A Geographical Information System (GIS) based approach for assessing the spatial distribution and seasonal variation of biogas production potential from agricultural residues and municipal biowaste

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ABSTRACT

Bioenergy can be produced from a wide range of feedstocks and can be utilised for production of renewable electricity, thermal energy, chemicals or transportation fuels. Anaerobic digestion technology (AD) for biogas production has an important role in achieving circular economy goals, as it may not only recover the energy contained in the biomass but also contribute to nutrient recovery and reduction of greenhouse gas emissions. The expansion of biogas production promotes the need for assessment of the technical potential of biomass, which is available for biogas production and is not in the competition with other purposes. This research work presents a Geographical Information System (GIS) based approach for the assessment of the spatial distribution of the biogas production potential by taking into consideration seasonal variation of biomass production, in order to assess the influence of biomass seasonality. The method developed in this research work is based on a combination of statistical and spatial explicit methods. The presented approach was tested in a case study of Croatia and the final results are representing the seasonal and spatial distribution of biogas potential at the spatial level of 1 km x 1 km. The results show that there is a strong need to include the influence of seasonality in assessment of biogas potential for lignocellulosic agricultural residues. The benefits are demonstrated in two examples that resulted in 12% and 40% lower storage facility capacity by using the proposed approach, compared to currently used approaches.

KEYWORDS

GIS, biogas, agricultural residues, seasonal variation

INTRODUCTION

Energy produced from biomass can be in form of bioliquids, biogas or solid biomass and may represent one of major options for substituting fossil fuels in the energy mix [1]. AD technology has a high potential for significant reduction of waste through the generation of high value products [2]- biogas, which can be used for electrical and thermal energy production, transport or as the substitute for natural gas (if upgraded to biomethane) and digestate, which is suitable as a fertiliser for agricultural production, due to high ammonium-N/total N ratio [3].

Those advantages have been recognised by the European Commission, which has regarded in EU waste legislation [4] AD as a recycling operation in the waste hierarchy.

The number of European biogas plants has increased steadily over the past decade. By the end of 2017, there were 17783 biogas plants and 540 biomethane plants in operation in Europe [5]. This has resulted with a significant increase in food and feed crops (mostly maize silage) utilization for biogas production, due to high biogas yields and favourable support. However, utilization of feedstocks grown on agricultural land indicates that bioenergy production may be in competition with alternative demands for food and material [6] and leads to negative environmental impacts due to direct and indirect land use change.

In December 2018 the revised Renewable Energy Directive entered into force, which set up the targets and constraints for future biogas utilization in transport, as well in electricity, heating and cooling production. The new directive defines numerous sustainability and GHG emission criteria that biogas used in transport, electricity, heating and cooling production must fulfil. Furthermore, it sets a target that the contribution of advanced biofuels and biogas produced from the feedstock such as algae, straw, animal manure, husks, industrial waste etc., should be at least 3.5% in 2030. New directives and concerns about the sustainability of the biogas production have resulted in increased interest in underestimated feedstocks for biogas production, such as lignocellulosic agricultural residues. Their utilisation does not bring ethical conflicts [7] and can lead to a significant improvement in the environmental sustainability of energy production [8]. In order to define the perspective of shifting to renewable energy systems, first step is to estimate the potential of domestic renewable sources [9].

There have been numerous studies on the assessment of the biomass technical potential. Two main groups of commonly used methods for potential-focused approaches are statistical analysis (non-spatial specific), which relies on statistical data to assess the potential of biomass for energy utilization and other uses, and spatially explicit analysis, which combines spatially explicit data and land use [10].

In the past years, application of GIS tools has been recognised as very useful for biomass potential mapping, as it gives valuable insights into the spatial distribution of the biomass potential and enables optimisation of bioenergy production plants. In the work [11], a GIS tool was used for assessing the spatial distribution of agroforestry residues annual potential and in the work [12] it was used for the assessment of the spatial distribution of annual sustainable crop residue potentials. Spatial distribution of annual biogas potential from non-woody biomass of conservation areas and roadsides for biogas was assessed with a GIS tool in the work [13]. Authors of the work [14] used a GIS tool to assess the annual theoretical and technical potential of chicken manure from various rearing systems in Polish provinces. In the work [15], author presented the method for assessing the annual economic potential of biomass supply from crop residues, in which he used a GIS based approach to identify the areas in China that are likely to produce crop residue. In the work [16], authors have presented a GIS-based combined approach for the determination of the most cost-effective investments in biomass sector. The proposed approach included GIS mapping of annual biomass potential and defining both storage and plant locations. Similarly, in the work [17], authors used a GIS tool to assess annual potential of corn stover, switchgrass and miscanthus in order to assess biofuel production potential and suitable biorefinery locations in the USA, while in the work [18], authors assessed annual potential of food waste, cattle slurry and wheat straw to locate bio-energy facilities. Annual potential of agricultural waste, co-products and by-products was assessed in the work [19], for the 28 member countries of the European

Union. Works such as [20] have already shown that the application of GIS tools enables assessment of biomass transportation cost. In the work [21], authors used a GIS tool to assess the annual biogas potential of citrus pulp, olive pomace, whey, poultry litter, cattle manure and corn silage. In accordance with the results, the authors conducted an economic assessment which allowed them to determine the size and location of four biogas plants in Sicily. The same feedstocks were considered in the work [22], in which authors developed a GIS-based spatial index of feedstock-mixture availability for anaerobic co-digestion. The developed spatial index describes the availability of the specific feedstock in each municipality, in accordance to annual production of respective feedstock and enables identification of municipalities which are most suitable for biogas production. Authors of the work [23] used a GIS tool to identify financially viable locations for biomethane injection to a natural gas network, in accordance with the spatial distribution of the annual potential from grass silage and cattle slurry. In the work [24], a GIS tool was used for annual biomass potential assessment in India, for which authors developed land use maps for the selected pilot regions. Authors of the work [25] developed a regional GIS based method to analyse suitable locations and capacities of biogas plants, based on theoretical annual potential of various biomass resources, as well as transportation distances. Similar to this, authors of the work [26] developed a model to solve the multi-criteria decision problem of identifying the most suitable location for biogas plant, taking into consideration annual potential of slurry, population density, distance to heat plants and transportation-optimal sites.

In general, the efficiency of the waste-to-energy technologies is strongly affected by the distance of the biomass supply and the rate available during the year [25]. Seasonal availability of the cereal and horticultural crops, as well as residual forest biomass on the administrative region level, for the Party of General Pueyrredón (Argentina), was investigated in the work [27].

Seasonality of biomass production affects requested storage facility capacity and consequently, the cost of the logistic supply chain. Authors of the work [28] developed a model to maximize the profit of the biomass supply chain. In this research, one of the variables included in the optimization was a unit land cost, which was used to determine capacity and locations (counties) in which a storage facility would be most economically feasible to install. Total storage capacity for all considered regions was determined in accordance with the annual biomass availability (corn silage, layer hen manure, broiler hen manure and cattle manure).

As can be seen from the literature review, considerable amount of research has been conducted on the development of GIS based approaches for assessment of the biogas potential available on an annual basis. However, generation of agricultural residues is not continuous during the year and since those feedstocks have a low energy density, there is a need for significant storage capacities in case of large time gap between supply and demand. Considering this and the fact that a GIS approach that integrates the seasonal and spatial distribution of biogas potential from agricultural residues and municipal biowaste has not been presented in the previous research, this research work aims to address this research gap. It can be assumed that the integrated assessment of the spatial and seasonal variation could give better insight into the biogas potential and feasibility of its utilization.

METHOD

This work focuses on the assessment of the biogas potential from municipal biowaste and agricultural residues, derived from plants (maize stover, wheat straw, barley straw, oat straw, triticale straw, rapeseed straw, soya-beans straw, sugar beet tops, damaged vegetables) and livestock (manure). As the technologies used to produce biogas are strongly influenced by the structure of the feedstock, the considered feedstocks are divided in two groups:

lignocellulosic and non-lignocellulosic biomass. Figure 1 illustrates the biomass classification used in this research work.

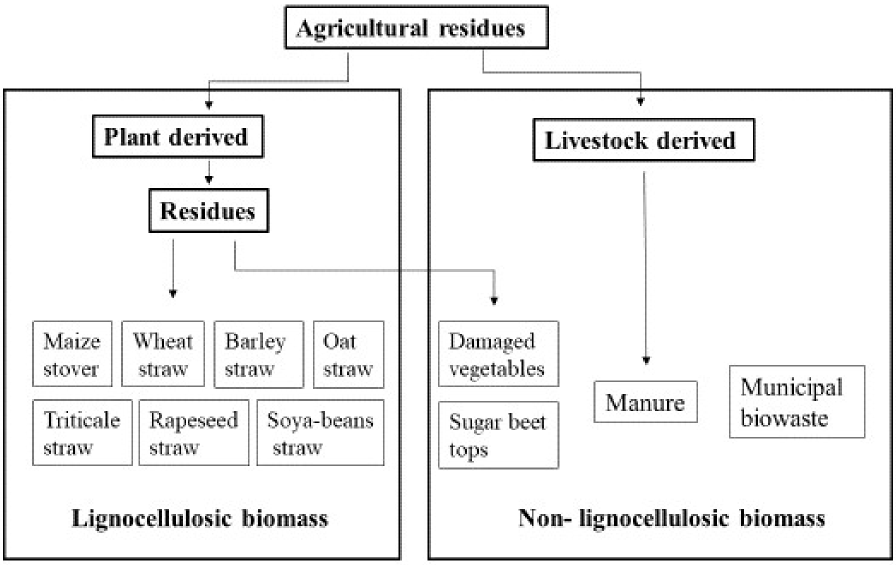

Figure 1 The classification of biomass used in this work

The developed method is based on the combination of statistical and spatial explicit methods. The developed method is divided into the following main steps:

- Biomass technical potential assessment at regional level;
- Energy valorisation of the technical potential;
- Seasonal assessment;
- GIS mapping.

In the next sub-sections, more detailed elaboration of the mentioned steps will be provided.

Biomass technical potential assessment at regional level

In order to assess the technical potential of biomass available for biomass production, this research work aims to investigate the part of the theoretical potential (total production of residues) which is available due to competition with other uses (food, feed, land protection etc.)

The technical potential assessment is conducted at regional level, by using the bottom-up approach. The process itself is handled in two steps:

1. theoretical biomass potential assessment at regional level

Theoretical potential of residues from plant production is defined as the annual production of residues generated during agricultural production. As it is shown in equation (1), it is a function of agricultural production and residue to product ratio:

$$P_{th,pl(i,k)} = M_{(i,k)} * RPR_{(i)} \quad (1)$$

where $P_{th,pl(i,k)}$ stands for the theoretical potential of residues from the agricultural category *i* in the region *k* [kg], $M_{(i,k)}$ for the production of the agricultural category *i* in the region *k* [kg] and $RPR_{(i)}$ for the residue-to-product ratio for the agricultural category *i* [kg/kg]. RPR factors are obtained from the literature and their values for the considered agricultural categories are presented in Table 1.

Table 1 Residue-to-product ratio for different types of agricultural residues

Biomass type	Residue i	$RPR_{(i)}$	Source
Lignocellulosic biomass	Maize stover	196%	[29]
	Wheat straw	128%	[29]
	Barley straw	135%	[29]
	Oat straw	128%	[29]
	Triticale straw	128%	[29]
	Rapeseed stalk	186%	[30]
	Soya-beans straw	153%	[29]
Non-lignocellulosic biomass	Damaged vegetables	153%	[29]
	Sugar beet tops	20%	[29]

Total production $M_{(i,k)}$ of the specific agricultural category is estimated according to equation (2):

$$M_{(i,k)} = y_{(i,k)} * A_{(i,k)} \tag{2}$$

where $y_{(i,k)}$ stands for the average biomass yield of the agricultural category i in the region k (kg/m^2) and $A_{(i,k)}$ for utilised agricultural land for production of category i in the respective region k (m^2).

Biomass yield $y_{(i,k)}$ represents the amount of biomass produced per unit area (1 m^2). Some of the agricultural cultures have a significant variation of the yield, mostly due to weather and climate conditions, as well as soil properties. For this reason, this approach takes into consideration minimum and maximum yield in the last five years, or more precisely, the average value of those two extremes for each considered region (equation 3).

$$y_{(i,k)} = \frac{y_{MIN(i,k)} + y_{MAX(i,k)}}{2} \tag{3}$$

where $y_{(i,k)}$, $y_{MIN(i,k)}$ and $y_{MAX(i,k)}$ stand respectively for average, minimum and maximum biomass yield of the agricultural category i in the last five years, for the region k (kg/m^2).

In the case of livestock derived residues, the theoretical potential of manure is estimated according to equation (4):

$$P_{th,liv(k,l)} = N_{(k,l)} * MPH_{(k,l)} \tag{4}$$

where $P_{th,liv(k,l)}$ stands for the theoretical potential of manure generated in the region k, for the livestock l [kg], $N_{(k,l)}$ for the number of heads of livestock l in the region k [head] and $MPH_{(k,l)}$ for manure per head ratio (Table 2); annual manure production per livestock type l [kg/head].

Table 2 Manure per head ratio for different livestock

L	Cattle	Dairy cow	Pig	Sheep	Poultry

$MPH_{(l)}$ [kg/head]	12,300	18,830	1,200	400	95
Source	[31]	[32]	[31]	[33]	[31]

2. technical biomass potential assessment at regional level

Technical potential is defined as the part of the theoretical potential which is available due to competition with other uses (food, feed, land protection etc.). The assessment of this potential is based on the previously calculated theoretical potential, sustainable removal rates and competitive uses (for livestock production), according to equation (5);

$$P_{tech\,(i,k)} = P_{th,pl(i,k)} * SRR_{(i)} - COMP_{(k)} \quad (5)$$

where $P_{tech\,(i,k)}$ stands for the technical potential of residues of the agricultural category *i* in the region *k* [kg], $P_{th,pl(i,k)}$ for the theoretical potential of residues from the agricultural category *i* in the region *k* [kg], $SRR_{(i)}$ for a sustainable removal rate for the agricultural category *i* [%] and $COMP_{(k)}$ for the amount of residues which should be left for the feeding and bedding of animals in the region *k* [kg].
Sustainable removal rate ($SRR_{(i)}$) refers to the share of residues which could be collected from the field, by considering the share of the residues which should remain in the field in order to protect the soil from wind and erosion, but also the share which is not possible to collect due to losses in the collecting process. Sustainable removal rates ($SRR_{(i)}$) for considered agricultural categories are listed in Table 3.

Table 3 Sustainable removal rates $SRR_{(i)}$ for considered agricultural categories

i	Wheat, barley, rye, oats etc.	Maize	Sunflower	Rapeseed	Sugar beet	Vegetable
$SRR_{(i)}$	40%	50%	50%	50%	50%	90%
Source	[34]	[34]	[34]	[34]	[30]	[30]

In addition to the residues, which should be left in the field, a part of residues (straw) should be used for competitive purposes, mostly livestock production. The amount of residues required for competitive purposes is calculated according to equation (6):

$$COMP_{(k)} = \sum N_{(a,k)} * SPA_{(a)} * s_{(a)} \quad (6)$$

Where $COMP_{(k)}$ stands for the amount of residues which should be left for the feeding and bedding of animals in the region k [kg], $N_{(a,k)}$ for the number of animals *a* (-) in the region *k*, $SPA_{(a)}$ for annual requirements of straw per animal *a* (kg/year) and $s_{(a)}$ for the share of animals to which $SPA_{(a)}$, refers, since not all farms use a straw for livestock production (%). The values of these parameters are listed in Table 4.

Table 4 The values of the parameters for calculating the competitive use of straw for cattle, pig and sheep [35]

a	Cattle	Pig	Sheep
$SPA_{(a)}$[kg/year]	548	183	37

$s_{(a)}$ [%]	25	12.5

Energy valorisation of the technical potential
Once the technical biomass potential is assessed, energy potential can be estimated from specific methane yield of fresh feedstocks and lower heating value of methane, according to equation (7):

$$E_{bio\,(i,k)} = P_{tech\,(i,k)} * y_{CH_4,i} * LHV_{CH_4} \quad (7)$$

where $E_{bio\,(i,k)}$ stands for the energy value of biogas potential from residues of the agricultural category *i* (or municipal biowaste) in the region *k* [MJ], $y_{CH_4,i}$ for the methane yield from 1 kilogram of fresh feedstock [m^3/kg] and LHV_{CH_4} for methane lower heating value [MJ/m^3]. Since the methane yield of lignocellulosic agricultural residues highly depends on the used pre-treatment method, Table 5 lists the methane yield for the respective pre-treatment method.

Table 5 Specific methane yield from lignocellulosic agricultural residues

Residue *i*	Pre-treatment method	Methane yield [m^3/kg]	Source
Maize stover	Pre-treated with 6% NaOH	0.315	[36]
Wheat straw	Pre-treated with 10% NaOH 100 C	0.305	[37]
Barley straw	Extrusion	0.305	[38], [39]
Oat straw	Steam fermention	0.195	[40]
Triticale straw	Pre-treated with with N-methylmorpholine-N-oxide	0.203	[41], [42]
Rapeseed stalk	wet oxidation pretreatment	0.28	[43]
Soya-beans straw	Trichoderma reesei RUT C30	0.08	[44], [45]

Seasonal assessment

Seasonality of feedstocks' availability is assessed according to the months of harvesting/ occurring of the considered feedstocks. Seasonal assessment of plant derived agricultural residues is calculated form the agricultural crops' harvest calendar. For the municipal biowaste, statistical data on monthly production is used.

Both for the lignocellulosic and non-lignocellulosic biomass the potential for the biogas production is assessed for each month of the year, according to equation (8):

$$E_{bio\,(k,m)} = \sum_i E_{bio\,(i,k,m)} \quad (8)$$

where $E_{bio\,(k,m)}$ stands for the energy value of biogas potential in the region *k* in the month *m* [MJ] and $E_{bio\,(i,k,m)}$ for the energy value of biogas potential in the region *k*, in the month *m,* for the specific commodity (residue or biowaste) *i* [MJ].

GIS mapping

In order to perform GIS mapping, the following set of data is necessary: monthly availability of the biogas potential of lignocellulosic and non-lignocellulosic biomass at regional level, georeferenced data on region boundaries and georeferenced land use maps. QGIS tool is used to conduct the mapping process.

Data on monthly availability of biogas potential of lignocellulosic and non-lignocellulosic biomass, calculated in previous steps, is joined to the georeferenced layer of regions' boundaries. In order to carry out a spatial distribution of biogas potential in each region, land cover maps are used. Those maps represent georeferenced information on different types (classes) of physical coverage of the Earth's surface, e.g. grasslands, forests, croplands, lakes, wetlands [46]. Based on two layers of georeferenced information (land cover map and biogas potential at regional level for each month of the year), a biogas potential map is developed. In order to assess the distribution of the biogas potential, the top-down approach is applied and the following equation is used:

$$E_{bio,fiel,m} = \frac{A_{fiel}}{A_k} * E_{bio,k,m} \tag{9}$$

Where $E_{bio,fiel,m}$ stands for the energy value of the biogas potential for the specific field in the specific month *m* [MJ], A_{fiel} for the area of the specific field [m^2], A_k for the total agricultural (or urban) area of the region *k*, in which specific field is located [m^2] and $E_{bio,k,m}$ for the energy value of biogas potential of the region *k*, for the specific month *m* [MJ].

CASE STUDY

The presented method was applied in the case study for the Republic of Croatia, for evaluating the spatial distribution and seasonal variation of biogas production potential from agricultural residues, livestock production and municipal biowaste.
According to Eurostat, in 2016 Croatia had 134 460 agricultural holdings (or farms), working 15 460 km^2 of utilised agricultural area, what is around one quarter (27.7%) of the total land area of Croatia [47]. Croatia's territory is classified in 21 administrative regions (20 counties and the city of Zagreb), which are grouped in 2 statistic regions (Continental and Adriatic Croatia) [48].
Prior to GIS mapping, biogas potential was assessed for each Croatian county (NUTS3 region). Data provided by Paying Agency for Agriculture, Fisheries and Rural Development [49] and the Croatia Bureau of Statistic [50] was used for calculating the theoretical biomass potential in each of the regions. The input data for assessing the potential of manure was taken from the register of domestic animals [51] and the list of utilised agricultural land and number of cottages and poultry of private households [52]. When assessing the seasonality of residue generation, data from Table 6 is used.

Table 6 Residue generation month

Biomass type	Residue	Residue generation month	Source

Lignocellulosic biomass	Maize stover	September	[53]
	Wheat straw	June	[54]
	Barley straw	June, July	[55]
	Oat straw	June	[54]
	Triticale straw	July	[55]
	Rapeseed stalk	June	[54]
	Soya-beans straw	September	[53]
Non-lignocellulosic biomass	Damaged vegetables	August, September	[53]
	Livestock manure	Whole year	[54]
	Municipal biodegradable waste	Whole year	[54]
	Sugar beet tops	September	[54]

In order to assess the spatial distribution of the biogas potential, CORINE land Cover map [56], which defines 42 different land classes was used to detect agricultural land, urban areas and dump sites.
Figure 2 shows the land cover of Croatia.

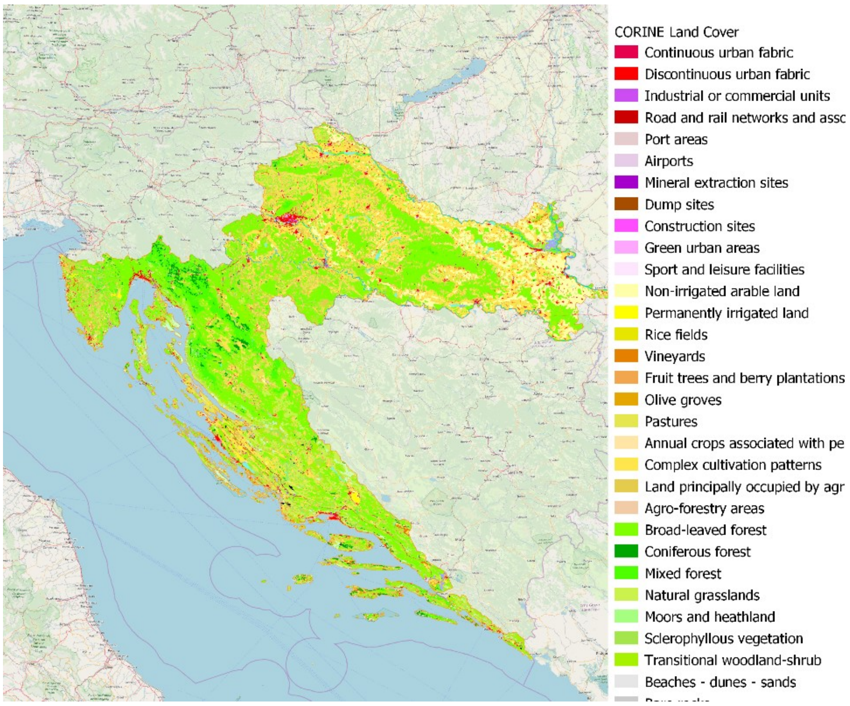

Figure 2 CORINE land Cover -Croatia

RESULTS

The biogas potential from the considered lignocellulosic and non-lignocellulosic feedstocks was calculated at regional level and the seasonal and spatial distribution assessment of the biogas potential at the spatial level of 1 km x 1 km was conducted, as described in the previous sections.

Biogas technical potential assessment at regional level

Non-lignocellulosic biomass

On the national level, the technical potential of non-lignocellulosic biomass available for biogas production is assessed as 3321 GWh (11.96 PJ). Figure 3 presents the energy value of technical potential of non-lignocellulosic biomass available for biogas production for each considered region (Croatian county). It also clearly shows that the highest contribution comes from cattle and dairy cow manure. Osijek- Baranja, Koprivnica-Križevci and Bjelovar-Bilogora counties have the highest potential from all Croatian counties.

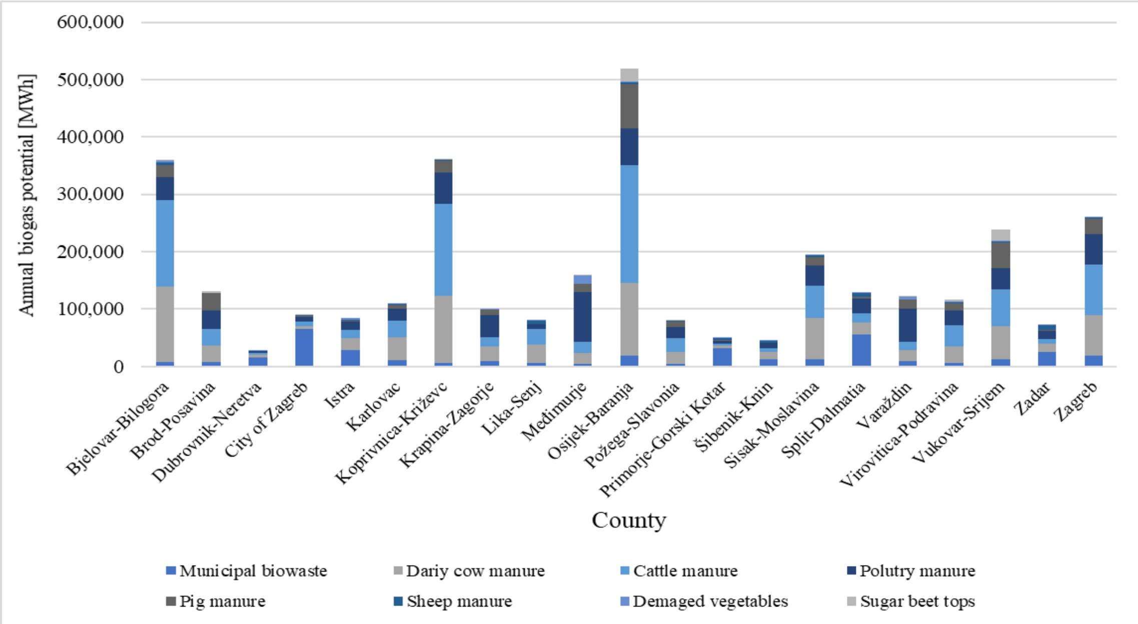

Figure 3 Results of technical potential assessment of non-lignocellulosic biomass available for biogas production

<u>Lignocellulosic biomass</u>

The technical potential of lignocellulosic biomass available for biogas production, which occurs during agricultural production is shown in Figure 4. On the national level, the total technical potential available for biogas production equals 6679 GWh (24 PJ). In all regions, maize stover contributes with the highest share, followed by wheat straw. As it was the case with the non-lignocellulosic biomass, Osijek-Baranja County again has the highest annual technical potential from agricultural production. This correlation can be explained by the fact that in Croatia around 80 % of farms have livestock [57].

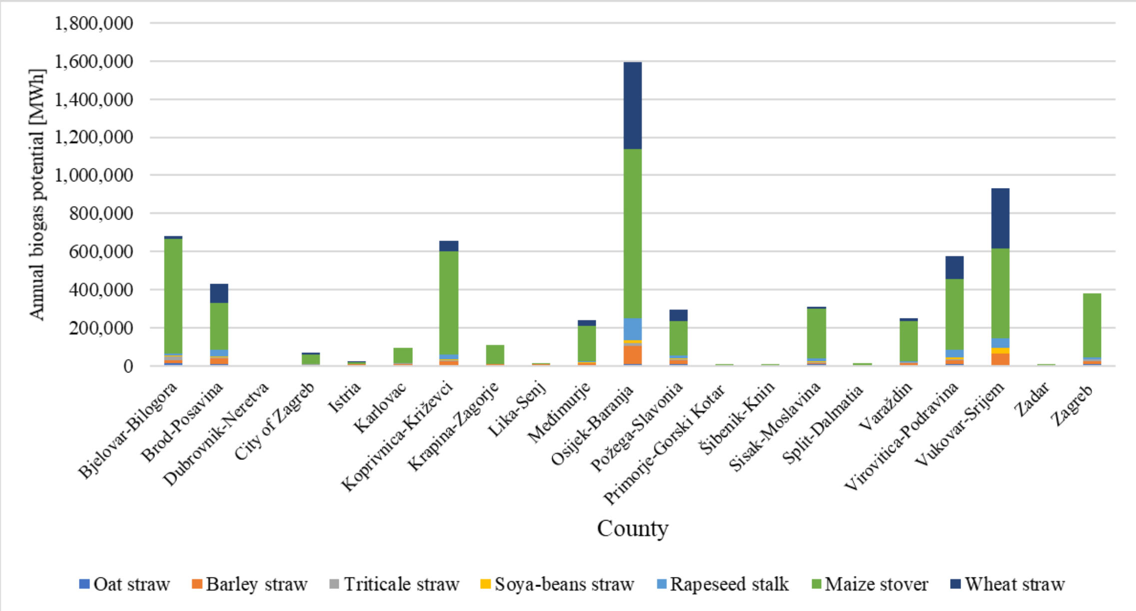

Figure 4 Results of technical potential assessment of lignocellulosic biomass available for biogas production

Seasonal assessment

The monthly availability of biomass potential was determined in accordance with the technical potential assessed at regional level and data on harvesting periods.

Non-lignocellulosic biomass

Table 7 presents the aggregated biogas production potential from non-lignocellulosic biomass for each month of the year for each of the Croatian counties. As it is shown in Table 7, the generation of non-lignocellulosic biomass does not have significant variation during the year. This is due to the nearly continuous production of manure and municipal biowaste, which has a significant share in non-lignocellulosic biomass potential. Therefore, seasonal variations of the considered non-lignocellulosic biomass can be neglected.

Lignocellulosic biomass

Table 8 presents biogas production potential from non-lignocellulosic biomass for each month of the year for each of the Croatian counties. As is it shown in Table 8, considered lignocellulosic feedstocks occur only during three months of the year. Thus, the spatial distribution of the biogas potential was evaluated for each month of its generation.

Table 7 Biogas production potential from non-lignocellulosic biomass

County	January [MWh]	February [MWh]	March [MWh]	April [MWh]	May [MWh]	June [MWh]	July [MWh]	August [MWh]	September [MWh]	October [MWh]	November [MWh]	December [MWh]
Bjelovar-Bilogora	22,355	22,355	22,355	22,355	22,355	22,355	22,355	22,784	25,032	22,355	22,355	22,355
Brod-Posavina	8,159	8,159	8,159	8,159	8,159	8,159	8,159	8,363	10,229	8,159	8,159	8,159
Dubrovnik-Neretva	2,038	2,038	2,038	2,038	2,038	2,038	2,038	2,239	2,201	2,038	2,038	2,038
City of Zagreb	6,883	6,883	6,883	6,883	6,883	6,883	6,883	7,076	7,169	6,883	6,883	6,883
Istria	5,661	5,661	5,661	5,661	5,661	5,661	5,661	7,161	7,119	5,661	5,661	5,661
Karlovac	6,957	6,957	6,957	6,957	6,957	6,957	6,957	7,111	7,989	6,957	6,957	6,957
Koprivnica-Križevci	22,623	22,623	22,623	22,623	22,623	22,623	22,623	22,867	23,308	22,623	22,623	22,623
Krapina-Zagorje	6,372	6,372	6,372	6,372	6,372	6,372	6,372	6,386	6,596	6,372	6,372	6,372
Lika-Senj	5,130	5,130	5,130	5,130	5,130	5,130	5,130	5,162	6,762	5,130	5,130	5,130
Međimurje	9,100	9,100	9,100	9,100	9,100	9,100	9,100	9,531	22,276	9,100	9,100	9,100
Osijek-Baranja	31,318	31,318	31,318	31,318	31,318	31,318	31,318	32,062	54,159	31,318	31,318	31,318
Požega-Slavonia	5,011	5,011	5,011	5,011	5,011	5,011	5,011	5,363	7,147	5,011	5,011	5,011
Primorje-Gorski Kotar	3,692	3,692	3,692	3,692	3,692	3,692	3,692	3,701	3,796	3,692	3,692	3,692
Šibenik-Knin	3,024	3,024	3,024	3,024	3,024	3,024	3,024	3,046	3,076	3,024	3,024	3,024
Sisak-Moslavina	12,384	12,384	12,384	12,384	12,384	12,384	12,384	12,535	12,715	12,384	12,384	12,384
Split-Dalmatia	9,098	9,098	9,098	9,098	9,098	9,098	9,098	9,273	9,465	9,098	9,098	9,098
Varaždin	7,422	7,422	7,422	7,422	7,422	7,422	7,422	8,148	11,881	7,422	7,422	7,422
Virovitica-Podravina	7,113	7,113	7,113	7,113	7,113	7,113	7,113	8,652	9,783	7,113	7,113	7,113
Vukovar-Srijem	13,849	13,849	13,849	13,849	13,849	13,849	13,849	14,911	32,811	13,849	13,849	13,849
Zadar	5,018	5,018	5,018	5,018	5,018	5,018	5,018	5,332	5,635	5,018	5,018	5,018
Zagreb County	16,543	16,543	16,543	16,543	16,543	16,543	16,543	16,732	17,170	16,543	16,543	16,543

Table 8 Biogas production potential from lignocellulosic biomass

County	January [MWh]	February [MWh]	March [MWh]	April [MWh]	May [MWh]	June [MWh]	July [MWh]	August [MWh]	September [MWh]	October [MWh]	November [MWh]	December [MWh]
Bjelovar-Bilogora	-	-	-	-	-	51,596	23,818	-	607,543	-	-	-
Brod-Posavina	-	-	-	-	-	156,991	21,205	-	252,630	-	-	-
Dubrovnik-Neretva	-	-	-	-	-	7	2	-	342	-	-	-
City of Zagreb	-	-	-	-	-	12,481	2,841	-	50,480	-	-	-
Istria	-	-	-	-	-	5,255	4,653	-	9,348	-	-	-
Karlovac	-	-	-	-	-	5,709	6,331	-	82,851	-	-	-
Koprivnica-Križevci	-	-	-	-	-	91,916	15,758	-	546,327	-	-	-
Krapina-Zagorje	-	-	-	-	-	4,055	3,770	-	101,689	-	-	-
Lika-Senj	-	-	-	-	-	4,810	5,180	-	5,005	-	-	-
Međimurje	-	-	-	-	-	47,273	7,725	-	185,605	-	-	-
Osijek-Baranja	-	-	-	-	-	627,659	59,533	-	906,401	-	-	-
Požega-Slavonia	-	-	-	-	-	98,965	13,508	-	182,916	-	-	-
Primorje-Gorski Kotar	-	-	-	-	-	477	450	-	6,801	-	-	-
Šibenik-Knin	-	-	-	-	-	776	689	-	1,338	-	-	-
Sisak-Moslavina	-	-	-	-	-	29,491	8,616	-	268,990	-	-	-
Split-Dalmatia	-	-	-	-	-	1,239	1,186	-	8,350	-	-	-
Varaždin	-	-	-	-	-	28,962	8,510	-	211,276	-	-	-
Virovitica-Podravina	-	-	-	-	-	178,600	15,579	-	383,519	-	-	-
Vukovar-Srijem	-	-	-	-	-	396,688	32,350	-	501,805	-	-	-
Zadar	-	-	-	-	-	2,125	2,055	-	5,695	-	-	-
Zagreb	-	-	-	-	-	22,684	14,738	-	343,882	-	-	-

GIS mapping

The final results present georeferenced maps of the seasonal and spatial distribution of the biogas potential at the spatial level of 1 km x 1 km. These maps were developed using open-source QGIS software.

<u>Non-lignocellulosic biomass</u>

As mentioned above, the seasonal variation of the considered non-lignocellulosic biomass can be neglected. Thus, the spatial distribution of non-lignocellulosic biomass was evaluated for one average month and is presented in Figure 5.

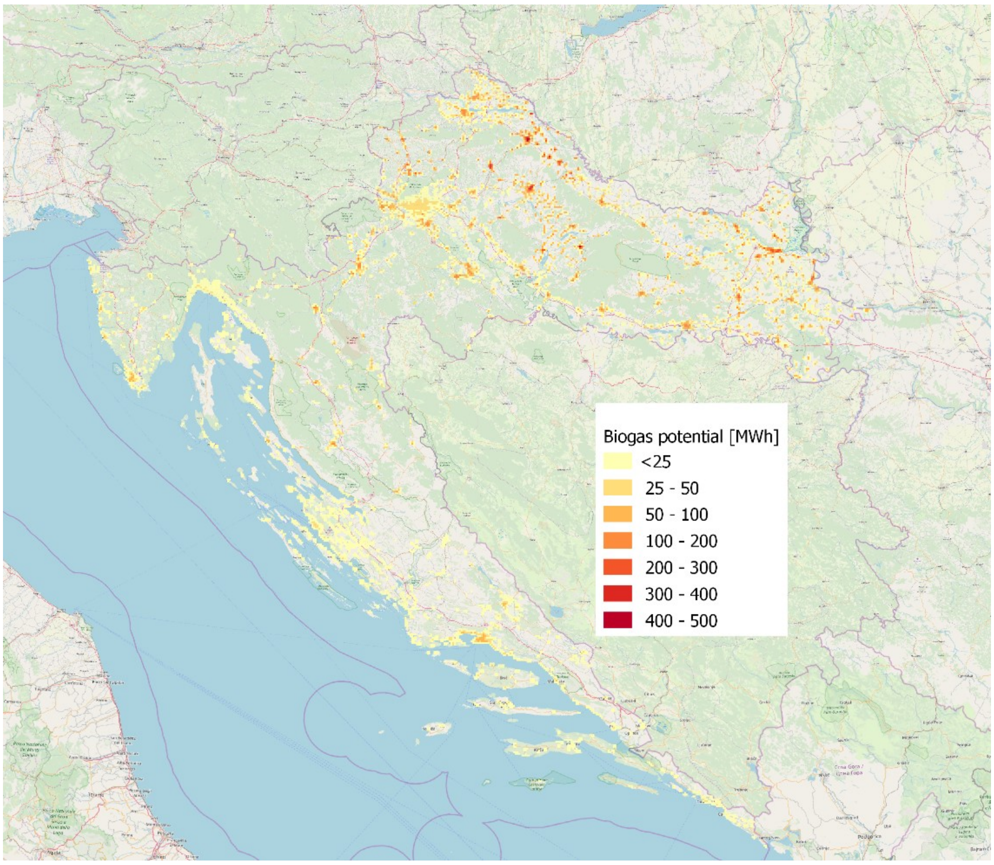

Figure 5 Biogas potential from municipal biowaste and non-lignocellulosic agricultural residues for one average month

Figure 5 clearly shows that biogas potential from biowaste and manure is mostly located in the continental part of Croatia, in rural areas. This can be confirmed by the fact that the city of Zagreb, which has by far the greatest population in Croatia, has the lowest density of biogas potential and lowest total biogas potential. On the other hand, biogas potential in Adriatic part of Croatia mostly follows the population density.

<u>Lignocellulosic biomass</u>

The spatial distribution of the biogas potential was evaluated for each month of its generation. As it is shown in Figure 6, the seasonal variation of the biogas potential significantly differs between the counties. Furthermore, Figure 6 clearly shows that the peak potential is in September. The results obtained for lignocellulosic biomass implies that utilization of lignocellulosic biomass for biogas production requires significant storage capacities.

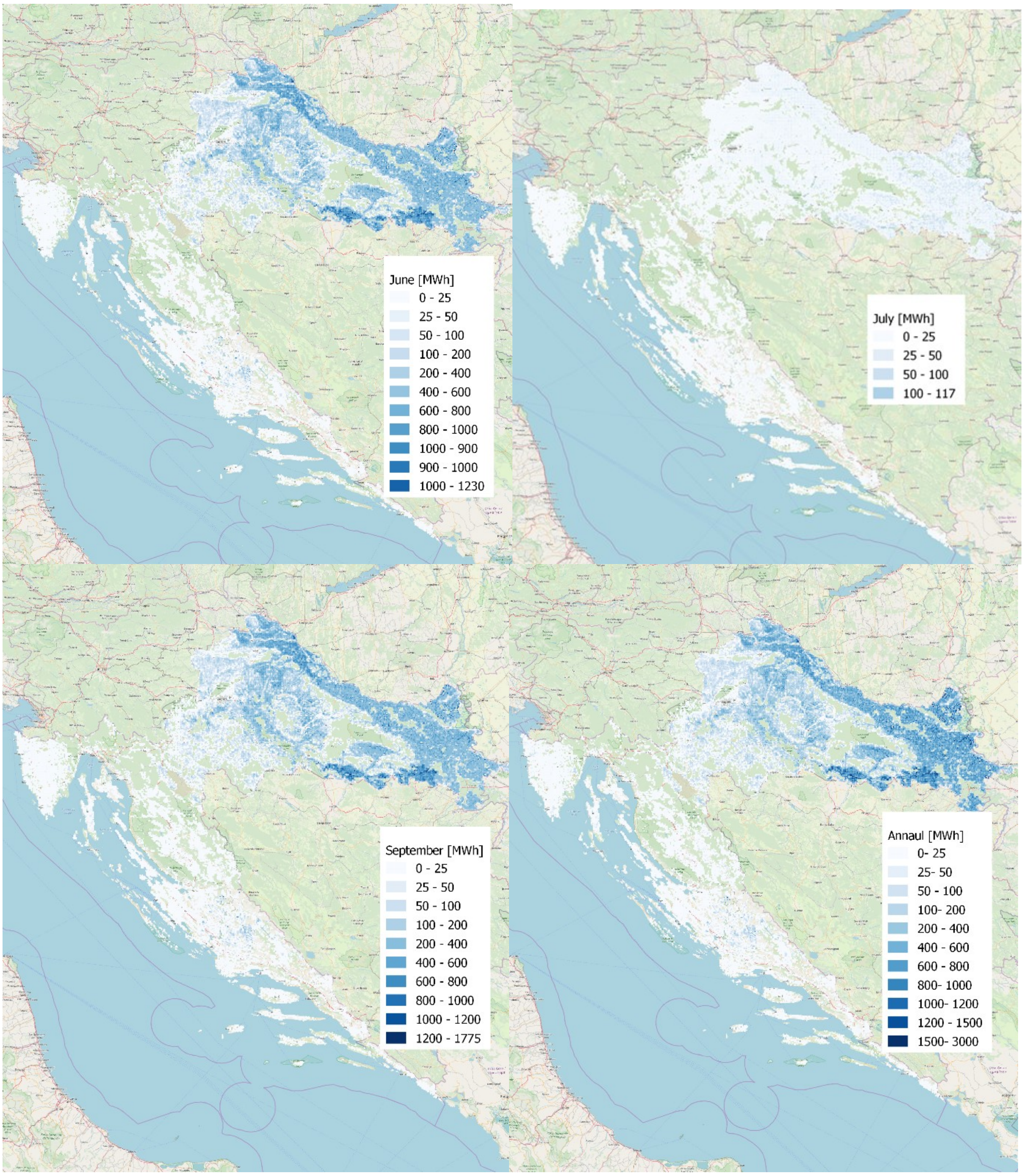

Figure 6 Annual and monthly biogas potential from lignocellulosic agricultural residues

The advantage of integrated seasonal and spatial mapping is the possibility of storage facility capacity assessment. In order to prove the benefits of the proposed approach, it was compared with currently used approaches. Therefore, required storage capacities were assessed for two examples selected from the area presented in Figure 6, for which spatial and seasonal assessment was conducted in the previous steps. For both examples, storage facility capacity is calculated for the lignocellulosic agricultural residues which are being produced in the area of 90 km^2 (grid with 90 cells). In order to handle supply risk of feedstock, the minimum stored amount at the end of one month is set to be sufficient to cover the feedstock demand for at least one and a half month. Furthermore, the demand for the feedstocks is expected to be continuous during the year, for both examples.

The first example is located in Varaždin county (northern Croatia) and presented in Figure 7.

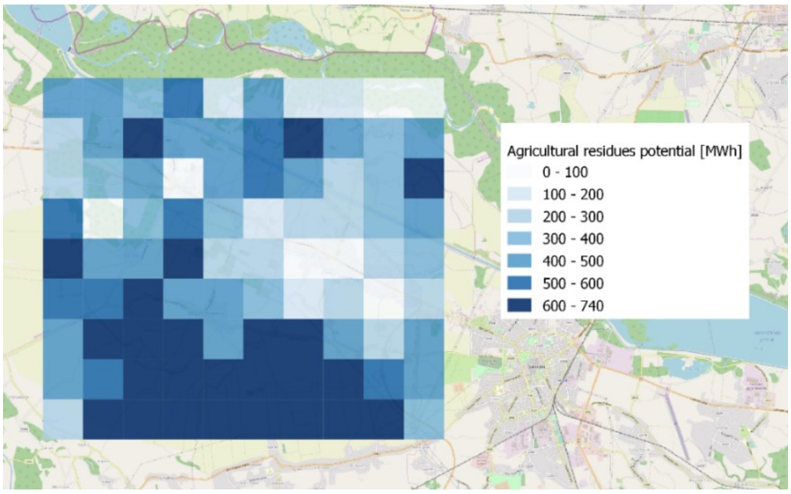

Figure 7 Annual potential of agricultural residues- Varaždin county (Example 1)

In the first example, annual technical potential equals 14105 tonnes of agricultural residues, which has the biogas potential of 0.143 PJ (39952 MWh). Annual variations of biomass potential (supply) and stored quantities are presented in Table 9.

Table 9 Seasonal variation of biomass potential (supply) and stored amount (Example 1)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Supply [t]	-	-	-	-	-	1,774	508	-	11,823	-	-	-
Demand [t]	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1175	1,175	1,175	1,175
Stored amount* [t]	7,708	6,532	5,357	4,181	3,006	3,605	2,937	1,762	12,410	11,234	10,059	8,883

*feedstock amount stored at the end of the month

As it is shown in Table 9, the maximum stored feedstock amount is in September and it equals 12410 t. Thus, 12410 t can be considered as the necessary storage facility capacity. In other cases where biomass availability is assessed at the annual basis and there is no information on the seasonal variation, it is assumed that the value of necessary storage facility capacity is the same as the annual biomass potential. By comparing the storage facility calculated with this approach to the one related to the annual assessment, it is shown that the application of seasonal assessment results in 12% lower storage facility capacity. The second example is located in Brod-Posavina county (eastern Croatia) and is shown in Figure 8.

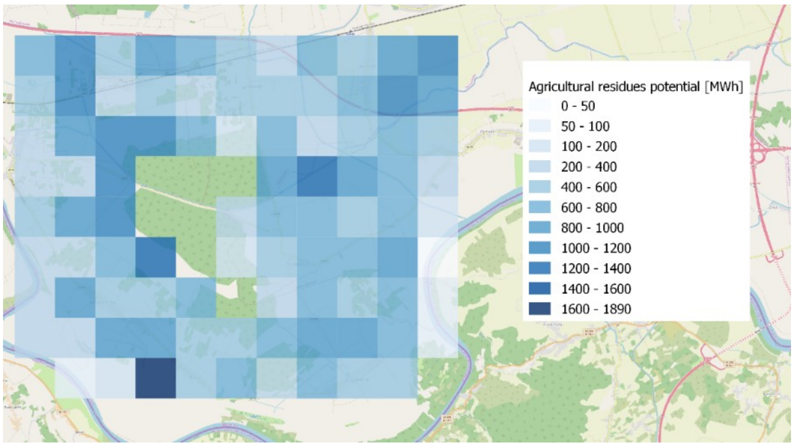

Figure 8 Annual potential of agricultural residues- Brod-Posavina county (Example 2)

In the second example, annual technical potential equals 20579 tonnes of agricultural residues, which has the biogas potential of 0.198 PJ (55017 MWh). Annual variations of the biomass potential (supply) and stored amounts are presented in Table 10.

Table 10 Seasonal variation of biomass potential (supply) and stored amount for example 2

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Supply [t]	-	-	-	-	-	4,105	670	-	15,803	-	-	-
Demand [t]	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1,175	1,175
Stored amount* [t]	7,708	6,532	5,357	4,181	3,006	3,605	2,937	1,762	12,410	11,234	10,059	8,883

*feedstock amount stored at the end of the month

As in the previous example, the maximum stored feedstock amount is in September. However, in this example, the difference between biomass potential in September and in other summer months is not so significant. When comparing the storage facility capacity determined with this approach, and the one related to the annual assessment, it is shown that the application of seasonal assessment results in 40% lower storage facility capacity for this specific example.

DISCUSSION

The developed method can be used for local, regional and national planning of biogas production projects, supply chain risk management and storage facility capacity assessment. The implementation of those projects have a potential to increase local renewable production, but also provide biological stabilization of manure, agricultural residues and municipal biowaste by AD and therefore decrease related GHG emissions that would otherwise occur without AD [58]. Furthermore, one of the positive externalities beyond renewable energy production and GHG reduction is increased soil organic matter, due to continuous return of digestate. This results in increased food and feed production, compared to the case prior to bioenergy production [59].
In the previous research works, the authors used GIS tools for the assessment of the spatial distribution of the annual biomass technical assessment. As it is shown by the results obtained in this research work, this gives a sufficient insight for the feedstocks with near continuous

monthly production, such as manure and municipal biowaste, what is not the case with lignocellulosic biomass.

The method developed in the work [27] which investigates the monthly availability of crop, horticultural and forestry residues, enables seasonal assessment of biomass potential on a regional basis. Due to wide geographic distribution of the agricultural residues and low energy density of the considered feedstocks, information on the biomass monthly availability on regional level is often not sufficient for the determination of the feasibility of biogas utilization. Therefore, the added value of the integrated approach presented in this research work is that it provides better insight into the biogas potential availability and required storage facility capacity. Assessment of the storage facility capacity is a part of the optimization of biomass supply chain in some of the research works, such as the work [28]. In this work, authors have determined the storage facility capacity in accordance with the price of the land unit where the storage unit is planned to be built, but with the constraint that capacities of all storage facilities should equal to the annual biomass potential in the considered regions. As it is shown from the two examples given in the section above, the approach presented in this research work results with lower storage facility capacity, due to better insight into the biomass availability. This shows the importance of including integrated seasonal and spatial variation in the assessment of the potential of lignocellulosic residues available for biogas production, in order to have more accurate input data for the feasibility projects for biogas utilization.

CONCLUSION

This paper presents a Geographical Information System (GIS) based approach for evaluating the spatial distribution and seasonal variation of biogas production potential. In detail, the biogas production potential was assessed in accordance with the technical potential which was calculated at regional level and takes into consideration the sustainable removal rate of biomass, as well as competitive purposes. This approach is used for the case study of Croatia. Furthermore, the potential of agricultural residues and organic municipal biowaste was assessed in order to define the potential for biogas production.

The results at national level show that the annual potential for biogas production from manure, damaged vegetable and municipal biowaste equals 11.96 PJ, while the potential of lignocellulosic agricultural residues is 24 PJ. The use of the GIS tool proved to be beneficial for the seasonal assessment as it enabled fast and accurate seasonal assessment. The results proved that seasonal variations of the potential of non-lignocellulosic agricultural residues and municipal biowaste can be neglected since the generated feedstocks which make the most significant share of considered feedstocks (manure and biowaste) have near-continuous generation during the whole year. It is not the case with the generation of lignocellulosic agricultural residues, which have a significant variation during the year. In this research work, it is shown in two examples that application of seasonal assessment approach leads to lower storage facility capacity requirements. For the considered examples, it resulted in 12% and 40% lower storage facility capacity requirements, compared with annual assessment approach. It also proved that seasonal variation of biogas potential from non-lignocellulosic biomass does not follow the same trend between the counties. As it is presented in the results, spatial and seasonal assessment of the potential of lignocellulosic agricultural residues available for biogas production provide more accurate input data. Therefore, there is a strong need to include seasonal variations in potential assessment of the considered feedstocks. The developed method can be used for development of a GIS based decision support system, that could be used for the national, local and regional development of biogas production. The integrated spatial and seasonal assessment gives planners and investors a detailed and clear view on the distribution of the biogas potential at high spatial level and monthly availability.

As further research, this method can be extended to include more feedstocks feasible for biogas production but barely valorised, such as industrial residues and by-products.

ACKNOWLEDGEMENT

This work has been financially supported by the Slovenia-Croatia bilateral project Interdisciplinary Research on Variable Renewable Energy Source and Biomass in Clean and Circular Economy (BIOVARES) and RESFLEX project, funded by Programme of the Government of Republic of Croatia for encouraging research and development activities in the area of Climate Change.

REFERENCES

[1] A. Chiodi, P. Deane, M. Gargiulo, and B. Ó Gallachóir, "The Role of Bioenergy in Ireland's Low Carbon Future – Is it Sustainable?," *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 3, no. 2, pp. 196–216, 2015, doi: 10.13044/j.sdewes.2015.03.0016.

[2] R. L. Smith, *Production of Biofuels and Chemicals with Microwave*, vol. 3. 2015.

[3] T. Losak, J. Hlusek, A. Zatloukalova, L. Musilova, M. Vitezova, P. Skarpa *et al.*, "Digestate from Biogas Plants is an Attractive Alternative to Mineral Fertilisation of Kohlrabi," vol. 2, no. 4, pp. 309–318, 2014.

[4] European Commission, "Commission decision of 18 November 2011 establishing rules and calculation methods for verifying compliance with the targets set in Article 11(2) of Directive 2008/98/EC of the European Parliament and of the Council," *Off. J. Eur. Union*, vol. 310, no. 2, p. 11, 2011.

[5] European Biogas Association (EBA), "European Biogas Association Annual Report 2018," 2018.

[6] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund *et al.*, "4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems.," *Energy*, vol. 68, pp. 1–11, 2014, doi: 10.1016/j.energy.2014.02.089.

[7] P. Saavalainen and R. L. Keiski, "Biobutanol as a Potential Sustainable Biofuel - Assessment of Lignocellulosic and Waste-based Feedstocks," *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 1, no. 2, pp. 58–77, 2013.

[8] J. M. Aberilla, A. Gallego-Schmid, and A. Azapagic, "Environmental sustainability of small-scale biomass power technologies for agricultural communities in developing countries," *Renew. Energy*, vol. 141, pp. 493–506, 2019, doi: 10.1016/j.renene.2019.04.036.

[9] W. Liu, H. Lund, B. V. Mathiesen, and X. Zhang, "Potential of renewable energy systems in China," *Appl. Energy*, vol. 88, no. 2, pp. 518–525, 2011, doi: 10.1016/j.apenergy.2010.07.014.

[10] B. Batidzirai, E. M. W. Smeets, and A. P. C. Faaij, "Harmonising bioenergy resource potentials - Methodological lessons from review of state of the art bioenergy potential assessments," *Renew. Sustain. Energy Rev.*, vol. 16, no. 9, pp. 6598–6630, 2012, doi: 10.1016/j.rser.2012.09.002.

[11] G. Lourinho and P. Brito, "Assessment of biomass energy potential in a region of Portugal (AltoAlentejo)," *Energy*, vol. 81, pp. 189–201, 2015, doi: 10.1016/j.energy.2014.12.021.

[12] M. Haase, C. Rösch, and D. Ketzer, "GIS-based assessment of sustainable crop residue potentials in European regions," *Biomass and Bioenergy*, vol. 86, pp. 156–171, 2016, doi: 10.1016/j.biombioe.2016.01.020.

[13] K. Van Meerbeek, Sam Ottoy, Annelies De Meyer, T. V. Schaeybroeck, J, V.

Orshoven, B. Muys *et al.* "The bioenergy potential of conservation areas and roadsides for biogas in an urbanized region," *Appl. Energy*, vol. 154, no. 2015, pp. 742–751, 2020, doi: 10.1016/j.apenergy.2015.05.007.

[14] M. Tańczuk, R. Junga, A. Kolasa-Więcek, and P. Niemiec, "Assessment of the energy potential of chicken manure in Poland," *Energies*, vol. 12, no. 7, 2019, doi: 10.3390/en12071244.

[15] X. Chen, "Economic potential of biomass supply from crop residues in China," *Appl. Energy*, vol. 166, pp. 141–149, 2016, doi: 10.1016/j.apenergy.2016.01.034.

[16] V. Vukašinović and D. Gordić, "Optimization and GIS-based combined approach for the determination of the most cost-effective investments in biomass sector," *Appl. Energy*, vol. 178, pp. 250–259, 2016, doi: 10.1016/j.apenergy.2016.06.037.

[17] B. Sharma, S. Birrell, and F. E. Miguez, "Spatial modeling framework for bioethanol plant siting and biofuel production potential in the U.S," *Appl. Energy*, vol. 191, pp. 75–86, 2017, doi: 10.1016/j.apenergy.2017.01.015.

[18] A. Comber, J. Dickie, C. Jarvis, M. Phillips, and K. Tansey, "Locating bioenergy facilities using a modified GIS-based location-allocation-algorithm: Considering the spatial distribution of resource supply," *Appl. Energy*, vol. 154, pp. 309–316, 2015, doi: 10.1016/j.apenergy.2015.04.128.

[19] R. Bedoić, B. Ćosić, and N. Duić, "Technical potential and geographic distribution of agricultural residues, co-products and by-products in the European Union," *Sci. Total Environ.*, vol. 686, pp. 568–579, 2019, doi: 10.1016/j.scitotenv.2019.05.219.

[20] A. Sultana and A. Kumar, "Development of tortuosity factor for assessment of lignocellulosic biomass delivery cost to a biorefinery," *Appl. Energy*, vol. 119, pp. 288–295, 2014, doi: 10.1016/j.apenergy.2013.12.036.

[21] F. Valenti, S. M. C. Porto, B. E. Dale, and W. Liao, "Spatial analysis of feedstock supply and logistics to establish regional biogas power generation: A case study in the region of Sicily," *Renew. Sustain. Energy Rev.*, vol. 97, no. May 2017, pp. 50–63, 2018, doi: 10.1016/j.rser.2018.08.022.

[22] F. Valenti, W. Liao, and S. MC Porto, "A GIS-based spatial index of feedstock-mixture availability for anaerobic co-digestion of Mediterranean by-products and agricultural residues," *Biofuels, Bioprod. Biorefining*, vol. 6, no. 3, pp. 362–378, 2018, doi: 10.1002/bbb.

[23] R. O. Shea, D. M. Wall, I. Kilgallon, J. D. Browne, and J. D. Murphy, "Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region," *Appl. Energy*, vol. 188, no. 2017, pp. 237–256, 2020, doi: 10.1016/j.apenergy.2016.11.121.

[24] K. Natarajan, P. Latva-Käyrä, A. Zyadin, and P. Pelkonen, "New methodological approach for biomass resource assessment in India using GIS application and land use/land cover (LULC) maps," *Renew. Sustain. Energy Rev.*, vol. 63, pp. 256–268, 2016, doi: 10.1016/j.rser.2016.05.070.

[25] J. Höhn, E. Lehtonen, S. Rasi, and J. Rintala, "A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland," *Appl. Energy*, vol. 113, no. 2014, pp. 1–10, 2014, doi: 10.1016/j.apenergy.2013.07.005.

[26] C. Franco, M. Bojesen, J. L. Hougaard, and K. Nielsen, "A fuzzy approach to a multiple criteria and Geographical Information System for decision support on suitable locations for biogas plants," *Appl. Energy*, vol. 140, pp. 304–315, 2015, doi: 10.1016/j.apenergy.2014.11.060.

[27] J. J. Roberts, A. M. Cassula, P. Osvaldo Prado, R. A. Dias, and J. A. P. Balestieri, "Assessment of dry residual biomass potential for use as alternative energy source in

the party of General Pueyrredón, Argentina,” *Renew. Sustain. Energy Rev.*, vol. 41, pp. 568–583, 2015, doi: 10.1016/j.rser.2014.08.066.
[28] Ş. Y. Balaman and H. Selim, “A network design model for biomass to energy supply chains with anaerobic digestion systems,” *Appl. Energy*, vol. 130, pp. 289–304, 2014, doi: 10.1016/j.apenergy.2014.05.043.
[29] Food and Agriculture Organization of the United Nations, “BEFS Rapid Appraisal Data Collection.” [Online]. Available: http://www.fao.org/fileadmin/user_upload/energy/befs/Data_collection_sheet/BEFS_RA_Data_Collection.xlsm.
[30] T. Ronzon, S. Piotrowski, and M. Carus, “DataM – Biomass estimates (v3): a new database to quantify biomass availability in the European Union,” 2015, doi: 10.2791/650215.
[31] X. Flotats, A. Bonmati, J. Palatsi, and A. Magri, “Inventory of Manure Processing Activities in Europe,” 2012.
[32] T. Nennich, J. H. Harrison, D. Meyer, W. P. Weiss, A. J. Heinrichs, R. L. Kincaid, *et al.*, “Development of Standard Methods to Estimate Manure Production and Nutrient Characteristics From Dairy Cattle,” *Conf. Present. White Pap. Biol. Syst. Eng.*, no. October, pp. 1–6, 2003.
[33] J. C. Barker and F. R. Walls, “Livestock manure production and nutrient content,” 2002.
[34] N. Scarlat, M. Martinov, and J. F. Dallemand, “Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use,” *Waste Manag.*, vol. 30, no. 10, pp. 1889–1897, 2010, doi: 10.1016/j.wasman.2010.04.016.
[35] N. Scarlat, M. Martinov, and J.-F. Dallemand, “Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use,” *Waste Manag.*, vol. 30, pp. 1889–1897, 2010, doi: 10.1016/j.wasman.2010.04.016.
[36] S. Khatri, S. Wu, S. Kizito, W. Zhang, J. Li, and R. Dong, “Synergistic effect of alkaline pretreatment and Fe dosing on batch anaerobic digestion of maize straw,” *Appl. Energy*, vol. 158, pp. 55–64, 2015, doi: 10.1016/j.apenergy.2015.08.045.
[37] C. Sambusiti, F. Monlau, E. Ficara, H. Carrère, and F. Malpei, “A comparison of different pre-treatments to increase methane production from two agricultural substrates,” *Appl. Energy*, vol. 104, pp. 62–70, 2013, doi: 10.1016/j.apenergy.2012.10.060.
[38] C. Akobi, H. Yeo, H. Hafez, and G. Nakhla, “Single-stage and two-stage anaerobic digestion of extruded lignocellulosic biomass,” *Appl. Energy*, vol. 184, pp. 548–559, 2016, doi: 10.1016/j.apenergy.2016.10.039.
[39] M. Hjorth, K. Gränitz, A. P. S. Adamsen, and H. B. Møller, “Extrusion as a pretreatment to increase biogas production,” *Bioresour. Technol.*, vol. 102, no. 8, pp. 4989–4994, 2011, doi: 10.1016/j.biortech.2010.11.128.
[40] D. Y. Dererie, S. Trobro, M. H. Momeni, H. Hansson, J. Blomqvist, V. Passoth *et al.*, “Improved bio-energy yields via sequential ethanol fermentation and biogas digestion of steam exploded oat straw,” *Bioresour. Technol.*, vol. 102, no. 6, pp. 4449–4455, 2011, doi: 10.1016/j.biortech.2010.12.096.
[41] A. Teghammar, K. Karimi, I. Sárvári Horváth, and M. J. Taherzadeh, “Enhanced biogas production from rice straw, triticale straw and softwood spruce by NMMO pretreatment,” *Biomass and Bioenergy*, vol. 36, pp. 116–120, 2012, doi: 10.1016/j.biombioe.2011.10.019.
[42] S. Kusch, B. Schumacher, H. Oechsner, and W. Schäfer, “Methane yield of oat husks,”

Biomass and Bioenergy, vol. 35, no. 7, pp. 2627–2633, 2011, doi: 10.1016/j.biombioe.2011.02.044.
[43] A. Petersson, M. H. Thomsen, H. Hauggaard-Nielsen, and A. B. Thomsen, “Potential bioethanol and biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba bean,” *Biomass and Bioenergy*, vol. 31, no. 11–12, pp. 812–819, 2007, doi: 10.1016/j.biombioe.2007.06.001.
[44] Y. Deng, B. Dai, J. Xu, X. Liu, and J. Xu, “Anaerobic co-digestion of rice straw and soybean straw to increase biogas production by pretreatment with trichoderma reesei RUT C30,” *Environ. Prog. Sustain. Energy*, vol. 37, no. 3, pp. 1050–1057, 2018, doi: 10.1002/ep.12782.
[45] Đ. Kovačić, D. Kralik, S. Rupčić, D. Jovičić, R. Spajić,a and M. Tišmac *et al.*, “Soybean Straw, Corn Stover and Sunflower Stalk…,” *Chem. Biochem. Eng. Q*, vol. 31, no. 3, pp. 187–198, 2017, doi: 10.15255/CABEQ.2016.985.
[46] Copernicus Global Land Service, “Land Cover.” [Online]. Available: https://land.copernicus.eu/global/products/lc.
[47] The European Commission, “Statistical Factsheet: Croatia,” no. June. 2019.
[48] The Croatian Bureau of Statistics, “Nacionalna klasifikacija prostornih jedinica za statistiku 2012. (NKPJS 2012.).” Narodne novine, 2012.
[49] “Paying Agency for Agriculture, Fisheries and Rural Development ; Statistic for 2017.” [Online]. Available: http://www.apprrr.hr/statistika-2017-2410.aspx.
[50] “The Croatian Bureau of Statistic-Database.” [Online]. Available: https://www.dzs.hr/. [Accessed: 08-Mar-2018].
[51] Croatian Agricultural Agency, “Central Register of Livestock,” 2016. [Online]. Available: http://www.hpa.hr/wp-content/uploads/2016/08/eGlasilo-HPA-kolovoz-2016.pdf.
[52] The Croatian Bureau of Statistics, “Area of used agricultural land and number of stocks and poultry of private households,” 2011. [Online]. Available: https://www.dzs.hr/Hrv/censuses/census2011/results/xls/Kucgrad_06_HR.xls.
[53] Ministry of Agriculture, “Works in the field in September.” [Online]. Available: https://www.savjetodavna.hr/2006/09/12/radovi-na-njivi-u-rujnu/. [Accessed: 11-Jan-2020].
[54] Cipro, “Field work calendar.” [Online]. Available: http://www.cipro.hr/kalendar-radova-polje.htm#.XK-c--gzZPZ.
[55] Ministry of Agriculture, “Works in the field in July.” [Online]. Available: https://www.savjetodavna.hr/2006/07/01/radovi-na-njivi-u-srpnju/. [Accessed: 15-Jan-2020].
[56] “CORINE Land Cover — Copernicus Land Monitoring Service.” [Online]. Available: https://land.copernicus.eu/pan-european/corine-land-cover.
[57] “Structure of agriculture in Croatia - Statistics Explained.” [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Structure_of_agriculture_in_Croatia.
[58] B. E. Dale, F. Sibilla, C. Fabbri, M. Pezzaglia, B. Pecorino, E. Veggia *et al.*, “Biogasdoneright^{TM}: An innovative new system is commercialized in Italy,” *Biofuels, Bioprod. Biorefining*, vol. 6, no. 3, pp. 341–345, 2016, doi: 10.1002/bbb.1671.
[59] R. Selvaggi*,* L. Rossi, S. Bozzetto, B. Pecorino, B. E. Dale, “Sequential crops for food, energy, and economic development in rural areas: the case of Sicily,” *Biofuels, Bioprod. Biorefining*, vol. 6, no. 3, pp. 246–256, 2017, doi: 10.1002/bbb.