Methodology for Defining of Eligible Capacity for Wood Fuel Based Cogeneration Plants in Small Towns in Estonia

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Abstract: There is a high potential for small-scale and medium scale wood-fired cogeneration in Estonia. The purpose of this research is to define the eligible capacity for wood fuel based cogeneration plant operating on the base of district heating systems in small towns. Results were checked and approbated by economical and environmental factors. Two optimal sizing methods were used: maximizing of amount of heat year-round while working at full installed capacity and maximizing of amount of heat year-round while working with partial loads. Results of defining optimal capacities for wood-fired cogeneration plants in small Estonian towns showed that method of maximizing of amount of heat year-round while working with partial loads is more adequate to real situation.

Key words: Biomass, CHP, cogeneration, primary energy efficiency, renewable energy, wood fuel.

1. Introduction

Cogeneration technology provides greater conversion efficiency than traditional generation methods as it harnesses the heat that would otherwise be wasted. This can result in up to more than a doubling of thermal efficiency. Fuel consumption can be reduced, which results in reduction of carbon dioxide emissions.

The potential for using cogeneration as a measure to save energy sources is in the focus of attention in the EU at present time, according to EU Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand on the internal energy market. Promotion of high-efficiency cogeneration (CHP) based on a useful heat demand is a Community priority given the potential benefits of CHP with regard to saving primary energy, avoiding network losses and reducing emissions, in particular of greenhouse gases [1].

Estonia is the member state of the European Union

and has a high potential for CHP development. The Estonian vision, according to the "Energy Sector Development Plan 2020" is that up to 20% of electricity should be produced by cogeneration plants [2].

Wood, biomass and biogas can be used for electricity production in cogeneration plants. But this potential is used partly. There are only two wood fuel based cogeneration plants in Estonia.

The main reasons to develop wood fuel based small scale and medium scale cogeneration in Estonia are necessity for additional energy sources, wood resources availability and high potential for small-scale and medium scale cogeneration development in Estonian small towns.

High potential for small-scale and medium-scale cogeneration in Estonia can be explained by various factors. One of the main factors is the high enough heat load in household area, which can be covered by heat produced by cogeneration plant. High heat loads in Estonian towns are explained by long and cold winters and cold climate in Estonia. Besides the district heating systems are typical for small and big cities in Estonia [3].

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In Estonia there are only 15 towns with population exceeding 10,000 inhabitants and there are also 181 administrative units with population ranging from 1,000 to 10,000 inhabitants. Small-scale and medium-scale cogeneration systems can be used in the small towns.

There are many small towns in Estonia where boiler houses should be renovated. During renovations the new boilers can be installed, the type of fuel can be changed or the new alternatives with cogeneration technologies can be used.

Wood fuel based cogeneration can be one of the alternatives for renovation or development of district heating systems. It is very important to choose an eligible size for the installed cogeneration plant.

The purpose of this research is to define the eligible capacity for wood fuel based cogeneration plant operating on the base of district heating systems in small towns.

2. Methodology

Before installation of a new cogeneration plant, an energy producer faces the basic question of how high a station's installed capacity should be. Due to the fact that cogeneration produces heat and power, it becomes crucial for both types of energy to be used appropriately. As concerns power, it may both be used on the spot and transported across great distances; heat, however, may only be used in the vicinity. Thus, the heat energy consumer is considered the main factor in selecting cogeneration plant capacity. The risks of installed cogeneration capacity are related to two scenarios: if a load is used that exceeds the optimum setting, the station will not be able to operate year-round due to insufficient heat load, while, should the load be installed below optimum, the potential of utilizing heat capacity will not be fully used.

2.1 Factors of Estonian Conditions, Which Affect the Capacity Size of Cogeneration Plants

One of the main factors is the heat load in household area, which can be covered by heat produced by cogeneration plant. High heat loads in Estonian towns are explained by long and cold winters and cold climate in Estonia.

Estonia is located in the northern part of Europe, and an average air temperature of the five coldest days ranges for Estonia ranges from -18.5 ℃ (Kärdla) to -25.5 ℃ (Tartu). Heating period in Estonia is from 216 days (Võrumaa) to 224 days (Järvamaa). It means that there is a necessity in high heating loads during a long period. It gives a possibility for consumption of heat produced by cogeneration, which solves the most important problem for cogeneration use [3].

Besides it is important that district heating systems are typical for small and big cities of Estonia. A district heating system makes it possible to join heat consumers and as a result the inhabited areas have sufficiently high heat loads to justify the installation of an efficient cogeneration facility.

Another factor is that wood is local fuel in Estonia. Estonia's forests cover about 48% of its entire territory. The country has a high potential for energy production from wood-based fuels. It is important to take into account that technologies for wood firing are preferable. Wood consumption by cogeneration is possible using steam turbine technologies.

2.2 Relative Heat Load Curve

As it has just been mentioned, heat consumer is the main factor for cogeneration capacity optimization, that's why the sizing should start with an assessment of consumer heat load. The optimal technology and facility capacity for cogeneration are selected based on the amount of heat demanded by consumers. Heat load values for residential buildings and load prevalence during the year are visualized by heat duration curve (Fig. 1).

There are different heat duration curve based approaches described in several references [4-6].

The approach used in previous research included maximizing of year-round amount of heat while working at full installed capacity [7]. This means that the facility's capacity will be determined by the
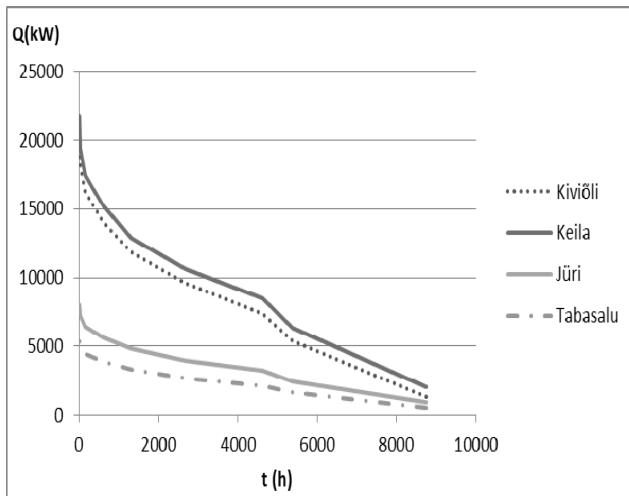
Fig. 1 Heat load duration curve for Kiviõli, Keila, Jüri and Tabasalu.

rectangle of maximum size that can be inscribed in the heat duration curve. Division of each hour's load values by the maximum load value yields a normalized or relative load curve [6].

Another approaches to installation include the following: the reduced-scale sizing, when the rated thermal power of a cogeneration unit is diminished while the annual use is increased; the partial-heat-usage sizing, when cogeneration extends its use to periods of lower heat demand and in this case a part of the generated heat is not used; the multiple cogeneration units, when instead of a single unit the separate cogeneration units are used; and finally, when cogeneration is operated at partial loads. During this research is realized an optimal sizing for wood fuel based cogeneration plants by the partial load cogeneration.

Steam turbines are the most appropriate for the small-scale and the middle-scale cogeneration plants based on wood fuel. Steam turbines can operate with high common efficiency when the load is higher than 75% [7-9].

It was assumed that the cogeneration plant operates by heat load lower than full installed cogeneration capacity; the plant stops to operate when the load becomes lower than 75% from the installed cogeneration capacity. The main factor compared for different installed capacities is the annual electricity

production by cogeneration.

2.3 Heat Production Maximizing Method

Method of year-round amount of heat maximizing while working at full installed capacity supposes that the optimization criteria is calculated by Eq. (1) [7].

$$Q_r = r_Q t \qquad (1)$$

where

Q_r is relative heat, produced by cogeneration, shows what part from annual heat amount is produced by cogeneration plant [1*h], optimization criteria.

But this method is appropriate for the situation, when cogeneration plant operates with maximal load; in case load becomes lower than the installed cogeneration capacity the plant should be switched off.

2.4 Calculation of Heat Produced by Cogeneration Plant, Operating Both with Partial Loads

Using above mentioned assumption, that cogeneration plant continues operation till heat load is lower than 75% from installed cogeneration capacity, it is calculated, that installed optimal capacity for cogeneration plants can be 75% from maximal heat load for consumer. For calculation of heat produced by cogeneration, when plant is operating both with maximal and with partial loads, Eq. (2) is used.

$$Q_r = r_Q t_Q + \int_{t_{0.75Q}}^{t_Q} f(t) \qquad (2)$$

where

$f(t)$ is Eq. (1);

t_Q is number of hours, when consumer heat load is higher, than installed cogeneration capacity [h];

$t_{0.75Q}$ is number of hours, when consumer heat load is higher, than 75% from installed cogeneration capacity [h].

2.5 Methodology Approbation

Results were approbated, using one of the most popular indicators for the evaluation of projects: NPV (net present value), which indicates how much value

an investment or project adds to the enterprise. In case of NPV > 0 the investment will add value to the enterprise. If different projects are compared, then the project with higher value is chosen.

Following data were used for calculations: data about annual heat load in the towns (data from municipalities); power to heat ratio was assumed as 0.22, total efficiency 0.88, investment amount was normalized for each case based on calculations realized during the previous research (1,200-1,600 EUR/MWel); heat price was defined as 50 EUR/MWh (for producer), electricity price was defined as 73.56 EUR/MWh (feed-in tariff for green electricity, defined by Estonian Electricity Market Act); wood chips were assumed as fuel with fuel price 10 EUR/MWh [10], other operation costs were added too.

Besides economical and technical factors the environmental factors are also significant. Wood chips consumption for heat and electricity production is a very positive environmental factor, because it reduces fossil fuel consumption for energy production. But wood chips are a natural energy source, that's why combined producing of heat energy and electricity allows reducing wood fuel consumption in comparison with separate energy producing.

EU Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market and Estonian Requirements for Efficient Cogeneration define the methodology for calculation of primary energy saving in cogeneration process.

$$PES = \left\{ 1 - \frac{1}{\frac{CHPH\eta}{REFH\eta} + \frac{CHPE\eta}{REFE\eta}} \right\} 100\% \qquad (3)$$

where

PES is primary energy savings, %;

$CHP\ H\eta$ is the heat efficiency of the cogeneration production;

$Ref\ H\eta$ is the efficiency reference value for separate heat production;

$CHP\ E\eta$ is the electrical efficiency of the cogeneration;

$Ref\ E\eta$ is the efficiency reference value for separate electricity production [11].

According to Estonian Requirements for Efficient Cogeneration efficiency, the reference value for separate heat production based on wood fuel is 0.86, but efficiency reference value for separate electricity production based on wood fuel for period 2006-2010 is 0.34 [11].

After modifying the Eq. (3) it is possible to define primary energy saving in natural units by Eq. (4)

$$\Delta B = \left\{ 1 - \frac{1}{\frac{CHPH\eta}{REFH\eta} + \frac{CHPE\eta}{REFE\eta}} \right\} \cdot \left\{ \frac{W}{REFE\eta} + \frac{Q}{REFH\eta} \right\} \div LHV \ (4)$$

where

ΔB is primary energy savings, t;

W is annual electricity from cogeneration, MWh;

Q is annual heat from cogeneration, MWh;

LHV is net caloric value, MWh/t.

3. Results and Discussion

3.1 Heat Load Curves

Four small towns in Estonia were chosen for evaluation: Kiviõli, Keila, Jüri and Tabasalu. Heat duration curves were built for these towns (Fig. 1). As the Fig. 1 indicates, the maximum capacities are different: 20 MW for Kiviõli, 21 MW for Keila, 8 MW for Jüri and 5 MW for Tabasalu. The heat load changes in the same way for all towns; the only difference is the heat load scale.

According to the Fig. 1 the high spikes are typical for the heat load duration curve. These spikes are explained by fact, that there are some especially cold days during the winter period in Estonia. These spikes are typical for Nordic countries such as Finland and Sweden. Heat load duration curve is more gradual for other countries.

Relative load curves were constructed by division of each hour's load values by the maximum load value
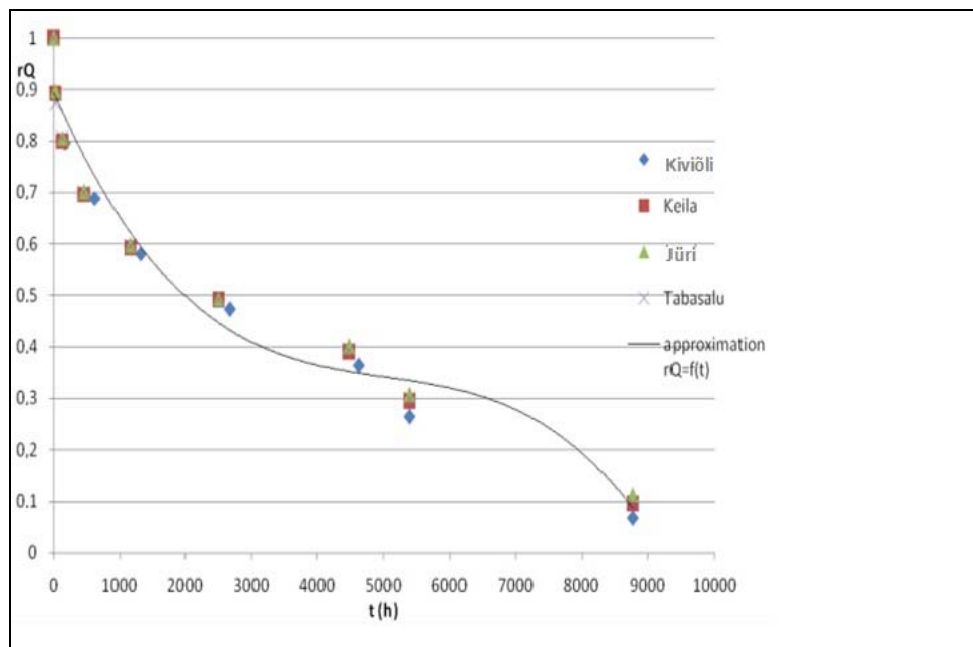
Fig. 2   Normalized heat load duration curves and approximation.

(Fig. 2). All data were approximated. Regression equation is following:

$$r_Q = -4\times10^{-12}t^3+5.4\times10^{-8}t^2-2.9\times10^{-4}t+0.895 \quad (5)$$

where

r_Q is relative heat load [dimensionless quantity];

t is time per year [h].

Regression function is displayed on Fig. 2.

The squared correlation coefficient is high ($R^2 = 0.964$) and therefore the function (5) describing the relative heat duration curves for the four towns is very close to real situation.

3.2 Defining of Eligible Capacity for Wood Fuel Based Cogeneration Plants

For year-round amount of heat maximizing heat production was calculated for different capacities using Eq. (1). According to calculation, the maximal value of Qr is equal to 1970.53 1*h and it is located in the point where r_Q is 0.298. It means that in the case when the cogeneration plant is operating only with maximal capacity, the optimal size for installed capacity is 29.8% from the maximal heat load. Optimal criteria dependence on relative heat load is shown in Fig. 3 with a dash line.

For calculation of heat production by cogeneration plant operating both with maximal and with partial loads, Eq. (2) was used. According to calculation the maximal value of Qr is equal to 2468.69 1*h and is located in the point where r_Q is 0.377. It means that in the case when the cogeneration plant is operating both with maximal and partial loads, the optimal size for installed capacity is 37.7% from the maximal heat load. Optimal criteria dependence on relative heat load calculated by offered method is shown in Fig. 3 with a solid line.

This method shows that installed capacity can be higher and plant can operate longer during the y ear and produce more electricity. Electricity production by cogeneration for four small towns in case of using optimal sizing is shown in Table 1.

The table indicates that electricity amount produced by cogeneration including partial loads is much higher.

Using this method it is possible to realize optimal sizing for cogeneration plant from the technical point of view. As a result of sizing, a cogeneration plant is chosen, which can produce maximal heat and electricity in cogeneration mode. But usually the main
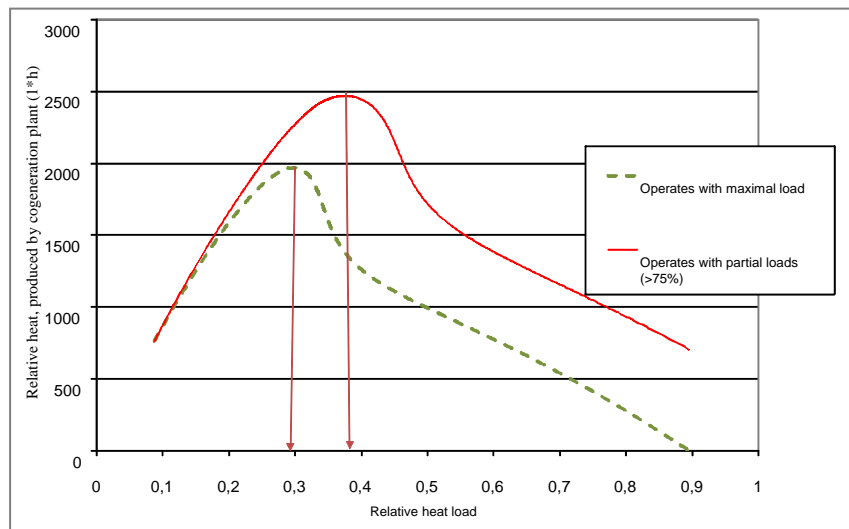
Fig. 3   Comparison of optimization criteria, calculated for cogeneration plant operating with maximal and partial loads.

Table 1   Electricity produced by cogeneration plant with optimal capacity.

Town	Electricity produced by CHP with optimal size (MWh)	
	Cogeneration plant operates with maximal load	Cogeneration plant operates with maximal and partial loads
Kiviõli	8,027.71	10,056.95
Keila	8,569.61	10,735.84
Jüri	3,165.13	3,965.21
Tabasalu	2,171.57	2,720.50

factor for cogeneration plant owner is the economical factor. This factor is the most significant for choosing the cogeneration plant size; therefore economical approbation is necessary for method validity check.

3.3 Evaluation of the Results Using Economic and Environmental Aspects

Using assumptions, provided in methodology section the net present value for 10 different capacities was calculated for 4 towns in case cogeneration plant was operating both with maximal and partial loads. Calculation results are shown in the Fig. 4.

It can be seen that maximal NPV for cogeneration plants, which are operating only with maximal capacity is achieved when cogeneration plant installed heat capacity is approximately 30% of maximal heat load. But when cogeneration plants are operating with partial loads (> 75%) maximal NPV is achieved by

installed heat capacity being approximately 40% from maximal consumer heat load.

For primary energy saving evaluation Eq. (4) was used. Results of calculation for each town are shown in the Fig. 5. The figure shows wood fuel saving for cogeneration plants with capacity defined by optimal sizing in case cogeneration is operating with maximal load and with partial loads. As it can be seen primary energy saving is also higher when cogeneration plant operates with partial loads.

4. Conclusions

Wood fired cogeneration topic is rather new for Estonia. Many municipalities are interested in installation of cogeneration plants, which will produce heat to cover heat demand and electricity, which can be used for municipality needs or sold. There are very few researches in this field in Estonia.

During the research an eligible size for wood fuel based cogeneration capacity in Estonian small towns was defined. Estonian conditions were taken into account: local energy sources, fuel and electricity prices, cold climate, and state of local district heating systems, Estonian legislation and support mechanisms for cogeneration plants.

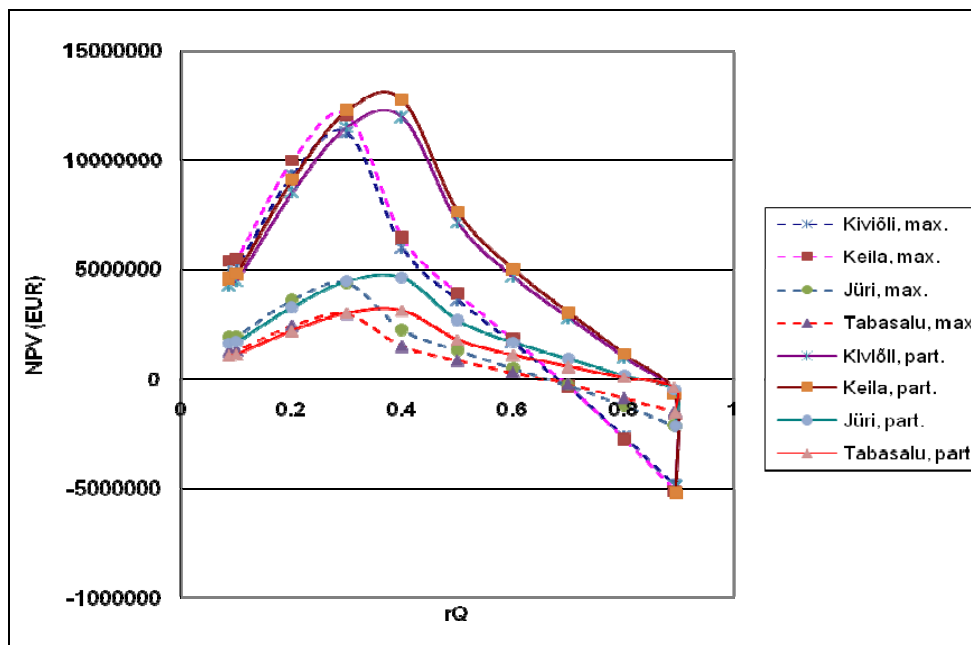Two optimal sizing methods were compared: maximizing   of amount   of heat   year-round while

Fig. 4   Economical approbation of optimal sizing with partial loads method.
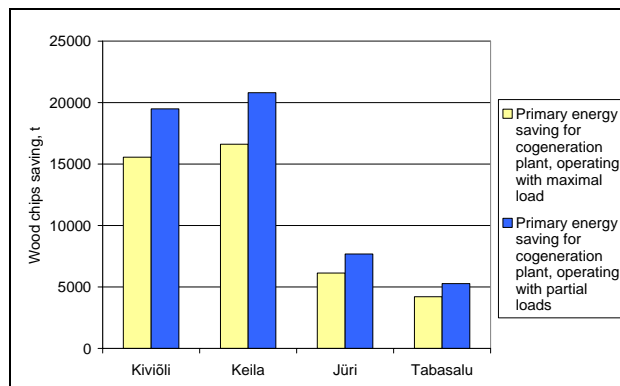

Fig. 5   Cogeneration plant primary energy saving in comparison with separate heat and power production.

working at full installed capacity and maximizing of amount of heat year-round while working with partial loads. Partial load cogeneration optimal sizing gave better results both from technological, economical and environmental point of view.

Using this method it is possible to realize optimal sizing for cogeneration plant from the technical point of view. As a result of sizing, a cogeneration plant is chosen, which can produce maximal heat and electricity in cogeneration mode. This optimal sizing for small cities with heat load 5-21 MW results that installed heat capacity for cogeneration plant should be about 37% from the maximal heat load. Real

installed capacity will depend on the parameters offered by cogeneration equipment producers. Methodology was approbated by economical and environmental factors: NPV and primary energy saving.

Typical towns were chosen for assessment and results can be expanded to all other small towns in Estonia. Results can be used for other Baltic countries and Nordic countries, where cold climate, biomass energy sources and district heating systems are typical.

Acknowledgments

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