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CO-GENERATION STRATEGIES AND DEVELOPMENT POSSIBILITIES IN CITIES OF NORTH-EASTERN EUROPE

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The high potential for utilization of co-generation power plants in the cities of North-Eastern Europe is illustrated in this paper. The features associated with climatic and economic factors are analyzed. The paper describes the methods for demand forecasting used in the case study and the chosen criteria and methods for economic assessment of different energy supply alternatives. The results of economic assessment support the decision about the optimal placement and parameters of CHPs, including small-scale CHPs. Application of cooperative Game theory in order to support the decision-making in the market environment is described and demonstrated on the real life case study.

Introduction

Awareness of the global society regarding issues related to production, distribution and consumption of both thermal and electrical energy is mainly induced by the following three factors [1]:

- Global reserves of primary energy resources are limited.
- Mankind activities increasingly influence the global climate changes.
- The demands of modern society towards reliable energy supply without interruptions are increasing.

In the countries of North-Eastern Europe, the issues of enhanced efficiency and reliability of energy supply are especially important due to climatic, historical and economic reasons. What are the prerequisites there?

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- Rapid economic development goes along with increasing energy demand.
- The existing energy supply system was built based on condition that there are inexpensive primary energy resources available. This system appears to be inefficient in a new situation due to low efficiency of the energy production sources, high transportation losses and utilization of excessively energy demanding technologies and buildings. Furthermore, a number of energy sources appear to be inefficient from the environmental and safety viewpoints.
- Due to climatic conditions (cold winters) there is especially high demand towards reliability of energy supply.
- There is a considerable number of industrial and domestic constructions, and there is a need for upgrade of energy production sources, which creates the possibility for utilization of progressive technologies for energy production and consumption.
- The systems of district heating are extensively used in cities of North-Eastern Europe. These systems are suited for efficient utilization of co-generation in combined heat and power plants (CHPs).

Based on the case study for the largest city in Baltic countries – Riga –, the paper illustrates the potential for utilization of co-generation power plants of different capacities. The paper describes the methods for demand forecasting used in the case study and the chosen criteria and methods for economic assessment of different energy supply alternatives. The results of economic assessment support the decision about the optimal placement and parameters of CHPs, including small-scale CHPs, which can be classified as distributed generation.

Traditionally for the problems of energy system planning the probabilistic choice decision-making criteria (such as expected cost, Laplace's, minimax or Hurwitz') are used [2, 3]. Minimal Risk criterion is suitable for the games with active intelligent opponent who intentially would choose the worst for the second-party conditions [2]. The approach suggested in this paper takes another step towards resolving real-life complexity, namely application of cooperative game, which allows taking into consideration the possibility of building the coalition between the competent parties in the market conditions [4].

Heat demand forecasting in Riga for the period 2006–2025

The principles used for heat demand forecasting in the cities of North-Eastern Europe will be described in the paper. The main conclusions from the analysis of the results for heat demand forecasts and the existing situation in Riga (see appendexes 1, 2, 3) can be summarized as follows:

- In order to satisfy the future demand, new heat energy sources must be introduced. There are several options including reconstruction and extension of existing large CHPs and industrial boilers as well as construction of new medium and small CHPs.

- Development of new domestic areas is foreseen. The energy supply of these areas can be provided either by connection to the district heating system or by introduction of local sources.
- There is a large number of alternative solutions, which can provide the energy balance of the city. The decision-making methods leading to the most favourable solution are necessary.

The decisions are taken in the market conditions, where the main actors are:

- Large power companies, who are the owners of large CHPs and produce both power and heat.
- Companies owning district heating system and providing heat transport and supply to the customers.
- Independent companies – owners of medium and small CHPs or industrial boilers or possibly local district heating systems.

This is of course a simplified approach. In reality, the power companies from the neighbouring countries are also participating in the market, and it can be a large number of independent companies. Furthermore, functioning of the market is influenced by the regulator.

The analysis of the situation in some other cities of the North-Eastern Europe shows that conclusion formulated for Riga are valid for the most of the cities in the Baltic countries and Russia, namely for Vilnius, Tallinn, Kaunas, St-Petersburg, Kaliningrad, etc.

Objective function and decision-making criteria

The actors in the market can make independent decisions within their own field of activities. Each actor attempts to maximize its revenues. The decisions taken by one actor influence the revenues of other market participants. Normally the interests of the actors are conflicting.

The revenue of the actor i can be generally described as:

$$R_i = E\left(\sum \psi S\left(P_i(t), C_i(t), N_i(t), K_i(t), B_i(t)\right)\right) \quad (1)$$

where $E\left(\Sigma \psi S\right)$ is mathematical expectation of the sum of the revenues for the considered period of time, which is described by the function ψS defined by the contents and structure of the energy supply system, including the parameters of CHPs, transmission lines, heat transportation lines, pumps etc.;

$P_i(t)$ is the time dependent function describing the changes of the parameters of the energy supply system elements;

$C_i(t)$ is the vector the fuel costs, electrical and heat energy prices as well as O&M costs;

$N_i(t)$ is the electrical and heat energy produced by the sources;
$K_i(t)$ represents the investments into the system and its elements;
$B_i(t)$ is the interest rate.

In general case $P_i(t)$, $C_i(t)$, $N_i(t)$, $K_i(t)$ and $B_i(t)$ are the functions of random or uncertain parameters. In order to avoid extensive complication of the analysis, in this paper it is assumed that uncertain parameters are random values with corresponding distribution functions [3]. Then optimization of energy supply system development could be formulated as a search problem (for example for devising algorithms), where the functions (1) describing the revenues of all tree actors are maximized. During the search the technical and regulatory constraints, controlling reliability and quality of supply, as well as environmental impact, must be taken into consideration. Therefore we are dealing with the task of maximization of three functions according to (1) for three actors restricted by the system of constraints [3]. To solve such a problem the methods for assessment of the functions (1) as well as constraints are needed. The description of these methods is out of scope of this paper. It can be presumed that in order to make these assessments the standard software packages modelling operation of different kinds of CHPs, estimation of the losses in thermal [5] and electric [6, 7] systems and calculation of the project economics [3] can be used.

Due to generally conflicting interests of the actors, simultaneous maximization of all three functions is impossible. The trade-off solutions must be achieved. For this purpose the methods from the Game theory can be applied assuming the following two strategies:

- Non-cooperative game with full information [4] (it is assumed that the actors have the full information about the possible actions of other players)
- Cooperative game [4] (groups of players may enforce cooperative behaviour).

In this case one can abandon the dominated or interior solutions and present to the decision-makers the assessed revenues for actors operating cooperatively or independently. In the case of cooperative behaviour there is a problem of revenue distribution between the members of the coalition. In Game Theory a Shapley value [8] describes one approach for the fair allocation of gains obtained by cooperation among several actors. The function has a property that each member of the coalition in addition to the guaranteed revenue independent from the actions of other layers will receive some additional revenues obtained as a result of participation of the actor i in the coalition. According to Shapley, the amount that actor i gets is:

$$\phi_i = \sum_{i \notin S \subseteq N} \frac{|S|!(n-|S|-1)!}{n!}\left(R(S \cup \{i\}) - R(S)\right), \qquad (2)$$

where n is the total number of players, and the sum extends over all subsets S of N not containing player i; $R(S)$ is the revenue of the coalition S; $R(S \cup \{i\})$ is the revenue of the coalition S without participation of the actor i.

Case study – strategies to provide heat energy supply in Riga

A. Analysis of energy supply alternatives for Riga

From the large quantity of combinations of the actor strategies (all of them cannot be described here due to space limitations given by this article) let us choose the most representative and interesting from the point of view of the decision-making:

- Two alternatives including expansion of large CHPs and construction of heat transportation lines.
- Three alternatives with construction of medium and small CHPs.

Table 1 presents the results of analysis of the energy supply alternatives of one large district of the city (with population about 150 000). The problem is formulated as a game of the following two players:

1) **P1**: The owner of the large CHPs (electrical power 400 MW) who can choose building of the heat transportation pipelines in order to supply the given district and depending on this decision to configure the CHPs.
2) **P2:** The owner of the industrial boiler and district heating system who can choose one of the following tree strategies:
   - Build up the boiler into CHP.
   - Extend the boiler in order to provide the energy supply for the whole district.
   - Reduce the capacity of the boiler in order to provide the reserve and heating during the cold months.

The results of the actors' revenue assessment (million EUR) for different strategies are presented in Table 1.

Table 1. **The Revenues of the Players Depending on the Chosen Strategy for the Period of 20 Years**

Strategies of companies		Strategies of independent companies (**P2**)					
		Build up the boiler into CHP		Extend the boiler		Reduce the capacity of the boiler	
		Revenues of **P1**	Revenues of **P2**	Revenues of **P1**	Revenues of **P2**	Revenues of **P1**	Revenues of **P2**
Owner of large CHP (**P1**)	Build the heat transportation pipelines	–25	43	–13.6	2.9	43	1
	Not to build the heat transportation pipelines	–11.5	43	0	2.9	0	0

B. Analysis of the results

First let us consider the game illustrated in Table 1 as a non-cooperative one with full information [8]. Both players have the information about possible outcomes of the game and are determined to maximize their revenues in spite of the actions of another player, which leads us to the conclusion that the owner of large CHPs will not build the heat transportation pipelines, instead the independent company will build CHP (the revenues are marked by dark gray in Table 1).

In the case of coalition, the best solution (maximizing the sum of revenues for both players) is the combination of strategies of building heat transportation pipelines simultaneously reducing the capacity of the boiler (marked by light gray). The total revenues of the coalition increase (from 32.5 to 44 million EUR), but they are reallocated between the players. To provide the viability of the coalition, the owner of CHPs must share his revenues with another member of the coalition. According to Shepley value calculated from equation (2), the independent company must get the revenues of 49.25 million EUR, and the owner of large CHPs – the cost of 5.25 million EUR.

One can add that, in reality, the coalition was not built due to risks involved, which are not considered here [2]. However, the example is very illustrative and situation like this must be considered during the analysis of market conditions.

Conclusions

In cities of North-Eastern Europe there is an urge for upgrading and improvement of the efficiency of energy sources and heat transportation system. There are processes of reallocation of energy consumers, increase of public service demand and development of district heating. Combination of these factors is a good prerequisite for construction of CHPs of different capacities.

Methods based on the game theory can contribute to making the right decision about the development of energy supply sources. In particular the cooperative game taking into consideration the possibility of building the coalition should be used. In due course this approach will result in more efficient energy supply system.

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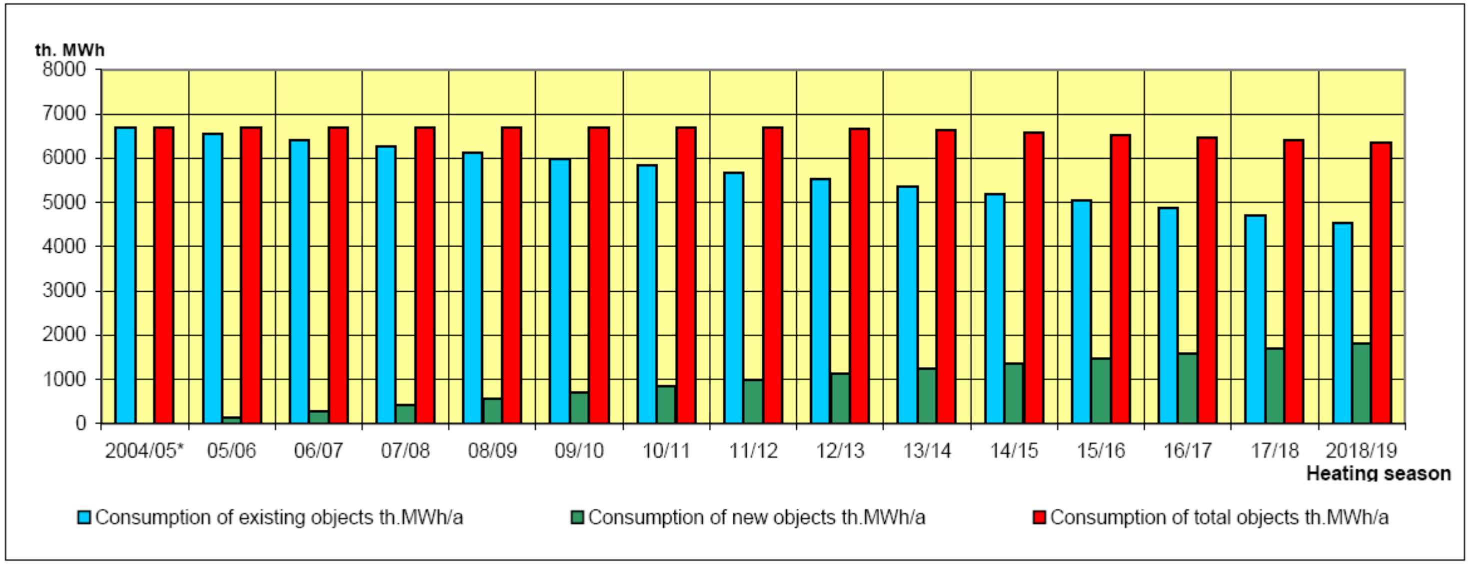
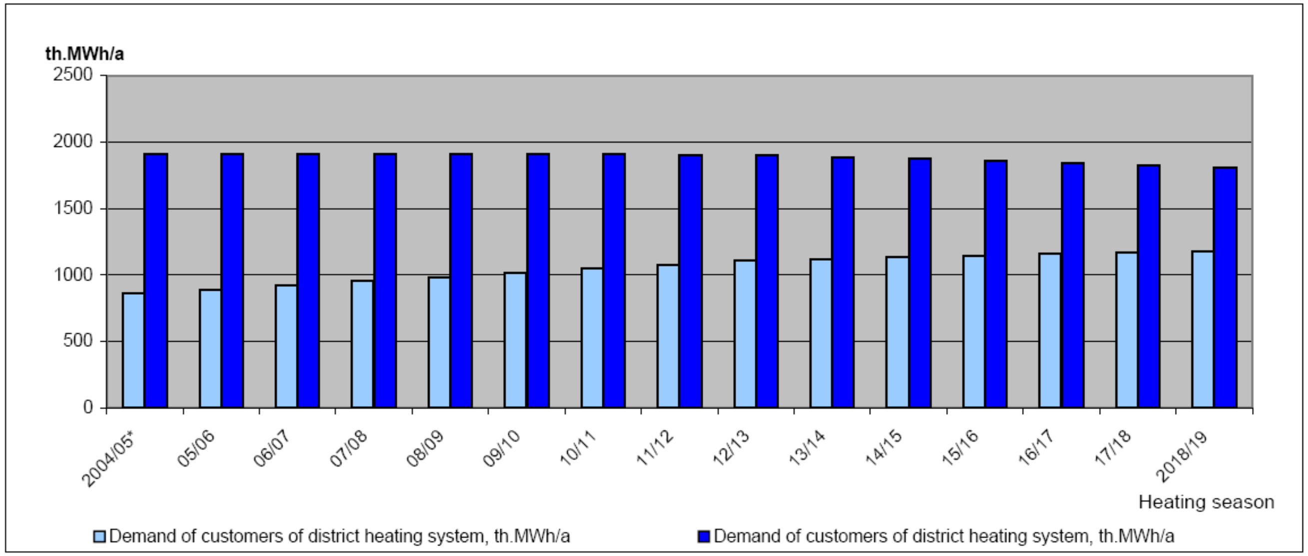


Heating season	**2004/05***	**05/06**	**06/07**	**07/08**	**08/09**	**09/10**	**10/11**	**11/12**	**12/13**	**13/14**	**14/15**	**15/16**	**16/17**	**17/18**	**2018/19**
Consumption of existing objects th.MWh/a	6697	6559	6418	6275	6129	5981	5830	5676	**5520**	5362	5201	5038	4872	4703	**4532**
Consumption of new objects th.MWh/a	0	144	287	431	574	718	861	1005	**1149**	1261	1373	1485	1596	1708	**1820**
Consumption of total objects th.MWh/a	6697	6703	6705	6705	6703	6698	6691	6681	**6669**	6623	6574	6522	6468	6411	**6352**

2004/05* heating season - 0,0 °C ; 203 d.

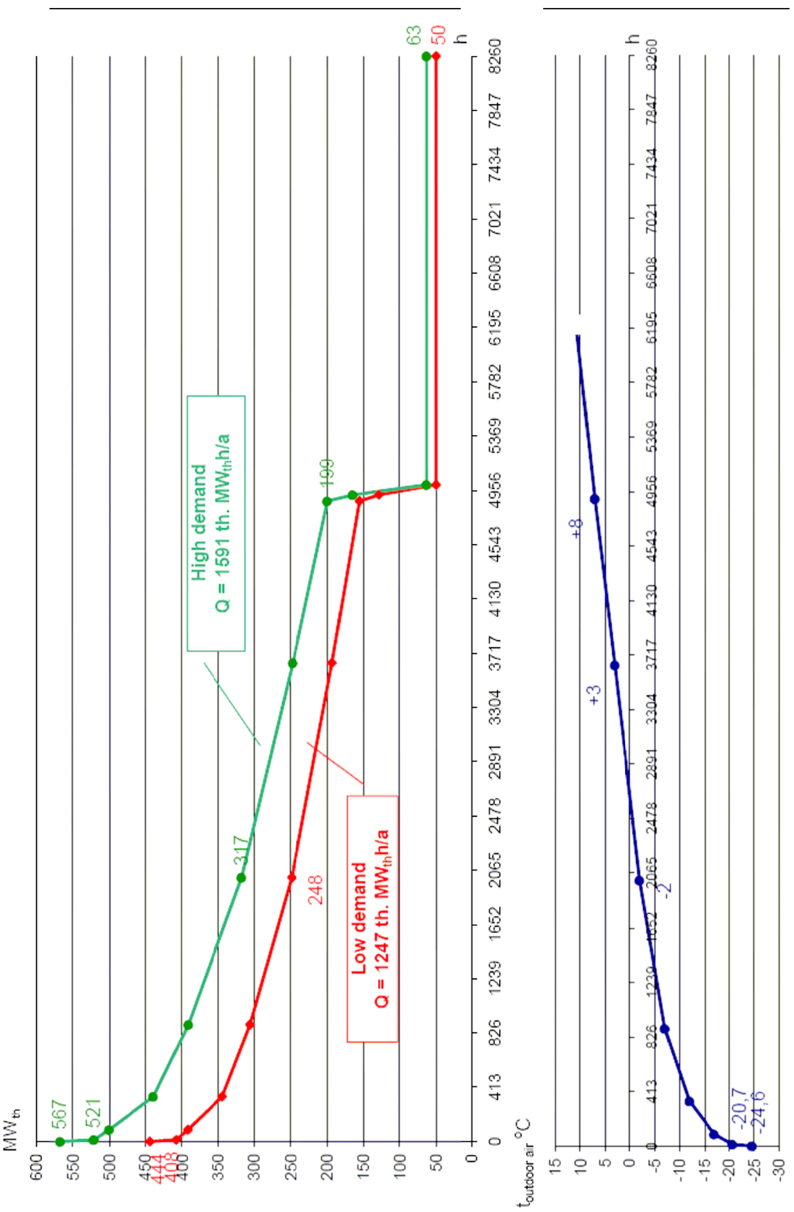
Apendix 1. Prognosis of total thermal energy consumption in Riga city



Heating season	2004/05*	05/06	06/07	07/08	08/09	09/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18	2018/19
Total thermal energy consumption, th.MWh/a	1909	1910	1911	1911	1910	1909	1907	1904	**1901**	1887	1873	1859	1843	1827	**1810**
Demand of customers of district heating system, th.MWh/a	859	891	922	954	985	1016	1046	1076	**1106**	1119	1132	1144	1156	1168	**1180**

2004/05* heating season - 0,0 °C ; 203 d.

Apendix 2. Average prognosis of total thermal energy consumption on the left bank of Riga city and demand of customers of district heating system



Appendix 3. Chart of heat load on the Left bank of Riga city in the season of 2018/19 depending on outdoor air temperature.