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METHOD OF THE BEST AVAILABLE TECHNOLOGY AND LOW CARBON FUTURE OF A COMBINED HEAT AND POWER PLANT

METODA NAJBOLJŠE RAZPOLOŽLJIVE TEHNOLOGIJE IN NIZKOOGLJIČNA PRIHODNOST TOPLARNIŠKEGA POSTROJENJA

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Keywords: alternative facilities, best available technology, combined plant, heat recovery, hydrogen, low-carbon, methanisation, natural gas, steam recovery Abstract

Abstract

The low-carbon development strategy and ecological awareness of a combined heat and power (*CHP*) plant is the key factor that enables further development of such systems. *CHP* plants are subject to rigid European ecological guidelines, which dictate the pace of development of global thermal power engineering. For this purpose, the European Union issued a special Directive for the promotion of heat and power cogeneration, and is established with the best available technology (*BAT*) method. Even though the production of electricity using carbon-free technologies is on the rise, the production of electricity by fossil fuel combustion cannot be avoided completely. The meaning of the operation of the *CHP* plant is reflected particularly in the provision of tertiary services to the electric power system, regulation of the network frequency, particularly in winter

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months, when electricity production using carbon-free technologies is limited. In *CHP* systems, the low-carbon future is linked intricately to high investment costs and these impacts the final price of energy. Using the *BAT* method, the article presents the advantages of energy production in a combined heat and power plant, an example of the restructuring of a larger *CHP* system into a low-carbon plant and guidelines for further development.

Povzetek

Nizkoogljična razvojna strategija in ekološka ozaveščenost toplarniškega postrojenja sta ključna dejavnika, ki omogočata nadaljnji razvoj tovrstnih sistemov. Toplarniška postrojenja so podvržena strogim evropskim ekološkim smernicam, ki narekujejo tempo razvoja globalne termoenergetike. V ta namen je Evropska unija izdala posebno direktivo za spodbujanju proizvodnje toplote in električne energije v kogeneraciji, ki se ugotavlja z metodo najboljše razpoložljive tehnologije. Kljub temu da je proizvodnja električne energije s pomočjo brezogljičnih tehnologij v porastu, pa se proizvodnji električne energije s sežigom fosilnih goriv ne bo mogoče popolnoma izogniti. Pomen delovanja toplarniškega postrojenja se še zlasti izraža pri nudenju terciarnih storitev elektroenergetskemu sistemu, pri regulaciji frekvence omrežja, še zlasti v zimskih mesecih, ko je proizvodnja električne energije s pomočjo brez ogljičnih tehnologij okrnjena. V toplarniških sistemih je nizkoogljična prihodnost tesno povezana z velikimi investicijskimi stroški, ki vplivajo na končno ceno energije. S pomočjo metode najboljše razpoložljive tehnologije so v prispevku predstavljene prednosti proizvodnje energije v kogeneraciji, primer prestrukturiranja večjega toplarniškega sistema v nizkoogljično postrojenje ter smernice nadaljnjega razvoja.

1 INTRODUCTION

The basic purpose of *CHP* systems is high-efficiency cogeneration of electricity. A *CHP* system is composed of a heat generator, a thermal engine and a heat sink. The heat generator serves for heat generation. A share of the generated thermal energy is converted by the thermal engine into mechanical work [1], and another share of the thermal energy may be used for industrial purposes in the form of industrial steam or for remote heating purposes [2]. The remaining part of unused heat is discharged into the environment. Unused heat refers to the heat which reduces the efficiency of the *CHP* plant [3]. In *CHP* systems where heat is generated by fossil fuel combustion, the largest share of such unused heat is exported to the environment through exhaust systems, and leaves combustion plants in the form of flue gases and through condensate systems. The advantages of energy production by means of *CHP* systems are expressed in the amount of heat discharged into the environment, because the minimisation of discharged heat increases the efficiency of such plant significantly. The simplest way of determining the suitability of a *CHP* plant is performed using the *BAT* method. What applies to *BAT* today, may be gone tomorrow. Using the *BAT* method, we have compared the co-generation of heat and power with separate production in alternative facilities [4]. Alternative facilities are facilities where electric and thermal energy are generated separately in separate facilities. Using alternative facilities, the *BAT* method, in addition to efficiency, also presents fuel savings. Because less fuel is used in *CHP* systems for the production of the same amount of energy than in separate facilities, the emissions of greenhouse gases are also correspondingly lower.

In addition to high-efficiency co-generation of energy, *CHP* systems are becoming increasingly more eco-friendly, because the adaptation to the best available technologies also contributes to the replacement of fuel types, thereby getting closer and closer to a carbon-free society and carbon neutrality [5]. This results in increased use of carbon-neutral fuels, such as biomass, biomass fraction of waste, hydrogen, etc. In addition to carbon neutrality, special attention should also be directed to the reduction of emissions of other greenhouse and toxic gases, which are released in the process of the combustion of combustible substances. Reduction of greenhouse and toxic gases in combustion plants is only possible with precisely targeted development strategies, but it is largely connected to high investment costs. In Slovenian thermal power engineering, heat is largely generated by the combustion of coal, lignite, thermo-degradable waste and gas. Due to the high prices of emission coupons and related financial unsustainability, *CHP* systems are forced to transition to the use of carbon-neutral fuels and gasification of *CHP* systems. With the gasification of *CHP* systems, a share of the primary fuel or coal can be substituted by gas. The advantage of gas is expressed mainly in lower emissions of CO_2 greenhouse gas, because it is largely composed of methane, CH_4, where hydrogen also undergoes combustion in addition to the carbon [6]. The advantage of the use of gas is also expressed in the production method, because, in addition to the utilisation of natural resources, in the process of methanisation gas can also be obtained by utilising energy surpluses, Power-to-Gas [7], and in a combination of biogas and hydrogen. Gas obtained in the process of methanisation can also be stored and used when energy demand increases. The European guidelines also provide for the construction of the European hydrogen pipeline, which would interconnect hydrogen producers, consumers and reservoirs. For this purpose, the European Union also established the European Clean Hydrogen Alliance [8], which indicates the first signs of the construction of hydrogen pipelines.

The article is structured so as to introduce the advantages of *CHP* systems initially in comparison to the generation of an equal amount of energy in separate alternative facilities using the *BAT* method. This is followed by the presentation of the steps of the low-carbon transformation of a large *CHP* plant and the guidelines for further development.

2 MODEL OF THE *BAT* METHOD OF ALTERNATIVE FACILITIES

The *BAT* method of alternative facilities refers to the European Directive 2004/8/ES [9] on the promotion of the production of heat and power in a co-generation process. The *BAT* method of alternative facilities compares the energy efficiency of a *CHP* system with the efficiency of facilities in separate production, or production of energy products in substitute facilities. The level of production efficiency is determined using the results of fuel savings. If heat and power production by means of the *CHP* system is more efficient than production in alternative facilities, the *CHP* system consumes less fuel, the system efficiency is improved, and the emissions of greenhouse gases and the toxicity of gases are lower. A schematic presentation of the model of the *BAT* method of alternative facilities is shown in Figure 1.

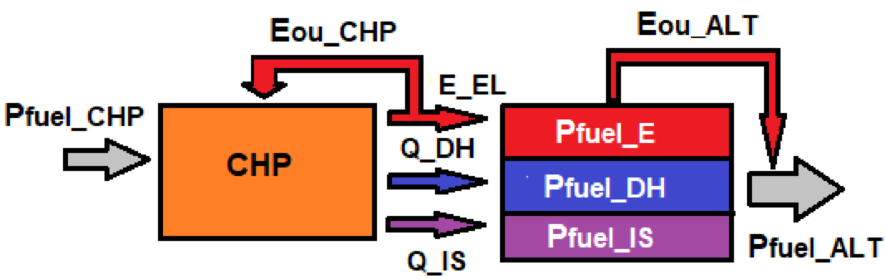

Figure 1: *Schematic presentation of the model of the BAT method of alternative facilities*

Figure 1 shows abbreviations, where *Pfuel_CHP* is the fuel power for electricity and heat production of the *CHP* system, *E_EL* is the generated electric power, *Eout_CHP* is the electric power of own use of the *CHP* system, *Q_DH* is the generated thermal power of remote heating, *Q_IS* is the generated thermal power of industrial steam, *Pfuel_E* is the fuel power for generation of electric power by means of an alternative facility, *Pfuel_DH* is the fuel power for the generation of thermal power of remote heating by means of an alternative facility, *Pfuel_IS* is the fuel power for the generation of thermal power of industrial steam by means of an alternative facility, *Eou_ALT* is the total electric power of own use of alternative facilities, and *Pfuel_ALT* is the total fuel power for the production of electric and thermal power of alternative facilities, where the generated electric and thermal power of the *CHP* system is equivalent to the electric and thermal power of the alternative facilities.

In our case, the *CHP* system consists of a combined cycle gas turbine (*CCGT*), composed of a gas turbine, steam generator and steam turbine. The analysis takes into account that, throughout the operation period, the *CCGT* steam turbine operates with a back-pressure at high efficiency. In an alternative facility, electric power is generated by means of a steam turbine in a pure condensation operation. The thermal power of remote heating in an alternative facility is generated by means of a hot water boiler. The thermal power of industrial steam in an alternative facility is generated by means of a steam boiler. Natural gas is used in the *CHP* system, as well as in substitute facilities. Fuel savings are calculated by means of the following equation [9]:

$$S_{fuel}=1-\left(\frac{1}{\frac{P_{fue_E}}{P_{fuel_{CHP}}}+\frac{P_{fuel_{DH}}}{P_{fuel_{CHP}}}+\frac{P_{fuel_{IS}}}{P_{fuel_{CHP}}}}\right)\cdot 100 \tag{2.1}$$

where S_{fuel} are the fuel savings. The fuel power for the generation of electric power and thermal power of remote heating and technological steam of the *CHP* system is calculated by means of the following equation [10]:

$$P_{fuel_{CHP}}=LHV_{fuel}\cdot \acute{m}_{fuel} \tag{2.2}$$

where HHV_{fuel} is the higher heating value of natural gas and $\acute{m}_{fuel}$ is the fuel mass flow. The calculation takes into account the lower calorific value of natural gas, which is 49,22 MJ/kg. Fuel power in alternative facilities is calculated by means of the following equations [9]:

$$P_{fuel_E}=\frac{E_{EL}}{\eta_E}\cdot 100 \tag{2.3}$$

$$P_{fuel_{DH}}=\frac{Q_{DH}}{\eta_{DH}}\cdot 100 \tag{2.4}$$

$$P_{fuel_{IS}}=\frac{Q_{IS}}{\eta_{IS}}\cdot 100 \tag{2.5}$$

where η_E is the efficiency of the alternative facility for generation of electric power, η_{DH} is the efficiency of the alternative facility for the generation of thermal power of remote heating, and η_{IS} is the efficiency of the alternative facility for the generation of thermal power of industrial steam. The total fuel power for the production of electric and thermal power of alternative facilities is calculated by means of the following equation:

$$P_{fuel_{ALT}} = P_{fuel_E} + P_{fuel_{DH}} + P_{fuel_{DH}} \quad (2.6)$$

2.1 Results of the *BAT* method of alternative facilities

The results of the *BAT* method of alternative facilities are structured so that they initially present the generated electric and thermal power and fuel power of the *CHP* system. This is followed by the presentation of fuel power for the operation of the alternative facilities. Fuel efficiency and savings are presented at the end. Figure 1 shows the fuel power required for the generation of electric and thermal power, depending on the *CHP* system load. At a 40% *CHP* system load the fuel power is 150 MW, while the *CHP* system generates 50 MW of electric power, 62 MW of thermal power of remote heating and 2 MW of thermal power of industrial steam. At a 100% *CHP* system load, the fuel power is 280 MW, while the *CHP* system generates 105 MW of electric power, 93 MW of thermal power of remote heating and 21 MW of thermal power of industrial steam.

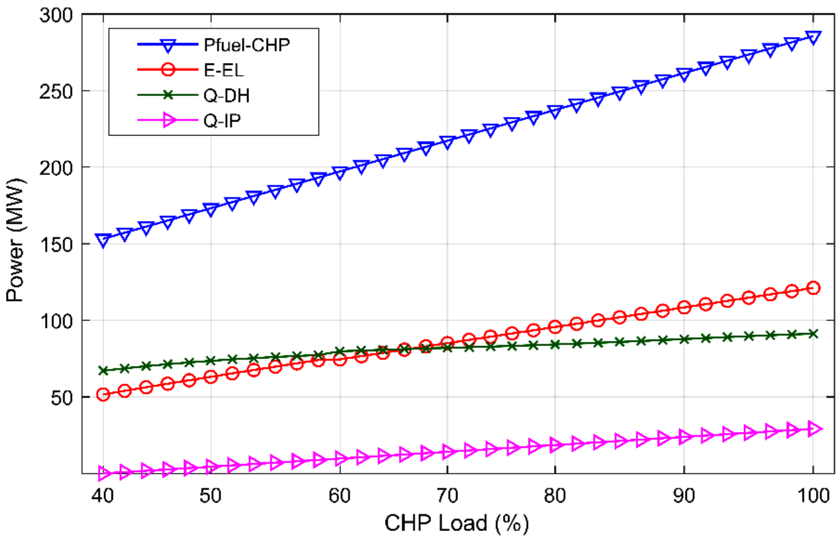

Figure 2: *Fuel power, generated electric power, generated thermal power of remote heating and generated thermal power of industrial steam, depending on the CHP system load*

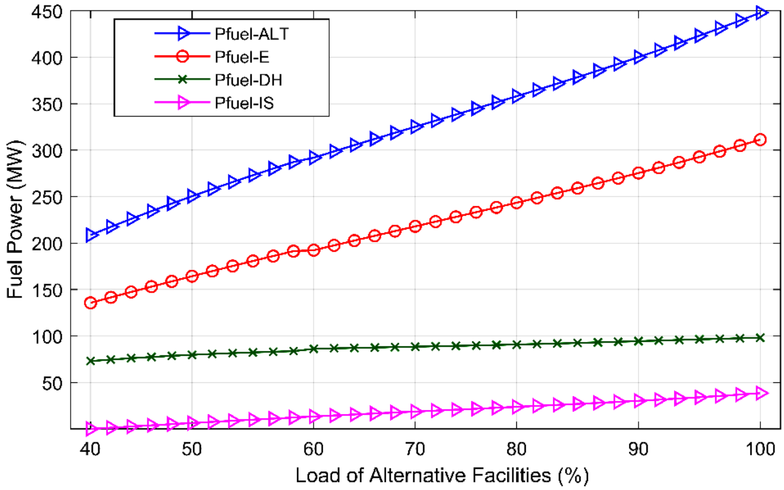

Figure 3: *Fuel power for the operation of alternative facilities depending on the load*

Figure 3 shows the fuel powers required for the operation of alternative facilities. At a 40% load of alternative facilities, fuel power for the generation of electric power is 140 MW, fuel power for the generation of thermal power of remote heating is 70 MW, fuel power for the generation of thermal power of industrial steam is 2.24 MW. At a 40% load of alternative facilities, total fuel power is 212.24 MW. At a 100% load of alternative facilities, fuel power for the generation of electric power is 307 MW, fuel power for the generation of thermal power of remote heating is 90 MW, fuel power for the generation of thermal power of industrial steam is 45 MW. At a 100% load of alternative facilities, total fuel power is 442 MW. Figure 4 shows the efficiency of the *CHP* system, total efficiency of alternative facilities and fuel savings in a cogeneration process.

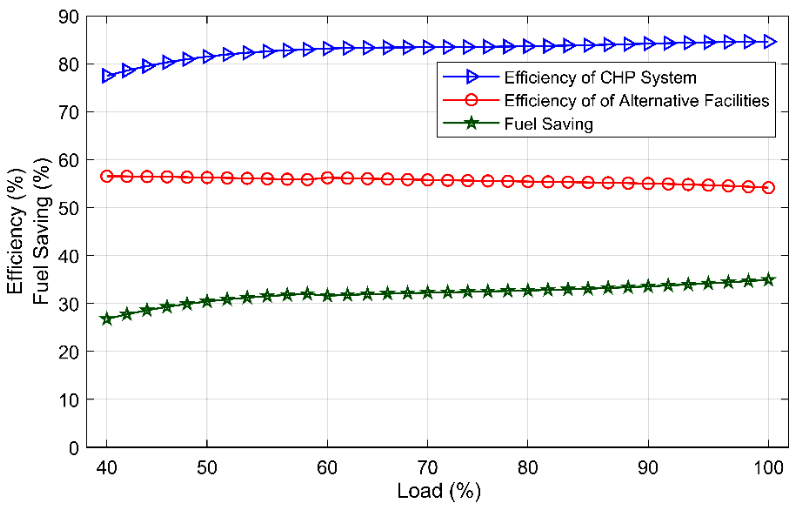

Figure 4: *Efficiency of the CHP system, total efficiency of the alternative facilities and fuel savings of the CHP system*

At a 40% load, the efficiency of the *CHP* system is 78%, and the total efficiency of alternative facilities is 58%. The fuel savings of the co-generation *CHP* production versus energy production by means of alternative facilities is 27%. At a 100% load, the efficiency of the *CHP* system is 87%, and the total efficiency of alternative facilities is 53%. The fuel savings of co-generation *CHP* production versus energy production by means of alternative facilities in this case amounts to 34%. By increasing the load the co-generation production efficiency by means of the *CHP* system increases, whereby the efficiency of production by means of alternative facilities decreases. Accordingly, increased load contributes to higher fuel savings. The cause of the reduced efficiency in an increased production load by means of alternative facilities is the increase in the dissipation of heat in the surroundings at pure condensation operation of a steam turbine or an alternative facility for the generation of electric power.

3 LOW-CARBON TRANSFORMATION OF A LARGE *CHP* SYSTEM AND GUIDELINES FOR FURTHER DEVELOPMENT

In large *CHP* systems the combustion process with the purpose of increasing the enthalpy of a working medium is carried out by means of fossil fuel combustion. The type of fuel combusted is linked intricately to the chemical composition and corresponding greenhouse gas emissions. The low-carbon transformation of a large *CHP* system is linked intricately to the use of low-carbon or carbon-neutral fuels, such as biomass, biomass fraction of waste, hydrogen, etc. Replacement of the fuel type in *CHP* systems is linked intricately to high investment costs, because, in order to achieve high efficiency, it is required to opt for *BAT*. This raises the question as to what extent does it make sense to preserve the existing plant? However, replacing solid fuel with gas fuel, taking into account the high-efficiency *BAT*, results in the replacement of the entire *CHP* system. Figure 5 shows two *CHP* systems, specifically, Figure 5 a) shows the classic Rankine *CHP* system, and Figure 5 b) shows the combined Brayton-Rankine CHP high-efficiency gas-fired system.

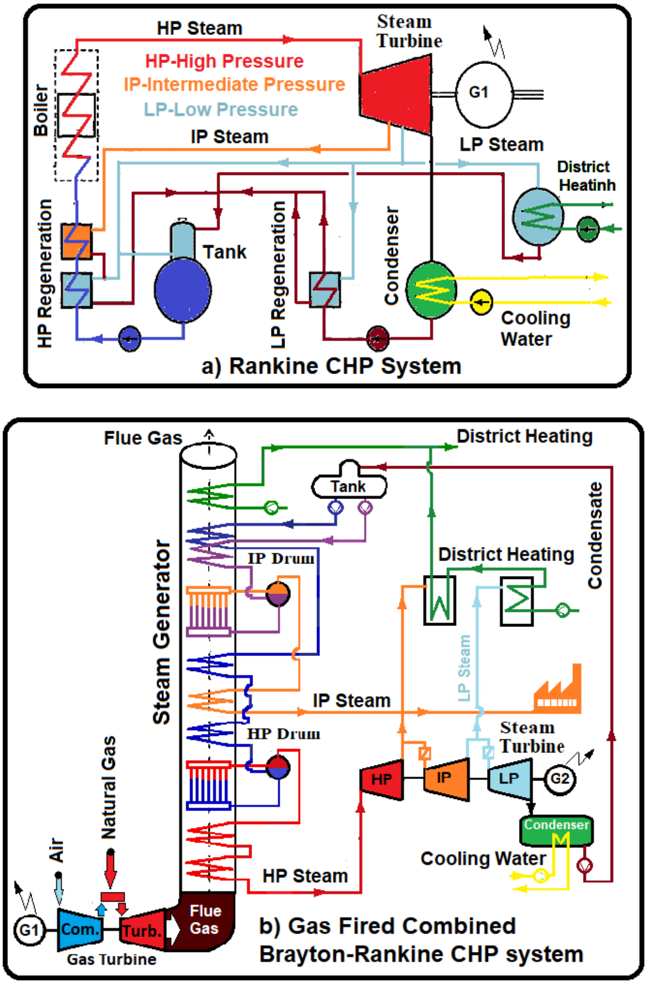

Figure 5: *a) Rankine CHP system and b) Gas fired combined Brayton-Rankine CHP system*

The classic Rankine *CHP* system for increasing the enthalpy of a working medium uses various heat sources, while a boiler is used largely in the combustion of fossil fuels. However, solid fuels and gaseous fuels may burn in a boiler. Gas-fired *CHP* systems, which are intended for achieving high efficiency, are composed of the combined Brayton and Rankine cycle, which is also called the combined gas-steam cycle. The combined gas-steam cycle is composed of a gas turbine, steam generator and turbine condensation system with a thermal station. The combustion of gaseous fuel takes place in a gas turbine. The high temperature of the exhaust gases of a gas turbine, by means of a generator, serves for generating various types of steam and heat for remote heating. The steam is exported from the steam generator to the steam condensing extraction turbine. The extraction steam from the steam turbine is used for industrial purposes, or for remote heating.

The low-carbon property of the gas-steam *CHP* system in comparison to the *CHP* solid fuel system is expressed mainly in the type of fuel, because gaseous fuels contain a lower content of carbon and a higher content of hydrogen. This corresponds to the combustion products of such fuels, because emissions of CO_2 greenhouse gas are decreased and emissions of water vapour or water are increased. Such gas-steam *CHP* plants can further improve their carbon footprint, because the most recent gas turbine, such as the gas turbine Siemens SGT 800, can, in combination with natural gas, operate with as much as a 75% hydrogen volume fraction [11]. With the further development of steam turbine burners, the hydrogen volume fraction in combination with natural gas will increase further. Likewise, gas turbines can also be powered by biogas.

With the purpose of increasing the ecological focus and promoting the self-supply of the European Union with natural gas, the European Union has established a special Association, the European Clean Hydrogen Alliance [8], which intends, in the first phase, to produce green hydrogen from surplus renewable electricity, and transport it to users with a special methanisation procedure by means of a gas network. Any surplus of green methane will be accumulated in natural gas reservoirs. In the second phase, by the year 2030, the plan is to build gas pipelines which will interconnect hydrogen producers, consumers and reservoirs. Figure 6 shows the development projects of the hydrogen technology and the outline of the hydrogen infrastructure.

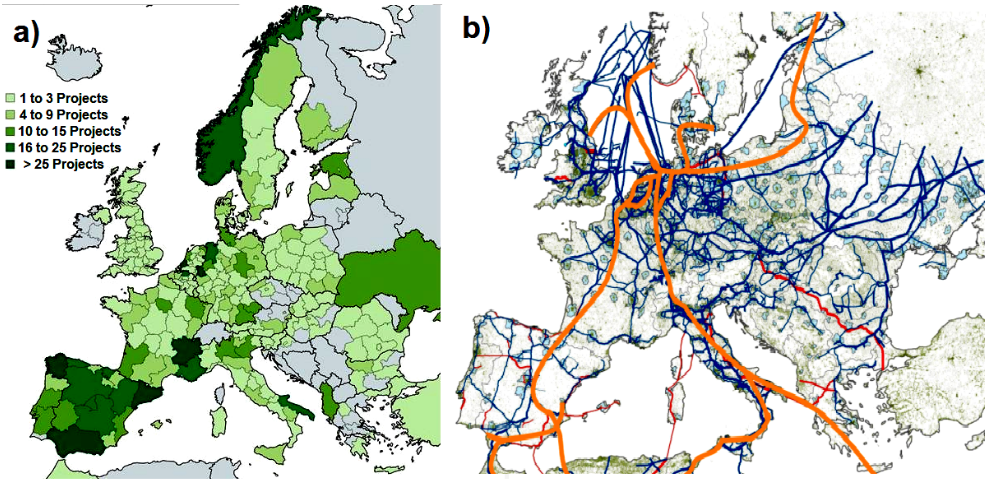

Figure 6: *a) project pipeline of the European Clean Hydrogen Alliance [12] and b) natural gas infrastructure in Europe (blue and red lines) with the first outline for a hydrogen backbone infrastructure (orange lines) [13]*

However, special attention must also be dedicated to the possibility of using the biomass fraction of waste, because the combustion of the fraction increases carbon neutrality. Biomass fraction of waste is formed in waste separation, and is, pursuant to the existing procedures, deposited at landfills or transported to incineration sites, largely abroad. If the biomass fraction of waste is deposited at landfills, CO_2 is produced in the processes of rotting and decay. In case of combustion of the fraction, heat is also generated, which may be used rationally by means of *CHP* systems for the production of electric and thermal energy. For this purpose, the location for the construction of such systems is essential with regard to the utilisation of the already existing infrastructure.

4 CONCLUSIONS

Using the model of the *BAT* method of alternative facilities, the article discusses the advantages of energy production by means of *CHP* systems and the low-carbon future of a large CHP system. The BAT method model is based on the calculation of the saved fuel of a *CHP* system in the event of generation of the same amount of electric and thermal power in alternative facilities. Alternative facilities are facilities where electric and thermal energy are generated separately in separate facilities. The results of the model of the *BAT* method of alternative facilities show that fuel savings of the *CHP* system depend on system load. At a 40% system load, the fuel savings of the *CHP* system equal 27%, and at a 100% system load, the fuel savings of the *CHP* system equal 34%.

The low-carbon transformation of a large *CHP* system is linked intricately to the use of low-carbon or carbon-neutral fuels. Replacement of the fuel type in a *CHP* system is linked intricately to high investment costs. In using gaseous fuel, and in order to reach high efficiency, an appropriate option seems to be gas-steam CHP plants. The low-carbon future of the presented plants may be improved further, because the latest gas turbines may, in combination with natural gas, operate with as much as a 75% hydrogen volume fraction, and hydrogen may be obtained from surplus green energy and mixed with natural gas in the methanisation process.

However, special attention must also be paid to the possibility of using the biomass fraction of waste, because the combustion of the fraction increases carbon neutrality. The biomass fraction of waste is currently deposited at landfills or transported to incineration sites, largely abroad. In the case of combustion of the fraction heat is also generated, which may be used rationally by means of *CHP* systems for the production of electric and thermal energy.

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Abbreviations

BAT	best available technology
CCGT	combined cycle gas turbine
CHP	combined heat and power
CH_4	methane
CO_2	carbon dioxide
HP	high pressure
IP	Intermediate pressure
LP	low pressure

Parameters

E_ou_ALT	total electric power of own use of alternative facilities
E_ou_CHP	electric power of own use of the *CHP* system
E_EL	generated electric power
LHV	lower calorific value of natural gas
Pfuel_ALT	total fuel power for the production of electric and thermal power of alternative facilities
Pfuel_CHP	fuel power for electricity and heat production of the *CHP* system
$\acute{m}_{fuel}$	fuel mass flow
Q_DH	generated thermal power of remote heating
Q_IS	generated thermal power of industrial steam
S_{fuel}	fuel savings
$P_{fuel_{CHP}}$	fuel power for electricity and heat production of the *CHP* system
$P_{fuel_{DH}}$	fuel power for the generation of thermal power of remote heating by means of an alternative facility
$P_{fuel_{IP}}$	fuel power for the generation of thermal power of industrial steam by means of an alternative facility
$P_{fue_{E}}$	fuel power for generation of electric power by means of an alternative facility
η_{DH}	efficiency of the alternative facility for the generation of thermal power of remote heating
η_{E}	efficiency of the alternative facility for generation of electric power
η_{IS}	efficiency of the alternative facility for the generation of thermal power of industrial steam.