KAUNAS UNIVERSITY OF TECHNOLOGY

EUGENIJA FARIDA DZENAJAVIČIENĖ

# Investigation of Efficient Use of Biofuel for Sustainable Development of Energy Sector

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (06T)

2012, Kaunas

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The research was carried out in 2007–2011 at Laboratory of Regional Energy Development, Lithuanian Energy Institute.

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The official defence of the dissertation will be held at 10 a.m. on January 8, 2013 at the public session of the Council of Energetics and Power Engineering science trend in the Session Hall at the Central building of Lithuanian Energy Institute (Breslaujos g. 3, Room No. 202, Kaunas).

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

LIETUVOS ENERGETIKOS INSTITUTAS

EUGENIJA FARIDA DZENAJAVIČIENĖ

# BIOKURO EFEKTYVAUS PANAUDOJIMO DARNIAI ENERGETIKOS ŪKIO PLĖTRAI TYRIMAS

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## NOMENCLATURE

### Abbreviations

| | |
|---|---|
| RES | - renewable energy sources, |
| EU | - European Union, |
| IRP | - integrated resources planning, |
| DH | - district heating, |
| DHS | - district heating system, |
| CHP | - combined heat and power, |
| IGCC | - integrated gasification combined cycle; |
| FEB | - fuel and energy balance, |
| PER (NPER) | - primary energy factor (non-renewable primary energy factor), |
| $CO_2R$ | - carbon dioxide emissions factor, |
| AEId | - renewable energy fraction, |
| 1G | - 1st generator, |
| 2G | - 2nd generator. |

### Measure units

| | |
|---|---|
| ktoe/a | - kilotons of oil equivalent per year, |
| kWh, MWh, TWh, GWh | - kilo-, mega-, tera-, gigawatthours, |
| kWh | - kilowatthour, |
| $m^3$, $sm^3$ | - cubic meters, solid cubic meters for wood fuel, |
| kg | - kilogram, |
| MJ, PJ, GJ | - megaJoule, picaJoule, gigaJoule, |
| ha | - hectare, |
| N | - capacity, MW, |
| n.v.k. | - coefficient of efficiency, |
| t | - tone, |
| MW | - megawatt, |
| $km^2$ | - square kilometers, |
| a | - annual. |

### Indexes:

el - electricity

f - fuel

# 1. INTRODUCTION

***Relevance of the work***

Energy generation using renewable energy sources is one of most significant priorities in energy policy of European Union. This way EU attempts to mitigate negative impact on environment from energy sector by reduction of $CO_2$ emissions; and reduce economic dependence on fuel import from third-party countries. This is important issue due to the growth of oil and natural gas prices. Biomass fuel is one of renewable energy sources the use of which stimulates development of local economics and creates new jobs. Besides, the use of RES forms possibilities to ensure security of energy supply via diversification of energy sources.

Planning of RES in Lithuania was performed exceptionally on national level till recently, and regional development, strengthening of self-governing is the strategic trend of management reform in most EU states. Law on Renewable Energy Sources empowers Lithuanian municipalities to elaborate, adopt and implement RES development action plans after having adjusted it with the Government. Such plans are envisaged to implement the aims of sustainable energy development and ensure the change of currently used fossil fuel with RES at economic range. District heating supply plays key role in municipal energy plans, as it enables efficient use of residual energy and renewable renewable energy sources, including biomass fuel. Expected introduction of energy efficiency labeling scheme in this sector seeks to define sustainable energy development indicators, which will enable comparison of DH systems with optional technologies used in individual boilers-houses and define which heating technologies will provide highest efficiency of the system.

There are still no reliable tools – methodologies and models – for assessment of RES potential in municipal area and for planning investment on the basis of marginal biomass fuel production costs, as well as for planning investment in heat supply sector based on the principles of sustainable energy planning and implementing modern technologies in autonomous and district heating sectors.

***The aim of the work***

The aim is to create methods for investigation of biomass fuel production potential and its' use for heat generation, evaluating the main sustainability indicators - primary energy factors, carbon dioxide emission factors and renewable energy fraction - of various technologies and to assess technological solutions regarding sustainability criteria as well as to define support needs for development of these technologies.

***Tasks of the work***

1. To develop methodology for assessment of biomass fuel potential and mastering range enabling to evaluate indicators influencing the use of biomass for fuel production;
2. To develop methodology for complex assessment of sustainability indicators for various heat generation technologies enabling to define:
    a. Factors, defining primary energy resources indicator;
    b. Factors, defining carbon dioxide emissions indicators; and
    c. Factors, defining renewable energy fraction when fossil and renewable fuel is combined for heat generation;
3. To assess heat generation expenses for various biofuel and fossil fuel using technologies, and the needs for supporting measures for development of biofuel technologies.

***Novelty of the work***

New original methodology and simulation model were developed for assessment of biofuel potential at municipal level based on forestry statistics data and enabling to assess biofuel production potential with regard to potential exploitation level.

New methodology and spreadsheet were developed for complex assessment – energy, environmental and economic – of heat generation technologies, enabling to assess the efficiency of biofuel and fossil fuel use for heat generation vs. such criteria as primary energy resources, carbon dioxide emission, renewability of resources and generation costs.

***Practical significance of the work***

The law on Renewable Energy Sources empowers Lithuanian municipalities to elaborate, adopt and implement RES development action plans. Tools – models were developed under this work enabling to assess biofuel production potential using forests statistics at municipal level. This model was used to assess biomass potential in Lithuanian regions as well as in municipalities of Kaunas Region under EU partly financed projects. Supplemented project enables to estimate biofuel production costs in full technological chain of biofuel production, evaluating sustainability criteria for biofuel production.

Spreadsheet for energy, environmental and economic assessment of heat generation technologies was used for estimating prospective investment into heat generation biofuel technologies for Utena district heating company. The same model will be also applied for the assessment of district heating generation criteria used for energy and environmental labeling. Such labeling is envisaged in currently elaborated Labeling Directive for District Heating/Cooling systems.

The developed model is supplemented with indicators, enabling the assessment of support measures for development of biofuel heat generation technologies for planning of promotion measures – subsidizing of investment and feed-in tariffs for electricity produced in cogeneration cycle – in national as well as municipal levels.

***Defensive propositions of the dissertation***

1. The use of forests cutting and management residues for biomass fuel production is mainly restricted by biomass extraction from forests, waste volume in the area and fuel transportation costs.
2. Primary energy factor of efficient heat generation can be achieved using co-generation technologies with optimal electricity-heat generation ratio and distribution of capacities with optimal distribution of capacities between generators and using biomass fuel.
3. The least values of green-houses gases emissions can be achieved via applying co-generation technologies and the use of biomass.
4. The use of biomass fuel permits to achieve renewable and recycled energy fraction close to 100 % in heat generation even while certain share of heat loading is covered by fossil fuel installations.
5. Applying of biomass co-generation technologies can be a good option for autonomous as well as district heating as meeting sustainability indicators in the best way in case respective support measures are applied.

***Approbation of the results***

The dissertation material has been published in 3 scientific articles in the ISI and the journals registered in international scientific information databases. 9 scientific articles were published in Lithuanian and international conference proceedings. Oral presentations have been presented in 4 international and over 12 national conferences.

***Structure of the dissertation***

The dissertation is written in Lithuanian, consists of three main chapters (overview of research in the dissertation field, description of methodology, discussion of research results), conclusions, list of references and main publications on the topic of dissertation. The works includes the total of 116 pages, including 56 figures and 16 tables. It consists of an introduction, references overview, methodology, results, conclusions, 108 references and bibliography.

## 2. BASIS OF THE WORK

Recent decades highlighted the shortcomings of the use of fossil fuel. Even without evaluating restricted resources of crude oil, natural gas and coal, the fact that our atmosphere cannot bear further emissions of greenhouse gases (mainly carbon dioxide), becomes more and more evident. This situation returned us to the use of RES.

Only relatively small share of potential biomass resources is used for energy generation at present. However, interest in these resources is growing constantly, which leads to formation of new policies, legislation, and awareness rising on climate change and new possibilities to forestry and farming activities in developing bio-energy market.

The two main driving forces for wider use of biomass for energy needs are climate change challenge and energy security.

The main principles of wood fuel exploitation policy were formed simultaneously with compatibility criteria to existing situation in all levels of hierarchy. It was defined that regional policy should encourage competition and regional independence of the regions, thus supporting the national development, i.e. should be integrated into national policy. This enables to create methodological background including environmental, economic and social aspects for sustainable technological development in energy sector in various governing levels. Municipalities should perform their functions based on energy programs or plans, where development of info data and respective mathematical planning tools are needed.

Every town (or region) has it‘s own structure of energy needs. Due to possibility to exchange energy sources, reasonable market of energy resources should be formed. Urban and regional municipal energy programs (or plans) are tools enabling optimal market redistribution, accumulating necessary resources and re-directing them towards measures reducing energy losses and energy demand as well as supporting wider use of RES.

These plans must contain assessment of economic, financial and other benefits, assessment of risk for every investment project and providing expected costs and income, allowing the control of project implementation success.

Different from other countries basic traditional promotion measures are still not implemented in Lithuania (energy or fuel taxes, obligatory audits, state support programs) to improve energy consumption efficiency. Subsidizing system of energy consumption for low income families does not stimulate energy savings either. Inadequacy between the assessed wood fuel resources potential and that assessed using adopted principles and criteria of sustainable RES development becomes more evident.

Sustainable energy development is based on replacement of fossil fuels by RES and improvement of energy efficiency in both production and consumption sides. International Atomic Energy Agency, United Nations Department of Economic and Social Affairs, International Energy Agency, Eurostat and European Environment Agency have formulated energy criteria for sustainable development. These criteria involved development guidelines and methodology for social, economic and environmental dimensions. For the purpose of this work several criteria were selected, which are most closely related to the use of biofuel and energy efficiency measures in autonomous and district heating technologies. Primary energy factor, carbon dioxide emission factor, renewable and recycled energy fraction as well as long-run heat generation costs and energy efficiency were selected.

Improvement of energy efficiency is here understood as any measure taken by energy producer or consumer and reducing primary energy use per unit of produced heat without negative impact on the quality of product or service.

The Lithuanian Heat law provides certain rights and obligations to municipalities, which are the owners of heat supply infrastructure. These are delivering of licences for small heat supply companies (with heat sales up to 10 GWh/a), approval of heat costs and investments. Providing population with heating is the exceptional role of municipalities.

Municipal energy plan should be adequate to general economic development strategy, in which providing resources plays the key role. In wide meaning municipal energy plan should include the activities of municipality and subordinate institutions, which have impact on the activities of energy sector. The main goal of such plan is to ensure reliable and secure meeting of energy needs for all consumers in the territory of the municipality with the least costs and impact to environment, as well as to define priorities for future actions and investments based on IRP principles.

Tools are required for assessment of biofuel potential and investment into biofuel production as well as its use in autonomous and district heating sectors for implementation of such planning and investment, as well as for comparing of technologies on the basis of sustainable energy criteria.

## 3. OBJECT AND METHODOLOGY OF THE WORK

### 3.1. Mathematical modelling for defining the potential of wood fuel production development at local level

Wood processing residues as well as natural forests, scrubs and energy plantations make the potential for production of wood chips (which is the main fuel in DHS). In general case technological process of wood fuel production includes:

a) Trees cultivation;

b) Collecting and extraction of wood cutting residues from forest to chipping sites;

c) Wood chips production;

d) Transportation to intermediate storage and supply to final consumers.

This process may employ various technological solutions in all 4 production stages. The first stage could be important for energy sector in case of energy plantations. Tree cutting, including collecting of reasonable part of cutting residues, is the prerogative of forestry. Planning of wood fuel demand and adequate infrastructure is the task of municipalities. Necessary information for implementation of such task could be available using respective tool.

Mathematical model on extraction of wood fuel should contain the following input data:

1) Data on forest areas in investigated region or areas available for energy plantations, soil productivity, roads and other characteristics;

2) Volumes of wood cutting waste, available for fuel production;

The **volume of wood waste** must meet material balance equation:

$$SGZ_r \leq KRV_r(\tau) \cdot \eta_r(\tau); \qquad (1)$$

here $SGZ_r(\tau)$ – the volume of wood for chips production during period $\tau$, mill. $m^3$, $KRV_r(\tau)$ – annual wood cutting volumes, mill. $m^3$, $\eta_r(\tau)$ – coefficient of wood resources used for energy purposes.

3) The **demand of wood chips for the needs of energy conversion**, expressed in equation:

$$\sum_e \sum_r SGZ_{re}(\tau) \cdot \eta_{re}(\tau) \leq \sum_e EP_e(\tau); \qquad (2)$$

here $SGZ_{\gamma e}(\tau)$ – volumes of wood for chips production, used for *e* - type energy generation, $\eta_{\gamma e}(\tau)$ – coefficient for transformation of wood chips into *e* - type energy; $EP_{\gamma e}(\tau)$ – *e* - type energy demand.

The activity on the use of wood waste for energy generation, including consistent production stages, starting with collection, chips production and delivery of any type of energy to final consumers can be considered as separate energy sub-sector. Simulation of this sub-sector activity would make projections closer to experimental research. These projections could be used for simulation of the impact of political tools, which might be used for regulation of market processes. The modelling results can also help state and municipal institutions in implementing and revising strategies in energy sector.

Statistical data on cutting volumes exists since 1990. Assessment of cuttings structure ($KRV(\tau)$) was restricted with 4 types of cutting sites: clear, intermediate cuttings and precommercial thinning, the latter divided into 2 parts (trees below and above 10 years age). In this case **material balance equation for all cuttings** is:

$$\frac{PLK(\tau)}{KRV(\tau)}+\frac{TRK(\tau)}{KRV(\tau)}+\frac{JAT10(\tau)}{KRV(\tau)}+\frac{JAT20(\tau)}{KRV(\tau)}=1; \qquad (3)$$

here *KRV* – cutting volumes, mill. $m^3$, *PLK* – clear cutting residues, mill. $m^3$, *TRK* – intermediate cutting residues, mill. $m^3$, *JAT10* – residues from precommercial thinning of trees below 10 years, mill. $m^3$, *JAT20* – residues from pre-commercial thinning of trees over 10 years, mill. $m^3$, $\tau$ - time period, years.

The structure of wood residues potential from research references was estimated for 1 $m^3$/a cutting volume, and was divided into 5 components: 1) tops, small stems, branches, etc.; 2) non-liquidated branches; 3) stumps and roots; 4) needles and leaves; and 5) bark.

These **potential components** are assessed using balance equations:

$$\frac{KR_{POT}(\tau)}{KRV(\tau)}=\frac{KR_{POT1}(\tau)}{KRV(\tau)}+\frac{KR_{POT2}(\tau)}{KRV(\tau)}+\frac{KR_{POT3}(\tau)}{KRV(\tau)}+\frac{KR_{POT4}(\tau)}{KRV(\tau)}+\frac{KR_{POT5}(\tau)}{KRV(\tau)}. \qquad (4)$$

or,

$$d(\tau)=d_1(\tau)+d_2(\tau)+d_3(\tau)+d_4(\tau)+d_5(\tau). \qquad (5)$$

Where d, $d_1$, $d_2$, $d_3$, $d_4$, $d_5$ – are generalised components of wood residues potential in Eq. 4.

The data of research is insufficient for more detailed investigation of non-liquidated wood structure. Approximate assessment allows to assume that tops, small stems and branches make about 34.3 %, non-liquidated branches – 28 %, stumps – 14.9 %, needles and leaves – 1.4 %, and 11.4 % is left for bark. Such residues could be considered as potential reserve for biofuel production in case waste extraction is feasible.

### 3.2. Methodology for competitiveness simulation of biofuel technologies against fossil fuel technologies

DH enables to use co-generation and/or alternative fuel such as solid biofuel (chips) instead of heavy oil fuel or natural gas, which is technically and economically not feasible in autonomous heating systems in buildings. On the other hand, new technologies appear on the market which can be used in buildings for autonomous heat and power generation.

While assessing competitiveness of technologies using renewables with those using fossil fuel one should evaluate important sustainable energy indicators, such as: primary energy factor *PER,* $CO_2$ emissions factor $CO_2R$; and, in case technological solution is using combined fuel (wood and fossil), renewable energy fraction *AEId*. For assessment of DH system efficiency 3 levels of indicators can be used: mean default EU values, national, and case specific for energy system (boiler-house or CHP plant). The model here uses default fuel values, which were adopted on EU level under standard EN 15603:2007.

On the other hand, renovation strategies for DHS of small towns should be based on economic costs analysis. For this purpose "green field" heat supply costs from DHS and autonomous heating sources should be compared. As heat supply is closely related to electricity and fuel sub-sectors, power, natural gas and other fuel costs have inevitable impact on analysis results of heat supply systems.

The new technological solutions penetrating current heat market are: gas turbines, reciprocating engines, biofuel gasification, etc.) for heat and power generation.

The model was developed for this investigation for comparison DH and autonomous heating, usual and innovative technologies in typical buildings, as well as technologies used for the needs of DHS. Fast development of new heat generation technologies makes serious challenge in terms of competition for DHS, especially in small towns due to low heat demand density, resulting in higher heat generation and distribution costs. Possibilities for new CHP solutions appear in residential, administrative and other buildings.

For assessment of modernization options for heating installations one should assess local environmental and socio-economic issues. This requires information not only on heat costs at current DHS but also at future modern ones. Below the main indicators of energy and environmental efficiency of energy technologies are presented:

**Primary energy factor** *PER* (primary energy factor for supplied heat), $MWh/MWh_{CŠT}$:

$$PER_{P,CŠT,neAEI(i)} = \frac{\sum_{i=1}^{n} E_{K(i)} \cdot PER_{P,K,neAEI(i)} - (E_{el,CHP(i)} - E_{el.te}) \cdot PER_{P,el,neAEI}}{\sum_{j=1}^{n} Q_{t,j}}; \quad (6)$$

here, $PER_{P,CŠT,neAEI(i)}$ –primary energy fact or for heat delivered to the building from a DH grid and/or individual heating system within a considered period (one year); $PER_{P,K,neAEI(i)}$ - non-renewable primary energy factor for the fuel *i*, $E_{K(i)}$ - net energy content of fuel *i* delivered to the gate where it is finally converted to heat (using lower heating value); $PER_{P,el,neAEI}$ - primary energy factor for electricity is set to 2.6 as average for EU fuel mix; $E_{el,CHP(i)}$ - net produced electricity in co-generation plants measured at the output of the plant. Only applicable for electricity produced in CHP mode; $E_{el,te}$ - all use of electrical energy for operating the heating network; and $Q_{t,j}$ - delivered heat to the building, $j$, at system boundary. For DH this is the same as measured heat at building system boundary which is the primary side of the substation.

**Carbon dioxide emission factor** $CO_2R$ define the fuel supply chain $CO_2$ emissions, when one energy unit, lower heating value, of a fuel is extracted, refined, stored and transported and finally converted to useful heat, kg $CO_2/MWh_{tšil}$.

$CO_2$ emission factor $CO_2R$:

$$CO_2R_{tšil} = \frac{\sum_{i=1}^{n}(E_{K(i)} \cdot CO_2R_{K,bendras(i)}) - \dfrac{\sum_{i-1}^{n}(E_{el,CHP} \cdot CO_2R_{K,bendras(i)})}{\eta_{el}}}{\sum_{j=1}^{n} Q_{t,j}}; \qquad (7)$$

here $CO_2R_{tšil}$ – $CO_2$ emission factor for delivered heat provided to the building, kg $CO_2$/MWh; $CO_2R_{K,bendras(i)}$ – $CO_2$ emission factor for fuel $i$, kg $CO_2/MWh_{kuro}$; $E_{K(i)}$ - net energy content of fuel $i$ delivered to the gate where it is finally converted to heat (using lower heating value); $E_{el,CHP(i)}$ - net produced electricity in co-generation plant from fuel $i$ (Produced electricity minus auxiliary electricity use). Only applicable for CHP. If more than one fuel is used in CHP mode the electricity produced from fuel $i$ can be approximated the energy input fraction from fuel $i$ to the CHP ($E_{K(i)}/ E_{el,CHP(i)}$); $\eta_{el}$ - default electrical efficiency condensing for a conventional thermal power plant set to 40 %; $E_{el,nh}$ - all use of electrical energy for operating the heating network; and $Q_{t,j}$ - delivered heat to the building, $j$, at system boundary. In case of DHS heat delivered to building sub-station.

Criterion **renewable and recycled energy fraction** *AEId* is introduced to specifically support the use of renewable and surplus energy in district heating systems. The criterion visualise the use of non-fossil fuels. The criterion is calculated as the percentage of renewable and recycled energy content of the fuels delivered to the gate where they are finally converted.

Renewable and recycled energy fraction *AEId* is calculated:

$$AEId = 100 * \frac{\sum_{i=1}^{n} E_{K(i)} \cdot AEId_{K(i)}}{E_K}; \qquad (8)$$

here *AEId* - share of renewable and recycled energy of the district heating system, %; $AEId_{K(i)}$ - renewable and recycled energy factor for fuel $i$, between 0 and 1; $E_{K(i)}$ - energy content of fuel $i$ allocated to DH (lower heating value); and $E_K$ - energy content of all fuels allocated to DH (lower heating value).

Assessment of heat supply costs in DHS is not less important than evaluating environmental criteria, as these costs should be competitive to that of heat generated in autonomous boilers. Justification of prospective decisions is the matter of strategic planning and should be based on long-run marginal costs analysis.

**Heat generation costs** are the main factor for economic analysis:

$$ŠS = KAPS + KS + KES_{O\&M} + PES_{O\&M}.; \quad (9)$$

here $ŠS$ – heat generation costs, Lt/MWh,
$KAPS$ - capital costs, Lt/MWh,
$KS$ - fuel costs, Lt/MWh,
$KES_{O\&M}$ - variable operation and maintenance costs, Lt/MWh,
$PES_{O\&M}$ - fixed operation and maintenance costs, Lt/MWh.

For comparison of various technologies in boiler-houses break-even investment and break-even electricity costs are extremely important.

**Break-even investment** is relative investment, when capital costs in cost price of heat are equal to heat generating costs from alternative source. It is calculated:

$$RI = ((ES \cdot ŠP) - KES_{O\&M} - PES_{O\&M} - KS + P_{EL})/KAK; \quad (10)$$

here $RI$ – break-even investment, Lt; $ES$ – cost price of energy generation from alternative source, Lt/MWh; $ŠP$ – heat demand, MWh/a; $P_{EL}$ – income for sold electricity, Lt/a; and $KAK$ – capital recovery factor.

Break-even investment shows what should be investment into the unit of heat capacity to make capital costs feasible and summary generation costs should be not higher than those in alternative production source.

**Break-even electricity costs** – electricity sales price when heat generation costs are equal to those from alternative source. It is calculated:

$$RK_{EL} = -(N \cdot ES - KAPS - KES_{O\&M} - PES_{O\&M} - KS)/G_{EL}; \quad (11)$$

here $RK_{EL}$ – break-even electricity costs, Lt/kWh$_{el}$; $N$ – installed capacity, kW; $ES$ – energy generation costs of alternative heat source, Lt/MWh; $G_{EL}$ – electricity generation volumes, MWh.

Break-even electricity costs show the least price for sales of electricity produced at CHP plant at which income compensates higher capital and operation& maintenance costs in CHP installations comparing to alternative heat generation source, which is usually water heating boiler-house.

For the simulation purpose the following heat and electricity technologies were selected: direct incineration of natural gas and solid biofuel boilers, CHP plants with internal combustion engine, gas turbine and biofuel CHP plant.

***CHP plant with gas turbine*.** Gas turbine is recently becoming popular type of CHP installation. Usually such power generation capacities vary between

1 and 100 MW. Recently gas turbines technologies with capacities less than 250 kW were developed. Compressed fuel and air mixture is burnt and high pressure flue gas transfer mechanical energy to gas turbine, which is driving power generator.

***CHP plant with internal combustion engine*.** Internal combustion engines are widely developed and well known technology with power generating capacity ranging between several kW to 5 MW. Internal combustion engines can be used in CHP plants, where besides electricity generation hot water and low parameters steam is produced. Electricity is generated more efficiently in gas engines than in gas turbines; however, the use of recycled heat is more complicated as it is distributed between flue gas and engine cooling system.

***Biofuel gasification with CHP plant*.** Biofuel gasification is one of biofuel CHP plant options. Integrated gasification combined cycle (IGCC) is one of the most progressive and environmentally friendly technologies, which is used for energy generation from the big variety of fuels, including biofuel, waste, oil refinery residues, etc. Biofuel or any other fuel is converted to combustible gas in synthesis reactor with supplied air or pure oxygen. Afterwards achieved gas is cleaned from solid particles and harmful components and later burnt as fuel in CHP installations. These are usually steam or gas turbines, various engines, recycled heat from steam condensation and flue gas is also used to improve higher thermal efficiency of the plant.

## 4. MODELLING OF BIOFUEL PRODUCTION AND USE DEVELOPMENT

### 4.1. Simulation of biofuel production potential in energy sector

For assessment of resources potential available for wood fuel production one needs data on distribution of forests cutting sites by type. According to various forest research references it was assumed that share coefficients in the unit of final products are as follows: $a_1(\tau)=0.567$ for clear cuttings, $a_2(\tau)=0.343$ for intermediate cuttings, $a_3(\tau)=0.08$ for precommercial thinning where trees age more than 10 years and $a_4(\tau)=0.008$ for those below 10 years. Without information on the change of above coefficients the assumption was made that they were constant during the whole investigation period and Fig. 1 shows the simulation of cutting structure dynamics during 20 years period.

Increased cutting volumes (Fig. 1) were defined by the growth of demand for industrial and technological wood, also due to unpredicted windfalls and squalls and storms. Such disasters could also have impact on fuel wood production volumes; however this does not mean the growth of wood waste use.

After having distributed recalculated data of potential wood waste $d$ from eq. 5 into 5 components 1) $d_1$ - tops, small stems, branches, etc.; 2) $d_2$ - non-liquidated branches; 3) $d_3$ - stumps and roots; 4) $d_4$ - needles and leaves; and 5)

$d_5$ – bark of industrial wood, one can stimulate the dynamics of potential wood waste.

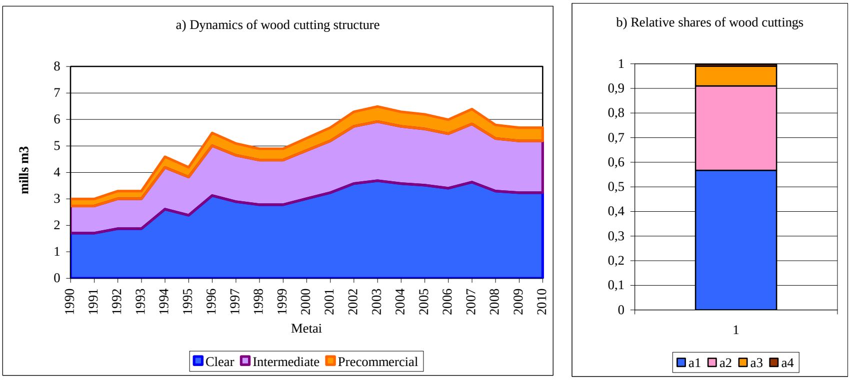



**Fig 1.** a) Dynamics of forests cutting structure and
b) relative cutting shares defined in Eq. 3

Estimate shows that parameter $\alpha$ (regression coefficient) could be increased towards better use of small stems, branches or stumps (Fig. 2).

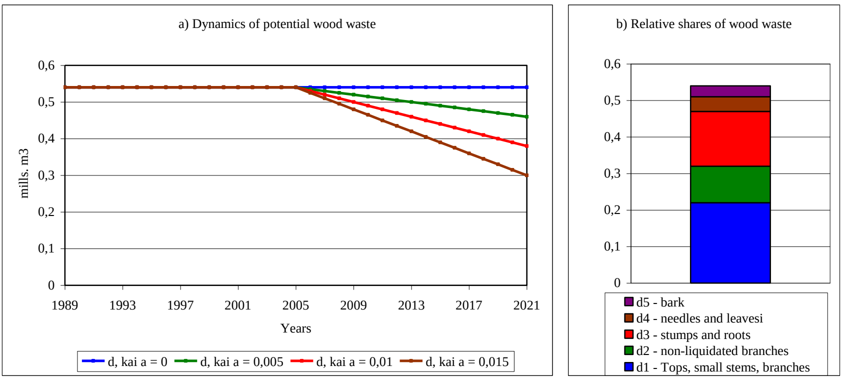



**Fig. 2.** Forecasts for biomass cuttings with increase of wood chips production on the account of wood waste from the forest: *d* – at $\alpha$ =*0*; *0.005; 0.01* and *0.015*

Mathematical model permits to overview not only retrospective of forest cutting activities, but also provide projections in relative as well as absolute values. Wood cutting residues would reduce by half only with the highest $\alpha$ and even in this case could reach approximately 3 mills. t/a.

As one can see from Fig. 3, even at $\alpha=0.01$, wood chips production from potential waste $KR_{POT}$ could be increased by 1 mill. $m^3/a$, and produce double volume of wood chips comparing to current volumes. The feasibility and investments of such activity will be presented in chapter 4.2.

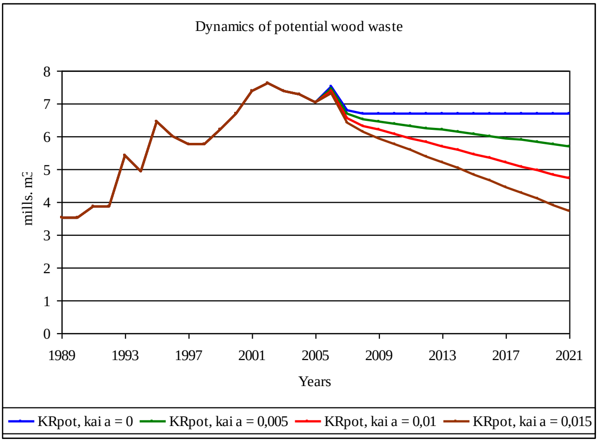



**Fig. 3.** The dynamics of unused potential wood waste: $KR_{POT}$ – at $\alpha=0$; *0.005;0.01* and *0.015*

The assessment of wood fuel demand can be assessed using several options, including also the data of Fuel and Energy Balance (FEB). However, this option is not very helpful for the needs of regional or municipal planning, as provides national data only. Thus here the installed wood energy capacities by municipalities are presented in the (Fig. 4).

Easily available wood biomass resources are nearly exhausted: over 700 ktoe of wood fuel is now being used out of nearly 900 ktoe. Wood cutting residues for chips production should be addressed to keep the existing and future growth rates in the use of biomass fuel.

Input data for forecasting possible resources is available from annual forest statistics, including cutting rates. However, there is no data for private forests, where cutting rates can be similar or even higher.

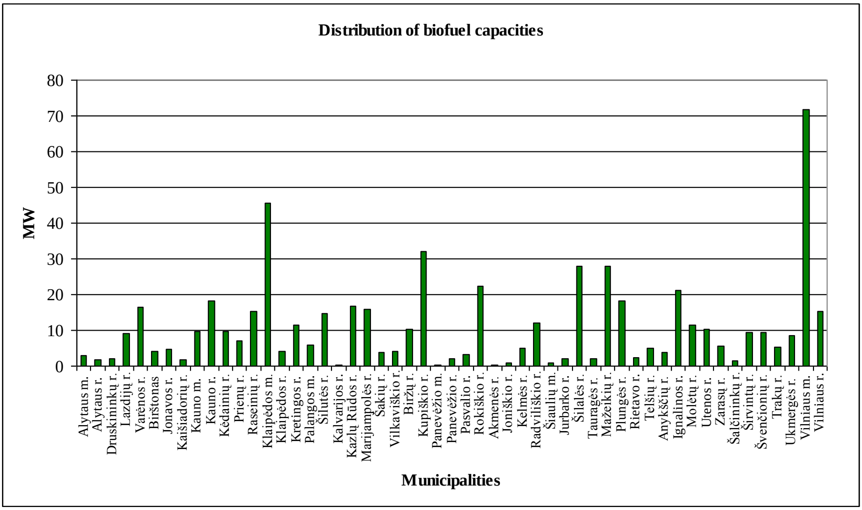



**Fig 4.** Installed solid biofuel using capacities in municipalities

The share of wood cutting waste, which is considered the main source for production of biofuel in the forests, is nearly 30% of total forests stands. Wood waste volume is mainly related to actual cuttings, which were not changing much during recent 10 years and was between 5.5 and 6.5 mills $m^3$/a.

Bearing in mind sustainability aspects (related to environment protection), these resources are even smaller. Thus with assumption that solid biofuel can be produced from forest cutting waste, fire-wood, and, in case of no demand from paper-wood and plane-wood industry, and evaluating cutting volumes from state and private forests), we can conclude that nearly 780 thos. $m^3$/a of cutting waste, 1660 thos. $m^3$/a of firewood, 1230 thos. $m^3$/a of paper wood and 600 thos. $m^3$/a of plane wood could be used for wood chips production, which in total could reach 4250 thos. $m^3$/a of wood fuel.

## 4.2. Modelling of long run marginal costs for wood chips production

Wood fuel production should be considered as extraction of energy resources, similar to extraction of peat or crude oil. Production of wood chips as energy fuel consists of three technological stages:

1) Extraction of resources for chips production,

2) Wood chips production,

3) Wood chips transportation to consumers (boiler-houses and CHP plants).

Every stage uses different technologies, defining specific costs. This means that introducing wood chips into the market of energy resources requires long-run marginal costs analysis for such fuel production.

Research shows that the costs of wood resources *ZRK* at chips production site depend on waste density *AT* and average distance to chipping site *ISA*. Thus the data of forests research can be defined by linear equation:

$$ZRK = 60.18 - 0.0545 * AT + 0.0218 * ISA; \qquad (12)$$

here *ZRK* – costs of wood resources, Lt/ $m^3$, *AT* – the volume of waste formed in 1 ha area, $m^3$, *ISA* – distance to chipping site, m.

Here long-run marginal costs analysis is restricted on technological solutions used in this study.

Simulation shows that possible reserves for reduction of biofuel production costs are in waste extraction operation of (Fig. 5).

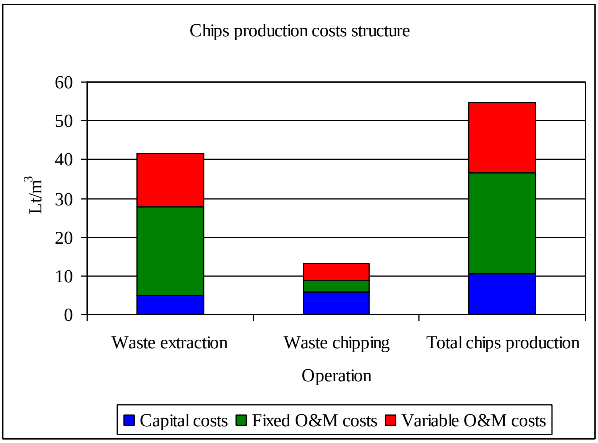



**Fig 5.** Costs structure of wood chips production

Relatively fixed operation costs consist of staff salaries and social insurance (Fig. 6). The highest costs are formed in operation of fuel extraction. It is known that such jobs do not need high qualification and here municipalities can see opportunities of employment of jobless persons.

Fuel costs are the main component of variable costs (Fig. 7). Tax on resources could encourage private forests owners for collecting wood waste. Significant volumes of dieseline are used in waste extraction. Variable costs could be reduced via VAT allowances for fuel (as in agriculture sector).

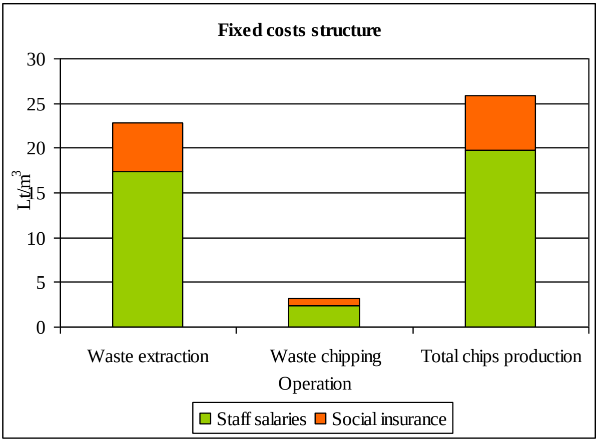



**Fig. 6.** Fixed costs structure

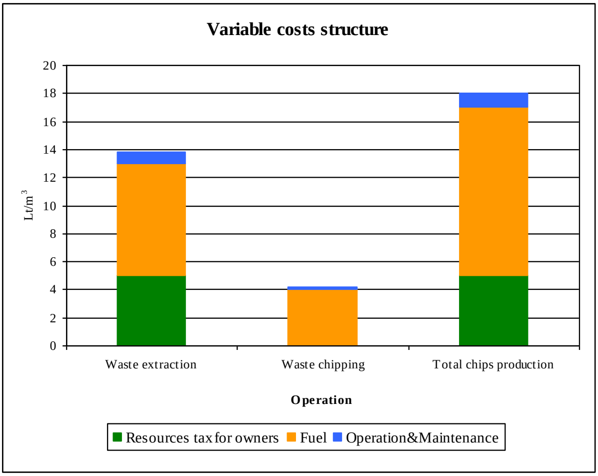



**Fig 7.** Variable costs structure

On the other hand, the efficiency of dieseline used for production of other type of fuel is not high (Fig. 8). This could be significant factor for development of wood fuel in pre-commercial thinning, where waste density is rather low and extraction distances are long. This issue could be solved on forests planting stage while planning paths for passage of more efficient transport.

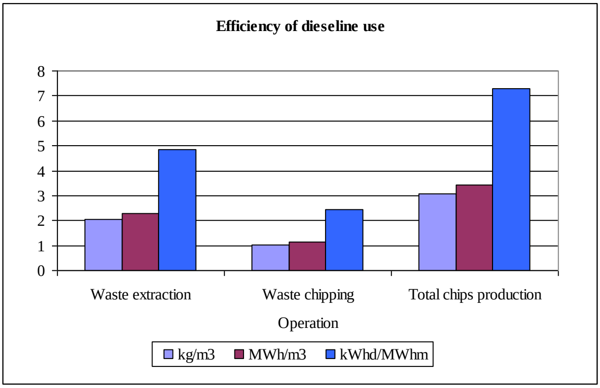



**Fig. 8.** Comparison of dieseline costs in natural and energy units with wood fuel values

Chips transportation to boiler-houses costs are defined not just by available transport but also by location of chips production site (Fig. 9). Costs could be reduced by planning intermediate storage sites, thus improving transportation of chips to consumers.

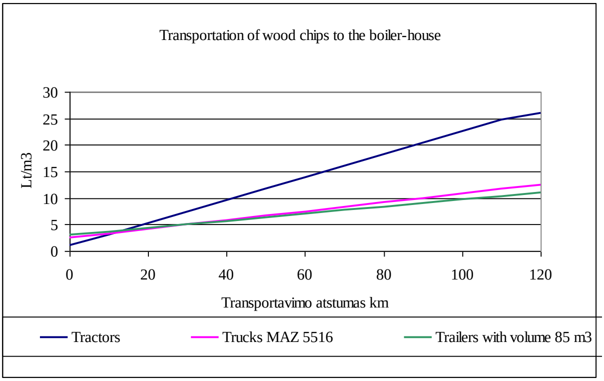



**Fig. 9.** Chips transportation costs for various transport means

Estimated chips production costs are lower than current market price. Reduction opportunities of these costs are in better planning and use of available resources.

## 4.3. Comparison of competitive ability of biofuel technologies with natural gas technologies, using created model

***Comparison of technologies in individual houses.*** Comparison of heat generation costs for individual houses permits not only to define the least costs solution, but to evaluate competitive ability of these technologies with DH option. Such assessment is required for implementation of DH development and optimization projects, when companies plan connection of new consumers or disconnection of the old ones, when DH is not feasible due to high transmission losses. Such situation is characteristic, when heat is supplied to distant consumers via old obsolete pipelines with excess permeability, which should be renovated. Besides, renovated public buildings have usually lower heat demand, and the question arises whether it is feasible to renovate pipelines or install autonomous heating with selected type of fuel and generating technology, which would be the least costs solution..

8 types of buildings, specific to small Lithuanian towns with average heat capacities and heat demand were selected for research, and main characteristics were defined from statistics provided by heat suppliers for this simulation. These are typical residential and public buildings.

Investigated technologies include biofuel and fossil fuel installations as the most prospective in terms of resources availability, and which technological installations are available on market. The selected technologies for individual houses are as follows:

1. Natural gas boiler;
2. Biogas boiler;
3. Modern automatic biofuel (pellets) boiler;
4. Natural gas CHP plant with internal combustion engine;
5. Natural gas CHP plant with gas turbine;
6. Biogas CHP plants with reciprocating engine.

Estimated heat generation costs for 6 selected autonomous heating technologies for 8 types of typical buildings (I – individual house, II, IV and V – block residential houses of various sized, III – commercial building, VI – administrational building, VII – hospital and VIII – school) shows (Fig. 10), that solid biofuel and biogas boilers are the least costs solution for all types of buildings. There is one more option – biogas CHP plant for larger consumers (types VII, VIII), where heat generation costs are close to those of solid biofuel (pellets) and biogas boilers. However, such costs are for installations operation with full loading only.

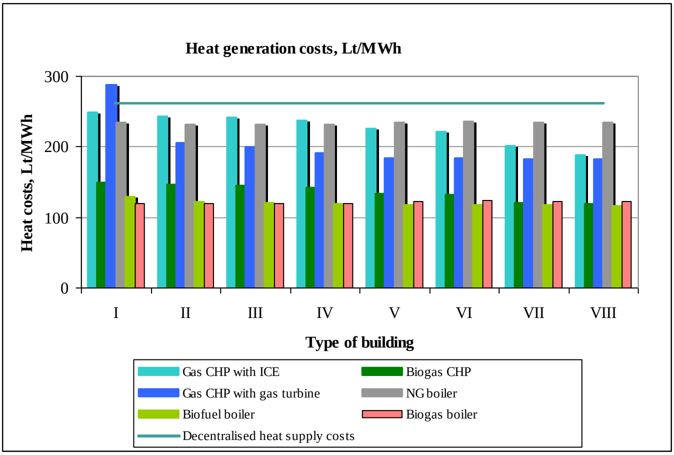



**Fig. 10.** Heat generation costs for 8 types of individual buildings and 6 selected heat generation technologies

In case electricity, produced in CHP units replaces electricity, purchased from the electricity network, results are better, however, this situation requires adequacy of heat and electricity demands vs. time.

Prepared methodology permits an analysis of electricity tariffs at which CHP installations could be competitive. Such analysis evaluates the support needs for new technologies, i.e. what feed-in tariffs for electricity from efficient CHP units or biofuel CHP, which are supported by Co-generation Directive or RES Directive and included into Services meeting public interest.

Promotion of new technologies development can be implemented using other measures – support for investment, reducing capital costs, subsides for fuel production from RES, which will reduce fuel costs, etc. The impact of all these measures can be assessed using this methodology.

***Comparison of technologies in DH boiler-houses and CHP plants.*** 3 heat generation technologies most frequently used in Lithuanian DHS and 2 modern technologies – gas turbines and biofuel CHP were used for simulation:

1. Natural gas boiler-house;
2. Biofuel boiler-house (fuel – wood chips);
3. Natural gas CHP with internal combustion engine;
4. Natural gas CHP with gas turbine;
5. Biofuel CHP plant (fuel – wood chips, power generation – steam turbine).

Comparison of 5 heat generation technologies was performed using 3 sustainability criteria: primary energy factor *PER*, together with non-renewable primary energy factor *NPER*, (for 2 generators using different fuel); carbon dioxide emissions factor $CO_2R$; and renewable energy fraction *AEId* (for 2 generators using different fuel). These indicators were used to compare DHS with autonomous heating technologies.

Currently elaborated draft Energy Efficiency Directive assumes that pursued primary energy factor for efficient DH system *PER* < 0.8; and pursued carbon dioxide emissions factor $CO_2R$< 172 kg $CO_2$/MWh.

With above assumptions we can define sustainability indicators for all technologies, selected for the research. As these indicators do not depend on the size of installation, it is evident that CHP technologies are in more favourable situation comparing to heat only boilers, since *PER* using current fuel primary energy coefficients is defined by EN 15603:2007 standard and uses "power bonus" method, assigning to electricity fuel amount, equal to average fuel consumption in EU electricity generation sector (Fig. 11). The new fuel primary energy coefficients are now being elaborated for the purpose of eco-labelling of DHS.

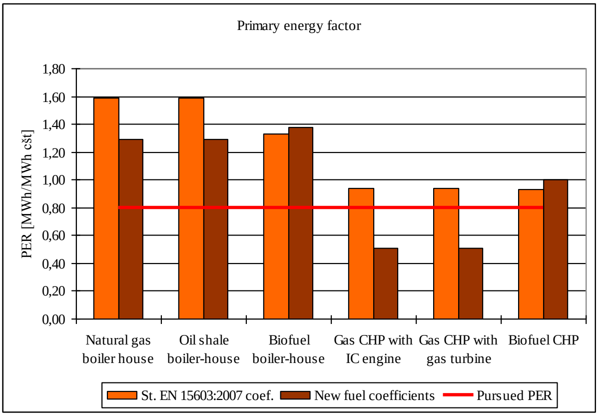



**Fig 11.** Primary energy factors for 6 selected heat generation technologies at standard and newly prepared fuel primary energy coefficient and pursued *PER*

Carbon dioxide emissions factor was evaluated and is presented in Fig. 12. This factor shows evident pros of biomass technologies against fossil fuel technologies, though emission factors for CHP plants are less than pursued carbon dioxide emissions factors.

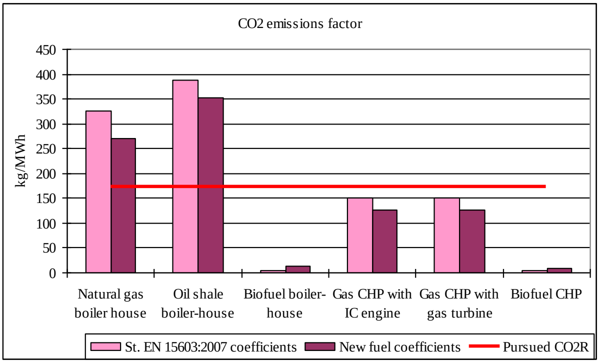



**Fig. 12.** $CO_2$ emissions factors 6 selected heat generation technologies at standard and newly prepared fuel $CO_2$ coefficients and pursued *CO2R*

For comparing of heat generation costs the average fuel prices were used from year 2010, available at the website of the National Control Commission for Prices and Energy.

Summary relative generation costs with above assumptions show that the least summary production costs are gained in biofuel boiler-houses, and they are higher in natural gas CHP plants in all cases. Fuel costs are the main costs component, defining lower summary costs for production unit in CHP plants comparing to gas boiler-houses (Fig. 13).

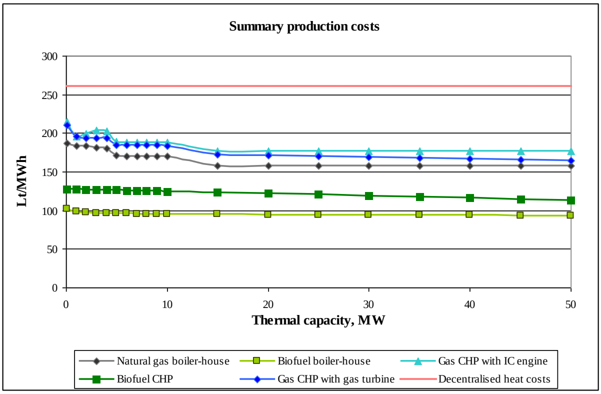



**Fig. 13.** Summary production costs for 5 selected heat generation technologies in boiler-houses and CHP plants comparing to decentralized heat generation costs

Above presented relative heat generation costs in CHP plants are estimated income from heat sales (Fig. 14). Income from electricity sales reduces relative heat generation costs and increase competitive ability of CHP plants, however, high price for natural gas do not allow significant reduction of heat generation costs event at existing feed-in tariffs. Calculations assume that duration of installations capacity operation is 8760 h/a

In this case biofuel CHP plants are more promising as they reduce heat generation costs by 30-40%.

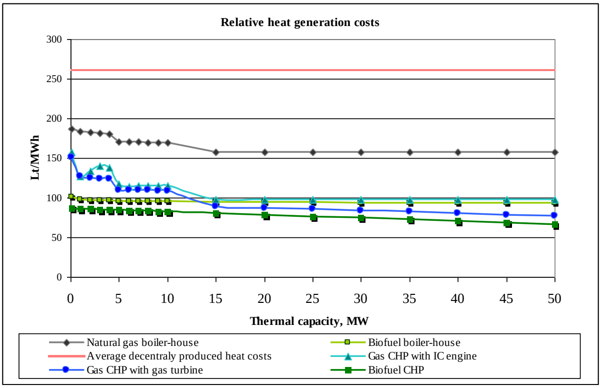



**Fig. 14.** Relative heat generation costs for 5 selected heat generation technologies in boiler-houses and CHP plants comparing to decentralized heat generation costs

***Comparison of technological solutions in boiler-houses of DHS.*** Modelling and comparison of separate technological solutions for operation in full loading conditions does not permit to make conclusions on their perks in the conditions of actual operation in boiler-houses of DHS. Usually one or more heat generators are operating in the boiler-house to cover varying heat demand of consumers. Thus annual use of installed capacities can be close to nominal in case it operates in basic load, or significantly lower, when it operates to cover the needs of winter season or for covering peak loadings only.

The typical loading curve of regional boiler-house was used for model testing. Total loading includes the needs of heating for buildings, hot water preparing, and technological heat demand in industry and heat losses in the pipelines. For optimal use of heat generation capacities 2 heat generators model was chosen (1G and 2G), where heat demand is distributed with priority to 1G, i.e. the 2G starts operation when loading exceeds the capacity of 1G.

Distribution of heat generation between 1G and 2G is shown in Fig. 15. The duration of operation of 1$^{st}$ generator at nominal capacity is app. 3177 h/a covering 90% of capacity demand. The operation time of the 2$^{nd}$ generator is much lower, i.e. 2205 h/a at the same capacity.

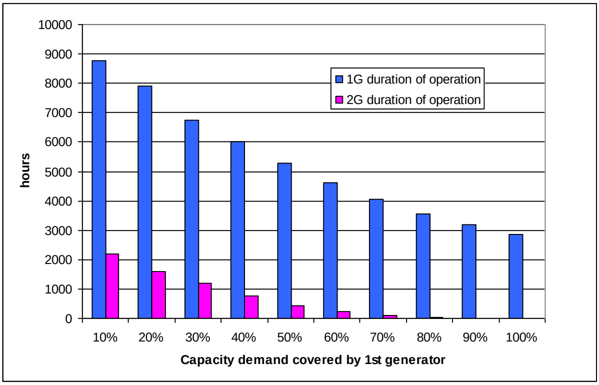



**Fig. 15.** Distribution of heat generation duration between 1G and 2G at full loading vs. change of maximal capacity share of 1G

While assessing primary energy factors it was notified that in case both heat generators use the same fuel, *PER* is constant. Situation changes and primary energy factor depends on distribution of generators capacities, when they uses different fuel, however trends are absolutely different for standard fuel coefficients and the newly prepared (Fig. 16).

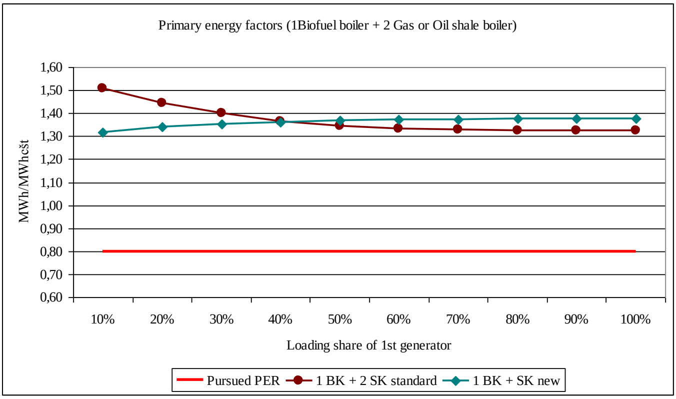



**Fig. 16.** PER vs. change of maximal capacity share of 1G using standard and new fuel coefficients, when 1G – biofuel boiler and 2G is natural gas or oil shale boiler

The influence on *PER* from capacities distribution was even more significant, when the first generator was CHP unit, and the second one – natural gas boiler (Fig. 17). In this case pursued *PER* = *0.8* is achieved, when the loading of CHP unit reaches 40% in case of natural gas; and 30%, in case of biofuel CHP unit.

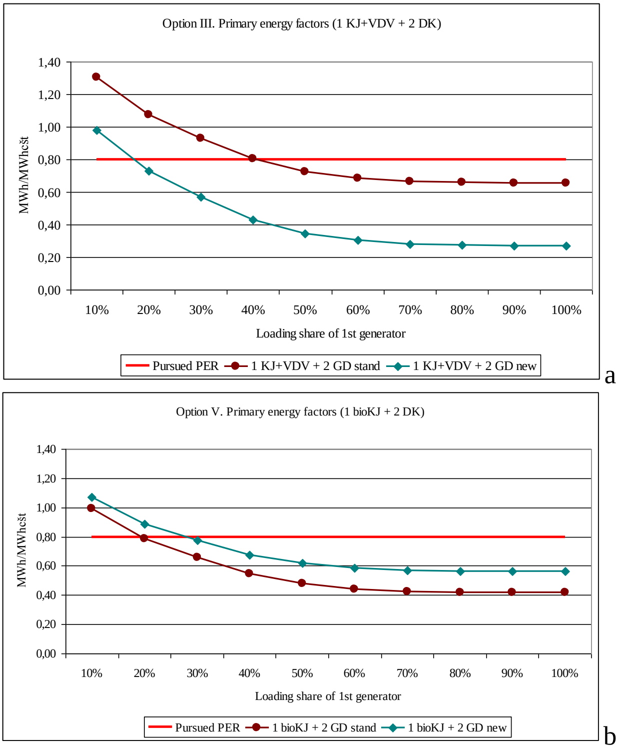



**Fig. 17.** *PER* vs. change of maximal capacity share of 1G using standard and new fuel coefficients, when 2G – natural gas boiler; and 1G is a - CHP unit with internal combustion engine or gas turbine and b - biofuel CHP unit

In cases when generators combine fossil fuel with biofuel, it is possible to assess the non-renewable primary energy factor *NPER*. It is notified that this indicator reduces while the loading of the 1$^{st}$ generator increases, when the 2$^{nd}$ generator uses fossil fuel (Fig. 18).

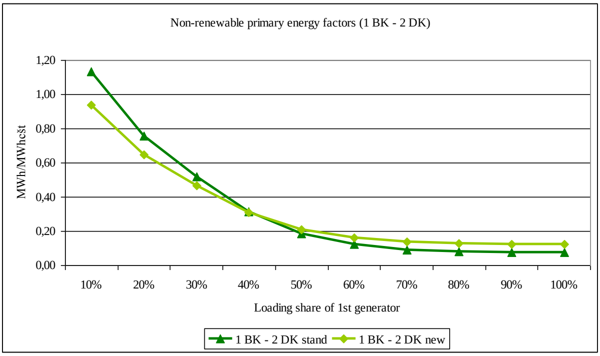



**Fig. 18.** *NPER* vs. change of maximal capacity share of 1G using standard and new fuel coefficients, when 1G is biofuel boiler, and 2G is natural gas or oil shale boiler

Assessment of carbon dioxide emissions factor shows that emission factor does not depend on the loading, when both generators are boilers and uses the same fuel. In all other options, when 1G is CHP unit, or biofuel is combined with natural gas or shale oil, the values of $CO_2$ emissions factor are reducing, while capacity loading of 1G is growing (Fig. 19). In case 1G is biofuel CHP unit and 2G is natural gas or biofuel boilers - $CO_2$ emissions factors are negative. The same is valid for both standard and newly elaborated fuel's $CO_2$ coefficients.

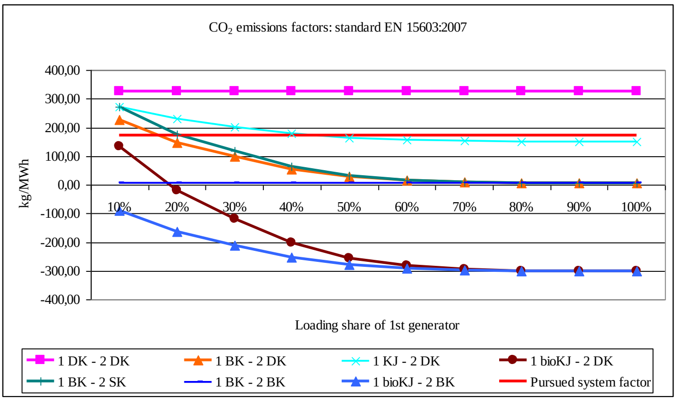



**Fig. 19.** $CO_2$ emission factors vs. change of maximal capacity share of 1G using standard fuel coefficients under EN 15603:2007

While using part of biofuel for heat generation, it is important to define which fuel fraction could be assigned to RES. Renewable energy fraction (*AEId*) is used for such cases. It is applied in cases when two generators in the system use different fuel (Fig. 20). Actually this share is close to 100%, when the loading of the first generator is close to 50%.

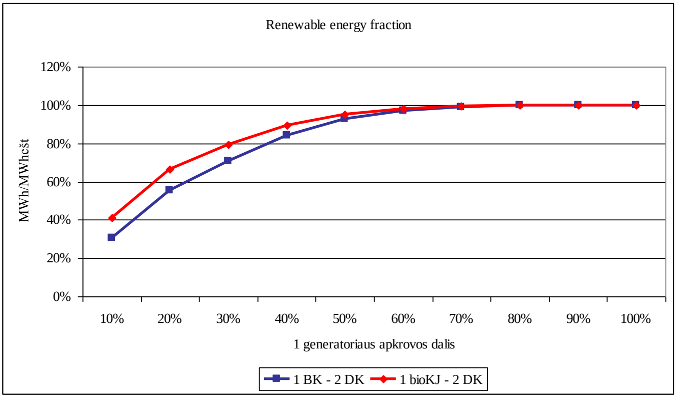
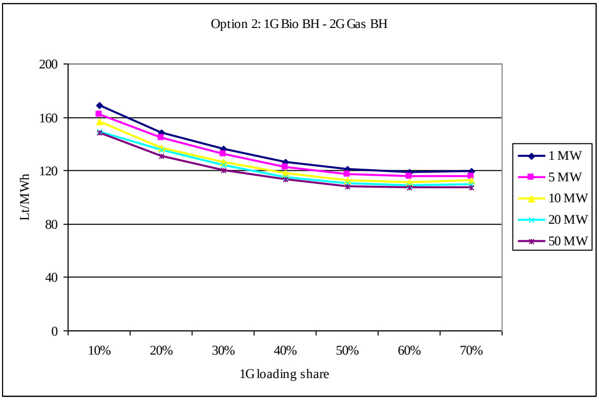



**Fig. 20.** Renewable energy fraction AEId vs. capacity share of 1G using new fuel coefficients

***Comparison of heat generation costs of technological solutions in boiler-houses of DHS.*** While assessing generation costs using our methodology it is seen that there is no significant change in heat generation costs in big capacity boilers after redistribution of production capacities between the two installations. In case of small capacities the effect of lower investment into the 1$^{st}$ generator reduces summary costs.

Meanwhile distribution of capacities between biofuel and natural gas boilers (Fig. 21a) shows clear minimum, which corresponds to approximately 60% of maximal capacity demand of biofuel boiler and 40% capacity demand covered by gas boiler.

Natural gas option is not available for locations without natural gas networks. In such cases shale oil is used for peak loadings. Heat generation costs for this fuel combination is similar as in case of biofuel – natural gas with clearly defined minimum (Fig. 21b.).

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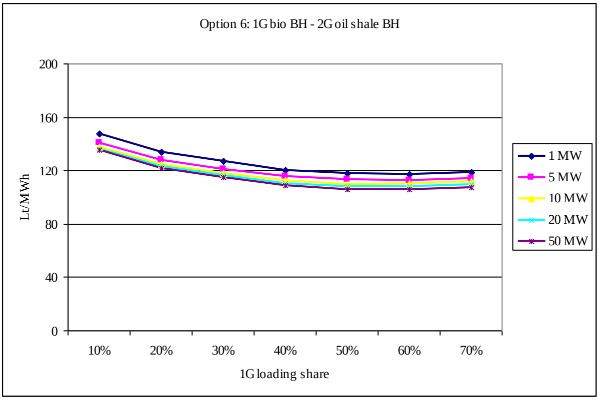



b

**Fig. 21.** Heat generation costs for various boiler-house capacities, when 1G is biofuel boiler and 2G is a)– gas boiler; and b) shale oil boiler

The impact to heat generation costs from distribution of capacities is higher for CHP plants with peak water heating boilers (Fig. 22a. Fig. 22b. in natural gas boilers and Fig. 23a. and Fig. 23b in biofuel boilers). In such options the impact of capital costs is more significant. While the capacity of CHP installation is growing, at first, growing volumes of generated electricity and income from electricity sales reduce heat costs, however, later high investment do not compensate income from electricity sales as volumes of generated electricity do not grow this much, and duration of capacity use reduces.

For CHP installations with internal combustion engines in most cases optimal capacity of CHP installations is 30-50 % of maximal heat capacity demand (Fig. 22a.). While gas turbine capacity is growing, relative investment and capital costs are reducing significantly. Thus for boiler-house of total capacity 50 MW heat generation costs are reducing even if the capacity of gas turbine covers up to 70 % of heat capacity demand (Fig. 22b.).

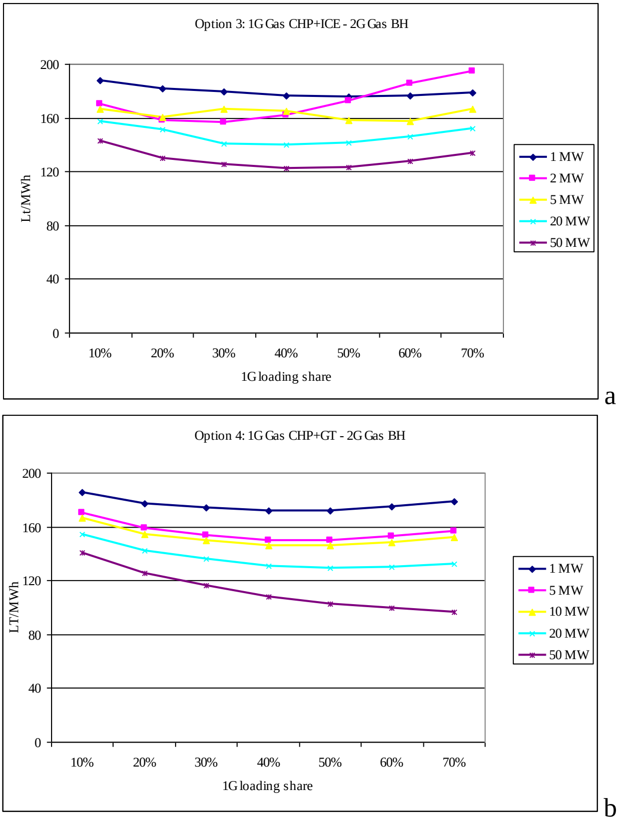
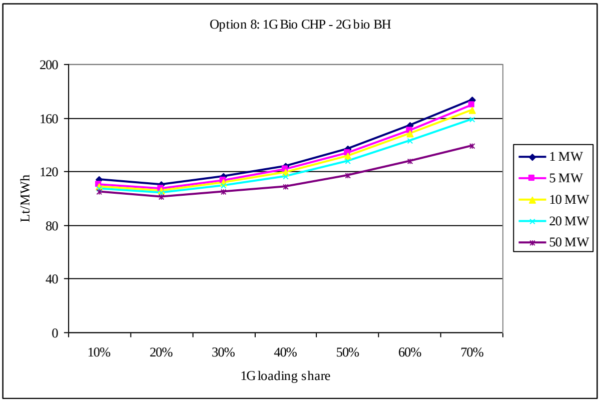


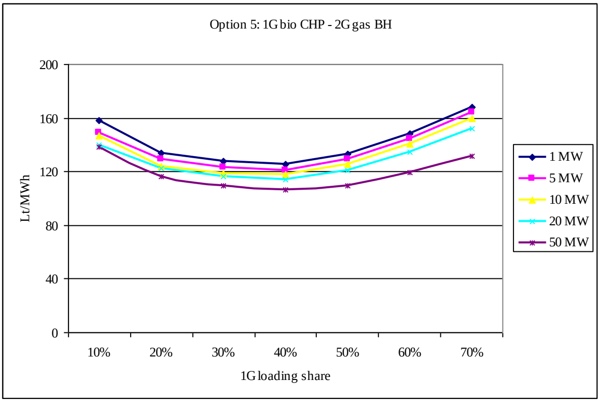

**Fig. 22.** Heat generation costs for various boiler-house capacities, when: a) 1G is natural gas CHP with internal combustion engine, and 2G – natural gas boiler; b) 1G natural gas CHP with gas turbine, and 2G is natural gas boiler

In case of biofuel CHP unit and gas boiler there is no significant dependence of heat costs vs. boiler-house capacity. Optimal capacity of CHP unit is in the range of 20-40%, and costs are growing rather fast in case of capacity increase (Fig. 23b.). This can be explained by the fact that capital costs are growing faster than income from electricity sales.

In the case of CHP plant and biofuel boiler heat costs increase in any case at current feed-in tariff for electricity due to higher heat generation costs in CHP unit comparing to biofuel boiler as CHP capacity is growing and exceeds 20% of total capacity demand. Small scale (1 MW) CHP units do not reduce heat costs (Fig. 23a.).




a




b

**Fig. 23.** Heat generation costs for various boiler-house capacities, when: a) 1G is biofuel CHP and 2G is biofuel boiler; and b) 1G is biofuel CHO and 2G is natural gas boiler.

Comparing of various technologies at optimal distribution of capacities (40% of heat capacity demand is covered by CHP unit in most cases) shows that the least costs are achieved for biofuel CHP unit and natural gas, liquid fuel or biofuel boiler for covering peak loading (Fig. 24).

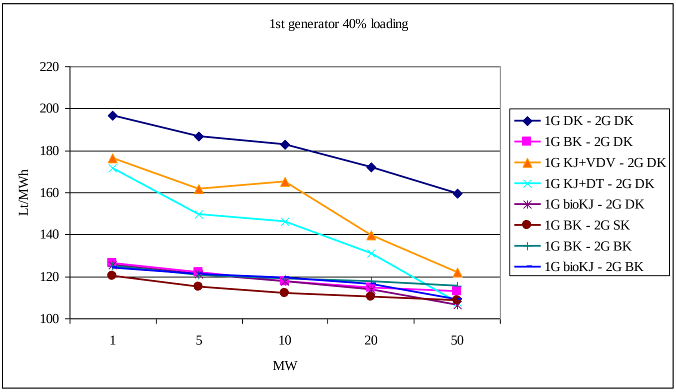



**Fig. 24.** Comparison of heat generation costs for various technologies when 1 generator covers 40% of heat capacity demand

This cost price can be also achieved for natural gas CHP plants of higher capacity. Heat costs of biofuel CHP plants are nearly 30% lower comparing to fossil fuel at current feed-in tariffs for electricity. Highest heat cost price is in natural gas boiler-houses. Here is the highest dependence on source capacity, as the impact of both, investment and fuel costs is significant and favourable for heat generators of higher capacities.

## CONCLUSIONS

Developed methodologies and respective models for biofuel production potential assessment and energy efficiency, environmental and economic assessment in heat generation as well as investigation performed using these models permit to make the following conclusions:

1. Developed biomass fuel production potential assessment methodology linking potential biomass resources available for biofuel production in the area of specific municipality with forest felling and management volumes, as well as biofuel production and transportation costs investigations shows, that biomass extraction and biofuel transportation distance to the boiler-houses are the main factors influencing the use of biofuel:
   a. Biomass extraction from forest operation in fuel production chain makes approximately 70 % of total wood chips costs structure;
   b. Biofuel transportation to boiler-houses costs increase costs by > 10 % with regard to the equipment efficiency and fuel consumption, in case transportation distance is more than 40 km.

2. The research performed on energy efficiency of heat generating technologies disclosed that Primary energy factors (PER) for autonomous heat generation technologies using co-generation depends on the ration between electricity and heat capacities. Evaluating the increase of electricity generating efficiency and using standard primary energy factors for the fuel, this indicator is close to pursued PER ≤ 0.8 when power/heat ratio is ≥ 0.77. The impact of generation capacities distribution to PER in boiler-houses is notified when the main generator is combined heat and power plant and the second – heating boiler. Pursued PER = 0.8 can be achieved when CHP loading reaches 40% in case of natural gas; and only 30% for biofuel.
3. Carbon dioxide emissions factors ($CO_2R$) for specific technologies show that CHP technologies have advantages against fossil fuel boilers, i.e. $CO_2R \leq 172$ kg $CO_2$/MWh. These advantages are more evident while combining CHP plants with biofuel, as in this case indicator $CO_2R$ = 8.6 kg $CO_2$/MWh. $CO_2$ emissions factor does not exceed pursued value in all cases, where CHP plants are combined with biofuel and the loading of the first generator is at least 50-60 % of total required loading.
4. When two generators in the system use different fuel – biofuel and fossil – Renewable energy fraction is close to 100% when the loading of the main biofuel generator is close to 70%.
5. Analysis of heat generation costs for various technologies based on fuel prices and electricity feed-in tariffs from year 2010 shows:
    a. Solid biofuel and biogas boilers in individual houses are the least costs solution for all types of buildings, however, for larger consumers (N > 250 kW), biogas CHP plant is a good option as heat cost price is close to that of solid biofuel (pellets) and biogas boilers;
    b. The main biofuel burning generator combined with natural gas or other fossil fuel installation for peak loading is the least costs solution in district heating boiler-houses. Optimal distribution of loadings between generators depends on fuel costs, capital costs and feed-in tariffs in case of CHP plants;
    c. Investigation shows that support measures applied were not sufficient for development of co-generation technologies.

## LIST OF PUBLICATION ON THE THEME OF DISSERTATION

### Publications in the journals included in the list of Institute of Scientific Information

1. Dzenajavičienė, Eugenija Farida; Kveselis, Vaclovas; McNaught, Colin; Tamonis, Matas. Economic anglysis of the renovation of small-scale district

heating systems – 4 Lithuanian case studies // Energy Policy. ISSN 0301-4215. 2007, Vol. 35, Issue 4. p. 2569-2578. [ISI Web of Science].

**Articles in the journals, referred in international Scientific databases**

2. Dzenajavičienė, Eugenija Farida; Kveselis, Vaclovas; Tamonis, Matas. Gamybos decentralizavimo ir naujų technologijų vaidmuo skatinant subalansuotą konkurenciją šilumos ūkyje // Energetika / Lietuvos mokslų akademija. ISSN 0235-7208. 2006, nr. 2. p. 16-22. [INSPEC]
3. Dzenajavičienė, Eugenija Farida; Vrubliauskas, Stanislovas;. Mozgeris, Gintautas; Buivydaite, Vanda Valerija; Tiškutė-Memgaudienė, Daiva; Lynikas, Martas; Palicinas, Michailas. Modelling of biomass resources suitable for fuel at regional level // Energetika / Lietuvos mokslų akademija. ISSN 0235-7208. 2008, nr. 3(54). p. 37-45. [INSPEC, Index Copernicus]

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4. Lynikas, Martas; Palicinas, Michailas; Tebėra, Albinas; Mozgeris, Gintautas; Radzevičiūtė, Aida; Vrubliauskas, Stanislovas; Dzenajavičienė, Eugenija Farida. Modeling the amount of cutting residues and timber volumes suitable for fuel // 3rd International Scientific Conference on Rural Development [Elektroninis išteklius]: 2007, 8/10 November, Kaunas, Lithuania : proceedings. RURAL DEVELOPMENT, 2007 : ISSN 1822-3230, Vol. 3, Book 2, p. 294-301. [ISI Web of Knowledge].
5. Mozgeris, Gintautas; Buivydaite, Vanda Valerija; Tiškutė-Memgaudienė, Daiva; Dzenajavičienė, Eugenija Farida; Vrubliauskas, Stanislovas;. GIS based modeling the potential of agricultural biomass suitable for fuel: a case study in Kaunas County // 3rd International Scientific Conference on Rural Development [Elektroninis išteklius]: 2007, 8/10 November, Kaunas, Lithuania : proceedings. RURAL DEVELOPMENT, 2007 : ISSN 1822-3230, Vol. 3, Book 2, p. 311-317. [ISI Web of Knowledge].
6. Dzenajavičienė, Eugenija Farida. Strategic planning of biomass use for energy needs in regions: problems and opportunities of Kaunas county // 5th conference of young scientists on energy issues CYSENI 2008 [Elektroninis išteklius]: May 29, 2008, Kaunas, Lithuania / Lithuanian Energy Institute, Young Scientists association : CD – CYSENI 2008. ISSN 1822-7554, p. 1-11.
7. Dzenajavičienė, Eugenija Farida. Regional possibilities to cover heat and electricity generation demand using biomass from forest cutting residues // 6th conference of young scientists on energy issues CYSENI 2009 [Elektroninis išteklius] : May 28-29, 2009, Kaunas, Lithuania / Lithuanian

Energy Institute, Young Scientists association : CD – CYSENI 2009. ISSN 1822-7554, p. 1-10.

8. Dzenajavičienė, Eugenija Farida; Masaitis, Sigitas. Difficulties, barriers and possibilities to define the demand and potential resources of wood biomass fuel on regional level // 7th conference of young scientists on energy issues CYSENI 2010 [Elektroninis išteklius]: May 27-28, 2010, Kaunas, Lithuania / Lithuanian Energy Institute, Young Scientists association : CD – CYSENI 2010. ISSN 1822-7554, p. 1-10.
9. Dzenajavičienė, Eugenija Farida; Lisauskas, Aurimas; Dzenajavičius, Danielius. Modelling of regional sustainable energy development opportunities: Kaunas Region case // 8th conference of young scientists on energy issues CYSENI 2011 [Elektroninis išteklius]: May 26-27, 2010, Kaunas, Lithuania / Lithuanian Energy Institute, Young Scientists association: CD – CYSENI 2011. ISSN 1822-7554, p. 1-12.
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## REZIUMĖ

***Darbo aktualumas.*** Energijos gamyba, naudojant atsinaujinančius energijos išteklius, yra vienas ryškiausių prioritetų Europos Sąjungos energetikos politikoje. ES siekia mažinti neigiamą energetikos poveikį aplinkai mažinant $CO_2$ emisijas ir sumažinti Europos Sąjungos ekonomikos priklausomybę nuo iš trečiųjų šalių importuojamo kuro. Tai ypač aktualu didėjant naftos ir gamtinių dujų kainai. Vienas atsinaujinančių energijos išteklių yra biokuras, kurio panaudojimas skatina vietinės ekonomikos augimą ir sukuria darbo vietas. Be to, atsinaujinančių energijos išteklių naudojimas sudaro galimybes užtikrinti energijos tiekimo patikimumą didinant energijos šaltinių diversifikaciją.

Atsinaujinančių energijos išteklių planavimas Lietuvoje dar neseniai vyko išskirtinai valstybiniu lygiu, o regionų plėtra, ypač savivaldos plėtojimas ir stiprinimas, yra strateginė valdymo reformos kryptis daugelyje Europos valstybių. Atsinaujinančių išteklių energetikos įstatymas įpareigoja Lietuvos savivaldybes ruošti ir, suderinus su Vyriausybe ar jos įgaliota institucija, tvirtinti bei įgyvendinti atsinaujinančiųjų išteklių energijos naudojimo plėtros veiksmų planus. Šie planai skirti įgyvendinti darnios energetikos plėtros tikslus ir užtikrina šiuo metu naudojamo iškastinio kuro pakeitimą atsinaujinančiais energijos ištekliais ekonomiškai pagrįstu mastu. Savivaldybių energetikos plėtros planuose svarbų vaidmenį vaidina centralizuotas šilumos tiekimas, leidžiantis efektyviai išnaudoti atliekinę energiją ir atsinaujinančius energijos išteklius, tarp jų ir biokurą. Energinio efektyvumo ženklinimo įvedimas šiame sektoriuje siekia nustatyti darnios plėtros rodiklius, kuriais būtų galima palyginti centralizuoto šilumos tiekimo sistemas su alternatyviomis šilumos gamybos technologijomis individualiuose pastatų įrenginiuose, nustatant, kokiomis technologijomis paremtos sistemos yra efektyvios.

Iki šiol nėra sukurta patikimų įrankių - metodikų ir modelių - tiek atsinaujinančių išteklių potencialo savo teritorijoje vertinimui, tiek investicijų planavimui ribinių biokuro gamybos sąnaudų pagrindu, tiek ir investicijų planavimui šilumos tiekimo sektoriuje, remiantis darnaus planavimo principais ir diegiant pažangias individualaus ir centralizuoto šilumos tiekimo technologijas.

***Darbo tikslas.*** Sukurti biokuro gamybos potencialo ir jo naudojimo šilumai gaminti tyrimo metodus, įvertinančius įvairių šilumos gamybos technologijų darnumo pagrindinius kriterijus – pirminės energijos rodiklį, anglies dvideginio emisijų rodiklį ir atsinaujinančių energijos išteklių dalį – ir jais naudojantis ištirti biokuro naudojimo technologinius sprendimus darnumo kriterijų požiūriu, o taip pat šių technologijų plėtros skatinimo poreikius.

***Darbo uždaviniai***

1. Parengti biokuro potencialo įvertinimo ir jo įsisavinimo analizės metodiką, leidžiančią ištirti veiksnius, lemiančius miškų biomasės panaudojimą biokuro gamybai;
2. Parengti įvairių šilumos gamybos technologijų, naudojant įvairias kuro rūšis, darnumo kriterijų kompleksinio tyrimo metodiką ir nustatyti:
    a. veiksnius, įtakojančius pirminės energijos rodiklį,
    b. veiksnius, įtakojančius anglies dvideginio emisijų rodiklį,

c. veiksnius, įtakojančius atsinaujinančiųjų energijos išteklių dalį, derinant iškastinio kuro ir biokuro naudojimą šilumos gamybai;

3. Įvertinti įvairių biokurą ir iškastinį kurą naudojančių technologijų šilumos gamybos sąnaudas ir skatinimo priemonių poreikį biokurą naudojančių technologijų plėtrai.

***Darbo mokslinis naujumas.*** Sukurta originali miškų biomasės potencialo vertinimo savivaldybės lygiu metodika ir imitacinis modelis miškų ūkio statistikos duomenų pagrindu, skirtas biokuro gamybos galimybių įvertinimui, atsižvelgiant į potencialo išnaudojimo laipsnį.

Sukurta įvairių šilumos gamybos technologijų kompleksinio - energinio, aplinkosauginio ir ekonominio - vertinimo metodika ir skaitinis modelis, skirtas įvertinti biokuro ir iškastinio kuro naudojimo efektyvumą pirminės energijos išteklių, anglies dvideginio emisijų, išteklių atsinaujinimo ir gamybos sąnaudų kriterijų atžvilgiu.

***Praktinė darbo reikšmė.*** Atsinaujinančių išteklių energetikos įstatymas įpareigoja Lietuvos savivaldybes ruošti, tvirtinti bei įgyvendinti atsinaujinančiųjų išteklių energijos naudojimo plėtros veiksmų planus. Šiame darbe paruošti įrankiai – modeliai, kuriuos naudojant galima įvertinti biokuro gamybos potencialą naudojantis miškų ūkio statistikos duomenis savivaldybės lygiu. Vykdant ES dalinai finansuotus projektus šio modelio pagalba yra atlikti biokuro potencialo vertinimai Lietuvos regionuose ir Kauno regiono savivaldybėse. Papildytas modelis leidžia apskaičiuoti biokuro gamybos sąnaudas visoje biokuro gamybos technologinėje grandinėje, įvertinant biokuro gamybos darnumo kriterijus.

Šilumos gamybos technologijų energinio, aplinkosauginio ir ekonominio vertinimo skaitinis modelis buvo naudotas vertinant Utenos rajono savivaldybės centralizuoto šilumos tiekimo įmonės perspektyvines investicijas į biokuro panaudojimo šilumos gamybai technologijas. Planuojama šį modelį naudoti apskaičiuoti centralizuotos šilumos gamybos kriterijus, reikalingus CŠT sistemų energiniam ir aplinkosauginiam ženklinimui. Šis ženklinimas numatytas naujai ruošiamoje centralizuotų šilumos/vėsumos tiekimo sistemų ženklinimo direktyvoje.

Sukurtas modelis leidžia vertinti biokurą naudojančių šilumos gamybos technologijų plėtrą skatinančias priemones ir planuoti paramos priemones – dalies investicijų subsidijavimą ir kogeneracijoje pagamintos elektros supirkimo tarifus – tiek valstybės, tiek savivaldybės lygiu.

***Ginamieji disertacijos teiginiai***

1. Miško kirtimo ir miškotvarkos atliekų techninio ir ekonominio potencialo išnaudojimą biokuro gamybai labiausiai riboja biomasės ištraukimo iš miško atstumas, susidarančių atliekų tūris ir sąnaudos biokuro transportavimui.

2. Efektyvios šilumos gamybos kriterijus atitinkančius pirminės energijos rodiklius galima pasiekti pasitelkiant kogeneracijos technologijas su optimaliu elektros ir šilumos galių santykiu bei galių pasiskirstymu tarp generatorių, ir naudojant biokurą.
3. Mažiausios šiltnamio efektą sukeliančių dujų emisijos vertės pasiekiamos naudojant kogeneracijos technologijas, ir jos nesiekia numatyto rodiklio, kai šilumos gamybai naudojamas biokuras, pasirinkus optimalų galios pasiskirstymą tarp šilumos gamybos įrenginių.
4. Biokuro naudojimas leidžia pasiektį artimą 100 % atsinaujinančių išteklių dalį šilumos gamyboje netgi tuomet, kai dalis galios poreikio padengiama iškastinį kurą naudojančiais šilumos gamybos įrenginiais.
5. Biokuro kogeneracinių technologijų taikymas gali būti gera alternatyva tiek individualiame, tiek centralizuotame šilumos tiekime, kaip geriausiai atitinkančių darnumo kriterijų rodiklius, jei joms taikomi atitinkami skatinimo mechanizmai.

**IŠVADOS**

Sukurtos biokuro gamybos potencialo vertinimo ir šilumos gamybos technologijų energinio, aplinkosauginio ir ekonominio vertinimo metodikos bei atitinkami modeliai ir su jų pagalba atlikti tyrimai leidžia daryti šias išvadas:

1. Biokuro gamybos potencialo vertinimo metodika, susiejanti potencialius biomasės išteklius biokuro gamybai konkrečioje savivaldybės teritorijoje su miško kirtimų ir miškotvarkos darbų apimtimis, ir atlikti biokuro gamybos ir transportavimo sąnaudų tyrimai parodė, kad svarbiausi veiksniai, lemiantys biomasės panaudojimą biokuro gamybai yra biomasės ištraukimo iš miškų atstumas, 1 ha plote susidarančių atliekų tūris ir kuro sąnaudos bei biokuro transportavimo į katilines atstumas:
    a. biokuro gamybos grandinėje biomasės ištraukimo iš miškų operacijos sąnaudos sudaro apie 70 % medienos skiedrų gamybos sąnaudų struktūroje;
    b. biokuro transportavimo į katilines sąnaudos, atsižvelgiant į naudojamos technikos našumą ir kuro vartojimą, padidina sąnaudas > 10 %, transportuojant daugiau kaip 40 km atstumu.
2. Šilumos gamybos technologijų energinio efektyvumo vertinimo tyrimai parodė, kad atskirų, kogeneracija paremtų šilumos gamybos technologijų pirminės energijos rodiklis (PER) priklauso nuo elektros ir šilumos galių santykio, galių pasiskirstymo tarp generatorių. Įvertinant elektros gamybos efektyvumo padidėjimą bei taikant standarte numatytus kuro pirminės energijos koeficientus, šis rodiklis priartėja

prie siektino PER ≤ 0,8, kai elektros ir šilumos galių santykis yra ≥ 0,77. Katilinėse generavimo galių pasiskirstymo įtaka pirminės energijos rodikliui pasireiškia tada, kai pagrindinis generatorius yra kogeneracinė jėgainė, o antrasis – šildymo katilas. Siektinas PER = 0,8 pasiekiamas, kai kogeneracinės jėgainės šilumos galios dalis yra virš 40 % visos reikiamos galios, naudojant gamtines dujas, ir virš 30 % - naudojant biokurą.

3. Atskirų šilumos gamybos technologijų įvertinti $CO_2$ emisijos rodikliai rodo, kad šis rodiklis priklauso nuo naudojamos šilumos gamybos technologijos ir kuro. Kogeneracijos technologijos turi privalumų, palyginti su iškastinio kuro katilinėmis, t. y. $CO_2$ emisijos rodiklis yra mažesnis už siektiną ≤ 172 kg $CO_2$/MWh. Šie privalumai dar akivaizdesni, kai kogeneracija derinama su biokuro naudojimu, kur šis rodiklis yra lygus 8,6 kg $CO_2$/MWh. $CO_2$ emisijų rodiklis praktiškai neviršija siektinos vertės visais atvejais, kai kogeneracijos įrenginiuose naudojamas biokuras ir pagrindinio generatoriaus galia yra bent 50–60 % visos reikalingos galios.
4. Esant katilinėje dviems generatoriams, kai vienas jų naudoja biokurą, o antrasis - iškastinį kurą, atsinaujinančiųjų energijos išteklių dalis artėja prie 100 % biokuro generatoriaus galios daliai artėjant prie 70 %.
5. Įvairių šilumos gamybos technologijų sąnaudų analizė remiantis 2010 metų kuro kainomis ir elektros supirkimo tarifais parodė, kad:
    a. individualiose pastatų šildymo sistemose kietojo biokuro ir biodujų katilai yra mažiausių sąnaudų sprendimas visų tipų pastatams, tačiau stambesniems vartotojams (N > 250 kW) gera alternatyva yra ir biodujų kogeneraciniai įrenginiai, kuriuose gaminamos šilumos savikaina yra artima biokuro (granulių) ir biodujų katiluose gaminamos šilumos savikainai;
    b. centralizuoto šilumos tiekimo katilinėse mažiausių sąnaudų sprendimas yra biokurą naudojantis pagrindinis generatorius ir gamtines dujas ar kitą iškastinį kurą naudojantys įrenginiai pikinėms apkrovoms. Optimalus generavimo galių paskirstymas tarp generatorių priklauso nuo kuro kainų, kapitalo sąnaudų ir elektros supirkimo tarifų, kai naudojama kogeneracija.
    c. Tyrimas taip pat parodė, kad taikytos skatinimo priemonės buvo nepakankamos biokuro kogeneracijos technologijų plėtrai.

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