Selection of the most appropriate regions for wood fuel based cogeneration plants using multi-criteria decision analysis methods

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Abstract: -Multi-criteria decision analysis is used both for location problems and for energy problems. For successful involving of wood-fired cogeneration in Estonia it is important to define the most appropriate region, where the wood-fuel cogeneration plants can be located. The method used for defining the optimal location is based on the multi-criteria decision analysis (MCDA), which includes the Delphi method for criteria selection, the Analytic Hierarchy Process (AHP) method as weighting method and the elementary weighted sum method (WSM) for the final decision defining. In the result the most appropriate county in Estonia for wood-fuel based cogeneration plant installation was defined.

Key-Words: -Analytic hierarchy process, Cogeneration, Multi-criteria decision analysis, Renewable energy, Wood fuel

I. INTRODUCTION

Cogeneration is the production of electricity and heat in a single process. Cogeneration technology provides greater conversion efficiency than traditional electricity 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.

The main targets of the above-mentioned EU directives are reflected in the National Development Plan of the Energy Sector until 2020. The Plan is based on the Sustainable Development Act and is the major strategic document

directing the development of the Estonian fuel and energy sector until 2020. According to the plan, the strategic objectives of the Estonian fuel and energy sector include increasing the share of renewable electricity up to 5.1% of the gross consumption by 2010, and increasing the share of electricity produced from combined heat and power production plants up to 20% of the gross consumption by 2020.

The use of wood in cogeneration plants is one of the most significant ways of achieving the concept of sustainable development in Estonia. There are two reasons for it. First reason is, that the use of wood for energetic purpose belongs to the socalled short-circuit of carbon where the carbon dioxide resulting from the burnt wood is believed to be completely consumed by the green plants. The energy obtained by burning wood is included into the category of regenerable energies. And second reason is that the use of energetic co-generation systems implies high energetic efficiency which, for a certain level of energy demand, leads to minimum CO2 gas emissions. [1]

The development perspectives for wood-fired cogeneration in Estonia are determined by the necessity for additional energy sources, wood resource availability and the high potential for cogeneration development in Estonia's towns.

The results of the previous research showed that there are high perspectives for the cogeneration development in Estonia. The wood-fuel cogeneration potential is partly used, but there are still plenty of possibilities to enlarge the share of electricity produced by the renewable cogeneration in the country [2].

For successful involving of wood-fired cogeneration in Estonia it is important to define the most appropriate places, where the wood-fuel cogeneration plants can be located. Despite Estonia being a small country, there are 15 counties, which are different in many respects. The evaluation of the differences may be used for the new wood-fuel based cogeneration plant location decision making.

The method used for defining the optimal location is based on the multi-criteria decision analysis (MCDA), which includes the Delphi method for criteria selection, the Analytic Hierarchy Process (AHP) method as weighting method and the elementary weighted sum method (WSM) for the final decision defining.

2. WOOD FIRED COGENERATION

A. *Current situation*

Estonian energy system is unique for its oil shale based electricity production, which has been an important energy source for many years. For more than 40 years, two world's largest oil-shale fired power plants have been producing over 90% of Estonia's electricity, sufficient also for export to Latvia and Finland [3].

Almost certainly the main reasons for that are the availability of oil shale, its low price and the fact, that there are enough installed capacities and a properly functioning infrastructure. The main positive sides of large-scale use of oil shale are the stability of the national energy supply and the independence from electricity import. The main disadvantages of oil shale use are the large-scale environmental damage caused by oil shale mining and the fuel use in the plants, and also the low calorific value of oil shale.

Nonetheless, in spite these disadvantages, oil shale remains the main fuel used for electricity production [4].

Implementation of cogeneration technologies in Estonia began already more than 70 years ago, and this technology was being used both in the Tallinn and in Narva power plants.

The share of cogeneration heat is 30% of the total heat production in Estonia. The electricity produced in Estonia by cogeneration makes up 12-14 % of the total electricity produced. The share of cogeneration comprised 10% of the final energy consumption during the last two years and earlier it had been in the range of 14–15% (Figure 1). This can be explained by the general economic downturn caused by the economy crisis due to which the output of some large industrial cogeneration plants has decreased or even ceased. At the same time, several new small plants have been opened but their energy output is relatively small.

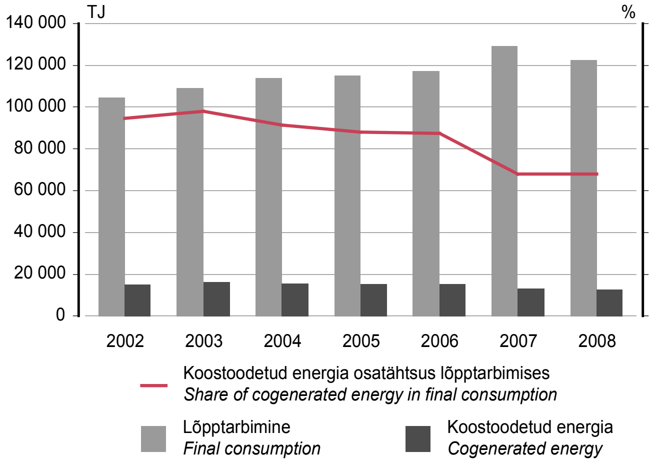

Fig. 1 Cogeneration energy in Estonia [5]

At present, the entire electricity sector in Estonia is dominated by the state-owned company AS Eesti Energia. There are only some private-owned companies dealing with small-scale cogeneration and some industrial cogeneration plants. The four big cogeneration plants: Balti, Iru, Eesti and Ahtme with a total electrical power of 460 MW, are owned by AS Eesti Energia. Thus, there are no problems related to the sale of the electricity produced to the grid. Heat consumers of the AS Eesti Energia cogeneration plants include the district heating networks and industries.

The main fuel types used by cogeneration in Estonia are oil shale (up to 85%), natural gas (11%), heavy oil, industrial gas (1%), and peat (2%). There were no wood-fired cogeneration plants in Estonia before 2009. In the beginning of 2009, two new wood-fired CHP units were put into operation (Table 1). Both wood chips and peat can be used as fuel for energy production in these plants.

Table 1 Wood-fired cogeneration plants in Estonia

Title	Tartu Elektrijaam	Tallinn Elektrijaam
Beginning of operations	January, 2009	December,2008
Electricity capacity	25 MW	25,4 MW
Heat capacity	52 MW	50(68) MW
Planned annual heat output	158 GWh/year	304 GWh/year
Planned annual electricity output	180 GWh/year	500 GWh/year

B. *Potential of wood fuel based cogeneration plants in Estonia*

High potential of wood fuel based cogeneration in Estonia can be explained by various factors.

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°C (Kärdla) to -25.5 °C(Tartu)[6]. Heating period in Estonia is from 216 days (Võrumaa) to 224 days (Järvamaa) [7]. 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.

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.

Other factor is that the estimated potential of biomass energy in Estonia exceeds 20 TWh/year. Estonia's forests cover about 48% of its entire territory. The country has a high potential for energy production from wood-based fuels.

Wood consumption by cogeneration is possible using steam turbine technologies.

There are two types of steam turbines, which can be used for electricity production from wood:

- back-pressure turbines – designed in such a way as to achieve on evacuation a several-bar pressure in a condenser from where the co-generated heat is extracted.
- condense turbines – keeping part of the steam in an intermediary opening in the carcass (either by direct use or by condensing for providing the co-generated heat) and allowing the rest of the steam to expand in the layers of low pressure, to be eventually condensed in sub-atmospheric pressures, as a rule.

Steam turbines are built in such a way as to be able to adapt to steam characteristics (flow, pressure, overheat) and depend on each constructor's own design.The power of these turbines ranges from few MW to tens of MW [8].

Back-pressure turbines are used in existing wood fuel based cogeneration plants in Estonia.

III. METHODOLOGY

A. Multiple criteria decision analysis

Multiple criteria decision analysis (MCDA) is a generic term for all methods that exist for helping making decisions in cases where there is more than one conflicting criterion [9]. MCDA is an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems[10]. The general objective of MCDA is to assist a decision maker to choose the best alternative from a range of alternatives in an environment of conflicting and competing criteria.

The MCDA methods have become very popular in decision-making for energy systems. These methods have been used for different energy system issue evaluation, such as energy resource allocation, energy planning and selection, energy exploitation, energy policy and others [11].

The MCDA methods have been applied for the evaluation of various cogeneration energy system aspects [12]-[16].

The MCDA methodology applied to determination of the optimal location for various facilities such as waste disposal, waste treatment plants, wind farms and power plants is described in the papers [17]-[20].

B. MCDA adoption

This research presents adoption of an MCDA approach to the task of wood fuel based cogeneration plant location.

Usually the decision making process, based on MCDA consists of four steps: the alternatives formulation and criteria selection, the criteria weighting, the evaluation, and the final treatment and aggregation.

Various methods, such as the Delphi method, the least mean square method, the Min-Max deviation method and the correlation coefficient method are applied to select the criteria.

Hence there were no certain quantitative dependencies between the various criteria and the efficiency of the wood fuel cogeneration plants, the experts' opinion was important.

Delphi method

For that reason the Delphi method was chosen for the task of the research. The Delphi method is widely used in forecasting. A panel of carefully selected experts is asked to answer questionnaires for criteria selection in two or more rounds. After each round of questioning, the experts receive feedback: the anonymous answers provided by the other experts. Then they are asked to revise their answers in the light of the other replies. This process is repeated until the number of answers has sufficiently decreased in order to determine the final answers via the median scores. It is considered that during this process the range of the selected criteria should decrease and a "correct" criteria should be selected.

The Analytic Hierarchy Process

Weighting methods are used for definition of weights that indicate the relative importance of criteria in MCDA. The criteria weights influence directly the ranking order of alternatives. Therefore the adequacy and rationality of criteria weights determine the reliability of the evaluation results. This has led to a variety of methods regarding how to assess the weight of the selected criteria [11].

The Analytic Hierarchy Process (AHP) method was chosen for the weight determination in current research. The AHP belongs to the rank-order weighting methods.

The AHP has proven to be a powerful decision analysis technique in the area of multi criteria decision making (MCDM), and has been successfully applied to the tackling of MCDM problems [21].

The latter are based on the importance of criteria and the preference of decision-makers. The weights are distributed on the simplex of rank-order weights (1).

$$w_1 \geq w_2 \geq \ldots \geq w_n \geq 0 \tag{1}$$

where

$$\sum_{j=1}^{n} w_j = 1$$

where w_j is weight for criterion C_i.

Generally, the rank-order weighting methods are classified into three methods: subjective weighting method, objective weighting method, and combination weighting method. The AHP belongs to the subjective weighting methods.

The AHP is based on the pair-wise comparison model, which was originally developed by Prof. Thomas L. Saaty [22].

A main strength of the AHP is that it is both methodologically sound and user-friendly. Its ease of use is due to a unique combination of design characteristics. The AHP frames a decision as a hierarchy. All inputs consist of comparisons between just two decision elements at a time; pair-wise comparisons like these are generally considered to be one of the best ways to get judgments.

Within the AHP it is necessary to structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which is a set of the alternatives) [23].

The matrix of pair-wise comparisons in general can be formed as

$$D = \begin{bmatrix} C_1/C_1 & C_1/C_2 & \dots & C_1/C_n \\ C_2/C_1 & C_2/C_2 & \dots & C_2/C_n \\ .. & .. & .. & .. \\ C_n/C_1 & C_n/C_2 & \dots & C_n/C_n \end{bmatrix} \qquad (2)$$

where

C_j is criterion.

The degree of consistency achieved in the pair-wise comparison is measured by a consistency ratio (CR) which both checks the reliability of the analysis and reduces the chance of making a procedural mistake. If the value of CR is smaller or equal to 10%, the consistency is acceptable. If the CR is greater than 10%, the subjective judgment should be revised.

The Table 2 shows the scale of numbers that indicates how many times more important or dominant one criterion is over another criterion.

Table 2 The fundamental scale of absolute numbers [23]

Intensity of weight	**Definition**
1	Equal Importance
2	Weak or slight importance
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance
Reciprocals of above non-zero number	If criterion *i* has one of the above non-zero numbers assigned to it when compared with criterion *j*, then *j* has the reciprocal value when compared with *i*

Normalization

The data about each alternative should be normalized. For the normalization is used the method called the Analysis and Synthesis of Parameters under Information Deficiency (ASPID) [13]. Using this method the factors in natural units are modified into indicators with values between 0 and 1.

If the competitiveness of an alternative is improved by increasing the criteria indicator, then the formula (3) is used

$$x_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \quad i=1,2,..m; j=1,2,..n \qquad (3)$$

where X_{ij} is indicator in natural units for criterion C_j for alternative A_i;

x_{ij} is normalized indicator for criterion C_j for alternative A_i.

If the competitiveness of an alternative is improved by decreasing the criteria indicator, then the formula (4) is used

$$x_{ij} = \frac{\max(X_j) - X_{ij}}{\max(X_j) - \min(X_j)} \quad i=1,2,..m; j=1,2,..n \qquad (4)$$

The Weighted Sum Method

After the data normalization is used the elementary MCDA method, also called the weighted sum method. In this case the score of an alternative is calculated as

$$S_i = \sum_{j=1}^{n} w_i x_{ij} \text{ , … } i=1, 2, .. m, \qquad (5)$$

The comparing of the alternative scores can be used for ranking. The best alternative is the one whose score is the maximum.

IV. OPTIMAL LOCATION

A. Problem formulation

For successful wood-fired cogeneration development in Estonia it is important to define the optimal region, where the wood-fuel cogeneration plants can be located. There are 15 counties in Estonia: Harju, Hiiu, Ida-Viru, Jõgeva, Järva, Lääne, Lääne-Viru, Põlva, Pärnu, Rapla, Saare, Tartu, Valga, Viljandi, Võru and the task of research is to determine the most optimal location for the new wood-fuel cogeneration plant installation.

B. Criteria selection

The Delphi method was used for criteria selection. Following criteria were selected by 5 independent experts during two rounds (Table 3)

Table 3 Criteria for choosing an optimal location for a wood fuel based cogeneration plant in Estonia

Nr.	*Title*	*units*
C_1	Wood fuel potential in counties	m3/km2 per year
C_2	Wood fuel consumption in counties	m3/km2 per year
C_3	Heat consumption in the county cities	MWh/km2 per year
C_4	Existing cogeneration plants	MW
C_5	Highway infrastructure	km/km2
C_6	Gross Domestic Product per capita	kroons/per capita
C_7	Unemployment level	%

Wood fuel potential criterion indicates the wood amount that can be generated in a given area according to the land type. This criterion is important, because the transportation expenses are significant and it is better to use the wood on-site. Values of this criterion are based on the research "Estimation of the potential resources of forest biomass", financed by the Estonian Rural Development Foundation. Calculations of wood fuel potential were realized using the Geographical Information System (GIS) data from the Estonian Base Map, the Estonian Digital Soil Map, the digital forest maps from the State Registry of Forest Data and the area maps of rural municipalities [24].

Wood fuel consumption: High wood fuel consumption can decrease the amount of wood available for the new cogeneration plant. The wood fuel consumption figures were obtained using the fuel consumption statistics per county, collected by the Industry, Construction and Energy Statistics Service of Estonia.

Values of the *Heat consumption in county* criterion were obtained from the data about heat consumption collected by heat producers. Due to the fact that cogeneration is the simultaneous production of heat and power, it becomes crucial for both types of energy to be used appropriately. As concerning power, it may be both 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 determining factor in selecting cogeneration plant capacity.

Highway infrastructure is important for the wood fuel consumption, because the transportation costs are usually rather high, as it has been mentioned before. Good transport infrastructure in the county increases its competitive advantage in comparison with other counties.

Unemployment level is the criterion, which is both required for the available workforce and for the social acceptance of the cogeneration plant installation in the county.

Gross domestic product per capita characterizes the achieved socio-economical development of the county. The already installed wood-fuel based cogeneration plants are located in the counties with the highest gross domestic product per capita: in Tallinn and in Tartu.

C. Criteria weighting

The AHP is used for criteria weighting. The pair-wised matrix is shown in the Table 4. The fundamental scale presented in the Table 2 was used for the evaluation. For a pair-wise comparison matrix to be accepted as consistent, the consistency ratio should be smaller than 10%.

Table 4 Pair-wise matrix

Criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	Weight
C_1	1	2	1/2	4	7	8	6	**0,2576**
C_2	1/2	1	1/2	2	6	7	5	**0,1796**
C_3	2	2	1	5	9	9	8	**0,3571**
C_4	1/4	1/2	1/5	1	3	6	2	**0,0938**
C_5	1/7	1/6	1/9	1/3	1	1	1/2	**0,0308**
C_6	1/8	1/7	1/9	1/6	1	1	1/4	**0,0262**
C_7	1/6	1/5	1/8	1/2	2	4	1	**0,0549**

In our case the consistency ratio is equal to 4.69%, which means that the criteria weight evaluation is consistent.

The weights for each criterion are showed in the last column of Table 5.

D. Data normalisation and calculation

All data for each criterion and alternative are shown in the Table 3. As it was discussed in the second section, the values of Table 3 were normalised in a common scale from 0 to 1.

The normalised values for the criteria C_1 , C_3 , C_5, C_6 and C_7 are calculated using the equation (3). The normalised values for the criteria C_2, C_4 are calculated using the equation (4). (See Table 6)

The weighted sum method was used to calculate the score of each alternative.

V. RESULTS

Following to the offered algorithm, the criteria selection, the weighting, the calculation of the normalised values and the weighted sum method, the most appropriate counties for the wood-fuel based cogeneration plant were found.

The calculation results using the formula (5) are shown in the Table 6. Ranks for alternatives were calculated and presented in the last column of Table 6.

The "optimal" county (Järva County, A_5) can be interpreted as a result of the county's performance in the Wood fuel potential ($x_{5\,1}=1$), the Wood fuel consumption ($x_{5\,2}=0.95$) and the Existing CHP ($x_{5\,4}=1$). The next best options for a new wood-fuel based cogeneration plants location are the counties Lääne and Saare, which have taken the second and the third place, respectively.

Table 5 Performances of the counties for the selected criteria.

Alternative	County	*C_1*	*C_2*	*C_3*	*C_4*	*C_5*	*C_6*	*C_7*
		Wood fuel potential	**Wood fuel consumption**	**Heat consumption**	**Existing cog.plant**	**Roads**	**Unemploy-ment**	**GDP**
		m3/km2 per year	m3/km2 per year	MWh/km2 per year	MW	km/km2	%	krones/per capita
A_1	Harju county	33,44	168,47	598,16	451,36	0,3589	12,9	279268,36
A_2	Hiiu county	43,36	10,75	0,00	0	0,4624	11,1	106460,41
A_3	Ida-Viru county	39,13	46,08	172,42	281,4	0,2702	18,1	109481,05
A_4	Jõgeva county	36,80	20,35	19,59	0	0,4282	20,1	81675,77
A_5	Järva county	52,92	18,29	27,38	0	0,3707	11,9	117529,61
A_6	Lääne county	45,38	13,01	32,85	0	0,3160	15,5	110697,11
A_7	Lääne-Viru county	36,74	23,70	15,38	3,1	0,3330	16,4	123913,90
A_8	Põlva county	28,55	17,55	4,41	0	0,5386	12	90549,59
A_9	Pärnu county	46,27	28,50	31,38	64	0,2975	10,6	137837,28
A_{10}	Rapla county	45,93	16,78	3,98	0	0,3389	15,5	99779,80
A_{11}	Saare county	45,40	16,77	30,49	0,0	0,3737	10,4	122097,04
A_{12}	Tartu county	32,59	60,14	172,96	63	0,4186	11,9	164045,14
A_{13}	Valga county	35,71	19,57	32,75	0	0,5455	17,8	89583,20
A_{14}	Viljandi county	47,03	22,21	12,76	0	0,3577	11,9	101805,70
A_{15}	Võru county	31,87	16,92	79,20	0	0,5445	16	98911,92

Table 6 Performance of the counties by the selected criteria

Alt.		Wood fuel potential	Wood fuel consumption	Heat consumption	Existing cogen. Plant	Roads	Unemploy-ment	GDP	**Score**	**Rank**
	Criteria weight ->	**0,2576**	**0,1796**	**0,3571**	**0,0938**	**0,0308**	**0,0262**	**0,0549**		
A_1	Harju County	0,20	0,00	1,00	0,00	0,32	0,26	1,00	**0,480**	**5**
A_2	Hiiu County	0,61	1,00	0,00	1,00	0,70	0,07	0,13	**0,460**	**8**
A_3	Ida-Viru County	0,43	0,78	0,29	0,30	0,00	0,79	0,14	**0,411**	**10**
A_4	Jõgeva County	0,34	0,94	0,03	1,00	0,57	1,00	0,00	**0,405**	**11**
A_5	Järva County	1,00	0,95	0,05	1,00	0,37	0,15	0,18	**0,564**	**1**
A_6	Lääne County	0,69	0,99	0,05	1,00	0,17	0,53	0,15	**0,495**	**2**
A_7	Lääne-Viru County	0,34	0,92	0,03	0,99	0,23	0,62	0,21	**0,389**	**14**
A_8	Põlva County	0,00	0,96	0,01	1,00	0,97	0,16	0,04	**0,305**	**15**
A_9	Pärnu County	0,73	0,89	0,05	0,84	0,10	0,02	0,28	**0,463**	**7**
A_{10}	Rapla County	0,71	0,96	0,01	1,00	0,25	0,53	0,09	**0,479**	**6**
A_{11}	Saare County	0,69	0,96	0,05	1,00	0,38	0,00	0,20	**0,486**	**3**
A_{12}	Tartu County	0,17	0,69	0,29	0,84	0,54	0,15	0,42	**0,392**	**13**
A_{13}	Valga County	0,29	0,94	0,05	1,00	1,00	0,76	0,04	**0,412**	**9**
A_{14}	Viljandi County	0,76	0,93	0,02	1,00	0,32	0,15	0,10	**0,483**	**4**
A_{15}	Võru County	0,14	0,96	0,13	1,00	1,00	0,58	0,09	**0,399**	**12**

The map on the Fig.2 displays the results of calculations. The darker is the colour, the more favourable is the corresponding district for the new stations installation.

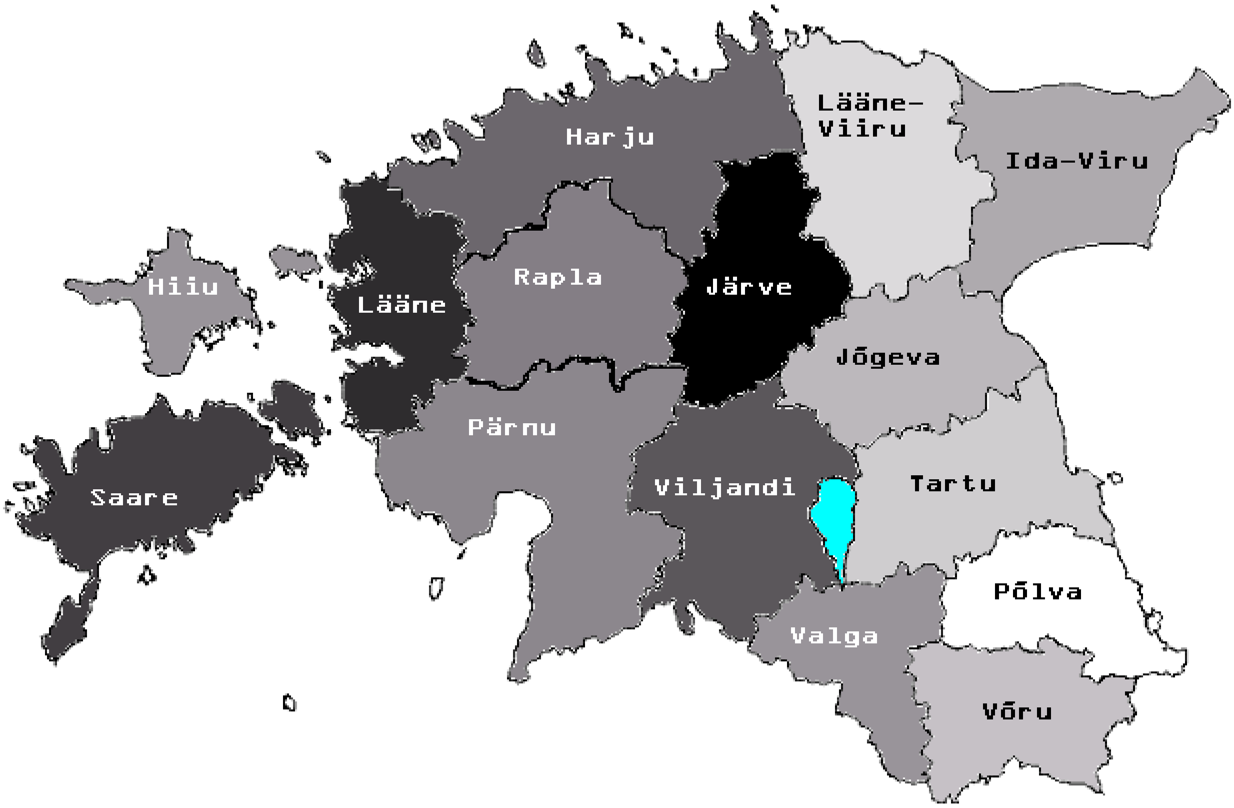

Fig.2. The results of the optimal location determination visualized on the map of Estonia. (The darkest colored counties are the most favorable ones for the wood-fuel based CHP installation)

VI. CONCLUSION

Applying the multi-criteria decision analysis in the energy field has received a lot of scientific attention over the last years. This paper offers a methodological framework for determination of the optimal location for a new wood-fuel based cogeneration plant. The framework includes the following steps: the problem formulation, the criteria selection by the Delphi method, the criteria weighting by the Analytic Hierarchy Process method, the data normalisation and the final calculation by the weighted sum method. The selected criteria are: the wood fuel potential in the counties, the wood fuel consumption in the counties, the heat consumption in the county cities, the existing cogeneration plants, the highway infrastructure, the unemployment level and the gross domestic product per capita.

The methodology is successfully implemented for the case of Estonia. The result of this methodology shows that the optimal county for new wood-fuel based cogeneration plant installation is the Järva County. The presented methodology can be used either by private investors, or by public authorities. This methodological framework can be adopted with minor modifications for solving the same problems in the Baltic and Nordic countries, where the similar criteria are important. The tool is not limited only to the specific wood-fuel cogeneration plant location determination; it can also be used for determining the optimal location for the plants running on biogas, on natural gas or on some other energy source. However, in those cases the other criteria should be selected.

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