Economic and environmental benefits from carbonized biomass use for energy purposes – case study for the community from southern part of Poland

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Abstract. The article describes the concept of renewable fuels production based on local biomass with addition of specific portion of carbonized biomass, which is feasible to be implemented in the vast majority of communities in Poland. The biomass carbonization process was not developed lately, but its current combination with state of the art technical solutions allow to make it almost fully automatic. Adjusting scale of Biochar production to potential of biomass residues allows to treat that mature technology as the most suitable for the sector of small and medium enterprises specialized in wood processing. In the calculation part the concept of “virtual district heating networks” has been presented, where significant reduction of “low-emissions” from the communal sector is achieved through substitution of fossil fuels by pellets made of carbonized biomass.

1. Introduction

Civilization development of societies, economic growth of countries and increase in consumerism is correlated with generation and consumption of energy. All elements connected with energy play significant role in both local, national and global politics. Facing challenges such as increased demand for raw materials, energy and improvement in comfort of living is one of the most important challenges of the 21st century. The current energy sector is still evolving and changes, which were already implemented in it caused that is far different than we used to over last decades. Due to piling up problems related to the energy sector among others the most important are environmental pollution and exhaustibility of resources scientists started looking for new solutions causing technological development or implementation of renewable energy sources. Many concepts were created (i.e. sustainable energy development), which show key directions where attention of decision makers shall be paid.

Three the most important goals of the Polish Energy Policy are improvement of energy security, cleanliness of the natural environment and increase of energy efficiency. New models of the “energy mix” are under preparation, which aim to achieve stable and reliable supply of energy to all consumers taking into account environmental security and access to energy resources for next generations [1].
Due to increasing energy demand, care for the environment (air quality, climate changes) and also inexhaustibility the renewable energy sources and its use for energy generation became the alternative for the future as the substitute of fossil fuels.

Figure 1. Share of renewable energy sources in the gross final energy consumption in Poland.

Figure 1 illustrates the share of renewable energy sources in the final energy consumption in Poland. In accordance with the so called “RES Directive” by year 2020 the share of renewable energy sources in the overall consumption shall reach level of 15% (approx. 11 Mtoe). The gross final energy consumption from RES includes specific energy consumption from three the following sectors: electricity generation, heat generation and transportation. From 2004 to 2014 share of energy generated in RES was constantly increasing (in 2004 – 4.3 Mtoe equals to 6.9%, in 2014 – 8.1 Mtoe equals to 11.4%). In the described period of time above mentioned increase reached level of 4.5% and the most significant role in that mix had respectively solid biofuels, liquid biofuels, wind energy and biogas.

Due to the local specificity of Poland solid biomass played the most important role in energy generation from RES and hard coal substitution with biomass for individual old boilers and stoves can bring significant reduction of pollutants emission. The problems of air pollution in the Małopolska region, especially near the city of Krakow has been described in articles [2,3]. Long and frequent exposure of live organisms to polluted air from old boilers, which burn low-quality hard coal and household waste, and inhalation of may lead to the loss of the antioxidant ability to generate, i.e. by heavy metals and other toxic substances. The loss of an organism protective barrier may lead to the development of various types of diseases and other handicaps of the people and other live organisms [2,3].

Biomass is treated as carbon neutral fuel due to the fact that it consists of carbon entirely assimilated from atmospheric CO2 during its growth. Assimilation of CO2 by terrestrial plants is feasible only via photosynthesis process with the contribution of solar energy [4].

2. Concept of virtual district heating network as an example of low-emission reduction and increased consumption of local renewable energy sources.

2.1. Characteristics of analyzed location

Analysis was performer for the Skawina community located in Małopolskie voivodeship. It covers area of 100.15 km² and has 43,235 inhabitants living in the city of Skawina and 16 villages: Borek Szlachecki, Facimiech, Gołuchowice, Grabie, Jaślakowice, Jurczyce, Kopanka, Krzęcin, Ochody, Polanka Hallera, Pozowice, Radziszów, Rzozów, Wielkie Drogi, Wola Radziszowska, Zelczyna –figure 2 [2].
Figure 2. Map of the community with division on villages.  
Figure 3. Map of the infrastructure in the Skawina community.

In figure 3 the most important elements of infrastructure were marked including roads (red and yellow lines), buildings (black dots) and district heating network (blue and violet lines in the selected square) representing length of 31.6 kilometers. Only part of inhabitants of the city have access to the district heating network. The remaining inhabitants part have to use their own sources of heat which are mainly old and fossil fuel fired. Due to restrictions imposed by the anti-smog resolutions regulating types of fuels and boilers allowed to be in use the local authorities are motivated to find new alternative solutions being low-capex and additionally compliant with above mentioned local regulations. Construction of new district heating network is capital intensive investment in the case of areas with low density of population doesn’t bring expected effects. Taking into consideration conclusions mentioned above the concept of “virtual district heating network” [6] was invented and tested. That concept is based on heat delivery services offered by the municipal company. Instead of hot water people are provided with renewable fuel in the form of pellets made of low quality local biomass with addition of Biochar representing LHV of 28-29 GJ/t. That concept excellently signs in the idea of energy clusters i.e. local association of businesses, local authorities, universities, non-governmental entities and inhabitants acting jointly in the area of heat and electricity generation. Energy clusters are targeting in development of dispersed and prosumer energy generation resulting in improvement of local energy security, energy efficiency and environment [7].

Size and productivity of the biomass carbonization installation shall be adjusted to the local potential of biomass and future fuel demand represented by the community and potentially neighboring areas. In order to cover needs of the community authors taken into consideration Biochar production in well-developed and market available high-temperature biomass processing. Due to the fact that Biochar produced in that process represent higher LHV, is less corrosive and does not burn with a clean smoke-free flame that material is more valuable for communities fighting with low-emissions [7]. Addition of high quality Biochar with other locally available kinds of biomass significantly improves parameters of the ready product making it less harmful for the environment and surfaces of boiler.

2.2. Key assumptions

- In accordance with the law heat generation in boilers, which fuel capacity installed exceeds 5 MW th require issuance of concession (Act on freedom of economic activity from 2004), so the virtual district heating networks will consist of boilers, which overall thermal capacity will not exceed above mentioned capacity.
- Pellets production of the complete system limited to 7000 – 8500 ton/a
- Final customer must have modern, adjusted to household’s needs, solid fuels fired class-V boiler meeting requirements of „Ecodesign”
- Measuring system with a possibility of its remote reading connected to the boiler;
- Analysis done for selected 185 households located in the area of Skawina community;
- Assumed LHV of other fuels illustrated in table 1.

| Fuel type               | LHV [GJ/t] | Fuel price [PLN/t] |
|-------------------------|------------|--------------------|
| Hard coal 200 – 80 mm   | 22.5       | 770                |
| Hard coal 80 – 25 mm    | 21.5       | 700                |
| Hard coal 120 – 0 mm    | 22.0       | 600                |
| Hard coal 20 – 0 mm     | 20.5       | 400                |
| Hard coal* „Flotokoncentrat” | 14.5   | 250                |
| Hard coal* 1 – 0 mm     | 14.0       | 160                |
| Coke                    | 25.0       | 1140               |
| Firewood                | 14.5       | 230                |
| Hard coal „Eco-pea”     | 25.0       | 950                |

Assuming that above mentioned pellet offered on the local market will consist of 25% of Biochar with LHV of 29 GJ/t and 75% of biomass with LHV of 15 GJ/t the average LHV of pellets will reach level of 18.5 GJ/t. Table 2 illustrates key assumptions taken to calculation of thermal efficiency increase in case of old coal fired boiler exchange to new low-emission solid fuel fired boiler.

* the analysis takes into consideration fossil fuels like „flotokoncentrat” and hard coal with granulation in range of 0 – 10 mm withdrawn from the market on July 2017. It is related with the fact that surveys, which were performed between years 2015 and 2016 shown that those two kinds of fuels due to attractive price were very often in use for heat production in individual households.
Table 2. Main parameters to calculate of heat efficiency in selected household.

| Parameter                        | Before modernization | After modernization |
|----------------------------------|----------------------|---------------------|
| Efficiency of heat production system | 46%                  | 70%                 |
| Capacity of the boiler           | 25 kW                | 16 kW               |
| Primary Energy demand            | 156 GJ               | 102,5 GJ            |
| Usable Energy demand*            |                      | 71,76 GJ            |
| Annual fuel consumption          | 5 t of hard coal (200-80 mm) 3 m³ of firewood | 6 t of pellets with Biochar |

*Energy demand includes seasonal efficiency of heating installation

3. **Calculations for the concept of „virtual district heating network”**

The company responsible for production and distribution of renewable fuels in the form of pellets provides scopes of services described below as two potential options:

1. Boiler is operated by the owner in accordance with the User’s Manual. The municipal company delivers contracted volume of renewable fuel with constant LHV and guaranteed unchanged price. Deliveries are realized when stocks of fuel stored at home are nearly empty. Control of fuel’s volume in the tank is feasible thanks to the measuring system installed with remote reading.

2. The municipal company provides the inhabitant with complete set of services including delivery of fuel, its loading and also boiler’s proper maintenance.

Taking into account local specificity of Skawina municipality and also new requirements related with a need to replace existing source of heat with a new class-V boiler authors assumed that all households will be equipped with Serigsad-Elektromet NES V boiler with capacity of 17 kW. Significant cost of the boiler will be partially covered by grants amounting to 350 PLN/kW (equals 5950 PLN) and the remaining 2 950 PLN will be paid in monthly instalments. The contract for delivery of fuel covers the whole year, which will help inhabitants to decrease monthly costs of heating in comparison with classical approach. It was assumed that the contract for delivery of fuel is signed for 3 years (36 months) whether the client intends to divide the amount mentioned above or not because already has the boiler meeting environmental requirements. Pellets will be delivered by municipal company to customers for a constant price amounting to 480 PLN/t.

Financial expenditures to be covered by the municipal company were presented in the table 3.
Table 3. Financial expenditures to be covered by the municipal company.

| Item                        | Cost [PLN]     | Number of items | Overall cost [PLN] |
|-----------------------------|----------------|-----------------|--------------------|
| Warehouse                   | 350 [PLN/m²]   | 300 [m²]        | 105 000            |
| Car (TTPM < 3.5 t)          | 50 000         | 1               | 50 000             |
| Laptop + telephone          | 3000           | 1               | 3 000              |
| Counters Apator Powogaz ELF | 530            | 185             | 98 050             |
| Total:                      |                |                 | 256 050            |

Assuming that the virtual district heating network will consist of only 185 customers and contracts are signed for 3 years each of them will have to spend 38.45 PLN/month to cover those costs. Monthly fixed costs were presented in table 4.

Table 4. Monthly fixed costs.

| Item                        | Cost[PLN] |
|-----------------------------|-----------|
| Office rental               | 1 000     |
| Water, electricity etc.     | 500       |
| Staff cost (2 employees)    | 6 000     |
| Others (fuel etc.)          | 1 500     |
| Total:                      | 9 000     |

Costs to be covered assuming 185 customers connected to the virtual district heating network will reach level of 48.65 PLN/month/customer.

3.1. Calculated cost of 1 GJ

Option I

Option I assumes that the customer already has his own class-V boiler and doesn’t need grants mentioned above. The only cost to be covered by the municipal company is for installation of heat counter with function of remote reading. The customer operates his boiler by himself and the contract covers only reliable and uninterrupted delivery of pellets.

Overall cost:

\[ K_c = 1.1 \cdot (12 \cdot (I + K_m) + m \cdot K_p) \]

where:

1.1 – assumed 10% of margin
12 – number of months
I – capital investment
\( K_m \) – monthly cost
m – amount of fuel
\( K_p \) – fuel cost

\[ K_c = 1.1 \cdot (12 \cdot (38.45 + 48.65) + 6 \cdot 480) = 4 317.72 \text{ PLN} \]

Heat cost per 1 GJ:

\[ K_{1GJ} = \frac{K_c}{Q} = \frac{4 317.72}{71.76} = 60.17 \frac{\text{PLN}}{GJ} \]
Option II
Option II assumes that the customer doesn’t have his own class-V boiler and needs to buy it. The gap between real price of the boiler and the grant received amounting to 2950 PLN is divided to 36 instalments. The additional cost to be covered by the municipal company is for installation of heat counter with function of remote reading. The customer operates his boiler by himself and the contract covers only reliable and uninterrupted delivery of pellets.

Monthly instalment for purchase of a boiler:
\[ R = \frac{2950}{36} = 81.95 \text{ PLN} \]

Overall cost:
\[ K_c = 1.1 \cdot (12 \cdot (I + K_m) + m \cdot K_p) + 12 \cdot R \]
\[ K_c = 4317.72 + 12 \cdot 81.95 = 5301.12 \text{ PLN} \]

Heat cost per 1 GJ:
\[ K_{1GJ} = \frac{K_c}{Q} = \frac{5301.12}{71.76} = 73.87 \frac{\text{PLN}}{\text{GJ}} \]

Option III
Option III extends option I by services related to fuel loading and maintenance of a boiler. The employee of municipal company maintains the boiler every 3-5 days due to automatic fuel storage and loading system which the boiler is equipped with. It was assumed that for such services margin of the municipal company shall be increased by 10%.

Overall cost:
\[ K_c = 1.2 \cdot (12 \cdot (38.45 + 48.65) + 6 \cdot 480) = 4710.24 \text{ PLN} \]

Heat cost per 1 GJ:
\[ K_{1GJ} = \frac{K_c}{Q} = \frac{4710.24}{71.76} = 65.64 \frac{\text{PLN}}{\text{GJ}} \]

Option IV
Option IV extends option II by services related to fuel loading and maintenance of a boiler.

Overall cost:
\[ K_c = 1.2 \cdot (12 \cdot (I + K_m) + m \cdot K_p) + 12 \cdot R \]
\[ K_c = 4710.24 + 12 \cdot 81.95 = 5693.64 \text{ PLN} \]

Heat cost per 1 GJ:
\[ K_{1GJ} = \frac{K_c}{Q} = \frac{5693.64}{71.76} = 79.34 \frac{\text{PLN}}{\text{GJ}} \]

4. Calculation of the ecological effect – reduction of GHG, CO₂ and dust

Emission factors attached to the table 5 were taken to calculate the ecological effect of boilers replacement. Those factors are commonly used by institutions supporting pro-ecological investments resulting in reduction of so-called low-emission and replacement of old boilers to class-V ones.
Table 5. Emission factors for boilers with capacity below 50 kW.

| Pollutant | Unit | Emission indicators |
|-----------|------|---------------------|
|           |      | Old boilers (excl. biomass) | New automatic boilers | Natural gas | Fuel oil | Biomass |
| Dust PM 10 | g/GJ | 225 | 78 | 0.5 | 3 | 480 | 34 |
| Dust PM 2.5 | g/GJ | 201 | 70 | 0.5 | 3 | 470 | 33 |
| CO₂ | kg/GJ | 93.74 | 93.74 | 55.82 | 76.59 | 0 | 0 |
| Benzo(a)pyrene | mg/GJ | 270 | 0.079 | no | 10 | 121 | 10 |
| SO₂ | g/GJ | 900 | 450 | 0.5 | 140 | 11 | 11 |
| NOₓ | g/GJ | 158 | 165 | 50 | 70 | 80 | 91 |

Calculation done for one household:

4.1. Estimated reduction of CO₂ emission

The formula for calculation of emissions:

\[ e = E_t \cdot w \]

where:

- \( E_t \) – annual usable energy demand (\( E_t = 71.76 \frac{GJ}{a} \))
- \( w \) – emission factor

\[ e = 71.76 \cdot 93.74 = 6727 \frac{kg}{a} \]

In accordance with figures attached to the table 5 and 6 the CO₂ emission factor equals 0 (in words: zero) for new generation of boilers with automatic feeding and adjustment of combustion. Taking into consideration the above information total annual CO₂ emission reduction for that household will reach 6727 \( \frac{kg}{a} \). All households taken into consideration in the case study annually will reduce CO₂ emission by 1046.2 \( \frac{Mg}{a} \).

4.2. Estimated reduction of dust emission

In accordance with figures attached to the table 6 the dust emission factor for boilers with thermal capacity below 50 kW are the following:

- old fossil fuel fired boilers:
  - dust PM10 – \( w_{e,PM10} = 225 \frac{g}{GJ} \)
  - dust PM2.5 – \( w_{e,PM2.5} = 201 \frac{g}{GJ} \)
- new generation of biomass fired boilers with automatic adjustment of combustion parameters:
  - dust PM10 – \( w_{e,PM10} = 34 \frac{g}{GJ} \)
  - dust PM2.5 – \( w_{e,PM2.5} = 33 \frac{g}{GJ} \)
- the amount of dust emission before replacing the boiler:
  - dust PM10 – \( e = 16 \frac{kg}{a} \)
  - dust PM2.5 – \( e = 14.5 \frac{kg}{a} \)
• the amount of dust emission before replacing the boiler:
  o dust PM10 \(-e = 2.5 \frac{kg}{a}\)
  o dust PM2.5 \(-e = 2.4 \frac{kg}{a}\)

• obtained emission reduction
  o dust PM10 \(-E_{PM10} = 13.5 \frac{kg}{a}\)
  o dust PM2.5 \(-E_{PM2.5} = 12.1 \frac{kg}{a}\)

Implementation of the virtual district heating network’s concept in the Skawina community only for 185 households aims to bring a significant ecological effect. Proposed actions seem to be acceptable for inhabitants, due to the fact that significant part of costs for replacement of old and inefficient boilers is financed from grants. The remaining part is divided into 36 instalments, which makes the whole process less problematic especially for low-income users. Taking into account the fact that inhabitants will be provided with fully renewable fuel for the price comparable with currently combusted hard coal the whole concept shall be implemented in all communities suffering from air pollution from fossil fuels combustion.

Table 6. Comparison of results – heat price calculated in PLN/GJ.

|                        | Current situation | Option I | Option II | Option III | Option IV | Situation after 3 years (services excl.) | Situation after 3 years (services incl.) |
|------------------------|-------------------|----------|-----------|------------|----------|-----------------------------------------|----------------------------------------|
| Minimum heat price [PLN/GJ] | 34.32             | 48.37    | 55.76     | 52.76      | 60.16    | 44.54                                   | 48.59                                  |
| Maximum heat price [PLN/GJ]  | 86.02             | 83.12    | 113.02    | 90.67      | 120.57   | 69.20                                   | 75.49                                  |
| Average heat price [PLN/GJ]  | 60.73             | 62.71    | 80.78     | 68.41      | 86.48    | 53.38                                   | 58.23                                  |

In the table 6 attached above one can notice that the most attractive from the economic point of view is Option I, where the average heat price was 62.71 PLN/GJ. A bit more expensive was Option III with heat price of 68.41 PLN/GJ, where scope of Option I was extended by delivery of services related to fuel loading and boiler cleaning. That option shall be dedicated to old and disabled inhabitants of the community not able to service and maintain individual boilers. Options II and IV with heat prices exceeding 80 PLN/GJ cover scope of Options I and III respectively and the key difference is related with the fact that remaining cost of boiler divided into 36 instalments is included in heat price. It is worth to mention that scope of Option IV reflects the most advantages of connection to the district heating network, but at the same time authors of the paper decided that inhabitants of the community shall have a free choice regarding terms and conditions under which the contract is signed. The concept of virtual district heating network perfectly types in the “green economy concept” because the poorest group of inhabitants has also an access to the efficient “state-of-the-art” heating technologies and renewable fuel for competitive price in many cases not exceeding current bills for heating. In some cases estimated cost of heating can differ from the real value achieved after replacement of the boiler due to the fact that calculations were done based on surveys performed among inhabitants of the community. Implementation of the virtual district heating network bringing profits to the whole society by ensuring
lower cost of heating and significantly improving air quality is reflected in the following numbers:

Reduced emission
- Avoided CO2 emission – 1046.2 Mg/a
- Avoided PM10 dust emission - 2 131 kg/a
- Avoided PM2.5 dust emission - 1 875 kg/a

The most significant advantage of the concept is the fact that after 3 years of system’s operation expected heat price shall be lower or comparable with currently valid heat price included in the tariff issued by MPEC Cracow, which is 57.73 PLN/GJ. That figure is unprecedented worldwide and at the same time very attractive taking into account lack of investment on construction of heat distribution infrastructure and cost for so-called ordered capacity which shall also increase cost of heating in Cracow. New environmental requirements imposed by the provincial authorities forbid combustion of low quality coal and wet wood, which due to low price to date is the most popular energy source in Poland. Transition to more calorific and expensive fuels will definitely make the above mentioned difference in prices more significant and attractive for local inhabitants. The next possible factor impacting decrease of heating cost is the scale effect, which shall also affect individual cost of fuel supply and boiler’s maintenance by decrease of margin assumed in calculations.

Analysis of the impact of virtual district heating network on local economy proven that it has many advantages like:
- Stable renewable fuel prices;
- Strengthened control of local authorities on combustion of forbidden fuels and wastes;
- Increased healthiness of the whole society through creation of new workplaces and decreased costs of heating;
- Increased local energy security and energy efficiency at community level;
- Decreased air pollution and its negative impact on human’s health;
- Compliance with locally valid legal acts imposed by provincial authorities;

5. Conclusions

The analysis done only for a single community proven that implementation of virtual district heating network concept as part of circular economy has the following advantages wider described below:

a) economic:
- Energy saving,
- Increase of market competitiveness,
- Protection against unstable prices,
- New opportunities for business and innovative solutions,
- Preparation of more efficient means of production and consumption,

b) Social:
- Creation of new workplaces,
- Social integrity and cohesion,

c) Environmental:
- Reduced emission of pollutants and wastes,
- Reduced consumption of non-renewable resources,
- Reduced impact on climate changes.

The concept of virtual district heating networks described in the article brings a lot of benefits to local communities. It is one of the most efficient ways to improve air quality combined with stabilization and competitiveness of fuel prices. The last element missing is project’s implementation on industrial scale, which requires brave decision of local communities. Entities coordinating energy clusters are the most suitable to invest in the concept described in this paper and gain all benefits coming from local production of fuels.
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