Techno-economic optimization of a local district heating plant under fuel flexibility and performance

Abstract

Brovst is a small district in Denmark. This paper analyses the use of local renewable resources in the district heating systems of Brovst. The present use of fossil fuels in the Brovst DHP (district heating plant) represents an increasing environmental and climate-related load. Therefore, an investigation has been made to reduce the use of fossil fuels for district heating system and make use of the local renewable resources (Biogas, solar and heat pump) for district heating purposes. In this article, the techno-economic assessment is achieved through the development of a suite of models that are combined to give cost and performance data for this district heating system. Local fuels have been analyzed for different perspectives to find the way to optimize the whole integrated system in accordance with fuel availability and cost. This paper represents the energy system analysis mode, energyPRO, which has been used to analyze the integration of a large scale energy system into the domestic district heating system. A model of the current work on the basis of information from the Brovst plant (using fossil fuel) is established and named as a reference option. Then four other options are calculated using the same procedure according to the use of various local renewable fuels known as "Biogas option," "Solar option," "Heat pump option" and "Imported heat option." A comparison has been made between the reference option and other options. The greatest reduction in heat cost is obtained from the Biogas option by replacing a new engine where 66% of the current fuel is substituted with biogas.

Keywords: Techno-economic; Fuel flexibility; District heating; Brovst.

1. Introduction

The Danish Government's policy is that Denmark must be a green sustainable society. At present the share of renewable energy is coming close to 20 %. From such point of departure, a scenario framework has been established in which the Danish system is converted to 100 % Renewable Energy Sources (RES) by the year 2060 including reductions in space heating demands by 75 % [1]. As an example, the conversion of the Danish city of Frederikshavn to a 100% RES based energy system within a short span of time has been studied [2]. In recent years, environmental issues have led to an even greater interest in DH supply in areas where fossil fuels are the most important energy source. The optimum use of the fuel and the cleaning of the exhaust gases and thereby limitation of the pollution is easier to realize in decentralized heat production. Therefore, one of the steps for those aims is to optimize the decentralized district heating plant by reducing fossil fuel use and introduce locally available renewable resources as the primary fuel for those power plants.

The problem of balancing heat and electricity production with restrictions in biomass fuels, grid connections and consumer demands has been analyzed thoroughly with a focus on specific systems [3, 4]. Different models of a district heating system have been described where some of the papers emphasized the dynamics of the network and others considered the unit sizing method [5-7]. Demand side management has also been well-described [8, 9], including analyses of the influence on demand distribution, such as peak load reduction or flexible demands. A technical scenario has been described and developed for the transition of a Danish local energy supply from being predominantly fossil fuelled to being fuelled by locally available renewable energy sources [10]. A study of the Danish experience with methodologies and software tools has been done to design investment and operation strategies for almost all small CHP plants [11]. The changes in such methodologies and tools in order to optimize performance in a market with fluctuating electricity prices have been presented and discussed in the same paper. A simple linear programming model has been presented to determine the optimal strategies that minimize the overall cost of energy for the CCHP (Combined cooling, heating and power) system. It has been shown that the optimal operation of this system was dependent upon heat load conditions to be satisfied [12]. A recent comparison [13] of the features of different software packages available in the market (for instance AEOLIUS, COMPOSE, energyPRO, EnergyPLAN, HOMER, INFORSE, TRNSYS16 and some custom built models) has shown some positive characteristics of using techno-economic optimization. This paper concluded that energyPRO is a powerful and flexible application in terms of modeling different scenarios. It allows prioritizing in terms of which production units operate first, which is an advanced capability that none of the similar software tools have. In Denmark, most small district heating and CHP plants have been designed using this computer tool [11]. For the above reasons energyPRO has been chosen for the analysis in this present study.

Some of the studies have been done to reduce the combustion of fossil fuels and to introduce or expand the use of CHP by which the fuel efficiency in the system is improved [14-17]. The Danish government subsidized the construction of cogeneration plants during the 1980s, even in small and medium scale applications [18], where most of them are using natural gas for their production. The government made these changes primarily for environmental reasons and also less dependent on oil imported from the Middle East.

Techno-economic analysis of energy system is a key issue in the design of more sustainable development models. The Brovst DHP is optimized by using a techno-economic program called energyPRO that helps to decide the type of components and fuels used as well as the most profitable method of operating. Furthermore, it is desirable that the system is efficient and environmentally friendly. The objective of this paper is to promote the most efficient and economic utilization of Brovst DHP according to fuel flexibility and reduce the dependency on fossil fuels.

2. Case study

Brovst is one of the district heating plants in the Jammerbugt municipality. Fig .1 shows the thermal basis for the 12 district heating plants in this municipality and the primary fuels used for those plants. The total heating base is 252,200 MWh/year, of which four major plants (Fjerritslev Aabybro, Jetsmark and Brovst) jointly produced 78% of the total heat production (Fig.1). Seven of the plants have natural gas as the primary fuel, four of them have woodchips, and one (Vr. Hjermitslev) has biogas. The Brovst is one of the plants that only use natural gas as its primary fuel for production. Brovst DHP was selected for this case study and shows ways of reduce the use of fossil fuels. The present heating system of this power plant is described here. Heat demand for this DHP is approximately 37,200 MWh/year (Fig.1). Fig. 2 shows the real hourly pattern of the yearly thermal demand of the Brovst district heating plant. In the summer season especially from June to August, heat demand is lower than others months of the year due to less use of hot water. The Brovst plant has 1,285 customers on its network both individual housing and industrial. Right now it has two natural gas generator sets with output of 3.1 MW electricity and 4.1 MW of heat. Produced electricity is sold to the public grid. It also has boilers with 8.15 MW heat production. Table 1 shows different units, primary fuels and their production rates. A 1600 m^3 storage tank has been installed in this plant. The boilers are of the condensing type and their efficiency is greater than 100% on an LHV basis. There is an emergency generator which can provide electricity in emergency situation, so heat is maintained at all times.

2.1 Method

The energyPRO computational procedure is used for this techno-economic optimization [19] and it is a software tool used for modeling energy systems including district heating plants [18]. Carrying out feasibility studies for district heating plant is one of the most important steps in the decision-making process, allowing a comprehensive, integrated and detailed technical-financial analysis.

energyPRO has three different modules: design, finance and accounts. The design module includes the design and optimization of a specific operation year. The finance module allows the project to evaluate over a number of years, and detailed cash flows can be obtained. The accounts module allows a deeper level of financial analysis including taxes, depreciation. In all these modules, the user must define the demand profiles, the equipment, fuel and electricity tariffs, and the plant control strategy. This model calculates annual productions in steps of, typically, one hour. The inputs are capacities, efficiencies and hour-by-hour distributions of heat demand and electricity sales prices. The period of optimization is divided into calculation periods, where everything is constant, for example temperature, solar radiation, priorities, heat demand, electricity demand, cooling demand, production capacities and fuel deliveries.

The traditional method of calculating energy production is to make chronological hour-by-hour calculations, trying to take into account that, for example, production during night hours may fill the thermal storage for future use [20]. This hinders more attractive production from being placed in the morning of the following day. To secure productions in the most favorable periods, energyPRO works in the opposite way, not performing chronologically but producing in the most favorable periods. This has the consequence that each new production has to be carefully checked not to disturb already planned productions, before being accepted. In the case of energyPRO, before accepting a new production it checks the new production does not create overflow in the thermal stores in the future – taking into account the already planned productions. In the simulation of thermal storage calculation need the following to be defined: volume, temperature in the top and bottom, capacity, operation restricted to period, annual non-availability periods and storage loss.

So for each future time interval the following formula is used:

$$ST_e[i,t] = ST_b[i,t] + (O_{ap}[i,t] - DE[i,t]) \times dt \tag{1}$$

Where, ST_e and ST_b are the end and beginning content in the storage for a time interval.

O_{ap} is output already planned.

DE is demand.

dt is length of time interval.

The Danish experience for CHP (Combine Heat and Power) plants has shown regulation strategies regarding the energyPRO simulations [21, 22]. In many cases, CHP plant has invested in an intelligent Programme Logic Controller (PLC)-based Supervisory Control and Data Acquisition system (SCADA) for controlling the plant. Using this system differentiates for each day when to switch on and off the CHP at different hours or at different contents of the thermal storage. Detailed energyPRO models of specific plants provide valuable information for the operators to identify input data for the SCADA systems.

Fig. 3 shows the different steps of this techno-economic optimization. Data collection has been done by visiting that plant. Spot market data was collected from Nordic power pool [23] using their website. After getting the economic evaluation from different options, best option will be selected by comparing the net heat production price.

Based on general experience of simulating CHP plant, a practice of adjusting energyPro simulations for DHP will be developed. This type of calculation can be used to identify economical plant configuration; the optimization results are strongly dependent on the sales pricing conditions and also fuel prices taxes and financial costs. Such kinds of calculation are included in this present study and will be discussed in the following analysis.

3. The energyPRO Model and Simulation

The energyPRO model is an input/output model which has three main sections: the input data structure, the editing window and the report structure. General inputs are demands, capacities and the choice of a number of different regulation strategies, putting emphasis on production of heat and electricity. Outputs are energy balances and resulting annual productions, fuel consumption and import/exports. The period of optimization is divided into calculation periods, where everything is constant, e.g. temperature, solar radiation, priorities, heat demand, electricity demand, cooling demand, production capacities, fuel deliveries etc.

The Brovst district plant has an arrangement of gas engines, boilers and a heat storage tank. Heat demand is specified either by an annual amount of energy and a distribution or by a time series. If for instance a demand is degree-day dependent, a time series folder with ambient temperatures must be placed in "External conditions" and selected when describing yearly variations in demand. There are several options to modify the distribution of a demand during a day, week, month or year.

In simulation the "External conditions" folder serves as parent folder for indexes, time series and its functions in each option. It can be accessed from several of the other editing windows in which the project is specified such as sunlight temperature in Denmark, Danish spot market analysis. In energy conversion units, it could change the fuel type and amount and operation time according to the requirement.

Five different options are calculated in this simulation. The first option of the present the Brovst district heating plant on the basis of information from the plant is established and this is known as the “Reference option.” The Reference option is then used as the basis for individual solutions. The simulations are done for Biogas, Solar, Heat pump and Import heat (heat from Aalborg) options.

There are five areas in energyPRO containing formula fields and each of those areas has a set of standard mathematical functions and some specialized functions [19], especially the time series, demand, energy and economy sections. Directly and indirectly, the time series is a core object in all of the five energyPRO models. Energy systems do often require the use of thermal stores to reach cost-efficient solutions. Two of the main reasons for this condition are heat load situations during summertime and fluctuating electricity tariffs.

The models in these simulations are based on different assumptions. The plant-specific assumptions informed by the work are also mentioned for the simulation. Time series covering the period from January 1, 2010 until January 1, 2011 are used in the simulations of the various systems. The general assumptions (for example energy prices) for these simulations are contained in Table 2. All the prices are in DKK (Danish kroner) and converted euro (€) by considering 7.5 DKK (Danish kroner) = 1 €. Table 3 shows the different emission charges of the Brovst plant which are used in the simulation. Process diagram was drawn in the editing window and then all the necessary data has entered in the input data structure. The five options use the same methodology. All those options are describing briefly bellow:

3.1 Reference option:

For the reference model, only natural gas is used as a fuel for both engines and boiler. Natural gas consumption is 4,952,694.6 Nm^3. The model of the energy system and the applied operation strategy (user defined or auto calculated) determines the production and consumption of the production units. All data provided on the present heating section, table 2 and table 3, is also used as assumptions for the simulation of this reference option.

3.2 Biogas option:

For this option, the plant's one engine is replaced by a new engine (enbacher 620) with a power of 2737 KW_{el} that can run on both biogas and natural gas. Another engine and boiler use natural gas. Biogas and natural gas consumptions are respectively 5,437,003 Nm^3 and 407,749.5 $Nm^{3.}$ Heat value of biogas is 6.50 KWh/Nm^3. The charges for rebuilding a biogas engine and other accessories are presented in table 4.

3.3 Solar option:

The area for establishing solar thermal collectors is around 10,500 m^2. Fig. 4 shows the time series in the planning period with daily temperatures in Denmark. The necessary data can be collected from the NCAR (National Center for Atmospheric Research) website [19]. There are some 100 m transmission lines with the existing heat storage tank. This option also uses natural gas, consumption is 3,152,694.6 Nm^3 for the engines and boilers as all of them are active for heat and electricity production and the operating expenses are assumed as 0.8 €/MW. Investment for solar collector is based on the price curve from ARCON[a] (for solar collector between 500 m^2 and 20,000 m^2). One year's production from a solar heating system is required energy savings. The market price for energy is assumed to be 33.33 €/MWh. With an output of approximately 500 kWh/m^2/year, this gives a value of 16.67 €/m^2 which is equivalent to 6% of the investment. In the solar heating calculation, the values of the energy savings have been subtracted from the investment.

a. http://www.arcon.dk/

3.4 Heat pump option:

A compression heat pump of 5 MW_{heat} is established for heating purpose and must be considered in the energy conversion unit with others engines and boilers. The heat pump uses groundwater as a heat source. Reservations are made to obtain the necessary amount of groundwater in the plant area. In this option, natural gas consumption is 1,956,981Nm^3. Table 5 shows some of the necessary information regarding "Heat pump option" simulation.

3.5 Import heat option (Heat from Aalborg):

There is one heat transmission pipeline of 40 km from Aalborg to Brovst. The capacity is 7.2 MW with a pipe dimension of DN (Diameter Nominal) 200. A DN 200 twin pipe Series 2 has a heat loss of 920 kW = 8,060 MWh / year. Heat losses for the different pipes are shown in table 6. Total investment for heat exchangers, pumps and other accessories is around 0.067 million. The investment for transmission twin pipe per meter (Series 2) is represented by the following equation: 4 * Ø + 133.33 [€/m], where Ø is the pipe DN number and this formula is based on pipe prices from DN 100 to DN 450.

3.6 Economic analysis:

For economic optimization, this study introduces a simple method using the results from the simulation. Table 7 shows some of the components of cost estimates. The optimization of DHP in the previous options has been performed to meet the Danish triple tariff and the price setting in the Nord Pool electricity market [23]. In the simulation, it is also necessary to select market type according to electricity market section. The production costs are defined as the long term marginal costs of producing electricity on a combined cycle power station. Such costs include fuel, operation and maintenance costs and investment costs. The investment costs are adjusted by the net price index, and the fuel costs are adjusted according to international fuel prices. The rest of the parameters are fixed by the law. The main result from simulation is the annual operating result (excluding income from sales of heat). Net Heat Production Cost (NPC) is calculated by dividing operating costs by the produced heat. After investment needs of the individual solutions are estimated, the cost of capital (CC) will be projected. A good comparison between the solutions will be obtained by allocating capital cost of the produced heat. The sum of the NPC and CC is called GPC (Gross Production Cost). And the appropriate fuel will be selected from different fuel sources according to the net GP. Finally, the data will be used for further simulation on a large scale and combined into one system which will be more efficient according to performance, environment and cost.

4. RESULTS

The techno-economic optimization of the Brovst district heating plant in a competitive market is both a matter of investment design as well as operation performance. Operation performance should be considered in the initial designing of the plant including the size and number of DHP-units as well as possible heat storage facilities. To best utilize heat sale prices and optimize revenue calls depend on the engine capacity and heat storage facilities as well as the ability to start, stop and, maybe, part load DHP units.

All of the following identification of optimal Brovst heating plant’s options are compared with the existing reference option consisting of natural gas engines and boilers. The comparison of heat production from engines and boilers for all the options are illustrated in fig.5. In the reference option, the heat is generated by natural gas, 41% by the engines and 59% by the boilers, respectively. For the Biogas option, engine 1 produced most of the heat (approximately 25000 MWh/year) as it uses both biogas and natural gas. This solution assumes that plant authority need to buy 7.4 million Nm^3 of biogas per year delivered to the plant. The financial benefit of this solution comes mainly from the subsidy for biogas based power generation at 0.054 € /kWh (1.11 million €/year). Heat production is produced by 66% of biogas, 13% natural gas engines and 21% natural gas boilers. The solar option proposal establishes a solar heating system of 10,500 m^2 which comes from an economic optimization point of view. More than 20000 MWh/year of heat is produced by the boiler from the 10,500 m^2 solar panel. The plant produces 5200 MWh per year, equivalent to an annual solar penetration of 14%. The remaining heat is produced from natural gas engines (31%) and boilers (55%). The Solar option leads to a reduction in heat price of 3.33 € /MWh. It has a relatively modest impact on heat cost due to limited sun coverage. The pump solution proposal establishes a groundwater heat pump based on 5 MW heat. The heat pump produces 72% of the heat and the remainder is produced with natural gas engines (23%) and boilers (5%). The solution proposed by heat from Aalborg establishes a 40 km long heat transmission line from Aalborg to Brovst. And in this case, Brovst has 42641.5 MWh/year (Fig. 5) of heat with the transmission loss is relatively higher than other options. The heat was purchased for 38.67 €/MWh, resulting in a total net generation price of 35.87 €/MWh. The solution was weighed down partly by the heat losses in the transmission line (22%) and partly by significant investment where the cost of capital is 20.93 €/MWh. In the heat pump option, 94% of the heat comes from Aalborg, 5% from natural gas engines and 1% from the boilers (Fig. 5). It should be mentioned that there is considerable uncertainty on the investment because the price of transmission lines is very flexible.

Fig. 6 shows that the amount of electricity produced from engine 1 is greater than that of engine 2 in all cases. For the biogas option, engine 1 has generated 20,499 MWh/year which is the highest electricity production similar to the previous heat production.

A thermal store is one way of solving this mismatch between the need for electricity and heat. The duration curve of heat demand and production from the all components for the Biogas option is shown in fig. 7, with the black single line expressing heat production. It shows that the production does not hour by hour match the demand. The reason is that a thermal store is displacing production in order to operate the plant more efficiently.

The annual demand for and annual generation of 37,200 MWh for the Brovst District Heating results in operating expenses of 1.95 million €/year, equivalent to a net generation price (NPC) of 52.53 €/MWh. The investment cost for different options is shown in table 8, as well as a comparison of NPC, CC and GPC. In the case of import heat from Aalborg, total investment cost and capital cost are relatively higher than the other options.

Fig. 8 shows the different heat production price according to the fuel options. The best option for saving money is the Biogas option where it is possible to save 28.5 €/MWh considering the reference case as zero savings. To transfer heat from Aalborg to Brovst, takes almost 4.4 € /MWh more than the reference option. Though the price per MW heat is 0.67 € higher for the heat pump case, it is preferable to select this option rather than the solar option as it uses relatively less natural gas.

It is important to be aware that the actual prices can be both higher and lower than the calculated values. Also, the dimensioning of the individual solutions are based on qualified estimates, and therefore it is possible that further optimization of the proposals could result in lower heating rates than those presented in this paper.

5. CONCLUSIONS

Locally available renewable energy resources should be considered when an energy system is designed and analyzed by a systems analysis model, yielding results on an aggregate annual level as well as on an hourly basis. The purpose of the calculations presented in this paper has been to optimize the Brovst DHP according to reduction of heat production price. The different combinations are ordered to provide for a qualified basis to make a preliminary sorting of the suggestions. It shows the price of heat production for different options. By getting individual solutions from simulations, this study combines all the economic outcomes for making a decision regarding fuel selection and engine performance. This work concludes that the best solution is to combine a gradual expansion of the district heating production with the biogas option where 66% heat is produced by using biogas, 13% natural gas engines and 21% natural gas boilers. The next best option is the Heat pump option as it uses less fossil fuel than the solar option. Furthermore, this municipality considers a joint distribution and production of geothermal heat to be established as a municipal cooperation which may serve the nearby localities. It also helps to reduce the heat production from natural gas in Biogas option.

This conclusion is valid both in the present systems, which are mainly based on fossil fuels, as well as in a potential future system based on 100 % renewable energy. Since the fuel prices and other taxes are similar in the Jammerbugt municipality, this techno-economic optimization method could be applied for the other heating plants in that municipality. The modeling approach is also usable for other investigators who want to optimize operation strategies and plant designs. In that case, they only need to change the input data according to the actual conditions.

ACKNOWLEDGMENTS

The project has been supported by The European Regional Development Fund, grant No: ERDFN-09-0060. The authors would like to thank Niels From from PlanEnergi for his valuable discussion and contribution in the simulation.

REFERENCES

[1]. Lund H, Moller B, Mathiesen BV, Dyrelund A. (2010) The role of district heating in future renewable energy systems. Energy 35, 1381–90.

[2]. Lund H and Østergaard P. A. Sustainable towns: The case study of Frederikshavn 100% renewable energy. Chapter 11.

[3]. Jurado F, Cona A, Carpio J. (2003). Modelling of combined cycle power plants using biomass. Renewable Energy 28,743–53.

[4]. Ro K, Rahman S. (2003) Control of grid-connected fuel cell plants for enhancement of power system stability. Renewable Energy 28, 397–407.

[5]. Ryohei Y. and Koichi I. (2002). Optimal design of energy supply system based of relative robustness criterion. Energy conversion and management 43:499-514

[6]. Atli B, Benny B and Hans F R. (1995) Operational optimization in a district heating system. Energy conversion and management 36(5), 297-314

[7]. Colmenar-Santos A. , Rosales-Asensio E. , Borge-Diez D., Mur-Pérez F. (2015). Cogeneration and district heating networks: Measures to remove institutional and financial barriers that restrict their joint use in the EU-28, Energy, 85(1), 403 – 414.

[8]. Lund H. (1999) Implementation of energy-conservation policies: the case of electric heating conversion in Denmark. Appl Energy 64:117–27.

[9]. Nielsen EH. Experience of environmental management in the Danish fish-processing industry. In: Environmental management systems and cleaner production, Wiley.

[10]. Lund H., Østergaard P. A. (2011). A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Applied Energy 88, 479–87.

[11]. Lund H., Andersen AN. (2005). Optimal designs of small CHP plants in a market with fluctuating electricity prices. Energy Conversion and Management 46, 893–904.

[12]. Kong XQ, Wang RZ, Huang XH. (2005). Energy optimization model for a CCHP system with available gas turbines, Journal of Applied Thermal Engineering 25, 377–91.

[13]. Connolly D, Henrik L, Mathiesen BV, Leahy M. (2010) A review of computer tools for analyzing the integration of renewable energy into various energy systems. Applied Energy 87, 1059–82.

[14]. Torchio MF, Genon G, Poggio A, Poggio M. (2009) Merging of energy and environmental analyses for district heating systems. Energy 34(3): 220–7.

[15]. Hvelplund H, Ingermann F, Kask K. (2000) Estonian energy system – proposals for the implementation of a cogeneration strategy. Energy Policy 28(10), 729–36.

[16]. Fragaki A, Andersen AN, Toke D. (2008). Exploration of economical sizing of gas engine and thermal store for combined heat and power plants in the UK. Energy 33(11), 1659–70.

[17]. Brkic D, Tanaskovic TI. (2008). Systematic approach to natural gas usage for domestic heating in urban areas. Energy 33(12),1738–53.

[18]. Hendriks, C, Blok K, (1996) Regulation for combined heat and power in the European Union. Energy Conversion and Management 37 (6–8), 729–734.

[19]. energyPRO Users Guide, EMD International A/S, Aalborg, < www.emd.dk > April 2014.

[20]. Lund H, (2010)The implementation of renewable energy systems lessons learned from the Danish case, Energy 35: 4003–09.

[21]. Andersen AN, Mæng H. EnergyProGrid- working paper 2 2004. Aalborg, Denmark: Department of Development and Planning, Aalborg University. See also: http://plan.aau.dk/GetAsset.action?contentId¼43592310&assetId¼43614793;2004.

[22]. Østergaard P. A. (2010). Regulation strategies of cogeneration of heat and power (CHP) plants and electricity transit in Denmark, Energy 35, 2194-2202

[23]. El-Spot, Time Values from 2008, Available from: http://www.nordpoolspot.com/

[24]. DONG Energy in 2008, Available from:

http://www.dongenergy.dk/erhverv/Naturgas/prisaftale/Listepris/Pages/erhvervspris_sep.aspx

Table captions

Table 1: Primary fuel, heat and power output of Brovst plant.

Unit	Fuel -	Thermal input KW	Heat Production(η) KW	Electricity Production(η) KW
Engine 1	Natural Gas	7654	4100(53.6%)	3100(40.5%)
Engine 2	Natural Gas	7654	4100(53.6%)	3100(40.5%)
Boiler 1-2	Natural Gas	7913	8150(103.0%)	-

Table 2: Technical input for the simulation

The annual heat demand	37 200 MWh
Temperature of hot water supply	around 80˚ C (winter) around 75˚ C (summer)
Recycle water temperature	around 37˚ C (both summer and winter)
Storage water temperature	around 95˚ C
Heat storage tank capacity	1600 m^3
Natural gas fuel price	0.472 €/Nm^3 [24]
El-Spot	Time Values from 2008 (unweighted annual mean = 56.13 € / MWh) [23]

Table 3: Charges for emissions

Fuel tax	0.3 €/Nm^3 (2010)
CO_2 tax, engine	0.047 €/Nm^3 (2010)
NO_X-duty engine	0.0037 €/Nm^3 (2010)
CO_2 tax, boiler	1.573 € / GJ (2010)
CO_2 allowances	13.33 € / ton

Table 4: Cost of rebuilding engine for biogas.

Biogas price	0.29 €/Nm^3
Reconstruction of Jenbacher Series 600	0.16 million €/piece
Reconstruction of Jenbacher Series 300 and 400	0.12 million €/piece
Miscellaneous:	0.067 million € / work

Table 5: Heat pump investment including groundwater drilling

COP	2.5
Investment, heat pump	0.4 million € / MW_{heat}
Investment, drilling and others. (10%)	0.04 million € / MW_{heat}
Investment, power supply	0.05 million € / MW_{heat}
Investing, switching to work	0.067 million €
Operating expenses	1.33 € / MWh_{heat}

Table 6: Heat loss of different pipes at 80 ° C/40 ° C

DN 80, 100, 125	13 W / m
DN 150	15 W / m
DN 200	23 W / m
DN 250	26 W / m
DN 300, 350, 400, 450, 500	35 W / m

Table 7: General requirements of capital cost estimates

Inflation rate	2% per year
Depreciation Period:	
For transmission Cables, district heating, solar and heat pump	20 years
For Other investments	10 years
Loan:	
Interest rate	5% per annum
Maturity	As the amortization period
Performance	Inflation is not applicable for first year

Table 8: Economic evaluation of Brovst heating plant according to the fuel selection

Brovst district heating plant		Investment	Net heat Production Cost (NPC)	Capital Cost (CC)	Gross production Cost (GPC)
Unit		M €	€/MWh	€/MWh	€/MWh
0	Reference	0.0	52.53	0	52.53
1	Biogas	1.33	19.33	4.67	24
2	Solar	2.44	43.87	5.2	49.07
3	Heat Pump	2.53	39.73	8.8	48.53
4	Heat from Aalborg	9.73	35.87	20.93	56.8

M €- million euro

Figure captions:

1. Fig.1: Heat demand and primary fuels for the 12 district heating plants in Jammerbugt municipality.
2. Fig 2: Heat demand during whole year
3. Fig.3: Steps of techno-economic optimization.
4. Fig 4: Variation of solar heat during a year.
5. Fig.5: The heat production according to different fuels.
6. Fig.6: The electricity production according to different fuels.
7. Fig.7: Duration curve of heat demand and production.
8. Fig. 8: Variation of heat production price according to different fuel options

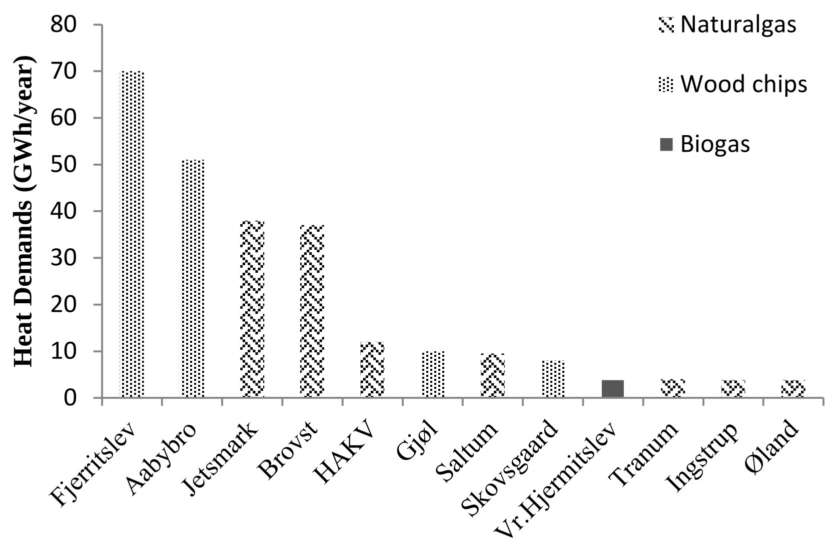

Fig.1: Heat demand and primary fuels for the 12 district heating plants in Jammerbugt municipality.

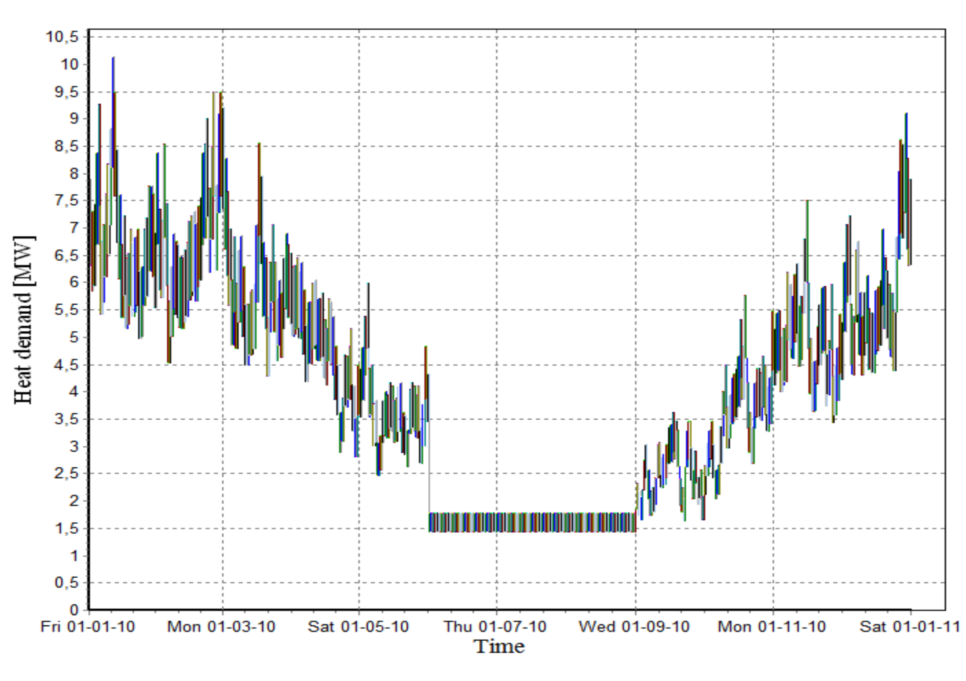

Fig 2: Heat demand during whole year

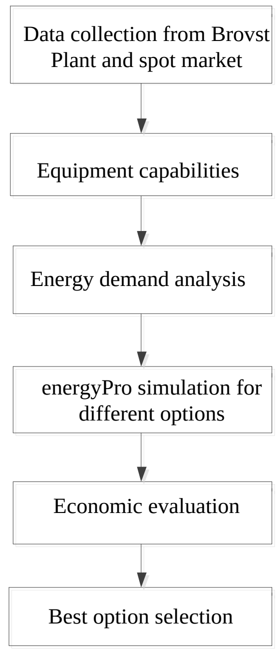

Fig. 3: Steps of techno-economic optimization.

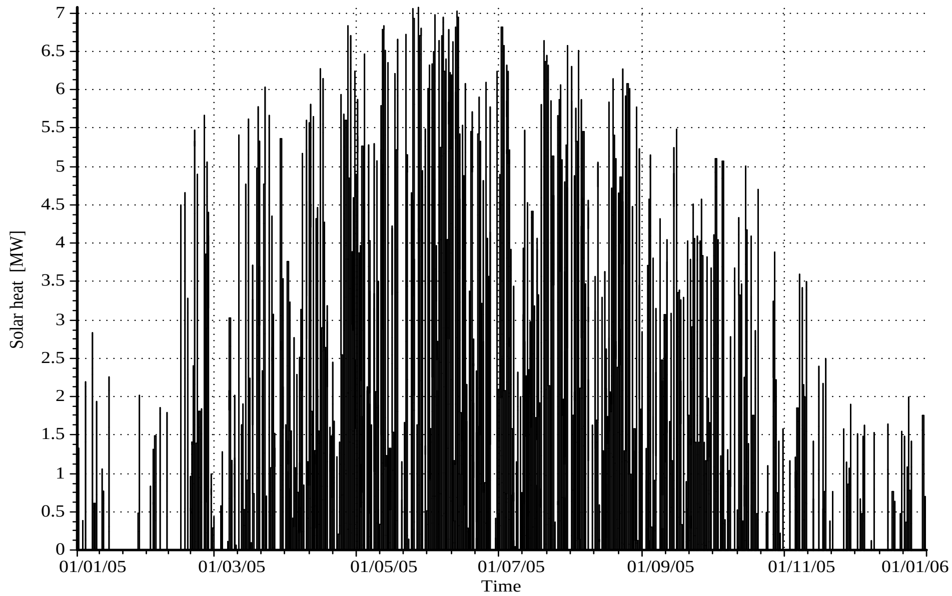

Fig 4: Variation of solar heat during a year.

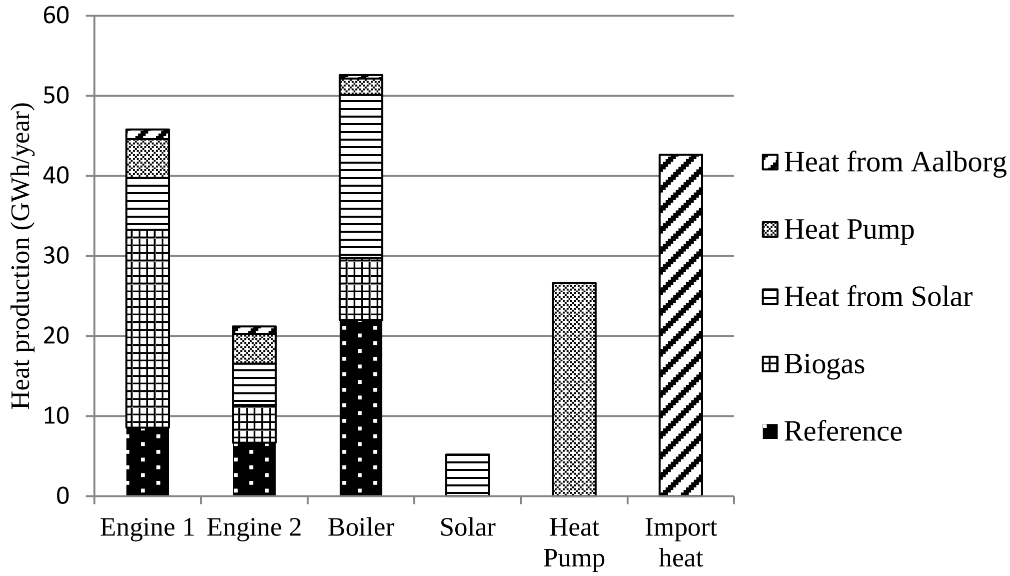

Fig. 5: The heat production according to different fuels.

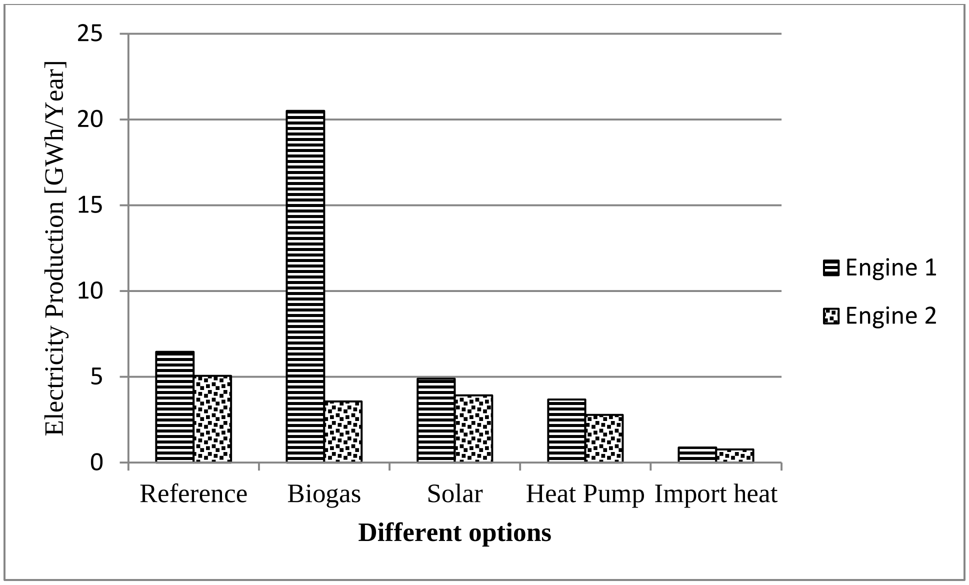

Fig. 6: The electricity production according to different fuels.

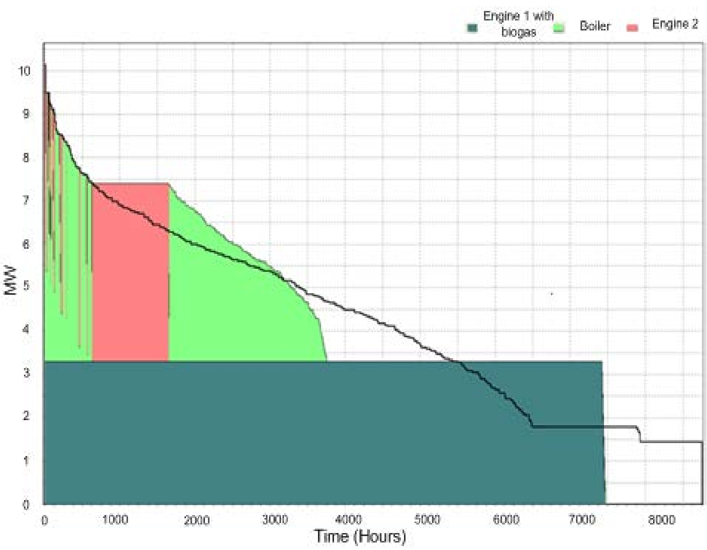

Fig. 7: Duration curve of heat demand and production.

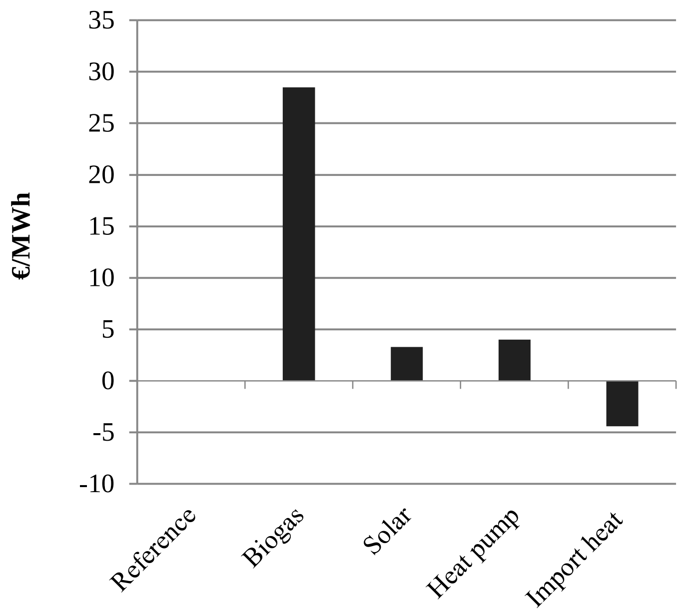

Fig. 8: Variation of heat production price according to different fuel options