Environmental and Climate Technologies
2020, vol. 24, no. 3, pp. 545–559
https://doi.org/10.2478/rtuect-2020-0123
https://content.sciendo.com

Spatial Economic Modeling of the Waste-driven Agricultural Biogas in Lubelskie Region, Poland

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***Abstract* – In this study, we aim to support the evidence-based policy in agricultural biogas production at regional level in Poland. To do so, we set up a decentralized decision framework, simultaneously taking into account the agricultural sector heterogeneity, the biogas technology state-of-the-art and the Polish institutional setting related to renewable energy production. A partial equilibrium model simulates the agricultural and the biogas sector interactions, estimating market clearing prices and quantities at the intersection of supply and demand. The optimal number, size and location of biogas plants are derived at the equilibrium. Considering the case study of Lubelskie region, we tested alternative incentive schemes for agricultural biogas development. Results indicate that limiting the use of energy crops in favour of other substrates, such as livestock, manure and agro-industrial waste, is decisive to preserve biogas profitability under all policy scenarios tested. However, it seems that only with the implementation of the current policy scheme there is a concrete perspective for the biogas industry take-off.**

***Keywords* – Agro-industrial waste; biogas, economic analysis; manure; optimization model; policy schemes; renewable energy sources**

1. INTRODUCTION

Recovery of biogas from agricultural residues, agro-food industry waste, manure and a limited amount of dedicated crops is an acknowledged cost-effective technology to counteract the greenhouse gas (GHG) emissions, as reflected by several bioenergy policies set in Europe [1]. In the strategic document "Energy Policy of Poland until 2040 – EPP2040" [2], biomass and more specifically biogas are recognized as the most important sources of renewable energy in Poland, at the same time solving issues related to bio-waste management. However, despite the high potential of biomass, only 94 agricultural biogas plants (ABPs) are currently operating in Poland, with a total installed capacity of 109 MWe [3]. In the neighbouring Germany, more than 9.000 agricultural biogas projects are already implemented, and the total installed power is approximately 5 GWe [4]. In order to keep pace with the take-off of the sector, relaxing legal barriers and compensating tight competitive incentive policy by reducing uncertainty of support schemes along with the enhancement of organizational and technological expertise need indeed to converge. The main structure of the current Polish

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incentive system is defined by the governmental Act on Renewable Energy Sources (Act No. 478/2015). This act introduces new forms of support, namely the auctioning system to replace the previous systems of green certificates, whose main limitation was their instability, volatility and lack of durability [5]. As a matter of fact, during the period 2005–2015 the certificate-based incentive scheme was set on tradable certificates of origin whereby RES producers were entitled to received: i) price for electricity sold at competitive market and ii) price for tradable certificates of origin granted to the RES operator (the so-called "green certificates"). From 2016 onwards, the support for renewable energy producers is subject to auction baskets. Successful bid allows the right to feed the national energy grid at a fixed price to the companies offering the most attractive energy prices with the overall target volume determined by the central authorities in an annual basis. The support period is limited to a maximum of 15 years and, in any case, ending not later than on 31st December 2035. For ABPs built before 1 July 2016, it is possible to switch to the auction if the operator gives up the certificate-based incentive scheme. However, this option is not attractive for operators who previously received subsidies for the initial investment: according to the new EU regulations, the offered price must be reduced by the amount of the subsidies received [6].

Several studies investigated the sustainability of the Polish agro-industrial biogas sector focusing on substrate availability, the technical and theoretical potential on biogas production, economical, technological and environmental issues as well. Igliński *et al.* [7] highlighted the theoretical annual biogas potential generated from manure and waste that, just considering pig and cattle slurry, reach 6 227 million m^3; Piwowar *et al.* [8] and Zubrzycka *et al.* [9] assessed the state of play and perspectives of the sector. Chodkowska-Miszczuk [10] and Chodkowska-Miszczuk *et al.* [11] focused on the role of energy policy in sector development, whereas Sulewsk *et al.* [12] investigated the contribution of the biogas industry in reducing GHG emissions. Estimations of the industry development and concrete deployment are mostly undertaken at the regional level, the most suitable for bio-based industry feasibility studies [13]. Sliz-Szkliniarz and Vogt [14] set a techno-economic assessment supported by GIS in Kujawsko-Pomorskie Voivodeship, a polish NUTS (Nomenclature of Territorial Units for Statistics) 2 region [15]. The authors estimated that 41 biogas plants of capacity ranging from 180 to 2850 MWe fulfil the economic viability for expansion after legal regulations promoting biogas since 2010. However, today there are still only 6 biogas installations, with total electric power installed of 8 MWe [16]. Oniszk-Popławska *et al.* [17] also estimated the expansion for the biogas sector focusing on Lubelskie region based on potential of various sources combined with explicit strategy scenarios on behalf of the involved supply chain stakeholders. The projected number of plants was rather overestimated: from 7 ABPs, recorded during 2014, to 40 ABPs estimated for 2020 that would reach 440 units, with a total installed power increasing from 25 up to 140 mWe by 2035. At the time being only 8 biogas plants are operating in the region.

In this modelling exercise we attempt an informed estimation considering backward and forward elements of the biogas supply chain built up on the basis of the business profitability principle. Considering different policy options and feedstock availability requirements (manure from livestock farms, agro-industrial waste and energy crops), the focus of this research is the Lubelskie region. Located in the eastern Poland, Lubelskie is divided into 20 rural districts (powiats – NUTS 4, Fig. 1 [15]), considered as the basic spatial unit for the model exercise. In order to approximate a realistic assessment, we considered the high geographical dispersion of substrates [18], focusing on options that enhance the economic performance (i.e. availability of agro-industry waste), the technical conversion efficiency for different biomasses considered (mix of energy crops, manure, and waste) and the environmental friendliness (iLUC neutral agricultural biomass) of biogas sector in Poland. Spatial data are used to ensure a bottom up modelling capacity since the daily supply of biogas plants has to be secured, an important element for location decisions. The economic potential of the system is estimated under resource competition conditions, where profit maximization is the driver of different players acting in the system, namely farmers and industrial partners. Building upon the existing literature, we set a decentralized decision-making framework, taking simultaneously into account the agricultural sector structure, the technology state-of-the-art and the current institutional setting related to biogas production. This is made possible by means of a partial equilibrium model that simulates the agricultural and the biogas sector interactions, estimating market clearing prices and quantities derived at the intersection of supply and demand. With this approach we aim to set up a tool to support the policy decision process concerning biogas production in Poland. As described in the next sections, through the examination of alternative incentive systems and operational constraints, it is possible to assess efficient policy suitable for the biogas industry take-off, estimating, at the same time, the optimal number, size and location of biogas plants.

Fig. 1. Lubelskie region and its division at NUTS 4 (powiat) level.

The paper is organized in five sections. Next section presents the methodology related to the setting of the PE model (agricultural-supply and biogas-demand models). Section 3 reports the case study, including the assumptions and the policy framework. In Section 4, results concerning number, size, technology and geographical distribution of the forecasted biogas plants are described and discussed. Conclusion and policy recommendations are provided in section 5.

2. METHODOLOGY

In this section, the agricultural-supply and biogas-demand models used to investigate the biogas policy in Poland, are described. For a selected range of energy crops prices, the model iteratively solved provides biomass quantity supplied at each price level. The industry model, taking into account exogenous manure and waste available, estimates the profitability of possible biogas plants at each biomass price level shaping a demand curve for agricultural biomass. Once the supply from the agricultural sector matches the demand from the biogas industry sector (market clearing point), the optimal number of biogas installations and their typology is displayed at the equilibrium. Various alternative policy schemes can be evaluated by means of this iterative modelling process indicating the minimum subsidy level that the Government should guarantee to enable the sector to grow.

2.1. The agricultural-supply model

The optimized agricultural sector model is a regional recursive dynamic (projection years 2020-2050) model, developed by Shu *et al*.[19] for the Polish context and specifically for the region under study. The model determines the optimal allocation of limited arable land resources as well as the unutilized land endowment among candidate crops to simultaneously meet the demand for food and biomass feedstock. Fifteen prevailing conventional crops along with the dedicated crop for biogas are covered (wheat, winter-wheat, spring-wheat, rye, barley, winter-barley, spring-barley, oats, triticale, winter-triticale, spring-triticale, maize-for-grain, maize-for-forage, buckwheat-millet-other, potatoes, sugar-beets, rape-and-turnip, leguminous-edible, sorghum). The objective function represents the sum of crops revenue after deduction of specific production costs, under a set of physical, agronomic and common agricultural policy – CAP constraints. A detailed description of the algorithm is provided in [19].

2.2. The biogas-demand model

To investigate the biogas sector, the ReSI-M (Regionalized Location Information System – Maize) model, developed by Delzeit *et al*. [20] for the German case study and readapted by Bartoli *et al*. [21] to the Italian case study, has been calibrated to the Polish context. This static comparative model considers ABPs technology, size and the related energy withdrawal price to maximize their Return on Investment (RoI), considered the driver to evaluate the possibility of sector's expansion. Through iterative maximization of biogas plants profitability, the model searches the optimal number and typology of biogas plants. A transport module completes the model, providing an interface to consider spatial information concerning biomass availability and its distribution, in order to optimize the siting of the biogas installations. The location is also determined considering the feedstock distribution in each region under investigation (powiat) and the share of each unutilized land unit available over the total surface. Collection costs are minimal where the share is highest. In so doing, the most profitable location is identified: the most profitable biogas plant is located in the region having the lowest feedstock transport cost. After each iteration, the ABPs profitability decreases as a consequence of biomass reduction and the related increase in its transport cost. The process terminates when either the profitability becomes void or the feedstock is exhausted. A detailed description of the algorithm is provided in [22].

3. Case Study Setting

The main advantage of biogas industry is that digesters do not mean only producing biofuels, but also managing industrial and domestic organic waste. Both technology [23] and composition of the mixed substrates are important to achieve high efficiency. Manure and food waste is suggested to mix with plant biomass for optimal efficiency of co-digestion. Several studies highlighted that indirect Land Use Change (iLUC) caused by energy crops substitution for food or feed crops leads to adverse effects in GHG emissions, strongly compromising the efficiency of the system in their reduction [24]. Alternative promising sources of plant biomass such as algae have not attained feasibility due not only to large capital investments, but also to uncertain supply and transport requirements to continental areas [25].

In this modelling exercise, the energy crops are considered to be grown on unutilized or abandoned land, which accounts approximately for 15 % of the total arable land in Lubelskie region, along with only up to 5 % of arable land allowed for non-food cultivation. The amount of unutilized land in Lubelskie is in fact 158,780 ha over 1 151 694 ha of arable land [26]. It is therefore assumed that, to generate the energy crops supply under the common agricultural policy (CAP) constraints, no more than 20 % of the total land theoretically available for biogas production can be considered by the agricultural model. The remained substrate is provided by manure and agro-industrial waste. In doing so, distortions of feedstock price and iLUC are minimized.

3.1. Manure and waste supply

Considering the parsimony of the subsidies provided by the Polish Government for Renewable Energy Sources (RES) production (see Section 3.4), an accurate estimation of substrate considered free of charge like livestock manure, waste and their distribution is of paramount importance for planning and optimize biogas production. Data on manure availability (cattle and swine) are collected from the Agency for Restructuring and Modernization of Agriculture (ARMA) database [27], where 74 232 farms with cattle or/and pigs activities, located in Lubelskie, are recorded. Data on dairy and pig populations were derived at farm level [28] and then aggregated at NUTS 4 level, considering available for biogas production only manure produced in farms with at least 50 Livestock Unit – LSU (approximately 1 % of the total). In this modelling exercise, we excluded micro-farms with less than 50 LSU since, in this case, the more realistic practice for manure management consist in its direct application at field level. For these farms, handling manure to a centralized biogas plants would be unprofitable due its loading and unloading cost. At the same time, we do not consider micro-installations (<130 kWe), assuming that this energy production can be devoted only to the self-consumption at the farm level.

As highlighted by the Polish Ministry of Energy, biogas activity could contribute not only to produce energy, but also to solve issues related to bio-waste management [2]. This stems from the fact that agro-industry waste utilization can alleviate pressure to the surrounding environment and improve the efficiency of GHG mitigation [29]. With the Act of 14.12.2012 on waste management [30], the Polish government provided new waste classification where are identified waste that can be used as substrates for biogas production (group 02 – wastes from agriculture, horticulture, hydroponics, fisheries, forestry, hunting and food processing [31]). The waste holder has to present annual reports concerning waste production and management. Data are collected at regional level and then transferred in the national Database of products, packaging and waste management. The database is divided in 5 main macroareas: 02.01 Waste from agriculture, horticulture, hydroponics, forestry, hunting and fishing; 02.02 Wastes from the preparation and processing of food products of animal origin; 02.03 Wastes from preparation, processing of food products and food and waste of vegetable origin; 02.04 Wastes from the sugar industry; 02.05 Waste from the dairy industry. The following groups of waste are provided by the Marshal Office of Lubelskie Voivodeship and are currently available for biogas production: waste animal tissue (cod. 02.01.02 and 02.02.02), waste plant mass (cod. 02.01.03); waste from the preparation and processing of food products of animal origin/raw materials and products unfit for consumption and processing (cod. 02.02.03); waste from preparation, processing of food products and food and waste of vegetable origin/waste from the production of plant feed (cod. 02.03.81); waste from the dairy industry/raw materials and products unfit for consumption and processing (cod. 02.05.01) and waste from the dairy industry/waste whey (cod. 02.05.80). Waste quantities (tons) at powiat level are displayed in Table 1.

3.2. Energy crops supply: sorghum

Although across Europe the most common energy crop used for biogas production is maize silage, its cultivation requires intensive use of agricultural resources such as water and fertilizers that may jeopardize the effectiveness of the system in GHG saving [32]. Originated from western Africa, sorghum represents an interesting alternative extensively studied in Europe as energy crop. Yielding up to 100 tons of green matter per hectare (t/ha) under the Polish climatic conditions [33], sorghum is suitable for silage and requires low soil quality, nutrient and water resources. Besides its energy value (18 MJ/kg [33]) and its resilience to water shortages and drought periods occurring frequently in recent years in Poland, sorghum is competitive with maize, the latter being highly vulnerable in the aforementioned conditions. For these reasons, sorghum is selected for the application of our modelling tool, as the main energy devoted for biogas production.

3.3. The biogas sector

We tested five size classes of biogas plants – c1, c2, c3, c4 and c5 – with 130, 250, 499, 999, and 2000 kWe, respectively. Representative of the most common typology surveyed in Poland, units of various sizes are operating in cogeneration (i.e. the combined production of heat and power – CHP) with different feedstock in the blend. In order to build our analysis as close as possible to the Polish context, we first carefully analysed technical coefficients and cost data reported in the literature related to biogas production in Poland, as well as feedstock and technology employed. One of the most detailed survey is provided by Zubrzycka *et al.* [9], in which the authors described the deployed feedstock, the energy production, the proceeds, the operational costs, and the related payback period, with a focus on three typologies of biogas plants (2000, 250 and 10 kWe). Excluding the micro-installation (10 kWe, see Section 3.1), we extrapolated data for all the typologies of ABPs under investigation. For a matter of model tractability, we have converted the various waste categories in manure equivalent on the basis of energy efficiency. As well as manure, various waste sources are considered spatially specific (Table 1) within the spatial decision making unit, assuming that the providers (farmers, food industry and/or distributors) are in charge of transport that limits waste flows across powiats (powiats' codes ranging from 601 to 620 [34]).

TABLE 1. SPATIAL DISTRIBUTION OF MANURE AND WASTE FROM VARIOUS SOURCES IN LUBELSKIE

Manure eq. coef.	**2.0**	**2.0**	**2.0**	**2.0**	**1.1**	**1.1**	**Total manure equivalent**	**Total waste and manure**	**Share waste/total manure**
powiat*	02.01.02/02.02.02	02.01.03	02.02.03	02.03.81	02.05.01	02.05.80	tons	tons	%
601	1 128.25		9.84	40.59			2 357.36	190 878.68	1.24 %
602	70.18	32.64	0.60				206.85	28 842.26	0.72 %
603		27.96					55.92	89 602.37	0.06 %
604		4 182.98					8 365.96	37 403.16	22.37 %
605	718.72	59.80	4.57			950.40	2 611.62	5 461.10	47.82 %
606	105.60	2.23					215.66	25 991.27	0.83 %
607		50.40	7.00				114.80	20 836.12	0.55 %
608					1.58		1.74	93 501.24	0.00 %
609		17.44	0.14	4.93	1.84	2 480.00	2 775.03	95 801.87	2.90 %
610							0.00	22 042.12	0.00 %
611	445.01		5 242.29		32.15		11 409.96	257 882.43	4.42 %
612		69.21	5.80				150.02	2 110.22	7.11 %
613							0.00	166 477.75	0.00 %
614	40.58	1 248.64	488.74				3 555.92	34 118.72	10.42 %
615	2 014.81						4 029.62	200 658.12	2.01 %
616	46.65		43.85				181.00	42 454.20	0.43 %
617						9.90	10.89	8 581.63	0.13 %
618	36.00						72.00	74 707.85	0.10 %
619							0.00	102 732.63	0.00 %
620			0.50				1.00	54 794.80	0.00 %

* 601 Bialski, 602 Bilgorajski, 603 Chelmski, 604 Hrubieszowski, 605 Janowski, 606 Krasnostawski, 607 Krasnicki, 608 Lubartowski, 609 Lubelski, 610 Leczynski, 611 Lukowski, 612 Opolski, 613 Parczewski, 614 Pulawski, 615 Radzynski, 616 Rycki, 617 Swidnicki, 618 Tomaszowski, 619 Wlodawski, 620 Zamojski (Central Statistical Office classification).

Basing on parameters of materials subject to fermentation in Poland [7], we identified conversion technical coefficients (Table 1, heading, left side) in order to extrapolate the manure equivalent (Table 1, heading, right side) necessary to feed the identified biogas plants. Even if the parameters concerning feedstock are directly proportional to the plant size, other key parameters identified by authors, such as construction costs and subsidies, are not linearly correlated with the plant size [9]. Reflecting the economies of scale, construction costs for biogas plants are fixed accordingly with the recent survey provided by Igliński *et al*. [5], where the investment costs of different agricultural biogas plants operating in Poland are described in detail. Finally, following the approach proposed in [20] and [21], for each typology of ABP under investigation, the RoI is estimated assuming CHP technology where the ICE (Internal Combustion Engine) operates 8000 hours per year and the plant self-consumption of electricity is approximately 8 % of the total [21]. On the grounds of prudence, in order to avoid overestimation concerning biogas profitability, we considered two options: i) proceeds deriving only from the sale of electricity and ii) proceeds deriving from the sale of electricity and no more than 1/3 of the heat produced. The sale of heat is in fact not always possible and the related cost for its distribution can be prohibitive, even if can be easily employed to heat residential buildings and livestock facilities, representing a considerable retrenchment at farm level [5]. Table 2 reports all the identified parameters necessary for the payback estimation of ABPs by size under the current policy scheme, showing the RoI estimation including the sale of heat produced. The horizon time used to calculate yearly operational profit has been set according to the current RES auction (15 years, Section 3.4).

TABLE 2. ROI ESTIMATION UNDER CURRENT RES AUCTION FOR ABP SIZE (C1 – C5)

Type of plant **kWe**	**c5** **2000**	**c4** **999**	**c3** **499**	**c2** **250**	**c1** **130**
Tons man. Eq	79 254.00	39 627.00	19 810.20	9 905.10	5 150.90
Tons e. crops	30 600.00	15 300.00	7 650.00	3 825.00	1 989.10
Operational costs, €	793 104	396 552	198 288	99 144	52 181
Construction costs, €	7 084 800	3 719 520	2 420 640	1 254 600	738 000
Electricity produced, MWh	14 720	7 360	3 680	1 840	957
Heat saleable, MWh	5 547	2 773	1 387	693	361
FIP, €/MWh	153.6	160.8	168.0	168.0	168.0
Annual proceeds, €	2 433 516	1 269 750	661 371	330 685	171 956
Operating costs, €	793 104	396 552	198 288	99 144	52 181
Amortization, €	472 320	247 968	161 376	83 640	49 200
Total annual costs, €	1 265 424	644 520	359 664	182 784	101 381
Profit, €	1 168 092	625 230	301 707	147 901	70 575
Profit/investment (RoI)	0.164873	0.168094	0.124639	0.117887	0.095630

Profits and RoI reported in Table 2 are estimated without considering costs of feedstock (for energy crops) and transportation (for all substrates). As matter of fact, this is endogenously determined by the model, considering feedstock density and its distribution at regional level (Section 2.2). Regions with high density of feedstock present lower transportation costs, and thus are the most profitable for biogas plants allocation to start with. This process leads to the optimal allocation of simulated plants. In this case study, transportation costs for energy crops are fully covered by biogas plant's owner; manure is assumed in charge of the biogas plant's owner only when it is collected beyond the first kilometre of transport. The assumption referred to manure management at farm level, the cost of which is charged to the farmers. As regards to digestate, suitable as fertilizer, it is assumed free of charge for the famers who have to cover only its transportations costs, from the biogas plant to the farm location. Finally, only energy crops are considered transportable between regions (powiat), while the maximum amount available of manure and waste is the quantity annually produced in each region under study.

3.4. The Policy framework

After its first approval, RES auction has been modified during the years: in 2018 the tariffs have been increased, distinguishing between ABPs < 500 kWe; 500 kWe – 999 kWe and ≥ 1000 kWe. The slow development of the sector leads the government to increase again the tariffs for 2020, introducing an additional bonus for agricultural biogas plants operating in CHP. Table 3 reports tariffs and the related RoI of biogas plants operating under alternative policy schemes, assuming: i) the full tariff as reference price, ii) all plant typologies are operating in CHP and iii) 1/3 of the heat produced is sold (optional).

TABLE 3. SCENARIO SETTING ACCORDING TO THE AUCTION TARIFFS AND ROI ESTIMATION PER PLANT SIZE (C1 – C5 ABPS)

	Type of RES installation	**Reference price, PLN/MWh**	**Reference price, EUR/MWh***	**c5 2000 kWe**	**c4 999 kWe**	**c3 499 kWe**	**c2 250 kWe**	**c1 130 kWe**
2016_Scenario	ABP ≤ 1MWe	550.0	132.0	–	0.111	0.070	0.065	0.049
	ABP > 1MWe	550.0	132.0	0.120	–	–	–	–
2018_Scenario	ABP < 500 kWe	630.0	151.2	–	–	0.099	0.093	0.074
	ABP ≥ 500 kWe	570.0	136.8	–	0.121	–	–	–
	ABP > 1MWe	550.0	132.0	0.120	–	–	–	–
2020_Scenario	ABP < 500 kWe	650.0	156.0	–	–	0.106	0.099	0.080
	ABP-CHP < 500 kWe	700.0	168.0	–	–	0.125	0.118	0.096
	ABP ≥ 500 kWe	590.0	141.4	–	0.129	–	–	–
	ABP-CHP ≥ 500 kWe	670.0	160.8	–	0.168	–	–	–
	ABP > 1MWe	570.0	136.8	0.129	–	–	–	–
	ABP-CHP > 1MWe	640.0	153.6	0.165	–	–	–	–

* exchange rate: 1PLN = 0.24 €

By combining tariffs and RoIs we set three main different scenarios (2016_Scenario, 2018_Scenario and 2020_Scenario) that are investigated in the next section.

4. THE MARKET CLEARING QUANTITIES - RESULTS AND DISCUSSION

The demand and supply models described in Section 2 run simultaneously with the same vector of sorghum silage prices. By doing so, the agricultural model provides the supply curve of sorghum on the one hand, and the biogas model generates the sorghum (and waste & manure) demand on the other. Ascending order of sorghum prices generate the growth of the supply and the decrease of the demand. Following the approach introduced by Delzeit *et al.* [20], [22] and readapted by Bartoli *et al.* [21], [32], market clearing prices and quantities are displayed at the equilibrium, when the supply from the agricultural sector matches the demand from the biogas industry sector, leading to the optimal number and size of simulated biogas plants. The so obtained PE model is run for all scenarios set in Section 3. Each scenario is in turn divided in two *sub-Scenarios*, function of different hypotheses: 1) the "restrictive" scenario, in which proceeds of all biogas plants are derived only from the sale of electricity and, 2) the "optimistic" scenario, in which the sale of 1/3 of the heat produced (whose price in Poland is around 8.64 €/GJ, [5]) is taken in to account in the RoI calculation. Simulation results are reported in Table 4, displaying the number and the typology of ABPs obtained at the equilibrium in each powiat under investigation.

Under the first auction scheme (2016_Scenario), medium (c3), medium-big (c4) and big plants (c5) are built. Above all sizes, the c5 – 2000 kWe ABP is the most profitable. This is due to the economies of scale ensuring lower unit cost for generating 1 kWe of power (3542 €/kWe in comparison with 5678 €/kWe for 130 kWe ABP, see Table 2) and lower cost for feedstock transportation due to different employed technologies. Following [20] and [22], transportation cost for energy crops are indeed computed in function of transportation techniques and truck capacity: for medium-big (c4) and big plants (c5) the unit transport cost is assumed 2.9 €/t for the first kilometre, including their up-and unloading, and 0.0833 € for each additional kilometre whereas for the smallest sizes (c3, c2 and c1 ABPs) the unit transport cost is assumed 1.5 €/t for the first kilometre but a higher costs of 0.2667 €/t is charged for each additional kilometre.

Switching from the *restrictive* to the *optimistic* hypothesis with inclusion of heat sales in the proceeds calculation, the overall profitability of the system grows. More ABPs are simulated but in several regions a significant amount of feedstock remains still unused, due to the lack of profitability of the sector under this policy scheme.

TABLE 4. SIMULATED BIOGAS PLANTS, INSTALLED POWER AND EQUILIBRIUM PRICES

Powiat codes	**2016 restrictive**					**2016 optimistic**					**2018 restrictive**					**2018 optimistic**					**2020 restrictive**					**2020 optimistic**				
	c1	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**
601					2					2			1		2			1		2		1	1		2		1	1		2
602			1			1		1			1		1			1		1			1		1			1		1		
603					1					1		1			1		1			1		1			1		1			1
604		1	1				1	1			1	1	1			1	1	1			1	1	1			1	1	1		
605						1					1					1					1					1				
606			1			1		1			1		1			1		1			1		1			1		1		
607			1					1					1					1					1					1		
608					1					1		1			1		1			1		1			1		1			1
609					1		1			1		1		2			1			1	1	1			1	1	1			1
610			1					1					1					1					1					1		
611					2					3			7	1				3		2			1	1	2					3
612																														
613				1						1		1	2						1	1				2	1					2
614			1				1	1				1	1				1	1				1	1				1	1		
615				1					1			1	1					2						3					2	1
616				1					1				2						1					1					1	
617						1					1					1					1					1				
618				1				1	1			1	3				1	1	1			1	1	1		1	1	1	1	
619					1					1			5					1		1										1
620				1			1		1		1	1		1		1	1		1		1	1		1		1	1		1	
Plants	**0**	**1**	**6**	**5**	**8**	**4**	**4**	**7**	**4**	**10**	**6**	**9**	**27**	**4**	**4**	**6**	**7**	**14**	**4**	**9**	**7**	**8**	**9**	**9**	**8**	**8**	**8**	**8**	**5**	**12**
Total	**20**					**29**					**50**					**40**					**41**					**41**				
MWe	0	0.3	3.0	5.0	16.0	0.5	1.0	3.5	4.0	20.0	0.8	2.3	13.5	4.0	8.0	0.8	1.8	7.0	4.0	18.0	0.9	2.0	4.5	9.0	16.0	1.0	2.0	4.0	5.0	24.0
Tot. MWe	**24.25**					**29.02**					**28.53**					**31.53**					**32.41**					**36.04**				
Price, €/t	**14.6**					**15.9**					**15.7**					**16.1**					**16.2**					**16.6**				

With the introduction of the 2018 incentive scheme, raising the level of the tariffs and introducing a distinction between plants size, the policy maker aimed to prompt ABPs lower than 500 kWe. Under this scenario, we observe a high number of medium size (c3-499 kWe) ABPs, particularly under the *restrictive* hypothesis (which increase from 6, simulated under 2016_Scenario, to 27). Considering also the sale of heat in the profit calculation the RoI of medium-big (c4-999 kWe) and big (c5-2000 kWe) ABPs grows faster, as result of the economies of scale characterizing these plants (see Table 3). As a matter of fact, under the *optimistic* hypothesis, the number of c3-499 kWe ABP decreases from 27 to 14, whereas the number of big plants (c5) is more than doubled (from 4 to 9). Considering the total installed power at regional level, this ABP typology reaches alone 57 % of the total (18 MWe on 31.5 MWe, see Table 4). Values reported in Table 3, could lead to a misleading interpretation: the RoI of the medium-big ABPs (c4) is the highest, although the number of simulated plants remains low (4) and constant under both tested hypotheses. This is reasonable considering that the RoIs shown in Table 3 are net of the unit feedstock procurement costs (feedstock price and feedstock transportation costs), decisional variables that can affect model's results at the equilibrium towards sizes with lower feedstock demand (*restrictive* hp.) or higher profitability (*optimistic* hp.). Results for 2020_Scenario show how the economies of scale can offset the effects of decreasing per unit subsidies with the increasing of plant size. During 2019, the Government introduced new tariffs, thereby raising once again the level of subsidies. Despite the medium-small (c1, c2, c3) ABPs are entitled to receive the most advantageous tariff per MWh of energy produced (168 €/MWh) the range of tariffs between ABPs is limited (Δmax = 14 €/MWh). The most profitable RoI is indeed computable to medium-big ABPs that are the most represented under the *restrictive* hypothesis. The effects related to the economies of scale are amplified under the *optimistic* hypothesis, when also the heat is computed in the proceeds calculation. Even if the medium-big plants are still the typology with the highest RoI without considering unit transportation and feedstock costs (Table 3), the overall increase of profits amplifies the effects related to the economies of scale: able to maximize the return on investment and minimize the unit transportation costs for feedstock, the biggest (c5) ABPs become again the most profitable and represented plants.

In all tested scenarios, the availability of manure and waste is a key factor for the development of the sector. Fig. 2 shows the location of biogas plants in terms of total MWe installed under two diametrically opposed scenarios: the less favourable (2016_Scenario/restrictive hypothesis) and the most profitable (2020_Scenario/optimistic hypothesis). The total quantities of manure and waste (tons of manure eq.) are also displayed in order to pinpoint the disparities in the resource distribution across Lubelskie region. Under all scenarios, powiats with high density of manure and waste provide the most interesting locations for the installation of biogas plants. As a confirmation of this observation, also the big majority of existing plants currently operating in Lubelskie are located in these powiats (601, 611, 613, 615). In this regard, it is important to point out that, although we notice a considerable differentiation in terms of plants size profitability across scenarios, as result of tariffs remodulation, the distribution of the total installed power presents a reduced variability. This is mainly due to the availability of agro-industrial sewage and by-products, which represents a limiting factor for the model projections in several regions, especially when a minimum level of sector profitability is guaranteed.

Switching from the first auction system (2016_Scenario) to the current (2020_Scenario), we observe indeed that the limiting factor for the model simulation process is rather represented by the shortage of manure and waste in the almost entirely of powiats inside the region. Thus, the resource quantification and enhancement play key roles for the future development of the sector.

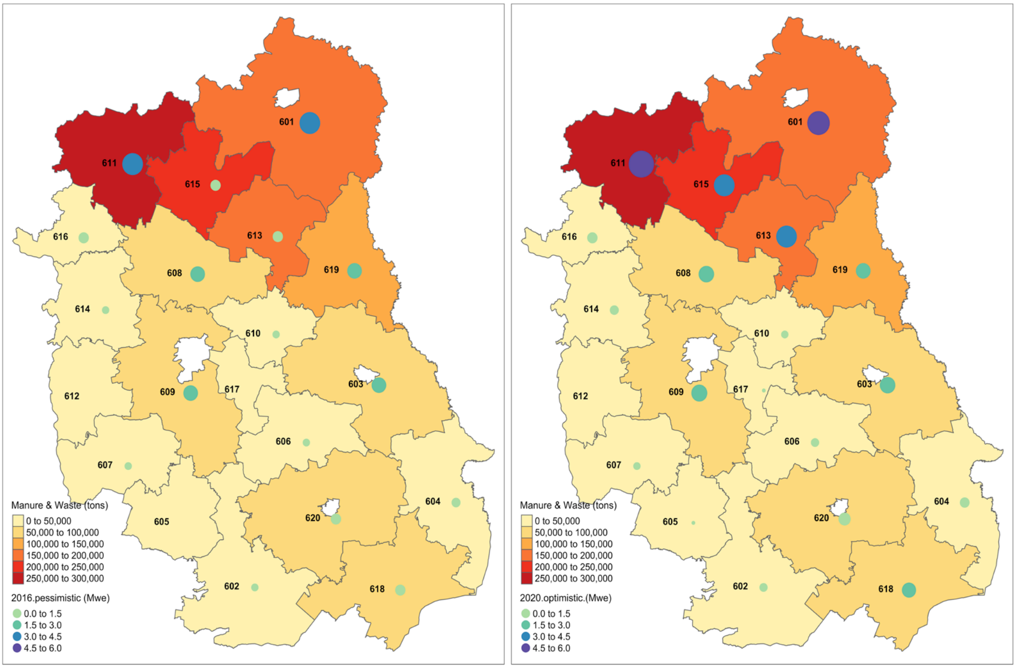

Fig. 2. Geo-location of installable power (MWe) in Lubelskie under 2016 (restrictive hypothesis, on the left) and 2020 (optimistic hypothesis, on the right) scenarios.

Another effect related with the centrality covered by manure and waste is the counteraction of any possible increase in energy crops prices due to their additional demand: under all simulations the sorghum equilibrium price never exceeds 17 € per ton. Unlike Germany and Italy, where biogas production has triggered an intense debate concerning both energy crops and farmland rental prices [20], [29], the development of the sector can be considered free of distortions under the tested hypotheses and policy settlement. This is due to the combined effects of low tariffs, which prompt biogas production from manure and waste where available, as well as to the marginal amount of energy crops considered in the blend for biogas production. This means that the development of biogas sector is mainly driven by the location of agro-food industries and large animal farms, as effectively reported in the case of Poland [36], for which biogas plants are particularly located in close proximity to these sites. Focusing on the four powiats with the highest share of installable power (601, 611, 613, 615) we counted for large livestock farms with more than 250 LSU (respectively 7, 3, 5 and 8 units). Farms with the highest LSU can minimize transport cost for manure and waste (Section 3.3), representing therefore the most profitable site to localize the simulated ABPs (respectively 4, 3, 3 and 2 units under 2020_Scenario/optimistic hypothesis, the scenario with highest installed Power).

Finally, knowing the total energy production at the equilibrium (*TPb*, MWh), we estimated, for all scenarios, the total expense borne by the government (*TPb* **Pb*), where *Pb* is the withdrawal price for the electricity produced by each typology of ABPs. Deducing from this expense the cost corresponding to the same amount of energy at the competitive market (*Pr*, PLN 241.81/MWh – approx. € 56.23/MWh [37]), we can calculate the overall biogas support cost. Table 5 shows the results obtained under the optimistic hypothesis.

TABLE 5. AUCTION COST – A COMPARISON OVER ONE YEAR

	2016 optimistic					2018 optimistic					2020 optimistic				
	c1	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**	**c1**	**c2**	**c3**	**c4**	**c5**
Pb, GWh	3.8	7.3	25.7	29.4	147.2	5.7	12.8	51.5	29.4	132.5	7.6	14.7	29.4	36.8	176.6
TPb, €/MWh	132	132	132	132	132	151.2	151.2	151.2	136.8	132	168	168	168	160.8	153.6
Pr, €/MWh	56.23					56.23					56.23				
Policy Cost, M€ y^{-1}	16.2					19.1					26.8				
Unitary cost, €/kWh	75.8					82.2					101.2				

As expected, while the policy cost raises with the increase of the level of energy produced, the unitary cost raises with the increase of subsidies. However, to estimate the deadweight policy cost, it would be appropriate to subtract the surpluses enjoyed by the stakeholders, namely the farmers and the industry. Integrated modelling frame makes this possible as in the case of biofuels in France [38]. Moreover, it is important to include in the analysis the carbon dioxide (CO_2) emissions avoided by the development of the biogas sector. In this regard, CO_2 emissions can be monetized and deducted by considering the global damage caused by one additional ton of carbon emitted into the atmosphere in relation to the net present value of climate change impacts [21]. Alternatively, the deadweight cost can be reported to the avoided CO_2 emissions providing the unitary cost of reduction that can be compared to other ways pinpointing the position of biogas in the GHG abatement cost curve and its ranking order comparing with other technologies [39]. This will be investigated in further research, in which a set of parameters and decision variables will be included in the modelling exercise to evaluate the overall environmental effects of biogas production in Poland.

5. CONCLUSION

With this study, we aimed to set up a tool to support policy makers and the policy decision process regarding biogas production in Poland. We tested three policy options under different profitability hypotheses. Results indicate that only with the introduction of the current incentive system, there is a fair possibility for the biogas industry take-off in Poland. In this regard, under the 2020_Scenario, not only the most incentivized biogas plants (c3 – 499 kWe) but also the more efficient in energy production (c4 – 999 kWe and c5 – 2000 kWe) are selected. If stabilized and guaranteed over time, this level of subsidization can therefore be considered suitable to attract new investors to the sector, starting from the livestock farmers with a considerable amount of agricultural by-products available to supply biogas plants. Limiting the amount of energy crops available for biogas production is, in fact, a key condition to preserve biogas profitability, preventing at the same time distortions on agricultural market in terms of feedstock price and land demand. A further implementation of the present study is to incorporate in the model a set of parameters and decision variables to evaluate the system efficiency in GHG emissions saving. Finally, setting a graphic interface allowing to make more easily affordable this analysis approach, different users and institutional players could test alternative hypotheses observing the reaction of the whole system, the effects of which, as shown in this contribution, can be inspected and counterintuitive.

ACKNOWLEDGEMENT

This research is supported by the project "New Strategies on Bio-economy in Poland", funded from H2020WIDESPREAD-2014-2: ERA Chairs grant agreement No 669062. Authors would like to express their much appreciation to colleagues Rafał Pudełko and Małgorzata Kozak who provided data concerning the arable land spatial allocation in Lubelskie.

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