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Allocating Production Cost at CHP Plant to Heat and Power using Cooperative Game Theory

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***Abstract*--This paper is dedicated to the task of cost determination for heat and power energy production for small size cogeneration plants. Cogeneration of heat and power is only possible if there is a demand for both types of energy. The consumers of both heat and power are considered as members of the coalition having a goal to gain additional revenues due to reduced investments and increased efficiency of power production. The suggested approach uses the cooperative game theory for distribution of the additional revenues between the members of the coalition. The examples from energy tariffs determination in the market environment show the rationality and efficiency of using the considered approach.**

***Index Terms*--Energy supply, distributed energy resources, cogeneration, district heating, game theory, decision-making.**

I. 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 [6]:

- 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?

- 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 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 the cities of North-Eastern Europe. These systems are suited for efficient utilization of cogeneration in combined heat and power plants (CHPs).

The intention for fuller utilization of fuel as well as the obvious advantages of cogeneration resulted in creating such equipment that provides for constructing CHPs with small capacities (in the order of tens kWe and larger). Such power plants can be located near the energy consumers, which can result in the essential reduction of energy losses in the heat and electricity supply networks.

The companies owning CHPs (which can include the consumers of the energy) have two possibilities to increase the incomes:

- By increasing the heat energy tariffs.
- By increasing electricity power energy tariffs.

The strategy chosen by the owners of CHP influences considerably the costs and behavior of the customers. High heat energy prices stimulate saving measures, for example better isolation in houses etc. Simultaneously measures for saving of electrical energy are not prioritized. It is obvious, that for the rational development of energy supply systems the objective relation between the prices on heat and electrical energy is needed. The methods for determination of costs and tariffs on different kinds of energy in case of cogeneration are known [1], [4], [5].

These methods are based on calculation of the summary revenue R_{Σ} that is sufficient for normal functioning of CHP.

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R_Σ is gained from selling thermal energy W_Q and electrical energy W_E, proceeding from the given rate of profit. The revenue that is gained from the production of each type of energy, R_E and R_Q respectively, is distributed on the basis of physical laws, for example, proportionally to the produced energy as follows:

$$R_E = \left(\frac{W_E}{W_Q + W_E} \right) \times R_\Sigma$$
$$R_Q = \left(\frac{W_Q}{W_Q + W_E} \right) \times R_\Sigma \tag{1}$$

In this case, the unequal value of thermal and electrical energy is not taken into account.

The method of *Exergy* is a more common method, by means of which a different value of energy is accounted for by coefficient β, that changes depending on energy production technology used.

$$R_E = \left(\frac{W_E}{\beta W_Q + W_E} \right) \times R_\Sigma$$
$$R_Q = \left(\frac{\beta W_Q}{\beta W_Q + W_E} \right) \times R_\Sigma \tag{2}$$

For the steam cycle, for example, β=0.6 is assumed. The main disadvantage of this method is the impossibility of objectively assessing the value of the coefficient β. It is obvious that this coefficient is different for different power systems. For example, in case of ample water resources, resulting in production of cheap electrical energy, the larger value of this coefficient should be selected.

When selling electrical energy via the power system grid, its price is determined by market. Hence, using (1) or (2), we can determine R_Σ and R_Q. However, in case of small CHPs, the consumers can receive the electrical energy from CHP, not using the power system grid. In this case, the conditions that are dictated by the global market become non-obligatory for these consumers. Even more, the considered approaches are not giving any advantage to the customers whose consumption profile suits cogeneration profile of heat and power best. Thus, the contribution of the heat energy consumers to the operational efficiency from the point of view of fuel savings and exhaust gases emission when producing two types of energy is not taken into consideration in the price setting.

The method based on the cooperative game theory, which overcomes the limitations described above, is presented in this paper. First the mathematical base for the method is given, and then the task of power supply is formulated as a game with participation of coalition with several players. Case study based on real-life data used in planning of power supply of Riga (Latvia) is presented.

II. The Theoretical Background

A. Game - Theoretical Approach to the Planning Task

Let us imagine the task of power supply development planning in the form of a static game with complete information [2]. The game is presented in normal form as following:

$$\{I,\ S = \prod_i \{S_n\} i \in I,\ R = \{R_1, R_2, ...R_n\}\} \tag{3}$$

i.e. a list of players I, all situation combinations $\{S = \prod_i \{S_i\}\} i \in I$ and revenues R of each player at all his strategies and at each combination of the competitors' strategies.

It is assumed that the list and number of the players, i.e. competing companies, is known; also, that each player knows the competitors' strategies, i.e. the list of their possible structures and parameters, as well as the revenues at any combination of structures and parameters of all the players.

It is known [2] that the solution of the game task, presented in the form of (3), is a collective choice of equilibrium strategies. The most often used is the Nash equilibrium [2], i.e. such a set of strategies $s \in S$ that for all players i and each alternate strategy $s_i^{/} \in S_i$, the following condition is fulfilled:

$$\forall i, \forall s_{-i} \in S_{-i} \quad R_i(s_i, s_{-i}) \geq R_i(s_i^{/}, s_{-i}) \tag{4}$$

i.e. the equilibrium is formed by such a set of strategies, with which the decision of one of the players to deviate from such set may only diminish his revenues.

The search for the equilibrium includes the following:

1. Forming the set of all the possible strategies, excluding the dominated strategies, i.e. strategies $s_i^{/}$ of player i, for which the following condition is fulfilled [2]:

$$\forall s_{-i} \in S_{-i} \quad R_i(s_i, s_{-i}^{/}) \geq R_i(s_i^{/}, s_{-i}^{/}) \tag{5}$$

i.e. the player's strategies are excluded, if there is a strategy that is better, irrespective of the competitors' actions.

2. Search for the equilibrium using (3). Let us suppose that as a result of such search the only set of strategies that complies with the Nash equilibrium conditions is determined. Theoretically, there may be much such equilibrium; however, some methods are known [2] that make it possible to diminish their number.
3. Considering the rationality and possibility of organizing a coalition among the players.
4. Choosing the methods for organizing the coalition and distributing additional revenues among the participants of the coalition.

If the possibility to form a coalition is taken into account, the formulation of the optimization task is modified once more. Due to the need to consider not only the strategies of individual companies, but also those of possible coalitions in various combinations, the dimension of the task increases considerably. Resulting from the solution of this task, the set of the sub-optimum plans for each company and their coalitions at various combinations of possible competitors' plans can be obtained.

B. Distribution of the Gain between the Members of the Coalition – Shapley Value

In case of cooperative behaviour, there is a problem of revenue distribution between the members of the coalitions. The simple approach would be to give to each player his contribution c_i :

$$c_i = R(S \cup \{i\}) - R(S) \tag{6}$$

where $R(S)$ is the revenue of the coalition S, $R(S \cup \{i\})$ is the revenue of the coalition S with participation of the actor i.

However, such an approach is not anonymous, i.e. ordering of the players makes difference in the amount they are rewarded.

In game theory, a Shapley value [3] describes one approach for the fair allocation of gains avoiding the mentioned drawback. Fair allocation ensured by selecting uniformly a random ordering and rewarding each player his expected marginal cost in ordering. Since players can form $n!$ possible random orderings, the probability of set S being ranked exactly before player i is: $|S|!(n-1-|S|)!/n!$. Thus the additional amount that the player i gets is:

$$\phi_i = \sum_{i \notin S \subseteq N} \frac{|S|!(n-1-|S|)!}{n!}\left(R(S \cup \{i\}) - R(S)\right) \tag{7}$$

where n is the total number of players, $|S|$ is size of the set S, the sum extends over all subsets S of N not containing player i.

In the simplest case, when only two players participate in the game, the expression (7) is simplified and obtains the following form:

$$\phi 1 = \phi 2 = \left(R(S \cup \{i\}) - R(S)\right)/2 \tag{8}$$

The Shapley value describes the fair (in a sense determined by the accepted axioms) [3] distribution of additional gains in case of formation of the coalition. In particular, the definition is based on the assumption that possible combinations of the players who form the coalition are equally probable.

III. Examples of Formation of the Additional Gains Distribution

A. Example 1

Let us assume that there is a search for the best schematic of power supply to a certain district "D". There are a great number of variants for this schematic (individual boiler houses, electrical heating, etc.). Let us suppose that as a result of comparing these variants, the dominating strategies have been rejected; the heat consumers come to a decision about interconnection, and it is decided to construct a CHP (see Fig. 1) for supplying the consumers of the district with heat and electricity. Part of electric energy can be exported or imported via the distribution grid. A chart of heat energy consumption that is typical for Latvia and the Scandinavian countries is presented on Fig. 2.

An alternative for the energy supply schematic presented on Fig. 1. is the construction of a boiler house, which produces only heat energy for the consumers.

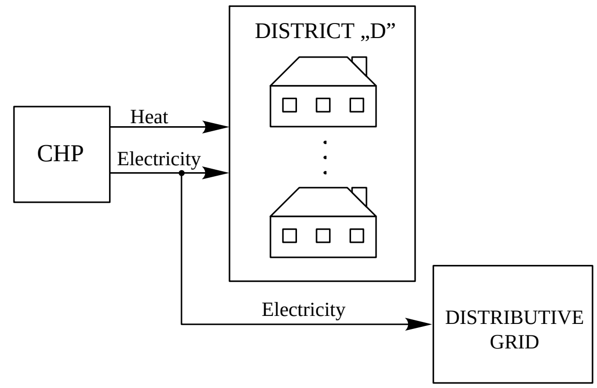

Fig. 1. The energy supply systems for district consumers

In this case, all the electricity is imported by the district in question (let us call this power supply variant as "Variant A").

In the event of CHP construction, two more variants of energy supply appear:

- Variant B1. CHP supplies heat to district D, and electricity is exported to the grid; the district imports the necessary electrictricity from the grid.
- Variant B2. CHP supplies both types of energy (heat and electricity) to district D, i.e. a coalition of consumers has been formed within the district. Such coalition is possible, if its expenses Ek are less than the summary expences E1+E2 of the consumers of heat (E1) and electricity (E2), acting independently, i.e., if:

$$Ek < E1 + E2 \tag{9}$$

The heat consumers provide the conditions for the functioning of a cogeneration plant. They are interested in the formation of a coalition with electricity consumers, provided that the sale price is fixed higher than the price of energy that is exported to the grid.

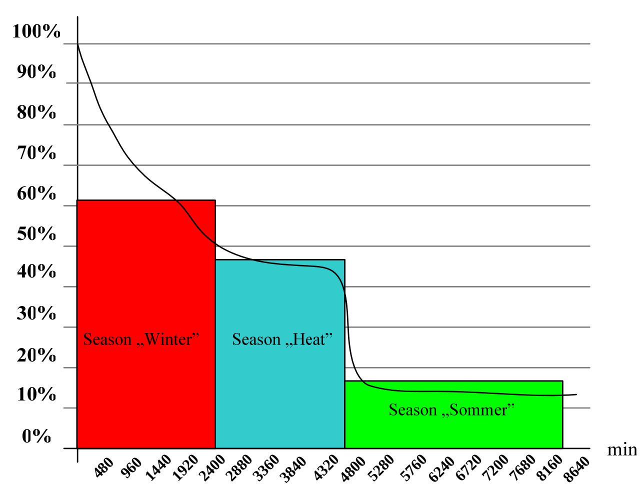

Fig. 2. Heat energy consumption chart

At the same time, the power consumers will be interested in a coalition, if the electricity price is lower than the price of energy imported from the grid. A question about fixing reasoned tariffs emerges. The structural schematic of CHP in question is shown on Fig. 3.

The principal data assumed in cost calculations are presented in Table I. The conditions of energy production essentially differ in time. As a consequence, one of the cogeneration units can operate the year around, while the second unit can operate only during the heating period, but the hot water boiler produces heat energy only in the winter period, when heat demand increases sharply. The different conditions of energy production dictate different tariffs for heat depending on the season.

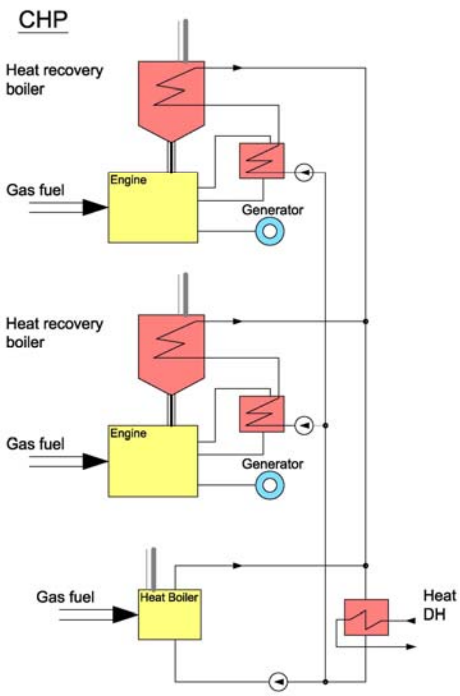

Fig. 3. The simplified structural schematic of CHP

In this paper it is assumed that it is possible to calculate the costs associated with providing energy supply for district D. The results of the calculation of energy prices for power supply variants A and B are presented on Fig. 4. In Variant A, electricity is imported from the grid, and its price is fully dictated by market. In this case, the price for heat is mainly determined by the price for fuel, capital costs for boiler house construction, operating costs and credit payment terms. The basic initial data used in calculations are provided in Table I and Table II.

TABLE I
YEARLY AVERAGE PRICES FOR FUEL AND ENERGY

No.	Name	Price
1	Cost of gas	451 EUR/1000m^3
2	Price of electricity exported	105 EUR/MWh
3	Price of electricity imported	126 EUR/MWh

In Variant B1, when all the electricity is exported, its price is also determined by market. On condition that there is a task for gaining the normalized profit, the revenue from selling electricity makes it possible to reduce the price for heat sharply. However, in this case, the district is forced to purchase the relatively expensive electricity from the grid. In power supply Variant B2, the coalition of the consumers of both types of energy gains the additional revenue at the expense of difference in the prices for imported and exported electricity. This enables to distribute the additional revenue on the basis of using (2) and (3) as well as to reduce the prices to an even greater degree (see. Fig. 4).

The highest tariffs are in the winter period, when considerable part of heat is produced by the boiler house.

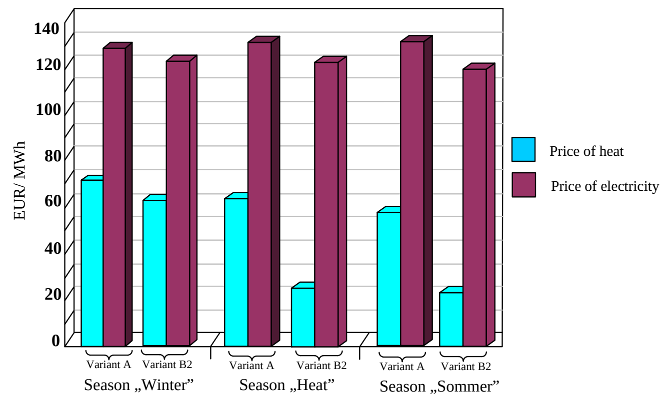

Fig. 4. Seasonal energy tariffs for energy supply variants A and B2

In price calculation (Fig. 4), it was assumed that the district is fully consuming the electricity produced. In case if some part of electricity is exported to the grid, the difference between Variants A and B2 will diminish. Fig. 5 shows the correlation between the prices for both types of energy and the amount of energy export (for CHP with a capacity of 1 MWe). Such dependence indicates that the coalition is interested in consuming the electricity of its own production. The considered approach regarding the distribution of the additional revenue can serve as a basis for creating an appropriate procedure of calculation with the consumers, depending on their heat and electric load charts. Notice that the results shown on Fig. 4 (along with the data indicated on the subsequent figures) have been obtained, using the real prices for fuel and equipment. Hence, these results substantiate, in the first instance, the efficiency of using small-capacity cogeneration plants, especially, with high prices for energy carriers.

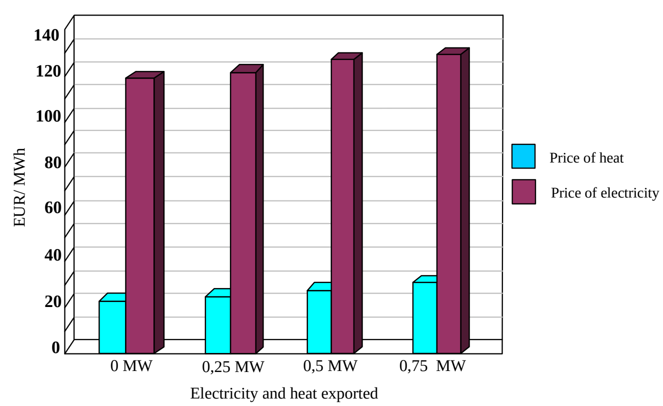

Fig. 5. Energy tariffs depending on the amount of electricity export

Fig. 6 represents the heat and electricity tariffs achieved by the suggested method, for CHP with a capacity of 1 MW, assuming that all the electricity is consumed by the local consumers. The methods give essentially different results. The application of the method based on the game approach results in electricity prices that are sufficiently close to the market prices as well as to relatively low heat prices. It appears that such price ratios stimulate the extensive application of cogeneration processes in energy production.

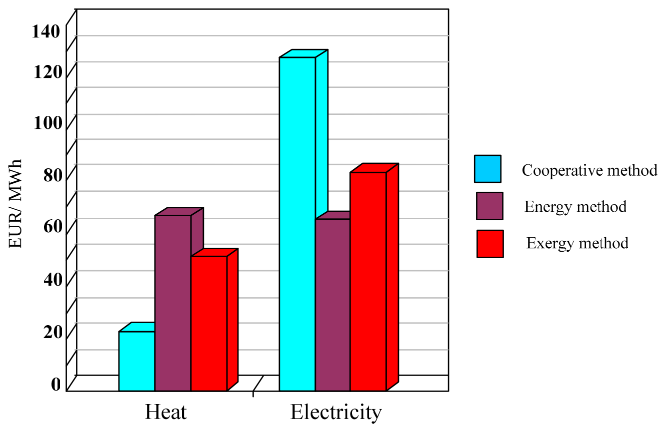

Fig. 6. Energy tariffs calculated by different methods, costs according to the Energy and the *Exergy* methods

B. Example 2

The process of production and retail of energy is depicted on Fig. 7 and Fig. 8. According to the process on Fig. 7, the owners of the House 1 (H1) and House 2 (H2) (there can be more houses) act independently and produce the energy for their own needs.

Surplus or deficit of electrical energy is exported or imported via the distribution grid. It is assumed that it is possible to calculate the costs associated with providing energy supply for H1 and H2. Let us denote these costs as E1 and E2 respectively. The alternative to the schematic considered in Fig.6 is depicted on Fig. 8. Let us assume that in this case, power supply costs are E12, and the condition (9) applies.

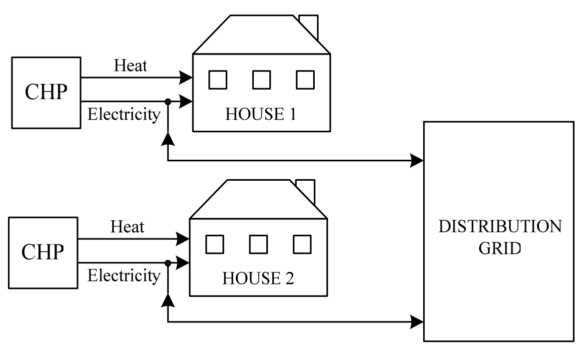

Fig. 7. The energy supply systems for independent consumers

Inequality (9) makes it rational to create the coalition between the owners of H1 and H2. Cost reduction can be explained by investment costs reduction due to larger capacity of CHP (compared to construction of two CHP units), costs reduction due to common gas supply line etc. Forming a coalition and cost reduction raises the question of gain distribution and determination of tariffs for consumed heat and electricity. The principal data assumed in calculations of energy production costs are provided in Table II.

For better visualization of the results, it is assumed that the heat consumption charts are uniform.

The results represented on Fig. 9 prove that the additional revenue emerges when the consumers are interconnected in order to construct more efficient CHPs with increased capacities.

TABLE II
THE PRINCIPAL DATA USED IN EXAMPLE 2

1	Electrical capacity of units (MWe)	1	0.75	0.5	0.25
2	Thermal capacity of units (MWh)	1.15	0.872	0.5	0.25
3	Efficiency	0.88	0.86	0.85	0.25
4	Gas consumption (7900 kcal/m^3), (m^3/h)	272	205	139	69
5	Capital costs, EUR/kWe	800	850	900	1000
6	Operating costs, EUR/MWh	11	11.5	12	13
7	Power-to-heat ratio in CHP	0.86	0.86	0.86	0.86

For example, when two CHPs with a capacity of 0.5 MW each are interconnected, the price for electricity will decrease from 115 EUR to 111 EUR per MWh_e. At the same time, the price for heat energy will decrease from 25.5 EUR to 24.5 EUR per MWh_h. The electricity and heat prices will also decrease, when two CHPs with different capacities are interconnected (for more details, see Fig. 9 and 10).

Notice that the interconnection gain in a great measure depends on the geographical location of the players – prospective members of the coalition. If there are considerable distances between the players, the cost of DH networks and losses in them will increase, and the condition (9) may not perform.

It should be noted that this paper describes only the simplest examples demonstrating the possibilities of using the methods of the cooperative game theory in order to distribute the energy tariffs. In the future, it is planned to study more common cases that include a larger number of players, possibly, with diverse heat consumption charts as well as with varying energy carrier tariffs and electricity tariffs.

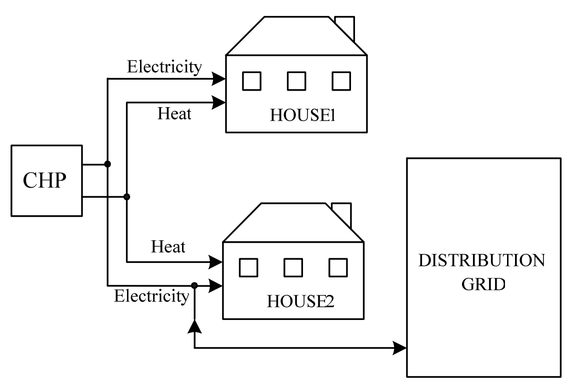

Fig. 8. The energy supply systems for independent consumers

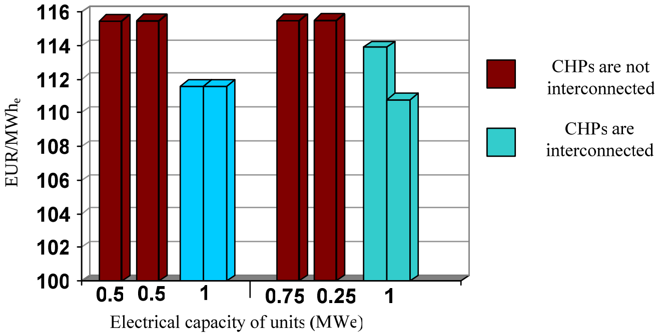

Fig.9. Electricity tariffs depending on the capacity of the coalition members

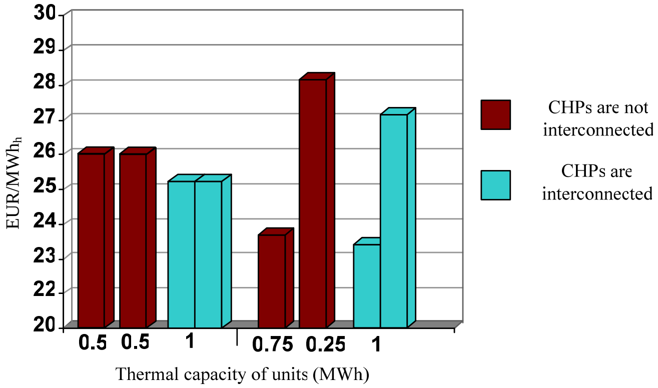

Fig.10. Heat tariffs depending on the capacity of the coalition members

IV. Conclusions

1. 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 a more efficient energy supply system and acceleration of DER implementation in power systems.
2. The known methods of determining tariffs for energy produced in the cogeneration mode are poorly adapted for application in the market environment.
3. Construction of CHP and formation of a coalition of heat and electricity consumers makes it possible to essentially reduce tariffs for both types of energy.
4. The formation of a coalition of energy consumers for the construction of CHP with increased capacity may result in the additional reduction of energy tariffs.

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Standards:

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VI. Biographies

Viktoria Neimane received MSc from the RTU in 1995 and PhD from the Royal Institute of Technology in Stockholm, Sweden in 2001. She joined Vattenfall Research&Development (VRD) as a Senior Research Engineer at 2002. Presently she is a Manager of Power Technology department at VRD.

Antans Sauhats received Dipl.Eng., Cand.Techn.Sc. and Dr.hab.sc.eng. degree from the Riga Technical University (former Riga Polytechnical Institute) in 1970, 1976 and 1991 respectively. Since 1991 he is Professor at Electric Power Systems. Since 1996 he is the Director of the Power Engineering Institute of the Riga Technical University.

Guntars Vempers received BSc and MSc degree from the Riga Technical University in 2001 and 2004 respectively. At present doctoral student at Faculty of Power and Electrical Engineering. Since 2000 he is working at engineering company “Siltumelektroprojekts”, at present – project manager.

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Inga Tereskina received BSc. and MSc degree from the Riga Technical University in 2005 and 2008 respectively. At present doctoral student at Faculty of Power and Electrical Engineering. Since 2006 she is working at engineering company “Siltumelektroprojekts”.

Galina Bochkarjova received Electrical enginneer degree from the Riga Technical University in 1970. At present she is Research Engineer at Faculty of Power and Electrical Engineering.