New Way of Producing Useful Energy from Biomass in Countries Decommissioning Coal-Fired Power Plants

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Abstrakt

This paper describes a new way of processing biomass using micro-CHPU devices (Micro Combined Heat and Power Unit). The micro--CHPU device is a new idea that allows to convert chemical energy in biomass into electricity for charging batteries in small electric vehicles and into useful heat for households. To make the device readily available and inexpensive, commercial Peltier modules were used, in which their operation was inversed to create the Seebeck effect. The presented research results show that the commercial Peltier module works very well as a thermoelectric generator. The proposed devices may turn out to be very useful in the times of the revolution that has begun on the energy market in most developing countries. Nowadays, many of these countries are intensively beginning to phase out energetics based on fossil fuels. A very popular and effective method of using biomass is mixing it with coal (in the proportion of 10% to 90%) and burning it in a coal-fired power plant or CHP plant. After closing these power plants, biomass will no longer be burned there. Then, the unused biomass could be burned in micro-CHPU devices. This will prevent biomass waste in agriculture.

Keywords: *biomass, thermoelectric generator, micro combined heat and power unit, primary energy consumption, emission reduction and renewable energy source*

1. Introduction

In developing countries electricity is still produced mainly in coal-fired power plants. However, with every year coal-fired power plants are successively replaced by renewable energy sources and nuclear power plants. For example, Poland is a rapidly developing country but still coal-fired power plants generate about 80% of total electricity [1-13]. The remaining part of electricity is produced in gas power plants and from renewable energy sources. Polish agriculture produces a lot of biomass, which unfortunately is mostly wasted as there is overproduction of this biomass. Mulching is rare and burning of grass in arable fields occurs quite often although it is illegal in Poland and causes fire hazard. As a result of global warming, winters have become very mild. The winter 2019/2020 was for the first time snowless in the history of Poland and many other European countries (except in the mountains). Since around 2008, biomass has been increasingly used to generate electricity. Biomass is added to fine coal (blending) and burned (co-firing, co-milling) in coal-fired power plants and coal-fired CHP (Combined Heat and Power) plants. The share of biomass in the blend with coal is usually less than 10%. Generally, there are three most popular ways to proceed with biomass in East-Central European countries: leaving biomass in the farmland or forest; mixing 10% of biomass with 90% of coal and burning it in a coal or CHP plant; burning it in households or local biomass incineration plants. It is very important to bear in mind that, regardless of the fact which method is chosen, carbon dioxide be emitted into the atmosphere in approximately the same amount. This may seem surprising, but leaving biomass in the farmland to rot will cause the formation of carbon dioxide in quantities similar to the process of burning. Transformation of organic matter into CO_2 gas is well known [14] and is discussed, among others, in works [15-17]. Small household or local biomass incinerators for heating purposes are usually not very efficient and do not generate electricity. To sum up, the most efficient and ecological way to generate electricity from biomass energy is based on mixing biomass with coal in a coal or CHP plant. Poland and other developing countries will face a radical energy transformation in the next several years. There will be a gradual resignation from coal energy. Currently, this process is intensifying, as the coronavirus pandemic has resulted in reduction in the industrial production and, consequently, a lower demand for electricity. In the second half of 2020, the closure of several coal mines has begun and the construction of new coal-fired power plants was abandoned. As a consequence, biomass combustion in coal-fired plants will be suspended. Retrofitting of currently operating coal-fired power plants for biomass fuel is complicated technologically and too expensive – it is necessary to build a new biomass-only power plant block from scratch. A typical European coal-fired power plant produces electrical power of 1000 to 5000 MW. By comparison, the world's biggest biomass power plant is Ironbridge, in the United Kingdom, with power of 740 MW [18]. That power plant was previously a coal-fired power station with installed power of 1000 MW. Two units of the plant were converted to biomass-based power generation in 2013 [18]. The world's biggest biomass power plants are presented in table 1. Biomass power plants have significantly lower electric power in comparison to coal-fired power plants.

There is actually a new power plant block built on the site of a functioning coal-fired power plant namely in Połaniec

Tab. 1. The world's biggest biomass power plants [18]

Tab. 1. Największe na świecie elektrownie biomasowe [18]

Biomass power plant	Installed power (MW)
Ironbridge, United Kingdom	740
Alholmens Kraft, Finland	265
Toppila,Finland	210 of electrical energy and 340 of thermal power
Połaniec, Poland	205
Kymijärvi II, Finland	160
Vaasa Bio-gasification plant, Finland	140

(Poland). That 205 MW block is a rare example in Poland of a block fully operating on biomass . Other power stations use coal mixed with biomass in the proportion of 90% – 10%. Recently, small-scale biomass power plants with the capacity of several megawatts have become commercially available – for example Matsuyama Biomass Power Plant (12.5 MW) constructed by Toyota Tsusho [19]. Unfortunately, it is not easy to replace a few large coal-fired power plants with hundreds of small-scale biomass plants. This would require a complete reconstruction of the electricity grid structure and additionally cause huge financial costs. In effect, there is a belief that as a result of the closure of coal-fired power plants, the biomass market has no future in Poland and many other countries. A new strategy for the development of the biomass market is urgently needed – a strategy which can be implemented after the coal power plants are shut down in countries decommissioning coal-fired power plants.

2. Primary energy consumption

Primary energy consumption grew at a rate of 2.9% in 2018. This increase is almost double the 10-year average of 1.5% per year, and is the fastest since 2010 [20]. All fuels grew faster than their 10-year averages, apart from renewables, although renewables are still accounted for the second largest increment to energy growth. China, the US and India together accounted for more than two thirds of the global increase in energy demand, with US consumption expanding at its fastest rate in 30 years [20]. Coal consumption increased by 1.4% in 2018, this is the double of the 10-year average increase [20]. The increase in consumption was led by India (36 mtoe) and China (16 mtoe). OECD demand has fallen to its lowest level since 1975. The share of coal in primary energy has fallen to 27.2%, the lowest level in fifteen years. World coal production increased by 162 mtoe, or 4.3%. The largest increases were achieved by China (82 mtoe) and Indonesia (51 mtoe) [8]. Coal power accounts for a major share within electricity production and significantly contributes to the overall greenhouse gas emissions [21]. Electricity generation increased by over 3.7%, which was caused by China (which accounted for more than half the growth), India and USA. Renewable energy sources accounted for one third of the increase in net power production, then coal (31%), and natural gas (25%). The share of renewable energy sources in energy production has increased from 8.4% to 9.3%. However, coal still accounted for the largest share in energy generating 38% [20]. Figure 1 shows how much electricity is produced from coal.

Poland produces over 80% of energy from coal, the next country is Hong Kong, with the share lower by as much as 15%. Austria and the Czech Republic are at a similar level. In other countries this level is much lower than 40%.

3. Emission reduction and renewable energy sources

Emission reduction aims to combat the climate change and reduce the impact of harmful emissions on the environment [23, 24]. World emissions are rising, as shown in figure 2.

In 2018, the level of global emissions of 32 840 * 106 Mg CO_2 was recorded. In relation to the previous year, it was an increase of 1.9%. Almost all countries in the world contributed to the increase in emissions, except for Europe and Latin America. In China, compared to the previous year, there was an increase of 3,1%, in India 4,2%, in Russia 3,9%, and in the United States 3,1%. All increases were caused by higher energy consumption, as well as, partly, by weather conditions. CO_2 emissions decreased in the European Union by -2,1% due to a diminishing energy demand, a greater share of renewable energy sources in electricity production and weather conditions, which were affected by mild winter and autumn. In Japan, CO_2 emissions have been falling for the fifth consecutive year, thanks to the growing share of solar energy since 2016 and the increase in nuclear energy production in 2018.

The decrease in emissions in the European Union is the result of the set goals of gradual reduction of greenhouse gas emissions by 2050. The key climate and energy goals are determined in the 2020 climate and energy package and in the 2030 climate and energy framework.

The 2020 package is a set of binding rules to ensure that member states reach their climate and energy goals for 2020. The package sets out three key objectives:

- 20% reduction in greenhouse gas emissions (from 1990 levels)
- 20% of energy in the EU from renewable sources
- 20% improvement in energy efficiency

The goals were determined by EU leaders in 2007 and adopted in 2009. They are also the main goals of the Europe 2020 strategy for smart and sustainable development [24]. The EU is taking action in several areas to achieve these goals. The next climate framework was adopted in October 2014, where the following objectives were agreed upon:

Reducing greenhouse gas emissions by at least 40% (since 1990 levels) [25]

- At least 32% share in renewable energy
- Improving energy efficiency by at least 32.5%
- This framework is expected to be achieved by 2030.

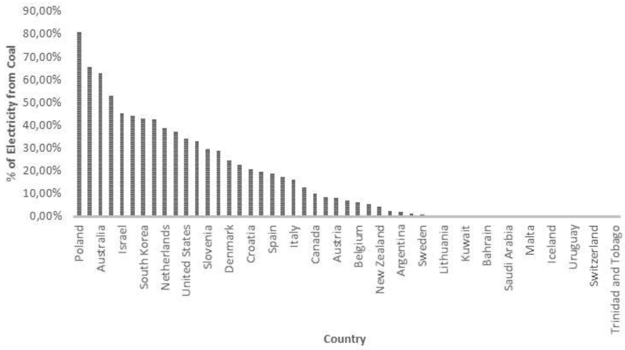

Fig. 1. Electricity from coal, 2018 (own study based on data [22])

Rys. 1. Energia elektryczna z węgla, 2018 (opracowanie własne na podstawie danych [22])

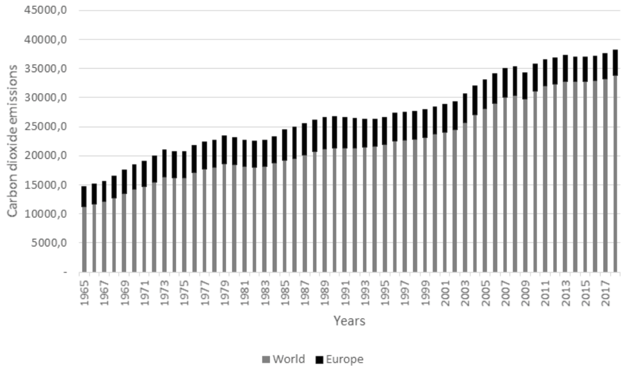

Fig. 2. World CO_2 emissions, Europe separately (own study based on data [20])

Rys. 2. Światowe emisje CO_2 (opracowanie własne na podstawie danych [20])

The term "renewable energy source" was defined in Polish law by the Act of 20 February 2015 on renewable energy sources, called the "RES Act", where RES are renewable, non-fossil energy sources including wind energy, solar energy, aerothermal energy, geothermal energy, hydrothermal energy, hydropower, wave, current and tidal energy, energy obtained from biomass, biogas, agricultural biogas and bioliquids (Article 2 of the RES Act). Renewable energy sources (RES) are generally energy carriers the use of which does not cause irreversible losses or deficits of this source in the environment. Their resources are constantly complementary and not exhaustive, and the process of supplementation can occur spontaneously and naturally, so for "renewal of the resource" no human intervention is necessary (e.g. wind). The sources of renewable energy are , among others, solar radiation, wind, heat from the Earth's interior, water, biomass, biogas, biofuels. From the indicated sources it is possible to obtain respectively: electricity, heat, cold and biocomponents. The use of energy from renewable sources has a lower negative impact on the environment than the use of fossil fuels to obtain energy. First of all, the use of renewable energy limits the emission of greenhouse gases as well as other harmful substances [26]. The current structure of renewable energy sources is shown in Figure 3.

According to the Accession Treaty signed with the European Union in 2004, Poland declared to increase the share of energy generated from renewable resources to 7,5% in 2010 and to 14% in 2020. Biomass production can therefore be a major factor contributing to the achievement of those objectives. Currently 4% of energy in the European Union is derived from biomass namely 190 million tons of biomass a year. By 2020 the use of biomass should increase up to 8% (360 million tonnes biomass a year) [28]. It is believed that Poland's potential of biomass is among the highest in Europe and is at 895 PJ [29]. The projected demand by professional energy suppliers in Poland is 8,3 million tonnes of dry biomass in 2020 and 10,6 million tonnes of dry biomass in 2030. At the same time, in accordance with the Regulation of the Minister of Economy (dated 14.08.2008), in the years 2015–2017 it was expected not to be possible to use forest biomass for co-burning (Journal of Laws No. 156, item 969). Therefore, an important part of the production of biomass for energy purposes in Poland will be the cultivation of fast-growing annual and perennial energy crops on plantations [30]. However, the implementation of these plans strongly depends on the future of coal-fired power plants.

Biomass accounts for over 60% of renewable energy in Poland [30-33]. The industry uses industrial and domestic waste as well as biomass to produce process heat. This represents around 10% of the energy generation sector. Biogas production has started relatively recently and currently there are about 200 biogas plants, which are unevenly distributed throughout the country [34]. Many rural households use biomass to heat houses and water, as well as for cooking. Table 2 summarizes the list of the largest biomass-fired power plants and their total biomass consumption in 2019.

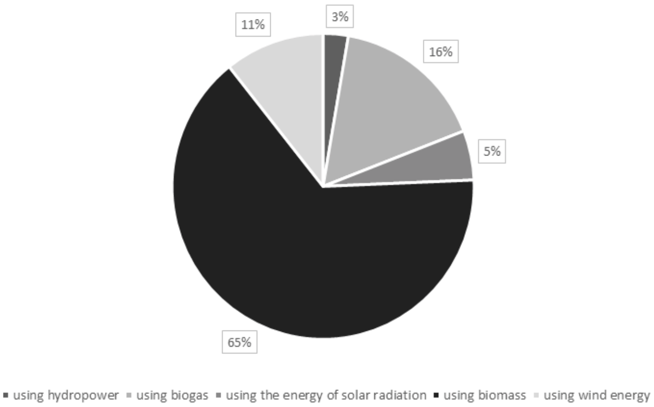

Fig. 3. Structure of renewable energy sources in Poland in 2019 (own study based on data [27])
Rys. 3. Odnawialne źródła energii w Polsce, 2019 r. (opracowanie własne na podstawie danych [27])

Tab. 2 Exemplary coal-fired and biomass power plants in Poland (own study based on data [35])
Tab. 2 Elektrownie węglowe i biomasowe w Polsce (opracowanie własne na podstawie danych [35])

Name	Total installed electric power [MWe]	Fuel
Opole Power Plant	3342,00	Hard coal, biomass
Połaniec Power Plant	1882,00	Hard coal, biomass
Turów Power Plant	1488,00	Lignite, biomass
Konin Power Plant	198,00	Lignite, biomass
Cogeneration biomass block at the Kalisz-Piwonice CHP plant	11,3 MWe i 21,3 MWt	Biomass (wood chips)
Lublin Power Plant	49,9 MW	Biomass

Some of these power plants are fully biomass-based, while others use a mixture of biomass and other fuels. These power plants will generate a significant part of Poland's demand for biomass for energy production by 2030 [35-37].

4. Materials and Methods

In the new biomass market development strategy, new biomass-only power plants should be built in places where is economically justified and it is not technically problematic. These new power plants should reach a high capacity of hundreds of megawatts, similar to those in Table 1. Currently, many new bioenergy projects, such as the Tychy CHP plant, are being implemented. There are also several other small units that use biomass gasification and syngas combustion. Several power plants use exclusively biomass, but their sizes are small and they are mainly scattered in minor Polish cities. Forest and agricultural residues as well as other organic waste are used as raw materials. Biomass is expected to serve a variety of applications, from energy and heating to enduse sectors such as construction, industry and transport ones. It is important that biomass is used locally and that high transport costs can be avoided. In addition, cogeneration systems using solid biomass and biogas are expanding in Poland. This is beneficial for the energy and heat supply sectors. According to the research of the Institute of Sustainable Development from 2018, approximately 25 TWh of electricity from solid biomass and 24 TWh from biogas can be produced by 2030. The Renewable Energy Council (2013) predicts electricity generation capacity of 4 GW by 2020 and 6 GW by 2030. Cogeneration has additional potential and is estimated to be at least 4 GW by 2030. Unfortunately, the decommissioning of coal-fired power plants may thwart these plans. Anaerobic digestion for biogas production will mainly be based on various residual organic materials. However, if the need arises, a mixture of dedicated short rotation energy crops can be used as another preferred biogas production option in Poland. The share of biomass in heating will remain high because the expansion of solar water heaters and heat pump solutions will be limited. In addition, biomass can be used in individual heating systems in buildings and industrial plants. Biomass is related to forestry and existing arable land or land that can be converted for arable or forestry use. It is available in most parts of Poland, but it varies locally. That is why, both solid waste power plants as well as biomass and biogas cogeneration plants can be found in areas where the local biomass potential is the highest.. In 2019, the average size of a biomass power plant was about 28 MW. The average size of industrial cogeneration may be 10-15 MW, depending on the industry. In district heating, larger cogeneration units with a capacity of about 50 MW are expected to arise depending on local demand. Dedicated multi-fuel combustion (co-combustion) and biomass boilers will coexist in current and newly built cogeneration power plants. The national energy policy, which is convergent with the energy and climate policy of the European Union, supports the development of renewable energy sources. The action plan aims to ensure the achievement of the goals of the Europe 2020 strategy, i.e. a 20% share of energy from renewable sources in the final energy consumption in the EU by 2020 and 27% by 2030. It should be noted that a large amount of biomass (probably most of it) in countries like Poland will still be burned in household furnaces. That biomass can be processed in household micro-CHPUs on agricultural land. The micro-CHPU (Micro Combined Heat and Power Unit) is a new idea and is presented in this paper in a general manner.

Fig. 4. Measurement setup for testing thermoelectric generators for micro–CHPU. 1 – hot water tank, 2 – cold water tank, 3 – cold water inlet, 4 – hot water outlet, 5 – electric heater (outside connectors), 6 – hydraulic hose connecting the tanks, 7 – tested thermoelectric generators, 8 – outside cables from temperature sensors (two 18B20 sensors in water–proof packed), 9 – additional temperature sensor (a thermocouple) for hot tank temperature control. In this figure Peltier modules TEC1–12715 are tested

Rys. 4. Układ pomiarowy do testowania generatorów termoelektrycznych, które zostaną zastosowane w urządzeniu micro–CHPU. 1 – zasobnik ciepłej wody, 2 – zasobnik zimnej wody, 3 – wlot zimnej wody, 4 – wylot ciepłej wody, 5 – grzałka elektryczna (zaciski zewnętrzne grzałki), 6 – wąż hydrauliczny łączący zbiorniki, 7 – badany moduł termoelektryczny, 8 – przewody wyjściowe czujników temperatury (dwa czujniki 18B20 w wodoszczelnej obudowie), 9 – dodatkowy czujnik temperatury (termopara) do kontroli temperatury na zasobniku z ciepłą wodą. W przedstawionym układzie badane były moduły Peltiera TEC1–12715

A new approach to the transformation of the biomass market is the use of dispersed micro-CHPUs not integrated with the electricity grid. Micro-CHPU is not to be confused with a biomass-powered genset. In recent years, biomass-powered gensets have become popular in areas where there is no electricity grid available. A very efficient solution is proposed, among others by All Power Labs, Berkeley, California - their aggregates achieve a continuous electric power of 25 kW and consume about 1 kg of dry biomass per 1 kWh of produced energy (heat + electrical energy) [38]. However, biomass-powered gensets are somewhat complex units. They have a biomass gasification module and spark engine. Like all internal combustion engines, biomass gensets have a limited lifetime. They do not find a wide application in Europe either - almost each village in Europe has access to the electricity grid. Unlike a biomass-powered genset, micro-CHPU is not dedicated to households without the electricity grid. This device is an ecological source of additional energy that can be used, among others, to recharge batteries in electric vehicles. Important advantages of the micro-CHPU are a no spark engine and no moving parts. The operating principle of the micro-CHPU is based on the thermoelectric Seebeck effect. This effect was discovered in 1821 but has been used more widely since the 20th century in thermocouples for temperature measurement. It should be noted that the thermocouple is a voltage signal source with a very low current-carrying capacity (it has high internal resistance). It is not a source of useful energy – it is a measurement instrument. The thermoelectric Seebeck effect is used to produce electricity in a thermoelectric generator (TEG). TEGs have gained more popularity thanks to their use in military and space technologies. TEG is usually shaped like a thin cuboid, the thickness of which is on the order of a few millimeters, and the remaining sides are several centimeters in size. This could be pictured as a plate a few millimeters thick. If there is a temperature difference between the opposite walls of the TEG module, an electric voltage is created in it. Physics of thermoelectric generators is discussed extensively in the book [39]. Nowadays, TEGs are more and more often used in various types of structures. The Authors in paper [40] show a low cost stove-top thermoelectric generator for regions with unreliable electricity supply. Research on that type of household device gained momentum at the beginning of the 21st century. In recent years, there has been development of stove-powered thermoelectric materials and generators [41]. This resulted in a significant drop in their retail price. In effect, this opens up a new application area for thermoelectric generators.

5. Results and discussions

The micro-CHPUs are dedicated to all agricultural regions, also the highly developed ones. They will be able to generate electric energy for batteries in small electric vehicles and heat energy for households. Today, this is a very attractive application area. The electric agricultural vehicle market is developing very fast and biomass could become indirectly (through electricity) a fuel for these vehicles. In recent years, many new fully electric propulsion farm vehicles have been constructed, e.g. Switchevglobal vehicles [42]. Currently, the micro-CHPU system is under construction. It contains a combustion chamber, an exhaust filter, heat collectors, boilers, thermoelectric modules and an electronics module (voltage converter and driver). In order to reduce construction costs, a consumer Peltier module was used as a thermoelectric module. This is a very important detail. Peltier modules are widely used in automotive refrigerators, medical and scientific apparatus and many other devices . The Peltier phenomenon is the opposite of the Seebeck phenomenon. The Peltier module, during its normal operation, pumps heat from one side of the module to its other side. This effect is fully reversible and the Peltier module can work as TEG. Our previous experiment has shown that it can be used for construction of a low cost solar thermoelectric water floating device to supply a measurement platform. Now the research has been extended for a larger temperature difference and has shown the great application potential of these modules. To test the properties of various Peltier modules working as thermogenerators in the temperature difference range up to 50˚C, the circuit shown in Fig. 4 was built. It is very important to investigate the perfor-

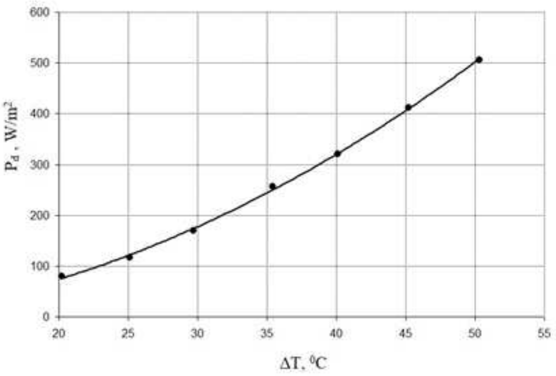

Fig. 5. Surface power density generated in Peltier modules working as TEG vs. temperature difference between the walls of the two boilers between which these modules are placed

Rys. 5. Generowana moc elektryczna na jednostkę powierzchni modułów Peltiera pracujących jako TEG w zależności od różnicy temperatur między ścianami dwóch zbiorników z wodą pomiędzy którymi umieszczono te moduły

mance and reliability of commercial thermoelectric modules, which could be applied in the micro-CHPU.

The above measurement setup (fig. 4) contains four tested modules placed next to each other (50 mm × 50 mm size single module) and two steel tanks (boilers) with a capacity of approximately 2.1 dm^3 each. The water pressure is reduced to approx. 0.2 bar – a pressure reducer is used before connecting to the water supply (waterworks). The sides of these modules were coated with thermal grease. An electric heater was placed inside tank 1 and was supplied from electricity grid via a transformer (it gives galvanic separation and voltage reduction) and a solid state relay. The heater imitates the heat produced in the combustion chamber. Thanks to this, a cheap and uncomplicated measurement system was built, which allows for small-scale testing of various solutions that will then be used in the micro-CHPU. While the water in tank 1 is heated, the heat flux travels to the colder tank (to tank 2) via the thermoelectric modules. The temperature was measured using two DS18B20 sensors in a water-proof casing (Dallas Semiconductor / Maxim). These sensors were attached to the walls of the boilers inside them at the point of contact with the Peltier modules. During the experiments, the water temperature varied from 14˚C to 72˚C in tank 1 and from 14˚C to 20˚C in tank 2. The measurement system in fig. 4 makes it possible to determine the surface maximum power density generated in Peltier modules working as TEGs vs. The temperature difference of the tanks walls (between which they were placed) is shown in fig. 5.

In order to obtain the maximum electric power in the modules for each of the temperature differences, the load resistance must be appropriately adjusted. Therefore, a dedicated electronic unit has been constructed that tracks the optimal operating point of the thermoelectric generator (Peltier modules in this case). The unit is a kind of DC/DC voltage converter, where the input resistance is matched. It will be discussed in another paper in the field of electronics. The measuring system was controlled by Arduino Leonardo board and driven via a laptop.

The measurement points in the temperature difference range 20˚C – 50˚C are well approximated by a power function (eq.1)

$$P_d = k \cdot \Delta T^n \quad (1)$$

where:

P_d – Surface power density generated in the thermoelectric generator in W/m2

ΔT – temperature difference (in Celsius degrees) between the walls of the two boilers between which these modules are placed

k, n – equation coefficients, k = 0.17(2) and n = 2.04(4)

Since the value of the coefficient n is near 2, it can be roughly assumed that the generated power increases with the square of the temperature difference. If the heat exchange surface between tanks is equal to 1 m2 and the temperature difference is 50 ˚C, these modules generate electric power of about 500 Watts. The above results indicate that Peltier modules perform very well as TEGs. This gives a great application potential in thermal biomass processing. Lowering the cost of the micro-CHPU device will make the final product easier to sell and more popular. The next stage of the research is the completion of the prototype. Fig. 6 shows a simplified schematic of the micro-CHPU prototype, which is currently under construction. The device in its basic version consists of two boilers (tanks) and a matrix of Peltier modules between them.

The first boiler will be heated by the heat collector from the combustion chamber. The second boiler will heat up from the first as a result of the heat flux passing through the thermoelectric modules. The water temperature in the tanks is always lower than 100˚C (less than the boiling point). Consequently, the temperature in the thermoelectric modules does not exceed the permissible values. In the micro-CHPU prototype (Fig.6), boiler 1 (hot water tank) with the capacity of 50 liters and boiler 2 (cold water tank) with the capacity of 14 liters will be used. In practice, boiler 2 is a thin cuboid approximately 2.5 cm thick (inside dimension). The contact area of each boiler with thermoelectric modules is 0.5 m^2 in the prototype. The heat flow from tank 1 to tank 2 is, contrary to appearances, very complicated. The water temperature distribution inside the tanks is not uniform. When electric current in thermoelectric modules is generated by the Seebeck effect, a simultaneously flowing electric current causes the Peltier effect. It is a kind of a negative feedback loop (a kind of dynamic effect) that significantly reduces the power of the generated

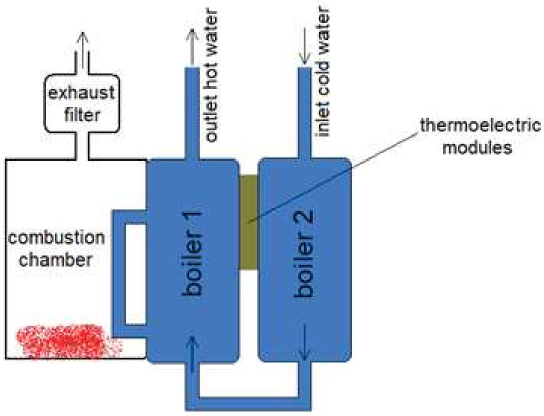

Fig. 6. Simplified schematic of the micro-CHPU prototype which is currently under construction
Rys. 6. Uproszczony schemat konstruowanego prototypu micro-CHPU

current. As a result, the temperature difference between the walls of the thermoelectric modules is smaller than the temperature difference of the water in the tanks - it is not only the result of the finite thermal conductivity of the steel walls. The device will only work properly if the adequate water flow is provided. If the water flow is too low, there will be a significant increase in the temperature in tank 2. This temperature can be calculated from the simplified equation 2 - hence boiler 2 will finally be thermally insulated, and energy losses to the environment are neglected.

$$P_2 = \frac{\Delta E_2}{\Delta t} \approx \frac{(m_w \cdot c_w + m_s \cdot c_s) \cdot \Delta T_2}{\Delta t} \quad (2)$$

where:
P_2 – heat power reaching tank 2
$\Delta E_2 / \Delta t$ – heat energy ΔE_2 reaching tank 2 in the time Δt
m_w – mass of water in boiler 2
c_w – specific heat of water
m_s – mass of the steel walls of boiler 2
c_s – specific heat of steel
ΔT_2 – temperature increase in tank 2 due to energy reaching this tank.

For example, if P_2 = 1 kW, $c_w \approx 4.2$ kJ/kg˚C, $c_s \approx 0.49$ kJ/kg˚C and water flow speed is at 30 dm³/h, then the temperature in tank 2 increases less than 28˚C. This increase in temperature should be regarded as a critical value. If the temperature of the entering water (in boiler 2) is at 15˚C, it will be heated up to 43˚C with that flow speed. This will decrease the temperature difference between the tanks and reduce the generated electrical power. When the average water flow is lower, it is necessary to use tank 2 with a larger capacity. Summing up, the prototype will give an opportunity to test many technical aspects while commercial Peltier modules are working as thermoelectric modules in the micro-CHPU. At the moment, the micro-CHPU is under construction. The current work is focused on the control system. The main purpose of the control is to maintain the optimal temperature difference between the boilers at the set water flow and output power in the thermogenerators. This is not easy because water-filled boilers are objects of very high inertia and output electric power influences the heat flux taken from boiler 1 and the heat flux reaching boiler 2. The basic fuel burned in the micro-CHPU will be pressed straw (mainly wheat, barley and rye one). Most developing countries have overproduction of straw – for example, in Poland a significant proportion of straw is burned on agricultural land after the harvesting. The conversion of thermal energy into electricity using the thermoelectric effect is generally characterized by low energy efficiency. This is the main reason why the thermoelectric effect is not used on a large scale to generate electricity. Thermal power plants (nuclear, gas, coal) based on thermodynamic processes of water vapor offer much higher efficiency. Unfortunately, these processes are too complicated to build small household generators based on them. Therefore, to obtain high energy efficiency in devices with thermoelectric modules, cogeneration should be used – as in the case of micro-CHPU. The heat flux flowing from boiler 1 to the thermoelectric modules is not dissipated into the environment but comes into boiler 2. The energy losses are low – similar to a typical water boiler (electric or gas). This is a significant difference in comparison to other thermoelectric devices generating electricity from biomass. First of all, commercial thermoelectric devices powered by biomass are designed to work in places without access to the electricity grid. In such devices, the heat flux coming out of the thermoelectric module is dissipated into the environment (air-cooled) and they usually do not contain any boiler (achieving high energy efficiency is not essential). A commercial example of such a device is a biomass stove with a 10 Watts thermoelectric power generator, produced by Thermonamic Electronics, China [43]. It is a biomass stove with thermoelectric modules, dedicated for mobile phone or battery charging and lighting during cooking. Thermoelectric applications for energy harvesting in domestic applications and micro-production units are broadly discussed in paper [44]. The authors show a theoretical model of a biomass thermoelectric generator with a water-flow cooling system. There is a description of the combustion-based thermoelectric conversion system, its physics and various thermoelectric materials. However, there are significant differences between the model analyzed by the authors and the micro-CHPU – in the former model the heat energy that comes out of the coolant is next dissipated into the environment . This results in a significant reduction in energy efficiency but at the same time simplifies the mathematical model in the field of the control system. In paper [45], the authors present a concept of a novel domesticscale integrated wooden pellet-fueled micro-cogeneration. This concept is based on a commercial 20 kW wooden-pellet fueled boiler and three methods of converting heat energy to electricity : indirectly (via mechanical energy) using a rotary steam engine and a Stirling engine, or directly using a domestic thermoelectric cogeneration system. The authors consider applying their concepts to charging an electric car. This concept is somewhat similar to the micro-CHPU presented in this paper. The main difference is that the micro-CHPU is based on commercial and commercially available Peltier modules, the temperature of which never exceeds 100˚C (the water temperature in the boilers is always below the boiling point). This will lower the price and raise the popularity of the final product, which will be easier to repair in the case of failure. An additional advantage of the micro-CHPU is obtaining a valuable fertilizer. Biomass-ash (mainly wheat, barley and rye ash) is a valuable raw material for the production of phosphorus, potassium and calcium-magnesium fertilizers, which are widely used in agriculture [46, 47].

6. Conclusion

Biomass is increasingly used to produce electricity, especially in many developing countries, like Poland. The most efficient method of producing useful energy from biomass is based on burning it in biomass power plants or after mixing with other fuels in coal-fired power plants.

In developing countries, most biomass is still burned in household stoves. These stoves heat houses and water (in a boiler). They have an average or low efficiency and may emit more pollutants into the air during combustion. On the other hand, they are mainly used in rural areas, where the use of CHP power plants does not make sense, because there are high heat losses during the transport via heat pipelines (houses and villages are scattered). In countries such as Poland, large amounts of biomass are burned in household stoves in rural areas, but unfortunately most biomass is wasted - there is overproduction of biomass. When coal-fired power plants are decommissioned, energy production from biomass will decrease significantly. This will reduce the share of biomass in the energy market and cause even more waste of biomass. It should be noted that leaving biomass on the farmland to rot causes formation of carbon dioxide in quantities similar to when burning it in a stove or a power plant. To sum up, refraining from burning biomass will not have a positive effect on the greenhouse effect. The presented paper introduces a new idea – a micro-CHPU (Micro Combined Heat and Power Unit). This solution is based on the thermoelectric effect, during which no noise is produced and no moving components are included. Its operating principle uses the Seebeck effect in commercial Peltier modules. Unlike many other solutions, in the proposed device the heat flux coming out from the thermoelectric modules is not dissipated into the environment, but reaches boiler 2. Currently, the micro--CHPU system is under construction. The obtained results indicate that the Peltier modules work very well as thermoelectric generators. The low price and easy availability of commercial Peltier modules will positively affect the popularity of the micro-CHPU. The previous research has shown that such thermoelectric generators based on Peltier modules are highly reliable and have a long service life. If the micro-CHPU generated a power of 120 - 250 W, this would be more than enough to charge batteries (in the normal charging mode, not the fast one) in an electric agricultural vehicle or in an electric quad. The currently small electric vehicle market is growing rapidly, which will increase the demand for electricity. The application of millions of micro-CHPUs may become a new way of developing the biomass market. Micro-CHPUs can be used anywhere and are not connected to the electricity grid.

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Nowy sposób wytwarzania energii z biomasy w krajach likwidujących elektrownie węglowe

W artykule opisano nowy sposób przetwarzania biomasy przy użyciu urządzeń mikro-CHPU (Micro Combined Heat and Power Unit). Urządzenie mikro-CHPU to nowy pomysł, który pozwala na zamianę energii chemicznej zawartej w biomasie na energię elektryczną do ładowania akumulatorów w małych pojazdach elektrycznych oraz w ciepło użytkowe dla gospodarstw domowych. Do budowy zastosowano komercyjne moduły Peltiera, w których działanie ich zostało odwrócone w celu uzyskania efektu Seebecka. Z przedstawionych wyników badań wynika, że komercyjny moduł Peltiera bardzo dobrze sprawdza się jako generator termoelektryczny. Proponowane urządzenia może okazać się bardzo przydatne w dobie rewolucji, która rozpoczęła się na rynku energii w większości krajów rozwijających się. Obecnie wiele z tych krajów intensywnie zaczyna odchodzić od energetyki opartej na paliwach kopalnych. Bardzo popularną i efektywną metodą wykorzystania biomasy jest mieszanie jej z węglem (w proporcji od 10% do 90%) i spalanie w elektrowni węglowej lub elektrociepłowni. Po zamknięciu tych elektrowni niewykorzystana biomasa mogłaby zostać spalona w urządzeniach mikro-CHPU.

Słowa kluczowe: *biomasa, generator termoelektryczny, mikro-CHPU, moduł Peltiera, zużycie energii pierwotnej, redukcja emisji i odnawialne źródło energii*