Energy Policy 68 (2014) 294–305

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Heat planning for fossil-fuel-free district heating areas with extensive end-use heat savings: A case study of the Copenhagen district heating area in Denmark

M. Harrestrup [1,*], S. Svendsen [2]

Building Physics and Services Section, Department of Civil Engineering, Technical University of Denmark (DTU), Building 118, Brovej, 2800 Kgs. Lyngby, Denmark

HIGHLIGHTS

- We investigate how much heating consumption needs to be reduced in a district heating area.
- We examine fossil-fuel-free supply vs. energy conservations in the building stock.
- It is slightly cost-beneficial to invest in energy renovation from today for a societal point of view.
- It is economically beneficial for district heating companies to invest in energy renovations from today.
- The cost per delivered heat unit is lower when energy renovations are carried out from today.

ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
17 January 2014
Accepted 21 January 2014
Available online 12 February 2014

Keywords:
Energy renovation
Fossil fuel free energy supply
Cost per delivered heat unit

ABSTRACT

The Danish government plans to make the Danish energy system to be completely free of fossil fuels by 2050 and that by 2035 the energy supply for buildings and electricity should be entirely based on renewable energy sources. To become independent from fossil fuels, it is necessary to reduce the energy consumption of the existing building stock, increase energy efficiency, and convert the present heat supply from fossil fuels to renewable energy sources. District heating is a sustainable way of providing space heating and domestic hot water to buildings in densely populated areas. This paper is a theoretical investigation of the district heating system in the Copenhagen area, in which heat conservation is related to the heat supply in buildings from an economic perspective. Supplying the existing building stock from low-temperature energy resources, e.g. geothermal heat, might lead to oversized heating plants that are too expensive to build in comparison with the potential energy savings in buildings. Long-term strategies for the existing building stock must ensure that costs are minimized and that investments in energy savings and new heating capacity are optimized and carried out at the right time.

1. Introduction

1.1. Meeting future long-term objectives

The Danish government has a long-term goal of having no need to use fossil fuels by 2050. By 2035, the goal is that the energy supply mix for buildings (electricity and heating) should be based on Renewable Energy (RE) sources (Danish Ministry of Climate, Energy and Buildings, 2011; Danish Energy Agency, 2010a). The European building stock accounts for about 40% of all energy use (Lechtenböhmer and Schüring, 2011). To meet the future energy goal, the energy consumption of the existing building stock will have to be reduced by increasing energy efficiency and converting the present heat supply from fossil fuels to renewable energy sources.

Investigations have shown that the energy consumption of existing buildings can be reduced by approximately 50–75% (Kragh and Wittchen, 2010; Kragh, 2010; Lund et al., 2010; Rasmussen, 2010; Tommerup et al., 2010), but that it will take significant investments to reach such low levels (Kragh and Wittchen, 2010). The existing building stock will remain in existence for many years, so a focus on energy savings in this segment is unavoidable. Future energy systems will have to be based solely on renewable energy sources, which is a challenge for society.

1.2. Future district heating systems

District Heating (DH) is a sustainable way of providing Space Heating (SH) and Domestic Hot Water (DHW) to buildings in

* Corresponding author.
E-mail addresses: marih@byg.dtu.dk (M. Harrestrup), ss@byg.dtu.dk (S. Svendsen).
[1] Tel.: +45 45 25 50 34.
[2] Tel.: +45 45 25 18 54

0301-4215/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2014.01.031

densely populated areas (Persson and Werner, 2011). DH systems are already established in many countries, but like the rest of the energy supply system, they face new challenges in the future. In Iceland and Turkey, a large share of the DH supply is based on geothermal heat, and some DH systems are also supplied from geothermal heat in China and the U.S.A. In countries like Denmark, Sweden, and Finland, the DH supply comes mainly from combined heat and power generation plants (CHP) (Gustafsson and Rönnqvist, 2008). The DH systems in Denmark will have to be converted from the present supply technologies based on fossil fuels to 100% renewable energy sources. Questions have been raised about whether there is a need for DH-systems in the future, since SH-demands will decrease to very low levels. The economic feasibility of future DH-systems has thus been questioned. A study of the DH-net in Malmö, Sweden, (Gustafsson, 1992) found the overall economic feasibility of DH systems to be problematic when end-use consumption in buildings is reduced. The overall costs strongly depend on the characteristics of the buildings and the district heating system (Gustavsson, 1994a, 1994b). However, a recent study in Denmark (Lund et al., 2010) has shown that even with a reduction of 75% in SH demand, it is beneficial to supply heat from DH. The study also shows that an expansion of the DH-network from the present 46% share of the total heat supply in Denmark to a 63–70% share would be beneficial. With low-temperature operation (a supply temperature of 55 °C and a return temperature of 25 °C), it has been shown that DH supply for low-energy buildings is competitive with the best alternatives, such as individual heat pumps (Lund et al., 2010; Dalla Rosa and Christensen, 2011). Low-Temperature District Heating (LTDH) is a cost-efficient and environmentally friendly way of supplying heat with linear heat densities down to 0.20 MWh/(m year) (Dalla Rosa and Christensen, 2011). LTDH reduces heat losses from the distribution pipes, and heat supply from renewable sources becomes more appropriate and efficient when low-temperature applications are implemented (Dalla Rosa et al., 2011).

1.3. The conversion to fossil-fuel-free societies with extensive end-use energy savings

Recent studies have investigated the potential in converting the existing energy system into a 100% renewable supply system in two local authorities in Denmark: Frederikshavn (Østergaard and Lund, 2011) and Aalborg (Østergaard et al., 2010). Both studies covered the heating, electricity and transport sectors and included energy-saving measures, but the focus was on the supply side and on production technologies. Both studies concluded that it is technically and economically possible to convert to a fossil-fuel-free society and that geothermal heat will play an important role in future district heating systems. A study from Sweden (Gustavsson et al., 2011) investigated how the end-use heat savings in buildings will affect district heating production, including costs and primary energy savings, but it included the use of fossil fuels. In the future, however, conversion to RE-supply will be as important as end-use heat savings.

The present paper considers both end-use-savings and 100% RE-supply, but has a more detailed focus on when and to what extent it is worth implementing end-use savings in the building stock. It describes a method for making use of the existing DH system in the future energy infrastructure of the Copenhagen area with the aim of society being fossil-fuel-free in 2050. The scope is limited to the heating sector, excluding other sectors such as electricity generation and the transport sector. The electricity sector will also have to be fossil-fuel-free, and much of the future electricity production will be based on fluctuating and vulnerable resources such as wind. If electricity is used for heating purposes, large, costly storage units may be required to meet peak loads. The use of DH in appropriate areas will protect the electricity sector from increasing peaks in very cold periods. That is why electricity for heating purposes is not considered in this study.

The focus of this paper is on the implementation of geothermal heat sources for future DH-systems, as well as on heat produced from municipal solid waste incineration.

Socioeconomic calculations of various energy renovation strategies are carried out and discussed. The cost per delivered unit of heat in buildings is estimated for the various scenarios based on the energy renovation strategies.

We have taken a very general approach with the aim of providing an overall picture for planning future heat sourcing with regard to heat savings and supply in the existing building stock. The cost of new buildings is generally not included in any of the scenarios, since it is assumed that when a new building is constructed, it automatically fulfils the energy requirements of the Danish Building Regulations. This means that the cost will be incurred whichever renovation strategy is carried out.

2. Methods

2.1. Background and approach for the case study

The investigation takes a long-term perspective and deals with the period up to 2070. According to current energy policy, coal will be phased out by 2030 (Danish Ministry of Climate, Energy and Buildings, 2011), but according to the Heat Plan of Copenhagen (CTR et al. 2009) coal will already have been phased out by 2025. This study assumed that fossil fuels will be phased out before 2025 and replaced with waste for incineration, geothermal energy and biomass.

Some CHP plants have already been converted for biomass in Denmark, but according to research (EEA (European Environment Agency) 2006) the biomass potential in Europe will only account for approximately 15–16% of the total primary energy demand in 2030. Furthermore the study (Ericsson and Nilsson, 2006) concludes that the biomass resource is limited and with the slow implementation of RES-policy in Europe it is unlikely that the biomass targets will be reached. This study therefore assumed that the biomass resource will be seen as a temporary solution only available until 2040, after which it will relocate to other sectors, i.e. the transportation sector that will have to be fossil-fuel-free by 2050. This is in good agreement with recommendations and other similar case studies (Danish Energy Agency, 2010a; Dolman et al., 2012). So this study focused on other renewable energy resources. This is in good agreement with the considerations in (Østergaard and Lund, 2011; Østergaard et al., 2010), although those studies still assume that a small amount of the available biomass-resource for CHP will be exploited indirectly for heating purposes.

Geothermal sources should be considered as a mix of various energy sources in the future heat supply infrastructure. Waste heat from industry could also be used in combination with either geothermal or solar heat, but the potential has been estimated to be low (3%) in the Copenhagen area, because the industrial sector is small (Danish Energy Agency, 2009). Geothermal water under Copenhagen can be tapped at temperatures of 73 °C at a depth of 2000 m (Mahler and Magtengaard 2010), so heat pumps are assumed not to be needed to further elevate the temperature of the water. Mahler and Magtengaard (2010) can be mentioned among newly developed geothermal heating plants in Denmark.

The priority of the utilization of the resources in this study was:

1. Waste for incineration;
2. Geothermal energy;
3. Biomass; and
4. Fossil fuels.

Municipal solid waste for incineration has the first priority since there are already established plants and there is a certain ethic in using the waste heat produced from the incineration instead of producing more geothermal heat. This may be different in other countries that do not already have established plants. Furthermore if the waste is not incinerated the problem of how to treat the waste and what to do with it appears and therefore it seems reasonable to prioritize the waste incineration.

When the heating demand in buildings is reduced to low levels, LTDH becomes an option, because the need for SH and the SH-peaks will decrease. Therefore it is possible to heat the buildings with lower temperatures, which allows for the use of LTDH. It has been shown (Worm et al. 2011; Tol and Svendsen, 2012a, 2012b; Harrestrup and Svendsen, 2013) that LTDH is feasible in existing buildings for most hours of the year. Periods with very cold climate conditions require an increased supply temperature. It is assumed that this can come from waste incineration plants.

2.2. Present heat demand and potential for conversion of individual natural gas heated buildings

The present DH network in the Copenhagen area consists of three waste incineration plants and four CHP-plants distributed as shown in Fig. 1. The supply area includes the supply companies VEKS, CTR, Vestforbrændingen and HOFOR.

The total heat supply by DH (2010) of the area shown in Fig. 1 is 35 PJ/year with a peak load of 2500 MW (CTR et al., 2011). This capacity was used as the starting point for the calculations in this paper. The overall network heat losses are assumed to be 15% and 8% of the annual production with traditional DH and low-temperature DH respectively (VEKS, 2012a; HOFOR, 2012). It is assumed that the DHW demand is 400 MW constantly over the year with the exception of the summer period when consumers are expected to use less domestic hot water due to vacations. In reality, the DHW will vary over the year, but these variations have been left out of account to simplify the study.

According to CTR et al. (2009), a potential of 10 PJ for heating individual homes can be converted from natural gas to DH. The total heat consumption then adds up to 45 PJ/year with a peak load of about 3200 MW. We have assumed that the ratio between the SH consumption and the DHW consumption remains the same as the conversion takes place. The capacity of the district heating plants is distributed across small plants in the Copenhagen area.

2.3. Energy renovation—annual heat demand and peak load

To calculate the investment cost in new RE-capacity when the building stock undergoes energy renovation, the study of Harrestrup and Svendsen (2013) has been used. The study investigated how the peak load changes when energy renovations are carried out on two old multi-storey buildings typical in Danish urban areas. The findings showed that, when 65% is saved on the annual heat demand, the peak load can also be reduced by 65% and the heating demand will have smaller variations over the year. Based on these findings the peak loads are reduced with the same percentage as the reduction in annual heat demand in the present study. The two buildings used for the investigation (Harrestrup and Svendsen, 2013) are from the beginning of the 20th century and are typical of a large proportion of the buildings in Copenhagen where energy renovations are needed to bring down the energy consumption. In the Building Regulations from 1977 the U-values were significantly tightened as a consequence of the energy crisis in the 1970s, implying that the thermal performance of the buildings constructed before the 1970s was significantly worse than the once constructed after. According to official statistics (Statistics, 2013), 83% of the buildings in Copenhagen are built before 1970, 72% before 1950 and 44% before 1930.

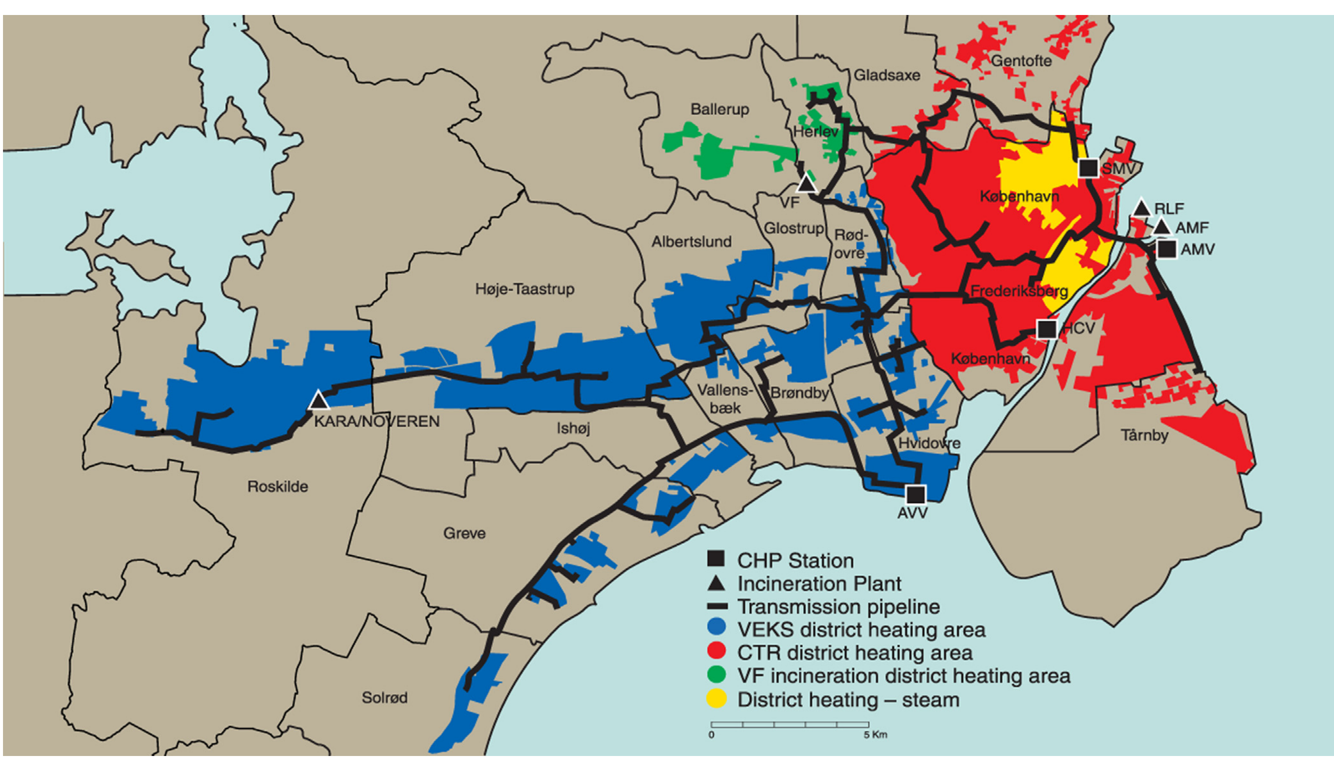

Fig. 1. Map of the existing DH network in Copenhagen area (CTR et al., 2011).

The annual energy consumption for space heating in the old building stock in Denmark is approximately (Kragh and Wittchen, 2010):

Before 1850:	520 MJ/m^2
1851–1930:	540 MJ/m^2
1931–1950:	610 MJ/m^2
1951–1960:	580 MJ/m^2
1961–1972:	470 MJ/m^2

Obtaining 65% savings the annual space heating consumption will then range from 165–210 MJ/m^2, which is at comparable levels with new buildings from the Building Regulations 2010 (BR10 (Danish Building regulations) 2012). The minimum requirements for new buildings since 2010 are: (189+5940/A) MJ/m^2/yr including the energy usage for supplied energy for heating, ventilation, cooling and domestic hot water (with A being the heated area). Furthermore, the Building Regulations specifies the expected energy performance framework in 2015 to: (108+3600/A) MJ/m^2/yr and in 2020 to: 72 MJ/m^2/yr.

2.4. Scenarios for the case study

Four different possible future scenarios with long-term approaches were examined. The calculations assumed a 1/3 decrease in the amount of domestic waste by 2070 compared to 2010 and that waste incineration will have higher priority than geothermal heat. This priority is assumed since there is an ethical value in using existing waste incineration plants before investing in new geothermal heating capacity. Furthermore, the municipal solid waste has to be treated in one way or another, either by incinerating it or storing it in land field lots. The priority is therefore to give it to the waste incinerating plants. According to the municipal solid waste plan of Copenhagen (Copenhagen Municipality, 2013) the prognosis is that waste for incineration will decrease by 8% in 2024 compared to 2010, as an average for household waste, waste from industry, and from construction due to more recycling. The assumption that the amount of municipal solid waste for incineration will fall by 33% before 2070 therefore seems reasonable (a rough estimation would be 70 years/14 years 8%=40%). Furthermore, the Danish government (Danish Ministry of the Environment, 2013) and the EU (European Commission, 2013) have a strategy of increasing recycling, which means less incineration of waste and therefore less heat produced from waste incineration.

The four scenarios are described below, and are referred to as the Reference Scenario, Scenario 1, Scenario 2, and Scenario 3. All scenarios assume existing buildings are replaced with new buildings at a rate of 1% per year (Barras, 2009). The Danish Building Research Institute (Kragh and Wittchen, 2010) has carried out an analysis that concludes that, if the energy consumption of the existing building stock is reduced by approximately 50% through energy renovation, the building stock will reach an energy level that corresponds to what is required for new buildings according to the Danish building regulations 2010 (BR10 (Danish Building regulations) 2012). The annual heat demand will then decrease by 0.5% per year in all the scenarios. The study does not consider a possible increase in the building stock over time.

LTDH is phased in all the scenarios except for the Reference Scenario. Two renovation levels are considered.

Comprehensive renovation will decrease the heat consumption by 65% and consists of (Kragh and Wittchen, 2010):

- Replacement of windows,
- Insulation of the building envelope, and
- Installation of mechanical ventilation with heat recovery.

Intermediate renovation will decrease the heat consumption by 32% and consists of (Kragh and Wittchen, 2010):

- Replacement of windows, and
- Installation of mechanical ventilation with heat recovery.

Reference Scenario—No energy renovation but only natural replacement of existing buildings with new buildings.

This scenario represents the scenario in which no energy improvements are made in the building stock until 2070, except for replacements with new buildings. The scenario therefore also represents a scenario in which focus is given fully to the RE-supply. A graphical sketch is shown in Fig. 2.

2.4.1. Scenario 1: Accelerated comprehensive energy renovation between 2030 and 2070

Scenario 1 represents the case where no energy efficiency improvements in the buildings are carried out before 2030. The DH supply will be converted from fossil fuels to biomass in the CHP-plants and prices will remain unchanged. When biomass is

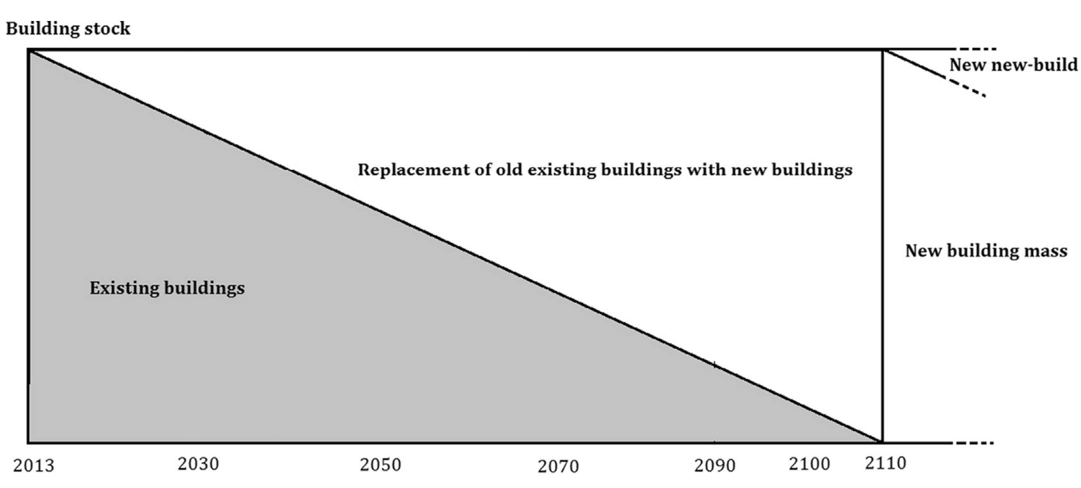

Fig. 2. Graphical sketch of the Reference Scenario—no energy renovations.

phased out between 2030 and 2040, geothermal heating plants are assumed to be established to cover the nearly unchanged heat load. The investment in geothermal energy will result in increased prices for DH. Comprehensive energy renovations in buildings will be carried out as a consequence of the increased heat prices. The coefficient of utilization of the geothermal heating plants will decrease and prices will rise further. LTDH will be phased in from 2035, proportional to the energy renovations.

A graphical sketch is presented in Fig. 3. As the figure shows, the entire building stock will undergo comprehensive renovation from 2030 phased in over 40 years. Assuming a lifetime of 60 years for such renovation measures, this share of the building mass will be replaced with new buildings from 2090.

2.4.2. *Scenario 2: Accelerated comprehensive energy renovations from 2013*

Scenario 2 represents the case where comprehensive energy renovations are implemented from 2013 to 2040. Biomass will be phased out between 2030 and 2040 and geothermal heating plants will be established. As a result of the energy efficiency improvements in the buildings, the investment in geothermal heating plants will decrease significantly. LTDH will be phased in from 2013 proportional to the energy renovations.

A graphical sketch is presented in Fig. 4. As the figure shows, the entire building stock will undergo comprehensive renovation from 2013, phased in before 2040. Assuming a lifetime of 60 years for such renovation measures this share of the building mass will be replaced with new building from 2073.

2.4.3. *Scenario 3: Accelerated intermediate energy renovations from 2013*

Scenario 3 represents the case where intermediate energy renovations are considered and as for Scenario 2 the energy renovations are implemented from 2013 (Fig. 5) and phased in over 30 years. The lifetime for this kind of energy renovation is considered to be 30 years, resulting in a reinvestment after 30 years. LTDH is phased in from 2013 proportional to the energy renovations.

2.5. *Economic considerations*

To calculate the economic consequences for each of the scenarios, socioeconomic analyses were applied. Using the present value (PV) method, all future investments and costs were discounted to present levels and the scenario with lowest costs was identified. This is in line with recommendations and guidelines

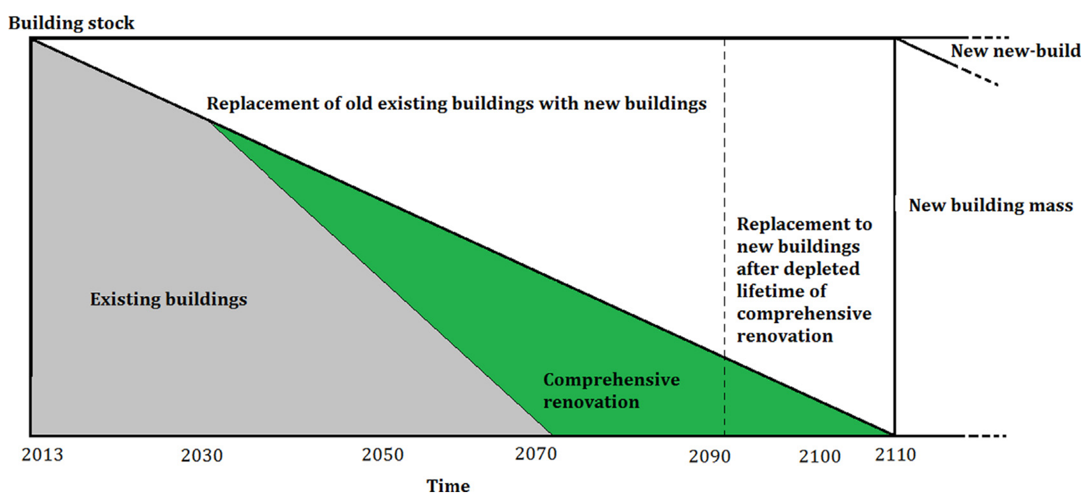

Fig. 3. Graphical sketch of Scenario 1—accelerated energy renovations later.

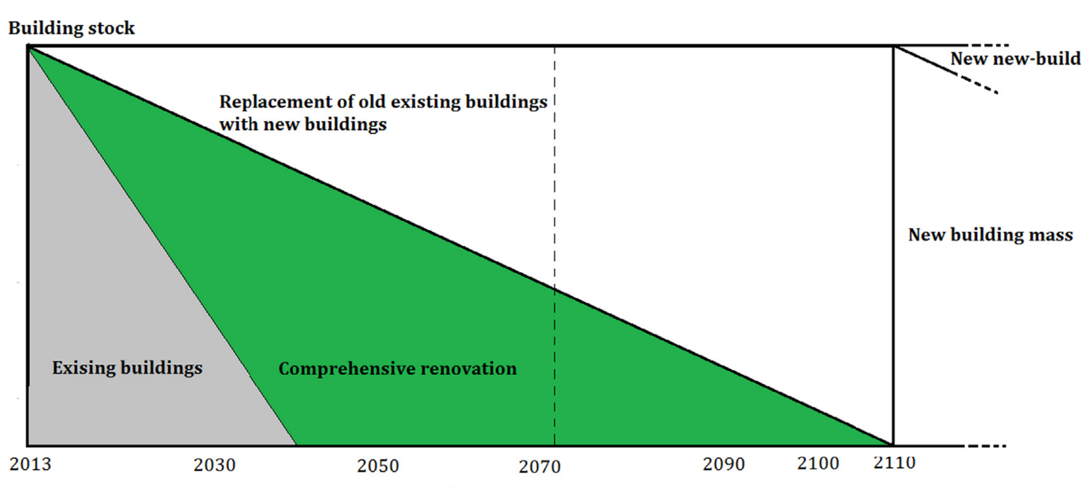

Fig. 4. Graphical sketch of Scenario 2—accelerated comprehensive energy renovations now.

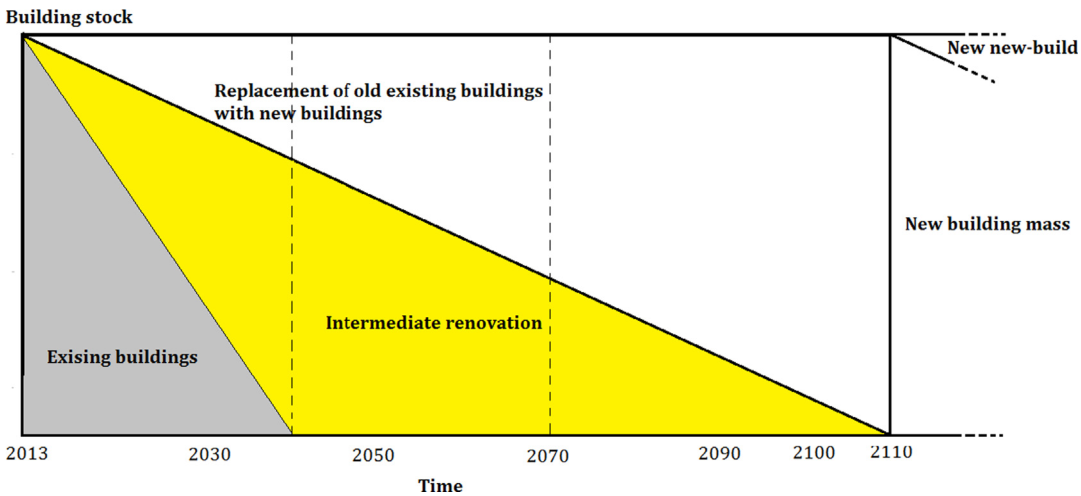

Fig. 5. Graphical sketch of Scenario 3—accelerated intermediate energy renovations now.

from the Danish Finance Ministry and the Energy Saving Trust Association (ENS) (Danish Energy Agency, 2007a). A sensitivity analysis on the influence of the discount rate was carried out using discount rates of 0%, 1%, 3% and 5%. According to the Danish Finance Minister and ENS a discount rate of 5% should be used for PV-calculations. The outcome from PV-calculations is very sensitive to the discount rate, and it is debatable whether this is a reasonable value for energy-related projects where the duration of the project is very long and affects long-term future conditions. Investments projected for many years from now will be discounted to smaller present values the higher the discount rate. This makes it appear more attractive to delay large investments, such as energy renovations (Ege and Appel, 2013; Atanasiu et al., 2013). Furthermore, (Stern, 2007) has elaborated this dilemma related to discounting in detail and states that if a project's costs and benefits are “allocated across generations and centuries, it is an ethical issue for which the arguments for low pure time discount rates are strong” and “if the ethical judgment is that future generations count very little regardless of their consumption level then investments with mainly long-run pay-offs would not be favoured. In other words, if you care little about future generations, you will care little about climate change. As we have argued that is not a position which has much foundation in ethics and which many would find unacceptable”.

Estimated costs of investment, maintenance and operation were included for the geothermal heating plants and for the DH-net. The energy prices of the fossil fuels and biomass were estimated from calculations carried out by (VEKS, 2012b). They were based on an expected weighted distribution of the resources in the Copenhagen DH-system. Waste for incineration was not priced due to the large uncertainties, but since the amount of waste is the same in all scenarios, this will not have any influence on their comparative costs. Moreover, the waste will have to be collected in all cases, and must be either incinerated or stored in a landfill lot, so the cost of waste is not included (Danish Energy Agency, 2007b).

All investments were included for the year they will take place in, and salvage values of the investments beyond 2070 were subtracted. The costs for the Reference Scenario (no energy renovations) were calculated solely for the supply-side, whereas the costs for Scenario 1 (energy renovation later), Scenario 2 (comprehensive energy renovation now), and Scenario 3 (Intermediate energy renovation now) also include the investment in energy renovation.

2.5.1. Geothermal

The capital investment cost is estimated to be €1.6/W for a geothermal plant with a capacity of 135 MW where approximately half of the capacity is coming from geothermal heat and the half from heat pumps (CTR et al. 2009; CTR et al. 2011; COWI, 2012). With LTDH, there will be no need for heat pumps to boost the temperature since the underground water can be drawn at 73 °C. The capital investment cost for geothermal heat is assumed to be 5 times higher compared to the capital investment cost for heat pumps, which result in an estimated capital investment cost solely for geothermal heat on approximately €2.7/W (COWI, 2012).

Operation and maintenance costs (O&M) are difficult to estimate since they vary depending on various factors and conditions. The O&M-cost was assumed to be €1.75/GJ (COWI, 2012).

2.5.2. DH-network

According to (COWI, 2012), the cost in capital investment for expanding the DH-network can be assumed to be €84/GJ. The investment cost is estimated based on experience from (COWI, 2012), and represents a cost for expansion of the DH net to less populated areas, which increases the cost compared to densely populated areas.

The O&M cost was set at €0.56/GJ based on the Danish Energy Agency (2010b).

2.5.3. Energy renovation costs

According to (Kragh and Wittchen, 2010), which is based on the entire building stock in Denmark (homes), the marginal cost of saving 102 PJ/year, corresponding to energy savings of 65%, is €51,000 M/year. The comprehensive renovation then results in a unit price per saved petajoule of €8.3 M/PJ, based on savings over 60 years.

$$\text{Comprehensive renovation} = \frac{€51,000\ \text{M/year}}{(102\ \text{PJ/year} \times 60\ \text{years})} = €8.3\ \text{M/PJ}$$

According to Kragh and Wittchen (2010), the marginal energy-saving price for windows is €111 M/PJ, and for ventilation with heat recovery (intermediate renovation), it is on average €296 M/PJ. Assuming the same energy-saving efficiency for both measures and a lifetime of 30 years, the energy-saving price per year becomes

$$\text{Intermediate renovation} = \frac{€(111+296)\text{M/PJ}}{30\ \text{years}} = €13.6\ \text{M/PJ}$$

Assumed lifetimes	
Geothermal:	40 years (Lako and Tosato, 2010)
DH network:	60 years (Tang, 2010)
Renovations of dwellings:	60 years (Aagaard et al., 2010)

2.6. Cost of delivered heat

The cost of the delivered heat to the buildings for the different scenarios was calculated to evaluate the scenario with the lowest cost per heat unit delivered. The heat delivered to the buildings is calculated as the heat produced in the DH plant minus the net heat losses. To calculate the cost of the delivered heat, the expenses for the DH companies based on the socioeconomic calculations are divided by the delivered heat

$$\text{Cost of delivered heat} = \frac{\text{Expenses for DH companies}}{\text{Delivered heat to buildings}}$$

3. Results and discussion of the case study

3.1. Reference scenario: No energy renovations

Fig. 6(a) shows the peak load and the distribution of resources. The heat demand will increase until 2035, due to the conversion of natural gas areas into district heating. In the same period, the existing building mass will be replaced with new buildings, decreasing the heat demand by 0.5% per year. Fig. 6(a) shows that with no accelerated heat savings an investment in geothermal heat corresponding to a capacity of 2800 MW will be required.

Fig. 7(a) shows the annual production of the different energy supply technologies until 2070. The geothermal heat production is expected to peak in 2040 at 32 PJ, after which it will decrease by 14% by 2070. The total geothermal production in the entire period is estimated to be 1100 PJ.

3.2. Scenario 1: Accelerated energy renovations later

Scenario 1 represents the case where accelerated comprehensive energy renovations are implemented from 2030. Fig. 6(b) shows the peak load and the distribution of the supply technologies. The heat demand peaks in 2030, after which it decreases. The build-up in geothermal capacity is 2500 MW, which is slightly lower than in the Reference Scenario (no energy renovations) due to the accelerated energy renovations.

Fig. 7(b) shows the annual production of the different energy supply technologies between 2010 and 2070. The geothermal production peaks in 2040 at 28 PJ. The accelerated energy renovations imply a decrease in the heat demand from 2030 until 2070. The coefficient of utilization drops significantly because the investment in geothermal heat capacity has already taken place. The production of geothermal heat decreases by 61% by 2070. The total geothermal heat production for the entire period is 838 PJ.

3.3. Scenario 2: Accelerated comprehensive energy renovations now

Scenario 2 represents the case where investment in accelerated energy renovations begins in 2013. Fig. 6(c) shows the peak load and distribution of the different supply technologies. The total heat demand decreases throughout the entire period. The investment in geothermal capacity is reduced to 1200 MW, corresponding to a reduction of 57% compared to the Reference Scenario (no energy renovation), and a reduction of 52% compared to Scenario 1 (energy renovations later).

Fig. 7(c) shows the annual heat production of the different supply technologies until 2070. The geothermal heat production

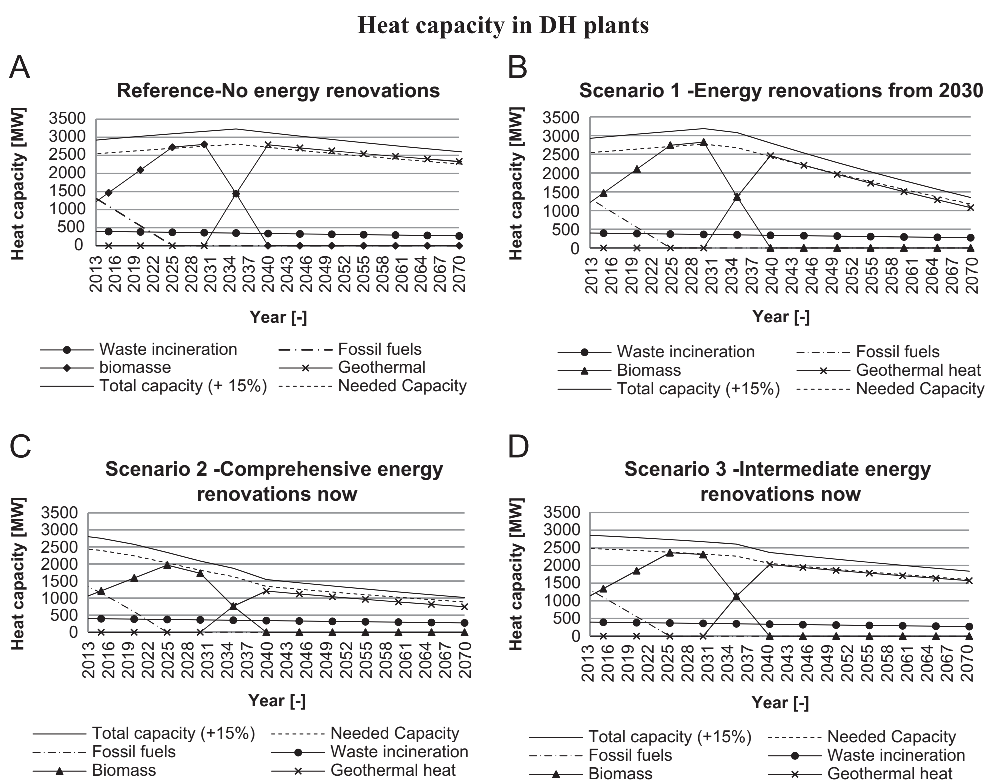

Fig. 6. Heat capacity for the different supply technologies for all the scenarios.

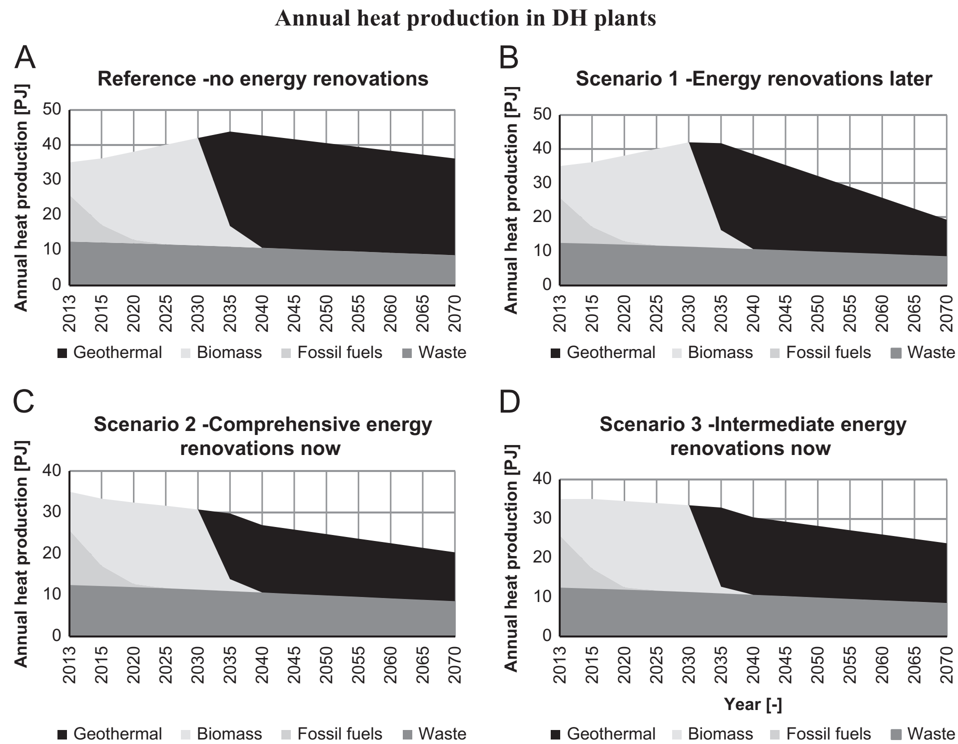

Fig. 7. Annual heat production for the different supply technologies for all the scenarios.

peaks at 16 PJ, which is 50% less than in the Reference Scenario (no energy renovations) and 43% less than in Scenario 1 (energy renovations later). The geothermal production decreases by approximately 25% by 2070 compared to the peak value. The total geothermal heat production throughout the entire period is 543 PJ.

3.4. *Scenario 3: Accelerated intermediate energy renovation now*

Scenario 3 represents the case where accelerated intermediate energy renovations are carried out from 2013. Fig. 6(d) shows the peak load and distribution of the different supply technologies. The total heat demand decreases throughout the entire period. The investment in geothermal capacity is 2029 MW, corresponding to a reduction of 28% compared to the Reference Scenario (no energy renovation), 19% compared to Scenario 1 (energy renovation later), and an increase of 69% compared to Scenario 2 (comprehensive energy renovation now).

Fig. 7(d) shows the annual heat production of the different supply technologies until 2070. The geothermal heat production peaks at 25 PJ, which is 22% less than in the Reference Scenario (no energy renovations), 11% less than in Scenario 1 (energy renovations later), and 56% more than in Scenario 2 (comprehensive energy renovations now). The geothermal production decreases by approximately 20% by 2070 compared to the peak value. The total geothermal heat production throughout the entire period is 675 PJ.

3.5. *Economics of the case study*

Table 1 shows the result of the socioeconomic analysis. The total cost for the Reference Scenario (no energy renovations) is €833 M less than that of Scenario 1 (energy renovations later) if a discount rate of 0% is assumed. This is due to the large investments in energy renovations in Scenario 1 (energy renovations later) at the end of the period in question, and the effect on the investment in geothermal heating plants is therefore relatively small. When the discount rate is increased to 1%, 3%, and 5% the Reference Scenario (no energy renovations) will cost €1106 M, €938 M, and €616 M less than Scenario 1 (energy renovations later), respectively.

Table 1 also shows that Scenario 2 (comprehensive energy renovations now) is less costly than the Reference Scenario (no energy renovations) by €509 M when a discount rate of 0% is assumed. However, if the discount rate is increased to 1% or more, Scenario 2 (comprehensive energy renovations now) is no longer beneficial compared to the reference, indicating the sensitivity of the cost estimates to the discount rate. The results of Scenario 3 (intermediate energy renovations now) are in between Scenario 1 (energy renovations later) and Scenario 2 (comprehensive energy renovations now). Table 1 also shows that investing in comprehensive energy renovation from today rather than later will save approximately half the investment cost in geothermal heating plants, which is beneficial for the district heating companies. If investment in intermediate energy renovation (Scenario 3) takes place now, it will save approximately 16% of the investment cost in geothermal heating plants compared to postponing the investment in energy renovation (Scenario 1). However, Scenario 3 with less investment in energy renovation is more likely to be realized fast, since replacing the windows and installing mechanical ventilation with heat recovery is an easier task than carrying out comprehensive energy renovations.

Table 2 shows the heat produced in the DH plants and the heat delivered to the buildings, i.e. after the network heat losses. Since the Reference Scenario (no energy renovations) does not have LTDH and Scenario 1 (energy renovations later) only implements LTDH from 2035, when the energy renovations are carried out, the network heat losses are higher than in the other scenarios where LTDH is implemented today proportional to the energy renovations. Taking the expenses for the DH companies and dividing it by the heat delivered to the buildings, the cost per delivered heat unit is calculated. As can be seen, Scenario 2 (comprehensive energy renovations now) provides the lowest cost per delivered heat unit, followed by Scenario 3 (intermediate energy renovations now), which indicates a more competitive price for the district heating

Table 1
PV for each scenario excl. waste for incineration. Discount rates of 0%, 1%, 3%, and 5%.

PV 2013–2070	**Reference.** No energy renovations **[M €]**	**Scenario 1** Energy renovations later **[M €]**	**Scenario 2** Comprehensive energy renovations now **[M €]**	**Scenario 3** Intermediate energy renovations now **[M €]**
Discount rate 0% Investments				
Geothermal plants	8736	7644	3744	6396
DH-net expansion	187	187	187	187
Renovations	0	7662	7662	6171
Salvage value				
Geothermal plants	−983	−860	−421	−720
DH-net expansion	−38	−38	−38	−38
Renovations	0	−5044	−1877	−3514
Fuels	879	874	669	774
O&M	3276	2465	1622	2524
Total cost for DH companies	12,057	10,272	5763	9123
Total cost renovation	0	2618	5785	2657
Total Discount rate 0%	**12,057**	**12,890**	**11,548**	**11,780**
Discount rate 1% Investments				
Geothermal plants	6986	6113	2994	5115
DH-net expansion	169	169	169	169
Renovations	0	5311	6776	4758
Salvage value				
Geothermal plants	−552	−483	−237	−404
DH-net expansion	−22	−22	−22	−22
Renovations	0	−2832	−1421	−1973
Fuels	780	776	601	690
O&M	2295	1730	1141	1763
Total cost for DH companies	9656	8283	4646	7311
Total cost renovation	0	2479	5355	2785
Total Discount rate 1%	**9656**	**10,762**	**10,001**	**10,096**
Discount rate 3% Investments				
Geothermal plants	4509	3945	1932	3301
DH-net expansion	141	141	141	141
Renovations	0	2679	5425	3092
Salvage value				
Geothermal plants	−177	−155	−76	−130
DH-net expansion	−7	−7	−7	−7
Renovations	0	−908	−821	−633
Fuels	731	728	578	655
O&M	1192	904	600	915
Total cost for DH companies	6389	5556	3168	4875
Total cost renovation	0	1771	4604	2459
Total Discount rate 3%	**6389**	**7327**	**7772**	**7334**
Discount rate 5% Investments				
Geothermal plants	2943	2575	1261	2155
DH-net expansion	119	119	119	119
Renovations	0	1434	4470	2224
Salvage value				
Geothermal plants	−58	−51	−25	−42
DH-net expansion	−2	−2	−2	−2
Renovations	0	−298	−479	−207
Fuels	513	511	415	464
O&M	667	510	341	513
Total cost for DH companies	4182	3662	2109	3207
Total cost renovation	0	1136	3991	2017
Total Discount rate 5%	**4182**	**4798**	**6100**	**5224**

companies when energy renovations are carried out already from today.

3.6. Policy implications

The approach to this investigation has been that biomass is a temporary resource that will disappear from the heating sector in the long-term for use in other sectors. There are different opinions on this subject, but most agree that biomass is a restricted resource that cannot be used as the primary resource for all future energy purposes. Most sectors would like to make use of biomass, but this is not possible and other non-fossil fuel energy solutions must be found. The authors of (Østergaard and Lund, 2011; Østergaard et al., 2010) concluded that the use of geothermal heating plants will play a significant role in future district heating systems, but they also made use of a small amount of biomass to cope with peak loads. Investing in sufficient geothermal heating plant to cover peak loads may in fact be unrealistic since the

Table 2
Produced and delivered heat. Cost for delivered heat for the scenarios with different discount rates.

	Reference No energy renovations	Scenario 1 Accelerated energy renovations later	Scenario 2 Accelerated energy renovations now	Scenario 3 Intermediate energy renovations now
Delivered heat at buildings [PJ]	2064	1819	1465	1652
Produced heat [PJ]	2379	2098	1640	1827
Net losses [PJ]	315	279	175	175
Cost per delivered heat [€/PJ]				
Discount rate 0%	5.84	5.65	3.93	5.52
Discount rate 1%	4.68	4.55	3.17	4.43
Discount rate 3%	3.10	3.05	2.16	2.95
Discount rate 5%	2.03	2.01	1.43	1.94

investment cost could be too high, and other technologies, such as energy storage, will probably be used to achieve peak load production. For example, surplus electricity produced from wind could be used to produce hydrogen, which along with biomass would form a "synthetic natural gas". This gas could then be used in CHP plants and the heat production could be used to cover the peak loads. However, peak loads in the future will be much reduced by energy renovations in buildings, so peak load production will have less importance.

Considering that the main investments will be in geothermal heating plants, it may be advantageous to phase in geothermal heating plants at an earlier stage in order to develop the technology and cope with the problems that might occur during development. However, this would not influence our results as long as the capacity needed in the different scenarios remains the same.

When estimating the costs for the energy renovation measures envisaged in the present study, we assumed that energy renovations are carried out only when buildings need renovation anyway. This means that only the marginal cost for energy conservation was used. It is reasonable to assume that the existing building mass will need renovation within a period of 30–40 years because a majority of the buildings in Copenhagen are very old. It is also in accordance with visions for the building stock in Europe (Staniaszek et al., 2013).

The results from the economic calculations are very sensitive to the discount rate assumed. According to the Danish Finance Ministry and the ENS, a discount rate of 5% should be used in making cost estimates, but such high discount rates distort results when dealing with projects that have durations of many years because they affect future conditions significantly. Investments taking place in the future are discounted to small present values, making it attractive to delay any investments. The smaller the discount rate, the more importance is given to future conditions. The choice of discount rate for the conclusions drawn in this paper was therefore 0%—in order to give full importance to future generations.

The choice of service lifetime of the building, district heating network and geothermal heating plant is important since it might affect the results of the paper. The time perspective is often discussed and lots of literature and research can be found here upon. Different literature uses a wide range of lifetimes for buildings ranging from 30 to 100 years (Mithraratne, Vale, 2004; Verbeeck and Hens 2010; Marteinsson 2003; Scheuer et al. 2003, Kellenberger and Althaus, 2009, p. 819, Sartori and Hestnes, 2007, Ramesh et al., 2010; Grant and Ries, 2013; Aagaard et al., 2010). However, often a lifetime on 50 years, 80 years and 100 years are used (Ramesh et al., 2010; Sartori and Hestnes, 2007; Grant and Ries, 2013) and it therefore seems reasonable to have a building lifetime on 60 years as was chosen for this study. The service life time of DH pipes have also been discussed in the literature (Hallberg et al., 2012; Tang, 2010; Röse et al., 2002; DFF, 2004). The study (Hallberg et al., 2012) discusses the service life time for DH pipes to be at least 30–50 years and states that change of future operating conditions should be considered, since they may affect the service lifetime. Since the DH system is converted into LTDH the operating temperatures will decrease, which according to (DS/EN 253, Annex A, 2009) will increase the service lifetime of the DH pipes. If the operating temperature is $T \leq 109$ °C the service lifetime is expected to be 100 years. A study from Germany concludes that DH pipes that had been in operation for 30 years had a remaining lifetime on 38 years resulting in a service life time of 68 years (Röse et al., 2002, DFF, 2004). Therefore the chosen lifetime for the present paper of 60 years seems reasonable. The lifetime of the geothermal heating plants are set to 40 years. According to literature, lifetimes in the range of 20–40 years is often used (Goldstein et al., 2011; Frank et al., 2012; Frick et al., 2010; Lako and Tosato, 2010; Guo et al., 2013). The choice of service life for geothermal heating plant is in the higher end, but taking into account the development and the improvement of the technology over the years, longer lifetimes can be expected (Goldstein et al., 2011 – chapter 4.6), and it therefore seems as a reasonable number in 2030 when they are assumed to be phased in. The importance of the choice of lifetime and how it affects the results should be investigated in future research. However, it is beyond the scope of this paper.

The results of the present paper are different from other studies (Connolly et al., 2012a, 2012b) dealing with the future of district heating in the EU27 countries. They conclude that future supply from district heating is a more cost-effective energy efficiency measure than end-use savings. However, those studies include a large share of fossil fuels, so investment in renewable energy capacity is not critical for them, as it is for the study carried out in the present paper.

4. Conclusions

For the DH-system in the Copenhagen area, socioeconomic calculations indicate that it is slightly more cost-beneficial to invest in energy renovations from 2013, so that we can reduce the heat demand, before investing in new renewable energy supply technologies. However, the results are very sensitive to the discount rate assumed and the results from the socioeconomic calculations are very similar for all the scenarios. It does not make a great difference which scenario is chosen from a socioeconomic point of view. The costs for supplying heat and saving heat are at comparable levels.

However, investing in comprehensive energy renovations from today will reduce the investment cost for new supply technologies by 50%, or by 16% if investments in only intermediate renovation are made: replacement of old inefficient windows and installation of mechanical ventilation with heat recovery. The Danish government has already decided to aim at a fossil-fuel-free society in 2050, by saving energy in the building stock and by converting to RE-based supply. Strategies with regard to energy renovation of existing building stock have already been implemented in the Danish action plan towards a fossil-fuel-free society. The Danish Building Regulations include obligations to energy-upgrade buildings when they undergo improvements. Energy savings will therefore be implemented in the building stock sooner or later, and with this in mind it will be more beneficial to carry them out from today. Reducing heat demand by renovation also results in smaller peak loads and a more stable supply situation over the year, which is an advantage for the future energy system based on renewable energy resources, and gives an increased security of supply. Energy renovations also provide added value to buildings, in terms of increased indoor comfort and future-proofing. When the building undergoes an energy renovation the energy standard of the building is upgraded and the building reaches comparable levels with new buildings. This results in more secured market values for future resale.

If we look at the cost per heat unit delivered to the buildings, it is clear that carrying out energy renovations from today will result in more competitive conditions for the district heating companies than if energy renovations are carried out later on. This is also reflected in the fact that, when energy renovations are carried out, low-temperature district heating can be implemented, which reduces heat losses from the distribution pipes and results in more heat delivered to the buildings.

Based on the aim of Denmark being a 100% fossil-fuel-free society, this paper has investigated various scenarios of how to achieve this aim for the Copenhagen district heating system. The conclusion drawn from the study is that the time at which energy savings are implemented in the building stock is crucial for the district heating companies from an economic point of view.

The paper also provides a method for making use of the existing district heating system in Copenhagen by carrying out long-term planning for energy supply based on renewable energy sources and saving energy in buildings. The long-term analysis can be the foundation for political decision making and action in both areas.

Acknowledgments

This project was financed by Gate 21–Plan C, and all of the participants in the project team have contributed significantly to the making of this paper.

References

Atanasiu, B., Kouloumpi, I., Thomsen, K.E., Aggerholm, S., Enseling, A., Loga, T., Leutgöb, K., Rammerstorfer, J., Witczak, K., Nolte, I., Rapf, O., Staniaszek, D., Faber, M., Verheyen, L., 2013. Implementing the Cost-Optimal Methodology in EU Countries—lessons learned from three case studies. The Buildings Performance Institute Europe (BPIE), Brussels

Aagaard, N.J., Møller, E.B., Hansen, E.J.P., 2010. Levetider for bygningsdele omfattet af ejerskifteforsikring og huseftersynsordningen [Lifetime for building components including insurance for transfer of ownership and inspection of homes] SBi. Danish Building Research Institute, 2012. Aalborg University, Denmark p. 05.

Barras, R., 2009. Building Cycles: Growth and Instability. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

BR10 (Danish Building regulations), 2012. Danish Energy Agency. At: ⟨http://www.bygningsreglementet.dk/⟩ (accessed 17.12.12).

Connolly, D., Mathiesen, B.V., Østergaard, P.A., Möller, B., Nielsen, S., Lund, H., Persson, U., Nilsson, D., Werner, S., Trier, D., 2012a. Heat Roadmap Europe 2050, First pre-study for the EU27. Department of Development and Planning, Alborg University, at: ⟨http://www.4dh.dk/hre⟩ (accessed 29.10.13).

Connolly, D., Mathiesen, B.V., Østergaard, P.A., Möller, B., Nielsen, S., Lund, H., Persson, U., Werner, S., Grözinger, J., Boermans, T., Bosquet, M., Trier, D., 2012b. Heat Roadmap Europe 2050, Second pre-study for the EU27. Department of Development and Planning, Alborg University, at: ⟨http://www.4dh.dk/hre⟩ (accessed 29.10.13).

Copenhagen Municipality, 2013. Ressource-og Affaldsplan 2018. Kortlægningsdel [Resource- and Wasteplan 2018. Mapping part]. Copenhagen Municipality, at: ⟨www.kk.dk/ressourceaffaldsplan⟩ (accessed 29.10.13).

COWI, 2012. Personal Communication. Kgs Lyngby Denmark.

CTR, HOFOR, VEKS, 2009. Varmeplan Hovedstaden—Analyse af den fremtidige fjernvarmeforsyning i hovedstadsområdet [Heatplan Copenhagen—Investigation of the future district heating in the Copenhagen area]. Copenhagen, Denmark.

CTR, HOFOR, VEKS, 2011. Varmeplan Hovedstaden 2 Handlemuligheder for en CO_2-neutral fjernvarme [Heatplan Copenhagen 2—Options for CO_2-neutral district heating]. Copenhagen, Denmark.

Dalla Rosa, A., Christensen, J.E., 2011. Low-energy district heating in energy-efficient building areas. Energy 36, 6890–6899.

Dalla Rosa, A., Li, H., Svendsen, S., 2011. Method for optimal design of pipes for low-energy district heating, with focus on heat losses. Energy 36 (5), 2407–2418.

Danish Energy Agency, 2007a. Vejledning i samfundsøkonomiske analyser på energiområdet, Beregningseksempler [Guidelines in socio-economic analysis for energy related projects]. April 2005, Danish Energy Agency, Denmark.

Danish Energy Agency, 2007b. Appendiks: Forudsætninger for samfundsøkonomiske analyser på energiområdet [Requisites for socio-economic analyses in the energy field]. Danish Energy Agency, Copenhagen, Denmark.

Danish Energy Agency, 2009. Virksomhedsrentabel udnyttelse af overskudsvarme—samt afdækning af evt. potentiale [Profitable utilisation of waste heat from industry—potential]. ISBN:978-87-7844-782-1www, Copenhagen, Denmark.

Danish Energy Agency, 2010a. Grøn Energi—vejen mod et dansk energisystem uden fossile brændsler [Green Energy—the road towards a Danish energy system without fossil fuels]. Danish Energy Agency, Copenhagen, Denmark.

Danish Energy Agency, 2010b. Geotermi varme fra jordens indre—Internationale erfaringer, økonomiske forhold og udfordringer for geotermisk varmeproduktion i Danmark [Geothermal heat—International experiences, economics and challenges for geothermal heat production in Denmark]. ISBN-nr www: 978-87-7844-840-8, Denmark.

Danish Ministry of Climate, Energy and Buildings, 2011. Vores Energi [Our energy]. Copenhagen, Danish Energy Agency.

Danish Ministry of the Environment, 2013. Danmark uden affald. Genanvend mere–forbrænd mindre [Denmark without waste. Recycle more–incinerate less]. Copenhagen, Danish Ministry of the Environment, at: ⟨http://www.mst.dk/Virksomhed_og_myndighed/Affald/Ressourcestrategien_virk/⟩ (accessed 29.10.13).

DFF (Dansk Fjernvarmeværkers Forening—Danish District Heating Plants Association), 2004. Vurdering af restlevetid af præ-isolerede fjernvarmerør [Assessment of remaining lifetime of pre-insulated district heating pipes]. Project number: 2002-01, Danish District Heating Plants Association, ⟨http://www.dff.dk/Forside/FOgUKonto/~/media/FogU%20Konto/2002-01%20Restlevetid%20for%20pr%C3%A6isolerede%20r%C3%B8r.ashx⟩ (accessed 15.01.14).

Dolman M., Abu-Ebid M., Stambaugh J., 2012. Decarbonising heat in buildings: 2030–2050. Element Energy, AEA, The Committee on Climate Change, Cambridge.

DS/EN 253, 2009. /prA1. District Heating Pipes—Preinsulated Bonded Pipe Systems for Directly Buried Hot Water Networks—Pipe Assembly of Steel Service Pipe, Polyurethane thermal Insulation and Outer Casing of Polyethylene.

EEA (European Environment Agency), 2006. How much bioenergy can Europe produce without harming the environment? EEA Report no. 7/2006, ISSN 1725-9177, Copenhagen, Denmark.

Ege C., Appel M., 2013. Sætter vi den rette pris på fremtiden? [Are we putting the right price on the future?]. Published 18th of February 2013, the Ecological Council, Blegdamsvej 4B, 2200 Copenhagen N, Denmark, (in Danish), ⟨http://ecocouncil.dk/udgivelser/artikler/okonomi/2092-saetter-vi-pris-pa-fremtiden⟩ (accessed 13.06.13).

Ericsson, K., Nilsson, L.J., 2006. Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass Bioenergy 2006 (30), 1–15.

European Commission, 2013. Bruxelles. At: ⟨http://ec.europa.eu/environment/waste/⟩ (accessed 29.10.13).

Frank, E.D., Sullivan, J.L., Wang, M.Q., 2012. Life cycle analysis of geothermal power generation with supercritical carbon dioxide. Environ. Res. Lett. 7 (034030), 10, http://dx.doi.org/10.1088/1748-9326/7/3/034030.

Frick, S., Kaltschmitt, M., Schröder, G., 2010. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Energy 35, 2281–2294.

Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutierrez-Negrin, L., Huenges, E., Muraoka, H., Ragnarsson, A., Tester, J., Zui, V., 2011. Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlomer, S., von Stechow, C. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Grant, A., Ries, R., 2013. Impact of building service life models on life cycle assessment. Build. Res. Inf. 41 (2), 168–186, http://dx.doi.org/10.1080/09613218.2012.730735.

Guo, M., Ding, J., Liu, Y., 2013. A life-cycle assessment of geothermal heating project with low-temperature reservoirs in china. Adv. Mater. Res. 807–809, 294–300, http://dx.doi.org/10.4028/www.scientific.net/AMR.807-809.294.

Gustavsson, L., 1994a. District heating system and energy conservation—part I. Energy 9 (1), 81–91.

Gustavsson, L., 1994b. District heating system and energy conservation—part II. Energy 9 (1), 93–103.

Gustavsson, L., Dodoo, A., Truong, N.L., Danielski, I., 2011. Primary energy implications of end-use energy efficiency measures in district heated buildings. Energy Build. 43, 38–48.
Gustafsson, S.-I., Rönnqvist, M., 2008. Optimal heating of large block of flats. Energy Build. 40, 1699–1708.
Gustafsson, S.-I., 1992. Optimization of building retrofits in a combined heat and power network. Energy 17 (2), 161171.
Hallberg, D., Stojanović, B., Akander, J., 2012. Status, needs and possibilities for service life prediction and estimation of district heating distribution networks. Struct. Infrastruct. Eng. 8 (1), 41–54, http://dx.doi.org/10.1080/15732470903213740.
Harrestrup, M., Svendsen, S., 2013. Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating. Int. J. Sustain. Energy , http://dx.doi.org/10.1080/14786451.2013.848863
HOFOR, 2012. (Personal communication), Copenhagen S, Denmark.
Kellenberger, D., Althaus, H., 2009. Relevance of simplifications in LCA of building components. Build. Environ. 44, 818–825.
Kragh, J., 2010. Energirenovering af etagebyggerier [Energy renovation of building blocks], 1st edition Danish Knowledge Centre for Energy Savings in Buildings, Taastrup, Denmark
Kragh J., Wittchen K.M., 2010. Danske bygningers energiforbrug i 2050 [Energy consumption in Danish buildings in 2050]. SBi, 2010, 56, Danish Building Research Institute, Aalborg University.
Lako, P., Tosato, G., 2010. Geothermal Heat and Power, Energy Technology System Analysis Programme (ETSAP). International Energy Agency (IEA), Paris, France
Lechtenböhmer, S., Schüring, A., 2011. The potential for large-scale savings from insulating residential buildings in the EU. Energy Effic. 4, 257–270.
Lund, H., Möller, B., Mathiesen, B.V., Dyrelund, A., 2010. The role of district heating in future renewable energy systems. Energy 35 (3), 1381–1390.
Persson, U., Werner, S., 2011. Heat distribution and the future competitiveness of district heating. Appl. energy 88 (2011), 568–576.
Mahler A., Magtengaard J., 2010. Country update report for Denmark, DONG Energy, World Geothermal Congress, Bali, Indonesia, 25–29, Denmark.
Marteinsson, B., 2003. Durability and the factor method of ISO 15686-1. Build Res Inf 31, 416–426.
Mithraratne, N., Vale, B., 2004. Life cycle analysis model for New Zealand houses. Build. Environ. 39, 483–492.
Ramesh, T., Prakash, R., Shukla, K.K., 2010. Life cycle energy analysis of buildings: An overview. Energy Build. 42, 1592–1600.
Rasmussen, T.V., 2010. Post-Insulation of Existing Buildings Constructed between 1850 and 1920. Department of Construction and Health, Danish Building Research Institute. Aalborg University, Hørsholm
Röse, A., Hoffmann, H.W., Grage, T., 2002. Remaining useful life of pre-insulated bonded pipes. Euroheat Power/Fernwarme Int. 31 (3), 72–76.
Sartori, I., Hestnes, A.G., 2007. Energy use in the life cycle of conventional and low-energy buildings: a review article. Energy Build. 39, 249–257.
Scheuer, C., Keoleian, G.A., Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy Build. 35, 1049–1064.
Staniaszek, D., Rapf, O., Faber, M., Nolte, I., Bruel, R., Fong, P., Lees, E., Verheyen, L., 2013. A Guide to Developing Strategies for Building Energy Renovation–Delivering Article 4 of the Energy Efficiency Directive. The Buildings Performance Institute Europe (BPIE), Brussels
Statistics Denmark, 2013. Sejrøgade 11, 2100 Copenhagen Ø, Denmark, 〈http://www.statistikbanken.dk/statbank5a/default.asp?w=1486〉 (accessed 13.06.13).
Stern, N., 2007. Stern Review: The Economics of Climate Change. Cambridge University Press, pp. 23–52
Tang J., 2010. Notat: Fjernvarmeprisen i Danmark 2010 (in Danish) [Note: District heating award in Denmark 2010] Danish district Heating Association, Kolding, Denmark. 〈http://www.danskfjernvarme.dk/Faneblade/HentMaterialerFANE4/Fjernvarmepriser.aspx〉 and http://www.danskfjernvarme.dk/Faneblade/HentMaterialerFANE4/~/media/Medlemmer/Cirkulærer/2010/Bilag%20til%20cirkulære%202689%2010%20%20%20Notat%202010%20varmeprisen.ashx (accessed 13.06.13).
Tol H.I., Svendsen S., 2012a. Operational planning of low-energy district heating systems connected to existing buildings. In: Proceedings of the International Conference on Renewable Energy: Generation and Applications, ICREGA 12, Al-Ain, United Arab Emirates.
Tol H.I., Svendsen S., 2012b. Optimal dimensioning of low-energy district heating networks with operational planning—case study for existing buildings. In: Proceedings of the 11th International Conference on sustainable Energy Technologies, Vancouver, Canada.
Tommerup H. et al., 2010. Energirenoveringstiltag—katalog [Energy renovation initiative—catalogue], DTU Byg-Rapport R-223, Department of Civil Engineering, Technical University of Denmark.
VEKS, 2012a. Vestegnens Kraftvarmeselskab I/S; DK-2620. Albertslund, (Personal communication), Denmark.
VEKS, 2012b. Excel-sheet: Samføko VEKS sep 2012 v1. Vestegnens Kraftvarmeselskab I/S, 2620 Albertslund, Denmark.
Verbeeck, G., Hens, H., 2010. Life cycle inventory of buildings: a calculation method. Build. Environ. 45 (4), 1037–1041.
Worm J. et al., 2011. EUDP 2008—II, part 2: Demonstration af lavenergifjernvarme til lavenergibyggeri i Boligforeningen Ringgårdens afd. 34 i Lystrup [EUDP 2008—II, part 3: Miscellaneous investigations, CO_2-reductions in low-energy buildings and communities by implementation of low-temperature district heating systems. Demonstration cases in EnergyFlexHouse and Boligforeningen Ringgården], 〈http://www.byg.dtu.dk/Publikationer/Byg_rapporter.aspx〉 (accessed 13.06.13).
Østergaard, P.A., Lund, H., 2011. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl. Energy 88, 479–487.
Østergaard, P.A., Mathiesen, B.V., Möller, B., Lund, H., 2010. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 35, 4892–4901.