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Can 'negative net CO_2 emissions' from decarbonised biogas-to-electricity contribute to solving Poland's carbon capture and sequestration dilemmas?

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ABSTRACT

The article analyses to what extent 'negative net CO_2 emissions' from decarbonised biogas-to-electricity can contribute to solving Poland's carbon capture and sequestration dilemmas. From the criteria-based evaluation of low-carbon power technologies it is found, that biogas-to-electricity is among technologies having increasing production potential in Poland. Therefore, in future biogas will be able to contribute to solving Poland's CCS dilemmas, because it offers carbon-neutral electricity. Moreover, by applying CCS into biogas-to-electricity the 'negative net CO_2 emissions' can be achieved. The article examines three biogas-to-electricity technologies involving CO_2 capture, i.e. biogas-to-biomethane, biogas-to-CHP and biogas-to-electricity via the ORFC cycle. It is emphasised that the ORFC cycle offers low-cost CO_2 separation from a CO_2–H_2 mixture, low O_2-intensity, and the opportunities for advanced mass and energy integration of involved processes. Besides, energy conversion calculations show that the ORFC cycle can offer comparable cycle efficiency with air- and oxy-combustion combined cycles. In regard to the design of biogas-based energy systems it is recommended to include (i) distributed production of biogas in order to avoid costs of long-distance transportation of high-moisture content biomass and (ii) centralised large-scale decarbonised biogas-to-electricity power plants since costs of pipeline transportation of gases are low but large-scale plants could benefit from increased energy and CCS efficiencies.

1. Introduction

The end product of existing fossil fuel-based electricity production technologies is CO_2, which is released to the biosphere. This anthropogenic CO_2 accumulates mainly in the atmosphere in a process which is practically irreversible in the modern era because natural carbon sequestration processes are very slow and due to industrialisation and deforestation terrestrial plants' potential for atmospheric CO_2 binding is now substantially lower than in previous centuries. Consequently, anthropogenic CO_2 emissions affect the equilibria of natural carbon cycles and CO_2 concentration in the atmosphere is increasing at a rate of around 2 ppmv yr^{-1}, currently reaching around 390 ppmv. At this rate the Copenhagen Accord target of 450 ppmv CO_2/+2 °C will be reached before 2040.

The main environmental challenge facing many European countries is how to produce more secure and cheap electricity in order to satisfy expected increasing demands, and at the same time, to reduce greenhouse gas (GHG) emissions. European and international energy decarbonisation policies are very unsuitable for the Polish energy system. In Poland, around 95% of electricity is produced in coal-fired power plants. 2007 Polish CO_2 emissions from fossil fuel combustion equal to 304.69 Mt of CO_2 yr^{-1} which translates to 7.99 t CO_2 $capita^{-1}$ yr^{-1} [1]. It is relatively difficult to reduce these CO_2 emissions because Poland has very low potential for most of renewable energies such as hydro (Poland is a lowland country), solar and geothermal. Polish potential for wind energy is much lower than that in for instance coastal areas of Ireland, UK or Denmark. Only renewable bioenergy [2] can be considered to have more than average potential than encountered in other European countries, due to moderate Polish climate and sufficient water availability which is beneficial for forestation and energy crops cultivation. Low-carbon nuclear power is to be deployed in Poland not earlier than in the period 2022–2030. Therefore, European and international decarbonisation policies constraints are central for future electricity supply safety in Poland.

Taking into account (i) large Polish CO_2 emissions, (ii) projections that CO_2 allowances price can reach the level of 60 € t CO_2^{-1} or even more in near future and (iii) CCS costs in coal-fired power plants which are expected to range from at least 15 to more than 30 € t

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Nomenclature

AD	anaerobic digestion
CCS	carbon capture and sequestration
CHP	combined heat and power
COE	cost of electricity (€ MWh^{-1})
E_{CO_2}	emission of CO_2 ($m^3\ s^{-1}$)
F	flow rate ($m^3\ s^{-1}$)
FC	fuel cell
GHG	greenhouse gas
GT	gas turbine
ORFC	oxy-reforming fuel cell
PC	pulverised coal
ST	steam turbine
ΔH	heat of reaction (J mol^{-1})

CO_2^{-1} it might be necessary to deploy CCS in Poland. Hence, any realistic technological solutions that could help to solve Poland's low-carbon electricity production dilemmas are of great interest.

Therefore, the aim of the present article is to analyse Polish electricity production technologies, energy market and energy policy and to discuss to what extent 'negative net CO_2 emissions' from decarbonisation of biogas might contribute to solving Poland's CCS dilemmas [3].

2. Main ideas behind a 'negative net CO_2 emissions' concept

Biomass includes carbon entirely assimilated from atmospheric CO_2 during its growth via photosynthesis with the contribution of solar energy, since terrestrial plants are unable to assimilate carbon from any other source. Hence, all bioenergy processes that simultaneously involve CO_2 capture are characterized by 'negative net CO_2 emissions' to the biosphere.

This relatively novel and attractive concept have received very little attention in technical or economic literature and in policy discussions so far [4]. No feasibility studies dedicated to decarbonisation of biogas are available in the open literature. However, taking into account that realistic CO_2 allowances price can exceed the level of 60 € t CO_2^{-1} in near future and that decarbonisation of coal-firing can cost more than 15–30 € t CO_2^{-1} it can be expected that decarbonisation of biogas can be economically justified. The lower costs of biogas decarbonisation arise from the fact, that flue gases derived from biogas-to-electricty are cleaner than flue gases derived from coal-firing. Besides, flue gases are much more enriched in CO_2 in the case of biogas processing (up to 70%) than in the case of air-coal combustion (less than 15%). From these two reasons decarbonisation of biogas processing must be significantly cheaper than decarbonisation of coal firing and thus deployment of 'negative net CO_2 emissions' concept is economically interesting. For instance, if flue gases from biogas-to-electricity cycle could be decarbonised at the cost of 20 € t CO_2^{-1} this process can be profitable if only CO_2 allowances cost more in future.

3. Criteria-based evaluation of low-carbon electricity production technologies in Poland

There are many low-carbon electricity generation technologies. Their attractiveness depends very much on national contexts. Thus the aim of this section is to provide criteria-based evaluation of low-carbon electricity production technologies in Poland with focus on biogas-to-electricity. Five main criteria are taken into account (i) CO_2 generation intensity, (ii) electricity production capacity, (iii) cost of electricity, (iv) perspectives for near-term deployment in Poland and (v) risks. More specifically, it is analysed to what extent these five criteria are and will be met in the near-term in Polish economy in relation to different low-carbon electricity production technologies. The evaluation will enable to determine the current and future role of biogas in the Polish energy system.

3.1. Criterion I - CO_2 generation intensity

The CO_2 generation intensity of renewable and nuclear electricities ranges from 10 to 50 kg CO_2 MWh^{-1}. In contrast, fossil fuel-fired electricity production is characterised by substantially larger CO_2 emission of around 400 kg CO_2 MWh^{-1} for natural gas, 850 kg CO_2 MWh^{-1} for oil and 900 kg CO_2 MWh^{-1} for coal.

Thus according to the criterion I only renewable and nuclear technologies are low-carbon technologies. Natural gas-firing offers moderate CO_2 generation intensity thus this technology can be considered as a technological bridge to low-carbon future in Poland. Electricity from coal-firing is extremely CO_2 intensive and thus in order to satisfy stringent decarbonisation policy constraints it necessitates integration with carbon capture and sequestration (CCS). CO_2 capture [5] can be realised in (i) a post-combustion mode by using a variety of processes such as reactive absorption [6] or membranes [7], (ii) a pre-combustion mode with conversion of fuel chemical energy into the form of H_2 followed by simultaneous low-cost carbon separation [8] and (iii) an oxy-fuel mode characterised by limited costs of CO_2 separation but necessitating O_2 supply [8]. CO_2 sequestration can be achieved via e.g. geological storage or via some much more interesting options such as CO_2 utilisation in chemical industries, fuel synthesis (e.g. solar CO_2-to-fuel technology [9] realised in the Sahara desert), algae cultivation, enhanced gas [10] and oil recovery or enhanced methane coal-bed recovery.

3.2. Criterion II - electricity production capacity

Table 1 provides data for current (2010), projected (2030) and potentially economical electricity production capacities from different power technologies in Poland.

Electricity production capacities from renewable energy sources such as hydro, wind, solar [11] and geothermal are limited mainly

Table 1
Available electricity capacities in Poland by 2010, projections for 2030 and economical potential [17].

Electricity production technology	Electricity production capacity [TWh yr^{-1}]		
	2010	2030	Economical potential
Low-carbon electricity production technologies			
Hydro: large (>10 MW_e)	1.5	1.8	3
Biogas	0.4	6.6	30
Nuclear fission	0	31.6	–
Wind: on-shore	5.2	17.1	105
Hydro: small (<10 MW_e)	0.9	1.2	2
Wind: off-shore	0	5	19
Coal: IGCC-CCS	0	0	large
Coal: PC-CCS	0	0	large
Natural gas: CCGT-CCS	0	0	large
Solid biomass	5.5	11.1	30
Solar: CSP	0	0	0
Solar: PV	0	0.03	0
Conventional fossil fuel-fired technologies			
Coal	112.9	114.1	large
Oil	1.9	3.0	–
Natural gas	4.4	13.4	large

by natural conditions. In Poland, hydro electricity production equals to around 2.4 TWh yr^{-1} and a maximal increase to around 3.0 TWh yr^{-1} is projected by 2030 since Poland is a lowland country. Wind technology produces 5.2 TWh yr^{-1} but is projected to achieve around 22.1 TWh yr^{-1} by 2030. Solar and geothermal technologies have and will have minor contribution mainly from techno-economic reasons.

Electricity capacities from fuel technologies are limited mainly by fuel availability. In Poland sharp rise in bioelectricity is expected in the period 2010–2030, i.e. from 0.4 to 6.6 TWh yr^{-1} for biogas and from 5.5 to 11.1 TWh yr^{-1} for solid biomass. Economical potential of bioelectricity is however much larger. It has been recently reported that bioenergy can potentially provide up to 30% of energy demands in China [12]. Assuming that Poland has similar natural potential for bioenergy production and similar energy consumption per km^2 as China it can be assessed that around 60 TWh yr^{-1} can be obtained from bioenergy in Poland. Moreover, according to the expected amendments to be implemented to the Polish system of green certificates [13] the most considerable support will be given to the development of new biogas plants, novel biomass technologies and onshore and offshore wind farms, thus to renewables having the greatest but still unused economical potential (see Table 1 for details).

Conventional energy carriers such as natural gas, coal, oil and uranium are limited worldwide and hence shortages are expected within the next few decades. Namely, known reserves of crude oil are projected to be earmarked by 2050, natural gas by 2070, coal by 2140 [14] and uranium by 2050–2065 [15,16]. Therefore, by these dates a sharp rise in relevant fuel prices is expected which will reduce economical potential of conventional electricity generating technologies. Moreover, in the perspective of 2030 Poland will not be able to reduce its GHG emissions and maintain electricity production capacity without involving CCS into coal-fired power plants due to large addiction to coal-firing, Table 1.

3.3. Criterion III - cost of electricity

Table 2 provides projected production cost of electricity from low-carbon power technologies in 2020. The reported referent values relate to average EU conditions and thus for Poland they might need an insignificant correction. It is shown that the lowest 2020 COEs characterise large-scale hydro, biogas, nuclear fission and on-shore wind electricities with 2020 COE ranging from 50 to 70 € MWh^{-1}.

Table 3 presents projected costs of CCS from power technologies by 2020. It is anticipated that CCS for coal firing will cost 30 € t CO_2^{-1} and CCS for biogas will cost 20 € t CO_2^{-1}. Interestingly, when CO_2 allowances will cost around 60 € t CO_2^{-1}, the deployment of CCS into both coal- and biogas-fuelled power plants might be economical.

Table 2
Production cost of electricity (COE) from low-carbon technologies by 2020 [16].

Low-carbon electricity production technology	COE in 2020 (€ MWh^{-1})	
	range	referent value
Hydro: large	30–140	50
Biogas	50–200	60
Nuclear fission	45–80	65
Wind: on-shore	55–90	70
Hydro: small	55–160	70
Wind: off-shore	65–120	75
Coal: IGCC-CCS	80–90	85
Coal: PC-CCS	80–110	90
Natural gas: CCGT-CCS	85–95	90
Solid biomass	80–200	95
Solar: CSP	120–170	145
Solar: PV	270–460	320

Table 3
Projected costs of CCS from two power technologies vs. CO_2 allowances by 2020.

CCS technology	Costs of CCS in 2020 (€ t CO_2)	
	range	referent value
CCS in coal-fired power plants	15–40	30
CCS in biogas-fuelled power plants	15–25	20
CO_2 allowances	40–80	60

Moreover, from comparison of Tables 1–3 it can be concluded, that in near future the greatest increase can be expected in relation to biogas, wind, solid biomass, nuclear fission and fossil fuel/CCS, because they can achieve both large production capacities and moderate COEs.

3.4. Criterion IV - perspectives for near-term deployment in Poland

Hydro electricity is the most mature technology. Wind farms undergo rapid development in Poland. Solar energy deployment is limited by very high COEs. Geothemal energy is available in Poland only as low enthalpy sources of minor importance in electricity production. Polish bioenergy is currently dominated by solid biomass co-firing with coal and to less extent by biogas from wastes, however in future, more rapid development of bioenergy is expected due to amendments implemented into the Polish system of green certificates [13]. The amendments considered by the Polish Ministry of Economy are to support new small-scale bioenergy power plants and wind farms.

The date of deployment of CCS in Poland is still uncertain. There are two large projects under consideration: Be³chatów (858 MW_e) using CO_2 reactive sequestration in underground alkali brines [18] and Kêdzierzyn-KoŸle (300 MW_e) involving IGCC-CCS technology [19] integrated with methanol co-production. It is anticipated that costs of CCS will significantly exceed the level of 15 € ton CO_2^{-1} at sufficiently high CO_2 capture rate. Thus taking into account that in Poland CO_2 generation intensity from coal-firing is around 1 ton CO_2 MWh^{-1}, 2020-COEs in Poland can be higher than those reported for CCS power technologies in Table 2. On the other hand, it is expected that CO_2 emission allowances can reach 60 € ton CO_2^{-1} in the period 2013–2020 thus Poland encounters considerable dilemmas in relation to CCS deployment.

3.5. Criterion V - risks

Nuclear fission electricity is characterised by relatively high capital costs and it needs steady supply of uranium during the whole exploitation period of a nuclear power station (at least around 40–60 years). Current estimated exploitable reserves of uranium are close to 15 Mt. The present global rate of consumption of about 67000 t yr^{-1} will rise to an anticipated 90,000 t yr^{-1} in 2025 for an installed world nuclear capacity of between 449 and 553 GW_e. Assuming the installed nuclear capacity increases linearly up to 1300 GW_e in 2050, the current known uranium resources would be completely earmarked by 2050. Knapp et al. have indicated that world uranium reserves might be exhausted by 2065 [15]. Therefore the considerable risk exists that nuclear power plants which will start operation in Poland after 2030 and from economic reasons must operate till 2070–2090 might encounter problems with cheap uranium supply in the future. This risk can be avoided by applying uranium enrichment from low-content sources but this option will be very expensive. Instead, thorium fuel might be considered but thorium-based nuclear fission is still not commercial. Besides, legal and social barriers of nuclear power exist in Poland which can be avoided but it will also be expensive. Moreover, failure and natural risks also must be taken into account.

Risks associated with sustainable renewable technologies are limited. The CCS technologies have no fuel risks since Poland has large coal reserves. However, some risks might relate to CO_2 transmission and sequestration technologies.

3.6. Summary of the criteria-based evaluation of low-carbon electricity production technologies

Based on the five evaluation criteria the summary of evaluation results for Poland is presented in Table 4. It is shown that low-carbon electricity production technologies which satisfy most criteria include: (A) biogas (7 points), (B) wind (6–7 points), (C) fossil fuel/CCS (6 points), (D) solid biomass (6 points). These technologies are thus recommended for low-carbon future in Poland.

From the criteria-based evaluation it is thus concluded that biogas is among leading technologies having increasing potential in Poland. With the increase of biogas production capacity its role in relation to the 'negative net CO_2 emissions' concept can increase and thus biogas can contribute to solving Poland's CCS dilemmas. However, the implementation of bioenergy-based renewable energy system [20] involving biogas into currently dominated by coal-firing Polish economy will need further studies, R&D and it must take sufficient time [21].

4. Prospects of biogas-to-electricity in Poland

The development of biogas-to-electricity technology can be enhanced in Poland by several economic and environmental reasons. The main driver is however national energy policy [17]. Agricultural- or forestry-derived biomass cultivation is favoured in Poland due to mild climate conditions and simultaneous sufficient humidity and thus biomass availability is above average. The market of biomass [22] is still in the developing phase, however, dominating co-combustion of biomass with coal has much contributed to its recent advancement. Biomass production can benefit from recently observed population trends such as increasing populations in large agglomerations, while agri-forestry areas become highly depopulated and thus are well-suited for biomass cultivation. In relation to social benefits, sustainable bioenergy can stimulate the development of agri-forestry communities with a high degree of unemployment. Further, bioenergy can stabilise renewable power systems since bioenergy is independent on short-term climate variabilities, in contrast to wind and solar power. Many of these advantages of bioenergy are even more evident in some southern Polish regions such as the Lower Silesia voivodship [23].

4.1. Environmental advantages of biogas

The production of biomass and conversion of bioenergy is characterised by several beneficial environmental impacts, which significantly increase the interest in biogas-fuelled power plants. Main environmental advantages of using sewage-derived biogas relate to the reduction of problematic sludge by about 50% (dry mass basis). Anaerobic digesters can be installed in municipal sewage treatment plants [4], in agricultural companies (e.g. in pig farms, cattle farms, poultry farms and crop production companies) and in food processing companies (e.g. in distillery and biofuel plants, brewery plants, sugar mill, meat processing factories, milk plants, bakery plants, chips and potato processing plants, juice and wine producers and fish processing plants) having beneficial impact on the reduction of quantity of their wastes. Further, biogas is naturally released from wastes in landfills and its oxidation is necessary for prohibiting the release of methane and volatile organic compounds to the atmosphere thus improving local air quality. Renewable biogas derived from crops [24] and wastes limits the utilisation of polluting conversion of fossil fuels thus adequately mitigating noxious and greenhouse gas (GHG) emissions. The digestate from anaerobic fermentation is a valuable fertiliser due to the increased availability of nitrogen and the minimised survival of pathogens in the anaerobic digestion process (AD) [25]. Digestate fertilisation reduces the need for energy intensive mineral fertilisers, to further mitigate GHG emissions. Biomass cultivation is a sink for noxious atmospheric emissions and it limits the utilisation of fossil fuels thus improving air quality. Moreover, in regard to organic wastes, the production of biogas, recycling and thermal incineration of wastes offer an interesting opportunity for designing a sustainable waste management system that can minimise landfilling of wastes.

4.2. Energy policy considerations

The development of renewable energy is highly stimulated in Poland via a system of green certificates. Currently, however, the amount of green certificates issued per unit of produced renewable electricity does not depend on the type of renewable energy technology. Therefore, the existing energy policy system inhibits the development of some renewable technologies, even if they have attractive potentials for sustainable electricity production in the near future. Recently, however, the Polish Ministry of Economy has informed that the system of green certificates will be amended. The main changes will involve the introduction of three new criteria which will affect the number of green certificates issued per unit of renewable electricity produced, i.e. (i) energy technology, (ii) output power of a renewable energy source, and (iii)

Table 4
The summary of the evaluation of low-carbon electricity production technologies in Poland.

Low-carbon electricity production technology	Is the criterion satisfied?					Σ points
	I CO_2	II capacity	III COE	IV deployment	V risks	
Hydro: large	v	–	vv	v	v	5
Biogas	v	v	vv	vv	v	7
Nuclear fission	v	v	vv	v	–	5
Wind: on-shore	v	vv	v	vv	v	7
Hydro: small	v	–	v	vv	v	5
Wind: off-shore	v	v	v	vv	v	6
Coal: IGCC-CCS	v	vv	v	v	v	6
Coal: PC-CCS	v	vv	v	v	v	6
Natural gas: CCGT-CCS	v	vv	v	v	v	6
Solid biomass	v	v	v	vv	v	6
Solar: CSP	v	v	–	–	v	3
Solar: PV	v	v	–	v	v	4

depreciation of a renewable power plant. Interestingly, according to the criterion (i) the most supported power technologies in Poland are to include bioenergy and wind energy. According to the criterion (ii), the number of issued green certificates is to decrease with increasing output power of a plant thus the modified system will stimulate the development of distributed renewable power systems. Finally, according to the criterion (iii) the largest support is to be given only to new investments in renewable energy, which can stimulate the adoption of innovative technologies such as biogas power and simultaneously limit support obtained by e.g. biomass co-firing with coal in old Polish power stations.

In view of the above, it must be emphasised that biogas as a technology of political choice in Poland meets the criterion (i). Further, biogas-to-electricity is particularly well-suited for distributed power systems due to relatively large transportation costs of solid biomass thus also meets the criterion (ii). Furthermore, the current development of biogas power plants is still minor in Poland, and hence the criterion (iii) is also very advantageous for the development of biogas-based power systems in the near term. Moreover, biomass co-firing with coal does not meet the criteria (ii) and (iii) thus it will obtain limited support, which, in turn, can significantly increase the availability of biomass resource for biogas production.

4.3. Summary of advantages of biogas-to-electricity in Poland

The main advantages of biogas-to-electricity in Poland can be summarised as follow: economic advantages:

- the costs of electricity from biogas can be lower than COEs from other renewable energies and from fossil fuel-based power plants involving CCS (Table 1),
- sustainable bioenergy can have large contribution in energy supply meeting around 30% of total energy demands, e.g. biogas economical potential can amount to 30 TWh yr^{-1},
- biomass cultivation benefits from current population trends such as increasing populations in large agglomerations and high depopulation of agri-forestry areas,
- Biomass production can stimulate development of agri-forestry communities with a high degree of unemployment, environmental advantages:
- The reduction of quantity of wastes (e.g. sewage sludge; municipal, agri-, industrial wastes).
- Reduced emission of greenhouse gases by fossil fuel substitution.
- Biomass cultivation is a natural sink for noxious atmospheric gases.
- Utilisation of landfill biogas prohibits the release of methane and VOCs thus improves local air quality,
- Anaerobic digestion produces valuable fertilisers such as digestate which can limit the production of energy intensive mineral fertilisers, energy policy considerations:
- Projected amendments to the Polish system of green certificates can significantly enhance the development of innovative biogas-to-electricity technologies and rather not biomass co-combustion with coal.

5. Technologies for biogas conversion integrated with CCS

5.1. Biogas-to-biomethane

Biogas can be upgraded to biomethane by separating CO_2 via absorption [6], molecular sieves [26] or membranes and injected into natural gas grids. The biogas injection to natural gas grids is regulated by law in several EU countries and will be soon regulated in Poland. The concept of 'negative net CO_2 emissions' can be easily applied to biogas-to-biomethane processes. However, biogas itself comprises CO_2 at concentrations of around 35%v and thus its decarbonisation involves the separation of a CH_4–CO_2 mixture which is more costly than separating of a H_2–CO_2 mixture.

5.2. Biogas-to-CHP

Biogas-to-CHP is widely accepted technology. CHP plants can involve gas engines, micro-gas turbines or dual fuel diesel engines [13]. CO_2 concentrations in flue gases from biogas air-combustion are however decreased due to significant nitrogen dilution. Thus also in this case the potential benefits of CO_2 enrichment are limited. Flue gases could be enriched in CO_2 by applying oxy-combustion followed by water condensation. However, due to the need for hydrogen oxidation by oxygen in such oxy-biogas-to-CHP plants the consumption of O_2 would be significantly larger thus decreasing the overall energy efficiency of this cycle.

5.3. Biogas-to-elecricity via oxy-reforming fuel cell (ORFC)

A power cycle that can fully exploit CO_2 enrichment [8] and thus achieve low CO_2 separation costs is a biogas fuelled oxy-reforming fuel cell (ORFC) [27]. In this cycle biogas is converted to a mixture of CO_2 and H_2 which can be separated at lower costs than CO_2–N_2 or CO_2–CH_4 mixtures due to different separation properties of carbon dioxide and hydrogen.

The objective of the ORFC cycle is to split CH_4 by means of oxy-reforming into free H_2 and simultaneously fully oxidise the remaining CO to CO_2. In order to avoid any dilution of reaction products by nitrogen, pure oxygen is supplied as an oxidiser. Therefore, the fully decarbonised ORFC cycle seeks improved conditions for separating a CO_2–H_2 mixture at the expense of using oxygen as an oxidiser [28]. Oxygen generation is beneficially integrated with a fuel cell unit [29] and the three reactors of the ORFC cycle. The consumption of oxygen is minimised to around 0.35 mol O_2/mol CH_4 because oxygen is also derived from water molecules.

According to the ORFC cycle CH_4 is split into CO and H_2 in the oxygen-steam atmosphere. CO is then oxidized to CO_2 providing energy for the endothermic CH_4 as well as H_2O splitting. H_2 is further separated and used as a fuel for electrically efficient H_2-fuel cells. Since steam methane reforming (SMR) (Eq. (2)) is thermodynamically an equilibrium reaction a resulting unreacted CO/H_2O mixture can be either recycled back into an oxy-reforming reactor [30] or shifted to a CO_2/H_2 mixture by selective catalytic water–gas shift (WGS) reaction [4,31]. These two options can also be combined as well WGS equilibria can be shifted by separating one of the two products of the WGS reaction, i.e. H_2 or CO_2.

The main components of biogas, i.e. CH_4 and CO_2 undergo in fuel reactors the following reactions:

CH_4 combustion (irreversible):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \Delta H^{298} = -802 \text{ kJ/mol} \tag{1}$$

steam methane reforming (SMR)/methanation or reverse SMR (reversible):

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H^{298} = 206 \text{ kJ/mol} \tag{2}$$

water–gas shift (WGS)/reverse WGS (reversible):

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H^{298} = -41 \text{ kJ/mol} \tag{3}$$

H_2 combustion (irreversible):

$$H_2 + 0.5O_2 \rightarrow H_2O \quad \Delta H^{298} = -242\ \text{kJ/mol} \tag{4}$$

CO combustion (irreversible):

$$CO + 0.5O_2 \rightarrow CO_2 \quad \Delta H^{298} = -283\ \text{kJ/mol} \tag{5}$$

By ensuring strict molar C/O ratio in substrates equal to 0.5 the overall reaction of the ORFC cycle can proceed according to the following overall reaction:

$$CH_4 + \frac{1}{1.8}CO_2 + nO_2 + 2(1-n)H_2O \leftrightarrow \frac{2.8}{1.8}CO_2 + 2(2-n)H_2 \tag{6}$$

Autothermal operation of the ORFC power cycle can be achieved when $n = 0.3412$ [30] and hence Eq. (6) becomes:

$$CH_4 + 0.5556CO_2 + 0.3412O_2 + 1.3176H_2O \leftrightarrow 1.5556CO_2 + 3.3176H_2 \Delta H^{298} = 0\ \text{kJ/mol} \tag{7}$$

From Eq. (7) it can be calculated that from biogas comprising e.g. 64.29%v CH_4 and 35.71%v CO_2 (i.e. CH_4:CO_2 = 1.8) with the addition of O_2 and H_2O in quantities satisfying $C/O = 0.5$ one can obtain by autothermal conversion a mixture comprising 68.1%v H_2 and 31.9% v CO_2. Consequently, by utilising the ORFC cycle H_2 can be autothermally produced from renewable biogas with the yield of 3.3176 H_2:CH_4 (molar basis) and the remaining gas beneficially includes almost solely high-pressure CO_2, i.e. is ready for sequestration.

The separation of this CO_2–H_2 mixture is technologically simpler than the separation of CO_2–N_2 or CO_2–CH_4 mixtures. However, the overall reaction given in Eq. (7) is reversible and hence the product gases from the ORFC process include some CO and H_2O, since process equilibria are dominated by the WGS reaction. In order to force shifting of CO/H_2O to CO_2/H_2 two selective catalytic WGS reactors are used. Accordingly, a high temperature WGS (HT-WGS) reactor and a low temperature WGS (LT-WGS) reactor are sequentially set up after the oxy-reforming reactor. Because different selective catalysts are used in both WGS reactors no methane is formed and only WGS reaction prevails (Eq. (3)).

The flowsheet of the ORFC power cycle is presented in Fig. 1. Accordingly, after the oxy-reforming reactor the reaction mixture still comprises some quantities of CO and H_2O which need to be shifted to CO_2 and H_2. This is accomplished by the inclusion of two WGS reactors. The ORFC process involves two elementary reversible chemical reactions, i.e. SMR and WGS. The SMR reaction is strongly endothermic and produces moles thus, according to Le Chatelier's principle it is favoured at high temperatures and low pressures. High temperatures are thus practised in industrial conditions [32]. However, in terms of pressure it must be noted that the SMR reaction requires catalysts, which are better utilized under high-pressure conditions. Therefore, the oxy-reforming reactions are usually carried out under elevated pressures [33]. Conversely, the WGS reaction equilibria are thermodynamically favoured by low temperatures since WGS is an endothermic reaction. However, in order to prevent too rapid reduction in the rate of WGS reaction, which drops with decreasing temperature, reactor temperatures must decrease gradually, i.e. by passing process gases from the oxy-reforming reactor through the HT-WGS reactor to the LT-WGS reactor.

Further, the mixture from shift reactors contains almost exclusively H_2 and CO_2 which can be conveniently separated by applying membranes [34] or pressure swing adsorption. The separated H_2 is sent to a fuel cell unit and converted to electricity. It is important that oxy-reforming and WGS reactors can operate under high-pressure conditions which is beneficial for H_2/CO_2 separations by increasing species separation driving force and leads to the production of a high-pressure CO_2 stream. Besides, high-pressure operation enables to improve the utilization of catalysts by increasing the amount of fuel gas flow per unit amount of catalysts. Finally, the fuel cell unit convert hydrogen energy into electricity with high electricity-to-fuel efficiency, e.g. 62% comparable with conventional combined cycle gas and steam turbines GT-ST (60% assumed in present calculations). O_2 is obtained by air separation and can utilise electricity and heat generated in the fuel cell stack. The whole ORFC cycle can thus be beneficially integrated by means of energy and mass recirculation loops.

In biogas processing CO_2 is an inert compound since it is a fully oxidised form of carbon. Therefore, energy analysis of biogas conversion can take into account only methane. Table 5 compares three CH_4-based power cycles: (i) air-combustion in a combined cycle (GT-ST), (ii) oxy-combustion (GT-ST) and (iii) the ORFC cycle (FC). Namely, air-combustion of CH_4 employs air as an oxidant and hence does not require any O_2 supply. The combustion energy (802 kJ/mol CH_4) can be converted into electricity in a combined cycle gas-steam turbine with ~60% efficiency, i.e. giving $0.60 \times 802 = 481.2$ kJ electricity/mol CH_4. Flue gases are disadvantageously diluted by N_2 and thus the costs of CO_2 separation from flue gases is estimated as 50 kJ electricity/mol CH_4. This results in net electricity-to-fuel cycle efficiency equal to around 53%.

Advantageous enrichment of flue gases in CO_2 can be attained in oxy-combustion. However, in order to oxidise CH_4 as much as 2.0 mol O_2/mol CH_4 are needed, Eq. (1). Pure O_2 can be generated by e.g. cryogenic technology with energy consumption of ~35 kJ/mol

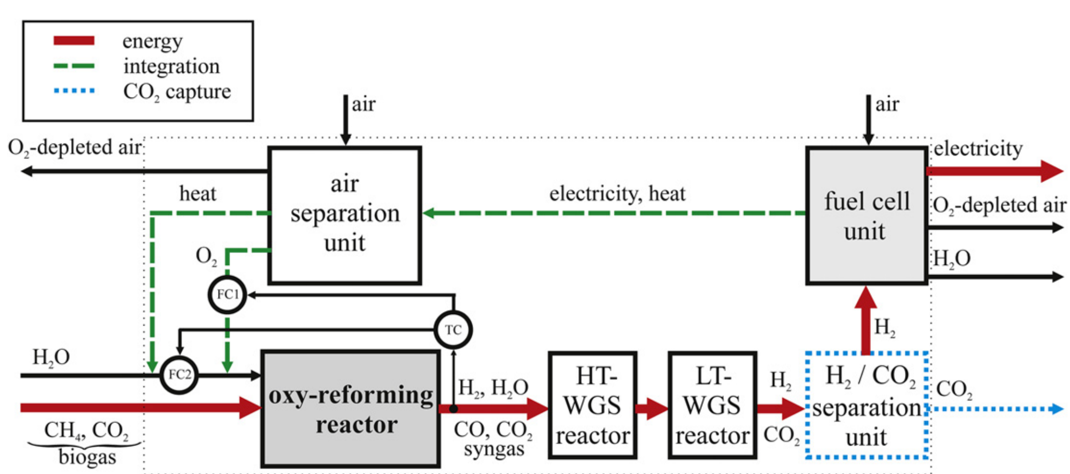

Fig. 1. The flowsheet of the ORFC power cycle. Notation: FC - flow controller, TC - temperature controller.

Table 5
The comparison of 3 electricity generating cycles involving CH_4 conversion.

Cycle:	Combustion	Oxy-combustion	ORFC
Substrates:	air-CH_4	O_2-CH_4	O_2-H_2O-CH_4
Fuel	CH_4	CH_4	CH_4
Oxidant	air	2 mol O_2/mol CH_4	0,3412 mol O_2/mol CH_4
Other reactant	–	–	H_2O
Energy input in O_2 generation (cryogenic)	–	−70kJ/molCH_4	−12,0kJ/molCH_4
Products	H_2O	H_2O	3,3176 mol H_2/mol CH_4
	CO_2 (diluted)	**CO_2 (enriched)**	**CO_2 (enriched)**
Energy output	802 kJ/mol CH_4	802 kJ/mol CH_4	0 kJ/mol CH_4
Fuel cell substrates	–	–	air / H_2
Fuel cell products	–	–	H_2O
Fuel cell electricity output	–	–	802 kJ/mol CH_4
Engine system	GT-ST	GT-ST	FC
Electrical efficiency	60%	60%	62%
Energy intensity of CO_2 separation from flue gases	−50,0kJ/molCH_4	–	–
Separation of H_2/CO_2 and purification of biogas	–	–	−35,0kJ/molCH_4
Net electricity output	431,2 kJ/mol CH_4	411,2 kJ/mol CH_4	450,2 kJ/mol CH_4
Net electricity-to-fuel cycle efficiency	**53%**	**51%**	**56%**

O_2, i.e. 70 kJ/mol CH_4 in methane oxidation. Finally, in the oxy-combustion GT-ST cycle 1 mol CH_4 generates 411.2 kJ electricity/mol CH_4. Hence, 51% net electricity-to-fuel is obtained.

The ORFC cycle can operate at stoichiometry that enables to convert CH_4 to CO_2 and H_2 without any by-products. From Eq. (7) it is seen that 3.3176 mol H_2/mol CH_4 can be generated without any external energy input. The heat of H_2 oxidation is 241.8 kJ/mol H_2 which also gives $3.3176 \times 241.8 = 802$ kJ/mol CH_4. However, pure H_2 can be converted into electricity in a fuel cell with ~62% efficiency, i.e. giving $0.62 \times 802 = 497.2$ kJ electricity/mol CH_4. In order to account for pure O_2 requirements it is seen from Eq. (7) that the oxyforming process requires only 0.3412 mol O_2/mol CH_4, which can be obtained by cryogenic technology at 12 kJ/mol CH_4. The energy intensity of the separation of H_2/CO_2 mixture and the purification of biogas is estimated at 35 kJ/mol CH_4. Finally, in the ORFC cycle 1 mol CH_4 gives $497.2-12-35 = 450.2$ kJ electricity/mol CH_4. This results in the net electricity-to-fuel cycle efficiency equal to around 56%.

These rough estimates are summarised in Table 5. It can be concluded that the air-combustion cycle benefits from utilising air as an oxidant and technological simplicity. Flue gases are however disadvantageously diluted by N_2 which necessitates involving energy intensive CO_2 separations. The oxy-combustion cycle suffers from the large consumption of O_2 which requires very cheap O_2 production technologies. Cheap O_2 can be produced by cryogenic methods but unfortunately this option is not well-suited for thermal integration with high-temperature units such as combustors. The ORFC cycle benefits from the increased electrical efficiency of H_2-fuel cells, low consumption of O_2 and offers CO_2-enrichment in the reaction mixture. The net electricity-to-fuel cycle efficiency is estimated at a comparable level with the other two technologies, i.e. at 56%. Thus the ORFC cycle is promising for the realisation of the 'negative net CO_2 emissions' from biogas-fuelled power units.

Anaerobic digestion of biomass can also beneficially utilise a part of heat arising from inefficiencies in energy conversion thus ensuring the thermal integration [35–37] of cycles.

6. Negative net CO_2 emissions

By integrating CCS into biogas-fuelled power plants negative net CO_2 emissions are achieved. Namely, at CO_2 capture rate of 100%, biogas composition having CH_4:CO_2 = 1.8 and biogas flow rate F m^3 s^{-1}, the resulting negative net CO_2 emission depends on the power technology involved. For biogas-to-biomethane CO_2 emission is $E_{CO_2} = -0.3571 \times F$. For biogas-to-CHP involving E_{CO_2} strongly varies depending among others on the oxidiser involved (i.e. air or O_2). Only for O_2 as an oxidiser and subsequent water condensation minimal $E_{CO_2} = -F$. For biogas-to-electricity via the ORFC cycle (characterised by smaller oxygen consumption) minimal E_{CO_2} equals also -F.

The above calculations relates only to a process of biogas-to-electricity. By considering Life Cycle Assessment (LCA) to the overall biogas production chain other sources of negative net CO_2 emissions can be found. Namely, by applying the fertilisation of soil by AD-derived digestate, carbon originating from the atmosphere is accumulated in the soil [38]. In general, carbon-intensity varies with agricultural technologies involved and is particularly small for low-input biomass production on degraded lands [39].

7. Biogas-based energy systems

Regarding the design of biogas energy systems one more observation must be emphasised here. Namely, biogas should be produced in a distributed system to avoid costs of long-distance transportation of high-moisture content biomass. However, produced biogas can be converted to electricity and undergo decarbonisation in centralised large-scale plants in order to achieve increased overall cycle efficiency. The centralised biogas conversion plants can benefit from the effect of scale which affects efficiencies of energy conversion and separation units while the overall costs are not much increased because pipeline transportation of gases is characterised by low energy intensity. These features of biogas-to-electricity cycles constitute a recommendation for the design of biogas-based energy systems, i.e. distributed biogas production and centralised decarbonised biogas-to-electricity conversion.

8. Conclusion

The article analysed to what extent 'negative net CO_2 emissions' from decarbonised biogas-to-electricity could contribute to solving Poland's carbon capture and sequestration dilemmas. From the criteria-based evaluation of low-carbon power technologies it was found that biogas-to-electricity was among technologies having increasing potential in Poland thus biogas production capacity was expected to grow. It was emphasised that biogas-to-electricity was characterised by several benefits in Poland, particularly including techno-economic and environmental advantages. It was also indicated that biogas technology could significantly benefit from Polish energy policy considerations, i.e. from amendments that were to be implemented to the Polish system of green certificates.

Therefore, the answer to the question posed in the title of the article is positive. Namely, if only future biogas production can achieve a significant capacity level it can contribute to solving Poland's CCS dilemmas because it offers carbon-neutral electricity. Moreover, by applying CCS into biogas-to-electricity the 'negative net CO_2 emissions' can be achieved which can partially offset CO_2 emissions from other Polish sources.

The article examined three biogas energy technologies involving CCS, i.e. biogas-to-biomethane, biogas-to-CHP and biogas-to-electricity via the ORFC cycle. It was emphasised that the ORFC cycle offered low-cost CO_2 separation from the CO_2–H_2 mixture, low O_2-intensity, and opportunities for advanced mass and energy integration of involved sub-processes. Besides, energy conversion calculation showed that the ORFC cycle could offer comparable overall cycle efficiency with air- and oxy-combustion combined (GT-ST) cycles.

Finally, recommendations for the design of decarbonised biogas-based energy systems included: (i) distributed production of biogas in order to avoid costs of long-distance transportation of high-moisture content biomass and (ii) centralised large-scale decarbonised biogas-to-electricity power plants.

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