracy of inlaid data has a major impact on final evaluation results. Therefore, it's recommended to alter some parameters based on the specific project context.

- Non-quantified advantages of lower temperature DH

  Lower temperature DH is expected to have better synergy with solar heating, geo-thermal, which is not quantifies in this project. In addition, potential use of existing return pipe to supply ULTDH will also lower the total costs for specific project.

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Appendix

DH & LTDH production curves and duration curves

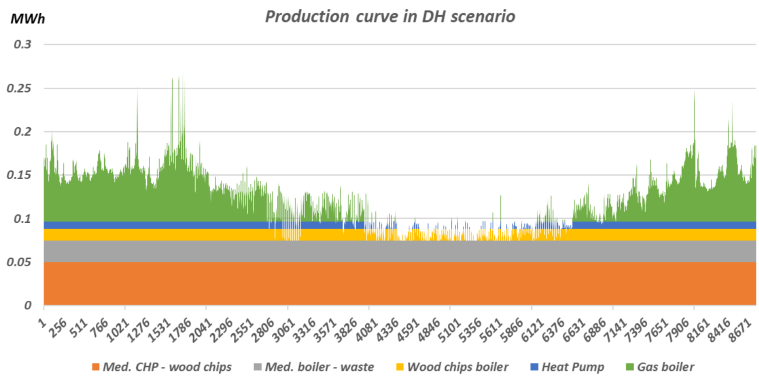

Figure 1: Production curve in DH scenario

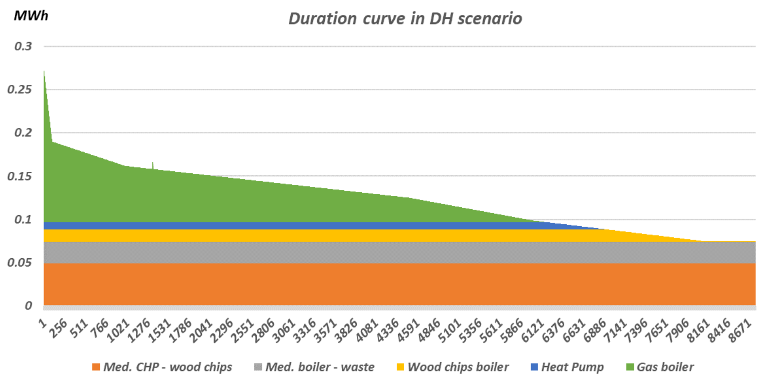

Figure 2: Duration curve in DH scenario

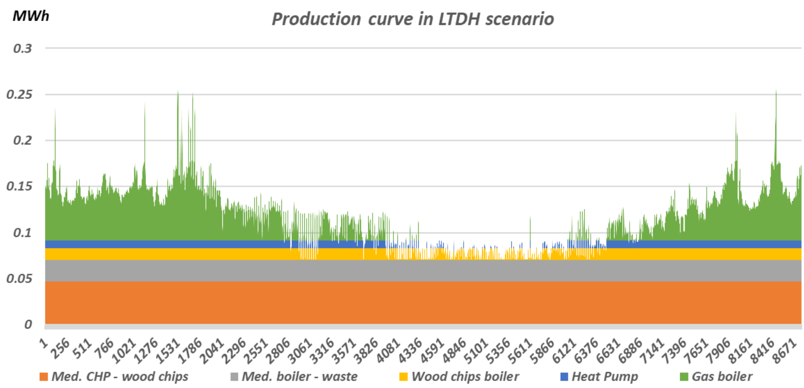

Figure 3: Production curve in LTDH scenario

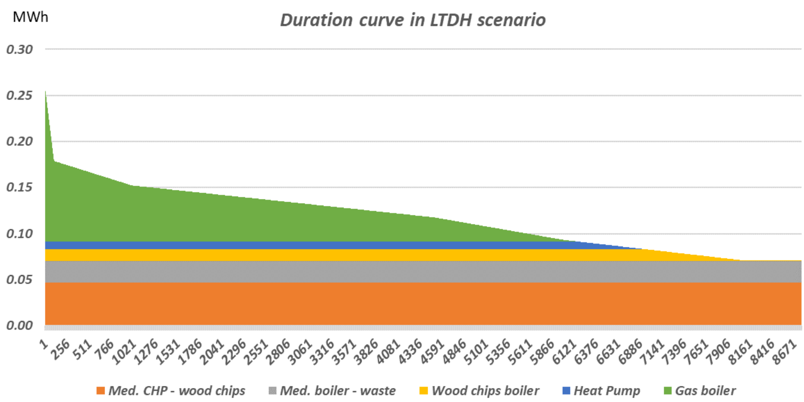

Figure 4: Duration curve in LTDH scenario