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Optimization methodologies for national small-scale CHP strategies (the case of Lithuania)

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In general, implementation of combined heat and power production (CHP) has the potential of reducing fuel consumption by 30 percent. Small-scale CHP offers an additional possibility of expanding the potential by including minor towns and villages and helps replacing fossil fuels by local biomass resources. This paper compares some optimisation methodologies for identification of small-scale CHP implementation strategies. The paper is based on a study of Lithuania who is facing the need of huge investments in both the replacement of the Ignalina Nuclear Power Plant and of district heat production units in many of the existing systems. The importance of calculating business economic optimal solutions for small DH companies is emphasised, and attention is focused on understanding the potential differences between business and socio-economic optimal solutions in the present situation of no CO_2 emission costs and possibilities of cheap import of Russian natural gas. Lithuania has a great potential of socio-economic benefits from the implementation of small-scale CHP. Meanwhile, such implementation needs public regulation to become feasible not only from the socio-economic but also from the business economic point of view.

Key words: combined heat and power production (cogeneration), optimization methodologies, small-scale CHP

1. INTRODUCTION

Reliability and sustainability are the major energy policy objectives in the European Union (EU). CHP production together with energy conservation and renewable energy are essential for implementation of the European climate change response objectives [1]. The EU guidelines in the electricity generation stage are characterised by replacing the energy systems based on large power plants by more decentralised systems. The goal is to double the CHP production in the EU from 9% in 1994 to 18% in 2010 [2]. The Baltic countries have an advantage for implementing CHP technologies, as the existing DH (district heating) systems already cover approx. 40–70% of the total domestic heat demand [37].

In Lithuania, DH systems supply approx. 45% of the national domestic heat demand [8]. Meanwhile, the share of small-scale CHP is very small. Instead, the Lithuanian electricity supply comes from relatively cheap nuclear power (NP) covering approx. 80% of the national demand. However, the existing Ignalina Nuclear Power Plant (NPP) is to be decommissioned in 2009, and consequently the conventional condensing plant "Lietuvos Elektrinė" with its total capacity of 1800 $MW_{el.}$ is expected to be the main electricity production unit. "Lietuvos Elektrinė" currently operates on three types of fuel: natural gas, heavy fuel oil and orimulsion.

Without nuclear power, the Lithuanian power system will have a substantial fuel saving potential by implementing CHP technologies. Thus, the National Energy Strategy (NES) in 2002 and again in 2007 stresses the promotion of CHP technologies in the DH sector [9, 10]. However, the optimal CHP capacities meant to ensure sustainable and reliable energy generation are still very uncertain.

From the business economy point of view, CHP plants are currently not feasible for the DH companies due to low electricity prices and complicated production quota mechanisms. Consequently, the DH companies are lead to invest in the modernisation of existing systems by replacing boilers or switching primary fuel (natural gas or heavy fuel oil) by renewable fuel, mainly wood chips, rather than converting to CHP, even though such technologies are given priority both by the Lithuanian Government and the European Commission. The same problem is known from the rebuilding of the energy system in East Germany in the late 1990s [11].

Compared to the conventional approach of producing heat and electricity in separate plants, CHP plants have the potential of decreasing fuel consumption by 20–30% while producing exactly the same amount of electricity and heat. Lithuania does not

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have primary fuel resources and relies on imports, mainly from Russia. In the early 1990s an energy crisis occurred, and Russia imposed an embargo on natural gas and oil supply to Lithuania. This experience showed that decreasing fossil fuel consumption can not only exert a positive effect on the national balance of payments but also increase the reliability of energy supply.

The discussion of how to replace the electricity produced by the existing nuclear power plants after 2009 is still open. New or reconstructed NPP are expected to have long-term marginal costs (LTMC) which are almost by 60–80% higher than the current price. This places NP on a comparable level with conventional centralized CCGT (combined cycle gas turbine) production [12]. Hence, even with the uncertainty regarding the future of NP, the feasibility of small-scale CHP should be compared with centralized conventional electricity generation.

The Exergo economics, the Theory of the Exergetic Cost and the Disaggregating Method of Valero and Lozano could be described as the thermo-economic methodologies. These methodologies are used to optimize the design and operation of energy production units (plants) in terms of both thermal and economical variables [13]. The energy flow optimisation methodologies are usually used in computer models like EnergyPLAN, EFOM, MESSAGE, etc. In these models, the optimisation process provides feasible generation settlements that take into account a possible installation of CHP, wind power, solid-waste and biomass exploitation together with industrial CHP on other energy generating and consuming systems [14, 15].

Based on the Lithuanian case, this paper analyses the feasibility of integrating small-scale CHP into the existing power system as compared to conventional electricity generation using generalized energy flow and thermo-economic methodologies.

2. METHODOLOGY AND MAIN ASSUMPTIONS

The possibility of integrating small-scale CHP into the existing system has been analysed by comparing the reference alternative of conventional centralised electricity production based on CCGT in combination with conventional boilers for district heating. The reference has been used to analyse CHP technologies that are based on natural gas and on biomass fuels. The following technologies are included:

- Internal combustion engines (natural gas)
- Gas turbines with heat recovery boilers (natural gas)
- Steam turbines (biomass), and
- Biomass gasification systems assumed to be available after the year 2010 in the range of 1 $MW_{el.}$ to 10 $MW_{el.}$ [16].

All technologies have been analysed for an expected lifetime of 20 years. To identify the LTMC for each of the different CHP technologies, the EnergyPRO operation and investment analysis tool has been used (for more details, see chapter 2.1). All calculations are based on typical Lithuanian weather conditions, i. e. typical season variations in the outdoor temperature. Besides, the DH companies' annual heat production was divided into 30% for hot tap water, 55% for space heating and ventilation, and the remaining 15% as network losses.

The analysis focuses on small-scale CHP, thus, the six largest DH companies in Lithuania were excluded. The range of annual DH companies' heat production was selected between 50 GWh and 200 GWh, which is the representative range for the remaining Lithuanian DH sector. The database for each of the DH companies' heat production was taken from [17, 18].

The economic assumptions and main technical data of the reference case and the different CHP technologies used in the calculations are shown in Table [10, 16, 19].

The natural gas price in Table 1 (180–190 Euro per thousand cubic meters) is based on the estimated price of natural gas imported from Russia. The price in use here contains two elements. One is the import price and the other is the payment of the Lithuanian natural gas pipeline system. It should be emphasised that the price is still lower compared both to the existing world market prices of oil and to the average prices of Russian export of natural gas to other countries of Western Europe.

2.1. The EnergyPRO tool

The EnergyPRO software is developed by EMD [20]. The package is designed to deal with the complexities of energy production (heat, electricity separately or CHP) plants. The first version was developed more than 15 years ago. Since then, the package has been tested and widely used by a large number of decentralized CHP plants in Denmark.

Basically, it is an input / output model typically calculating annual productions in steps of one hour. Technical and economic

Table. **Economic assumptions and technical data of the reference and CHP systems**

	Reference CCGT	Gas engines	Gas turbines with heat recovery boilers	Steam turbines	Biomass gasification
Loan period	20 years				
Interest rate	5%				
CO_2 costs (average for a 20-year period)	30 Euro / tCO_2				
Natural gas price, Euro / 1000 natural m^3 (9.3 kWh / natural m^3)	180 (annual grow 0.9%)	190 (annual grow 0.9%)			
Biomass fuel price, Euro / t (2.2 kWh/kg)				40 (annual grow 2.6%)	
Investment costs (million Euro / MW)	0.53	1.00	0.68	3.05	2.10
Variable O & M (operating and maintenance) costs (Euro / MWh)	1.50	8	3.25	7.10	15.00
Fixed O & M costs (Euro / MW / year)	14000		8000	61000	70000
Capacity range, MW	350	13	510	510	110
Electrical efficiency, 100% / 50% load	58/52	42/38	36/34	25/24	37/32

input data are processed to optimize the plant's performance. Calculations are based on price levels or what is also referred to as periods of priority. In this sense, the programme follows a hierarchical rather than a chronological order. Multiple loops of calculations are performed, starting by filling in the periods of highest priority. Limitations in fuel and heat storage can be taken into account. Heat demand and price series can be used in the case of market operation. Multiple energy production and storage units can be incorporated into the programme, and their operation is guided by a user-specified control strategy. More information regarding the methodology of calculations is presented in [20, 21].

2.2. Principles of technical and economic evaluation

The LTMC of electricity production from different technologies have been calculated assuming that district heat prices should remain the same as currently, i. e. alternative costs of heat production from existing boilers. The LTMC have been calculated in relation to four different typical heat demands, i. e. 50, 100, 150 and 200 GWh/year. In Fig. 1, the results for an annual heat production of 150 GWh are shown.

The LTMC of the two CHP technologies based on natural gas are able to compete with the reference case within the range of installed capacities up to 7–9 MW. Meanwhile, the two CHP technologies based on biomass are much more expensive than the fossil-fuel-based technologies. However, the result shown in Fig. 1 is calculated on the basis of a very low natural gas price, as described previously.

Figure 1 illustrates that the LTMC of electricity production has a minimum. Meanwhile, the minimum is not necessarily representing the optimal investment. In order to identify the optimal business economic situation, the net present value (NPV) of investments in different capacities has been calculated and shown in Fig. 2.

The possible installed capacity optimization of one or another technology is quite difficult. Usually, there are many possibilities to choose and many combinations, such as energy generation unit number, efficiency and technology price combination, etc. Figure 2 represents CHP capacity optimization based on internal combustion engines. The net present value (NPV) shows the gain in a 20-year period.

In Fig. 2, capacity optimization is done by optimizing only benefits from generating electricity in small scale CHPs instead of conventional generation (reference case). The optimisation methodology based on the socio-economic point of view seems more difficult. Here, one can analyse all possible positive and negative effects for different strategies.

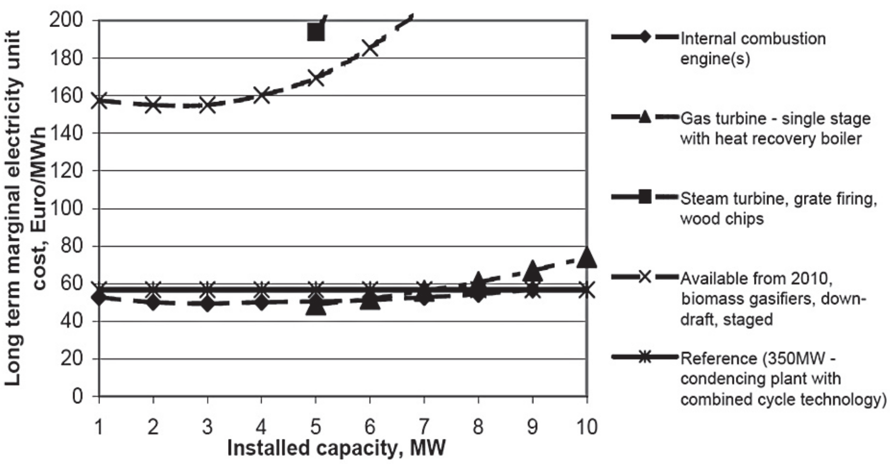

Fig. 1. Long-term marginal costs of electricity production dependence on installed capacity

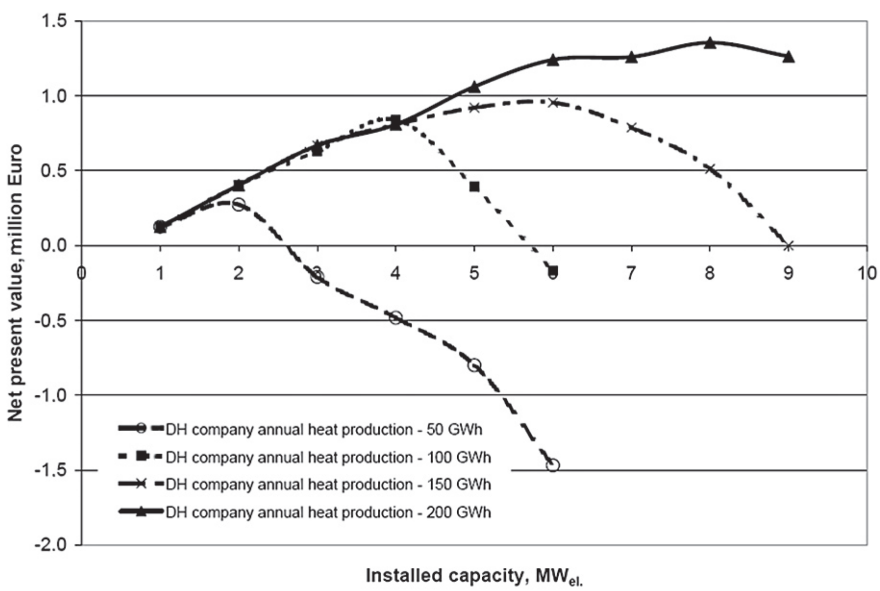

Fig. 2. Small scale CHP business economic capacity optimisation

The CO_2 costs and avoided investments into heat boilers renovation were included in this paper as an example of the socio-economic methodology for optimization of small-scale CHP.

3. RESULTS OF BUSINESS ECONOMIC OPTIMIZATION

Based on the methodology and data described in the previous chapter, optimal small-scale CHP capacities in the Lithuanian DH sector have been identified from the business economic point of view. The analysis compares the following four different options:

Reference electricity price: Compared to the present situation, this case assumes that the Lithuanian authorities have implemented an electricity price regulation securing potential for small CHP plants and electricity sales price equal the LTMC of the reference of CCGT production based on natural gas.

Reference electricity price plus CO_2 payment: In addition to the electricity sales price regulation of situation 1, here, small CHP plants are paid bonuses which are equal to the CO_2 reduction of 30 Euro/ton.

Reference electricity price plus CO_2 payment plus avoided heat investments: This situation represents the same electricity price regulation and CO_2 payment as in situation 2. Additionally, an individual DH company is supposed to be in a situation of needed investments in new boiler capacities.

Only renewable is allowed: Here, small-scale CHP capacities are optimized assuming that all DH companies are allowed to produce electricity only when based on renewable energy sources and feasible compared to conventional production.

The fourth case has been included into the analysis, because Lithuania generates approximately 3.2% of electricity based on renewable energy sources (mainly hydro), but, according to the EU Directive on renewable energy, Lithuania chould increase the share of electricity produced by renewable energy to at minimum of 7% by 2010 [22, 23]. One way to comply such obligations will be to implement the potential of small CHP plants on biomass.

In the first three cases, electricity based on renewable energy is produced in DH companies only when a small-scale CHP based on renewable fuel is more feasible than both conventional generation and CHP based on natural gas, or when natural gas is not available at a specific location.

Some main results of the analysis are shown for all four cases in the following three diagrams (Figs. 3–5).

Figure 3 shows the business economic feasible potential *capacity* in the four situations in total and also divided into the four different CHP technologies. As one can see, the potential is very sensitive to the issue of avoided investments in heat production units. If the DH companies need replacement of the existing heat production units, the business economic potential becomes

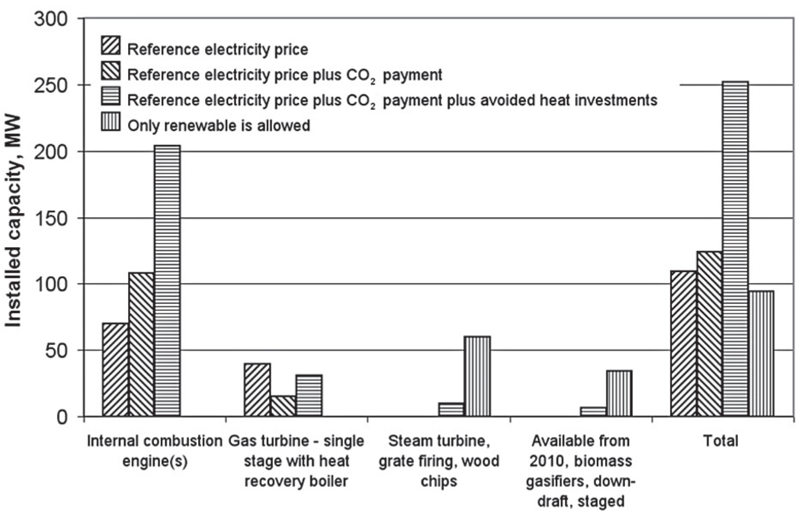

Fig. 3. Optimal installed capacities of different small-scale CHP technologies

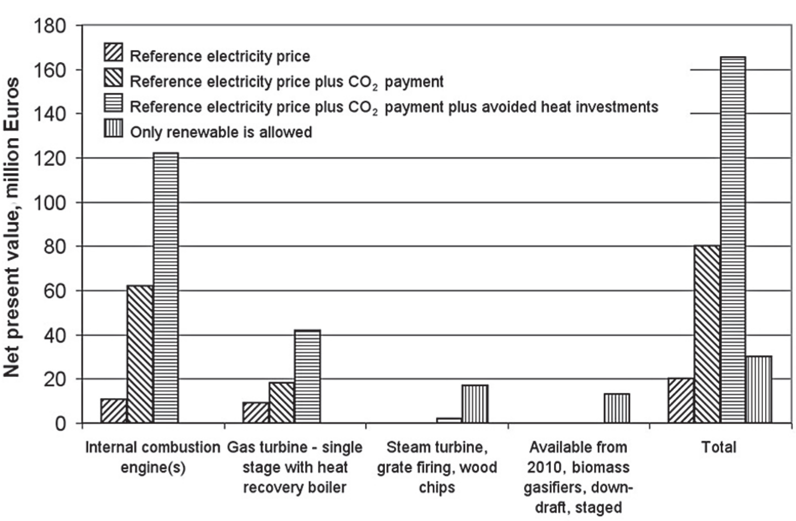

Fig. 4. Net present value of 2-year gain producing electricity in small-scale CHP

more than twice as large as in other situations. The most feasible technology is an internal combustion engine on natural gas. And the only reason why in some cases biomass CHP becomes the best alternative is either the fact that natural gas is not available or, as in situation 4, that natural gas is not allowed. The implementation of CO_2 payment influences the potential in a positive direction, however, not very much.

Figure 4 shows the *profit* to be made by the local DH companies in the four different situations. The profit is calculated in terms of the NPV of the investments during a period of 20 years. Again, the total profit is very sensitive to the issue of avoided investments into heat production units.

Figure 5 shows the annual *electricity production* in the four situations. The annual electricity production for Lithuanian internal needs in 2004 was approximately 9.5 TWh [24]. The business economic potential of small-scale CHP varies between 0.5 and 1.4 TWh per year as illustrated in Fig. 5. Consequently, the small-scale CHP electricity production could cover up to approx. 15% of the total demand (situation 3), or the potential could be used to increase the share of electricity production based on renewable energy, which means an easier fulfilling of the EU obligation of 7%.

In relation to the discussion of the replacement of nuclear power after the year 2009, it should be added that the potential under analysis takes into account only the existing small DH companies. The potential is even higher if potential new district heating areas are included, and substantially higher if the six large existing DH areas are also included. Nevertheless, the potential from the small companies alone is substantial and indeed relevant in the discussion of future strategies.

The result in terms of the environmental effects of the different technologies varies depending on the fuel savings and whether the fuel is natural gas or biomass. If only renewable is allowed (situation 4), the annually CO_2 reduction adds up to approximately 190,000 tons per year. In the three other situations, CO_2 reduction varies between 125,000 (situation 1) and 240,000 (situation 3) tons per year.

Hence, any investments for producing only heat in DH companies can negatively influence the environmental objectives in the long-term perspective.

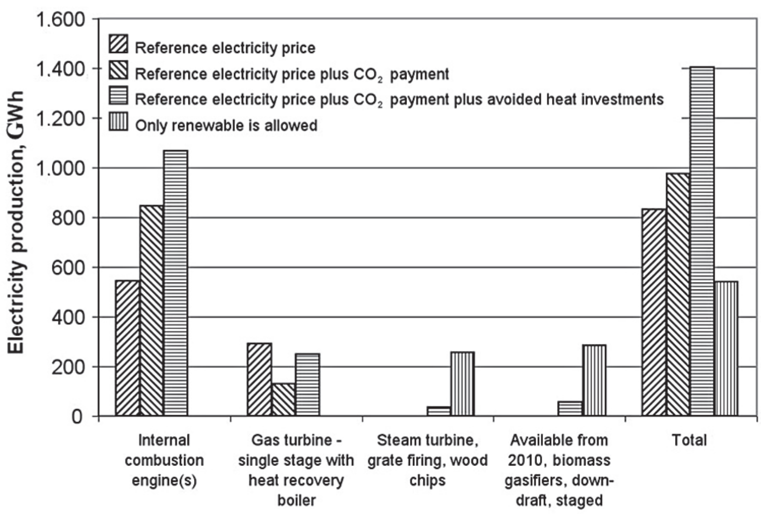

Fig. 5. Annual electricity production based on small-scale CHP

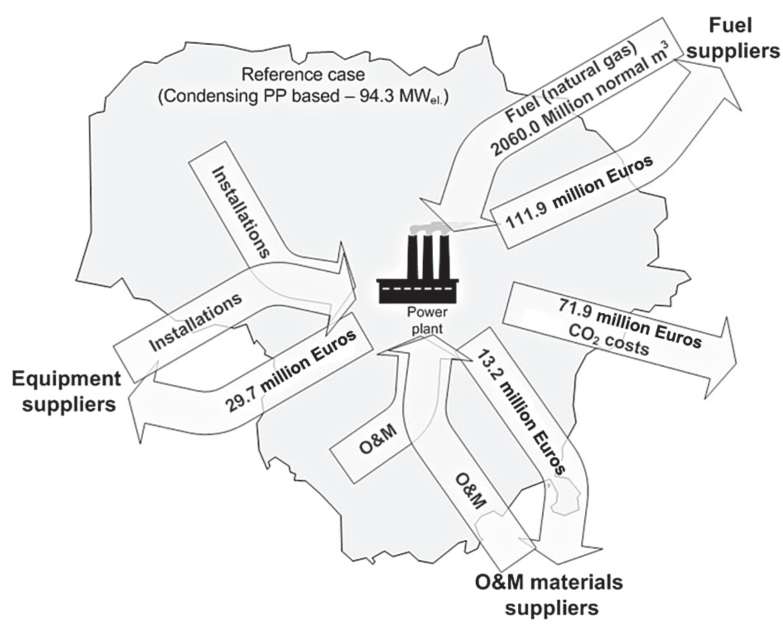

Fig. 6. NPV of the national balance of payments for reference case (20-year period)

4. RESULTS OF ANALYSIS FOR NATIONAL BALANCE OF PAYMENTS

As is shown, the business economic analysis leads towards implementing CHP technologies based on natural gas. However, from the governmental point of view, Lithuania needs to take a number of other issues into consideration when designing a proper strategy. One of the examples can be the Nordic countries like Denmark, where subsidies and taxes are designed to make small-scale CHP feasible in order to fulfil the socio-economic feasibility objectives [15, 25–27]. The issue of fulfilling the EU obligations on the share of renewable energy and CO_2 regulations has already been mentioned. Two other issues are the energy security of imported fossil fuels and the balance of payment. These issues are analysed below.

In the present situation, the Lithuanian balance of payment (NBP) is negative and the foreign debt is relatively high [28]. In such a situation, an increase in the import of fuels will aggravate the situation. In order to pay for the import, the government will sooner or later need to decrease domestic expenses and consequently to influence the gross domestic product (GDP) and the level of social wealth in a negative direction.

Here, the import and export of investing in the references have been compared to one of the CHP alternatives, namely situation 4 in which only renewable energy is allowed. As stated above, Lithuania needs to import all natural gas from Russia. The CHP technologies themselves also have to be imported (assumption – for the installations 60% from the costs stated in Table 1 and 20% for O & M costs). The existing infrastructure of the boiler plants (buildings, thermal and electrical connections, etc.) can be used for operating CHP.

The money flow in terms of the net present value of conventional electricity production (the reference case) with an annual electricity production of approx. 540 GWh can be seen in Fig. 6.

As shown above, the reference situation means an increase in the imports of approximately 230 Million Euros (20-year period). The major part of electricity payment by final consumers will not stay within the country, but instead it will end up paying for imports of fossil fuel and investments in new power stations.

Figure 7 shows the consequences of implementing the renewable CHP alternative. The figure includes the same annual electricity production as Fig. 6. Hence, the two diagrams are directly comparable.

By comparing two different alternatives one can be seen that the implementation of renewable energy results is an import of only approx. 180 million Euros. The spin-off of small-scale CHP is avoided investments for heat production units. Hence, the net result is an import of 110 million Euros or approx. 50% less than the reference case.

Based on the same methodology, it can be illustrated that the other CHP strategies will also result in a positive effect on the NBP: 117–202 million Euros or approx. 20–21% less than the reference case.

5. CONCLUSIONS

Until now, the task of electricity production has been left primarily to large production units based on nuclear power and conventional generation schemes. From the beginning of the construction of DH systems in Lithuania 30–40 years ago, all heat sectors, apart from a few of the biggest cities, were designed only for the production of heat for domestic purposes and steam for industrial purposes.

Today, the situation has changed: primary energy prices are much higher, the EU policies enforce a decrease in CO_2 emissions, existing DH systems need substantial investments for renovation, and the reliability of energy supply is more important than ever. Such changes set discussions on how to implement a number of new technologies, including CHP and renewable energy, in many countries including Lithuania.

Based on the Lithuanian case, this paper has compared four different cases in relation to the possible integration of small-scale CHP into the existing power system. The analysis shows that:

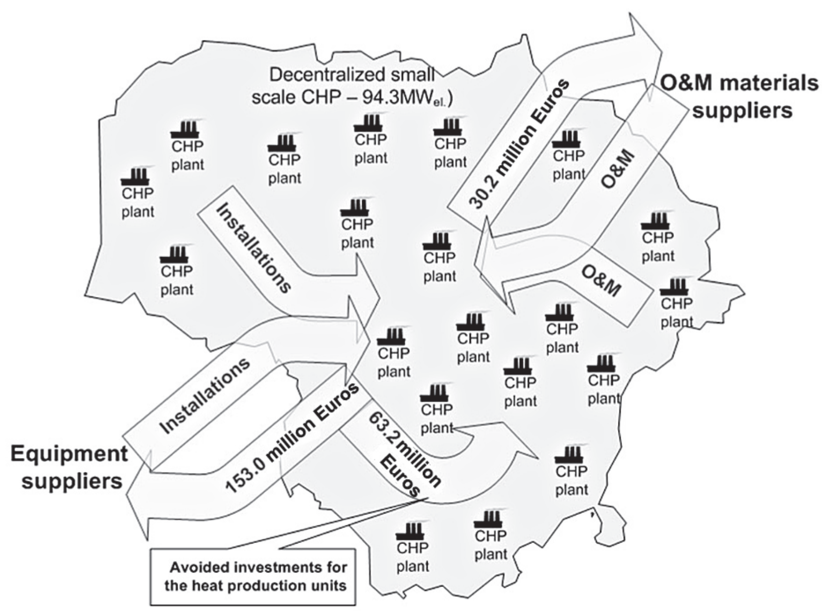

Fig. 7. Net present value of the national balance of payments for renewable case (20-year period)

in the present situation, absence of public regulation provides the rules for securing potential small CHP payments for electricity production, and consequently no business economic potential exists;

if electricity sale prices are provided on the basis of long-term marginal costs of electricity production from 350 MW CCGT plants, the potential of more than 100 MW small-scale CHP becomes economically feasible with a total electricity production of nearly 9% of the existing demand. Meanwhile, only small CHP based on natural gas become feasible. Due to relatively low natural gas prices, biomass CHP technologies cannot compete;

if a CO_2 payment of 30 Euro/ton is included in the calculation, the business economic potential of small CHP plants increases slightly, but even so, biomass solutions are still not feasible;

if small DH companies are in a situation when they need to invest in new capacities, the business economic potential is raised to 250 MW and in some cases biomass technologies become feasible, if natural gas is not available. In such cases, the business economic electricity production will rise to nearly 15% of the present demand;

if only biomass is allowed, the business economic potential decreases to approximately 100 MW, which is still enough to fulfil the EU obligations of increasing the share of electricity production from renewable energy to at least 7%;

should the potential of 250 MW be implemented, small DH companies will make a profit of more than 160 million Euros (NPV during a 20-year period). Meanwhile, if natural gas is not allowed and the biomass potential of 100 MW is implemented (situation 4), small DH companies will only make a profit of approx. 30 million Euros;

– should only renewable small-scale CHP be allowed (situation 4), the annual CO_2 reduction adds up to approximately 190,000 tons. In the other three situations, CO_2 reduction varies between 125,000 (situation 1) and 240,000 (situation 3) tons per year;

should only renewable small-scale CHP be allowed (situation 4), the positive effect on the national balance of payment would be 110 million Euros and equal to an improvement of approximately 50% compared to the same amount of electricity generated by conventional systems. By implementing the three other alternatives, the positive effect on the national balance of payment would be an improvement of approximately 20%.

In general, the optimization methodologies can be divided into two major types. The first type comprises business economic based optimisation methodologies in which small-scale CHP feasibility is evaluated only from the company's point of view. The second type is based on socio economic methodologies. In this case, wealth is maximised from the point of view of the whole society (a city, a country or the entire world).

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MAŽOS GALIOS KOGENERACIJOS PLĖTROS OPTIMIZAVIMO METODIKOS NACIONALINIO LYGMENS STRATEGIJOSE (LIETUVOS ATVEJIS)

Santrauka

Bendros šilumos ir elektros energijos gamybos (kogeneracijos) panaudojimas leidžia sumažinti kuro sąnaudas apie 30%, pagaminant visiškai tą patį šilumos ir elektros energijos kiekį. Mažos galios kogeneracija nedideliuose miestuose ar kaimuose leidžia dar padidinti jos teikiamą naudą, pakeičiant iškastinį kurą vietiniu biokuru.

Šis straipsnis paremtas Lietuvos, kuriai, viena vertus, reikia kompensuoti Ignalinos atominės elektrinės uždarymą, o kita vertus, būtinos didelės investicijos centralizuoto šilumos tiekimo sistemos rekonstravimui, atveju. Straipsnyje paryškinami verslo ekonomikos principai mažoms centralizuoto šilumos tiekimo įmonėms, taip pat galimas skirtumas tarp socialinės ir verslo ekonomikos požiūrių.

Lietuva turi didelį kogeneracijos plėtros potencialą ir galimą naudą ateityje socialinės ekonomikos atžvilgiu. Nepaisant to, kogeneracijos plėtrai reikia viešo reguliavimo mechanizmo, užtikrinančio jos tikslingumą ne tik socialinės, bet ir verslo ekonomikos požiūriu.

Raktažodžiai: bendra šilumos ir elektros energijos gamyba (kogeneracija), optimizavimo metodikos, mažos galios kogeneracija

Няриюс Расбурскис, Хенрик Лунд, Шарунас Прескенис

ОПТИМИЗАЦИЯ МЕТОДИКИ РАЗВИТИЯ КОГЕНЕРАЦИИ МАЛОЙ МОЩНОСТИ НА УРОВНЕ НАЦИОНАЛЬНОЙ СТРАТЕГИИ (СЛУЧАЙ ЛИТВЫ)

Резюме

Использование комбинированной выработки тепловой и электрической энергии позволяет сократить расходы топлива примерно на 30% при производстве одинакового количества тепловой и электрической энергии. Когенерационные устройства малых мощностей в деревнях и небольших городах позволяют повысить этот положительный эффект, заменяя ископаемые виды топлива на местное биотопливо. В статье рассмотрена ситуация в Литве, для которой, с одной стороны, необходимо компенсировать закрытие Игналинской атомной электростанции, а, с другой, неизбежно нужны большие инвестиции на реконструкцию централизованного теплоснабжения. Определены принципы предпринимательской экономики для малых предприятий, занимающихся централизованным теплоснабжением, а также возможность различных подходов в социальной и предпринимательской экономике.

У Литвы имеется большой потенциал для развития когенерации, поэтому в будущем предвидится польза с точки зрения социальной экономики. Однако для развития когенерации нужен механизм общественного регулирования, обеспечивающий ее целесообразность не только с точки зрения социальной, но и предпринимательской экономики.

Ключевые слова: комбинированная выработка тепловой и электрической энергии (когенерация), методика оптимизации, когенерация малой мощности