An integrated Geographical Information System (GIS) approach for assessing seasonal variation and spatial distribution of biogas potential from industrial residues and by-products

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ABSTRACT

Biogas production through anaerobic digestion technology offers numerous benefits as it may not only recover a part of the energy contained in the biomass but also contributes to circular economy targets. Concerns about biogas production from feed and food crops raise the need for the assessment of biogas potential produced out of biomass, which is not in competition with the other purposes, such as potential of industrial residuals and by-products. This research presents the approach for the assessment of biogas potential from industrial residues and by-products, by taking into consideration spatial and seasonal variation of feedstock production. In this work, considered feedstocks are those which occur in sugar, wine, vegetable and olive oil industries. This approach was tested through the case study of two Croatian counties. The

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results are presenting the spatial distribution and seasonal variation of the biogas potential from residues and by-products of considered industries. The results proved the hypothesis that there is a strong need to include a seasonal aspect when defining the biomass potential viable for biogas production, due to the low annual load factor calculated for potential biogas sites, which range from 0.1-0.24 for the case when feedstock storage is not available.

Keywords: biogas, GIS, seasonality, industrial by-products and residues

HIGHLIGHTS

- A novel approach for integrated assessment of seasonal and spatial distribution of biogas potential
- The influence of seasonality on the cost-effectiveness of biogas production is assessed
- The results proved a strong need to include seasonal aspect when defining biogas potential

INTRODUCTION

Degradation of organic materials under anaerobic conditions by microorganisms results in the production of biogas, renewable fuel used for production of electricity, heat or biomethane-biogas cleaned of impurities, which can be used as a natural gas substitution.

The EU policies on renewable energy production introduced various support schemes that encouraged the increase of biogas production [1]. By the end of 2018, there were 18,802 biogas plants and 610 biomethane plants in operation in Europe [2]. Those plants use, to the greatest extent, maize silage as a substrate for biogas production [3], due to high biomass and biogas yields, as well as feedstock storability [4]. However, utilization of feedstocks that have been grown on agricultural land has caused concerns over the negative environmental impact due to direct and indirect land-use change. Direct land-use change is defined as the land-use change that occurs when biogas feedstock cultivation displaces a prior crop that was cultivated on that land, for other use (i.e. food or feed production). Thus, a direct connection can be made between biogas production and land-use change [5]. On the other hand, indirect land-use change occurs when the cultivation of crops for biogas (or bioliquids, biomass) production displaces the traditional production of crops for food and feed purposes, which result in additional demand on land. This increasing pressure on land can lead to the extension of agricultural land into areas with high carbon stock such as wetlands, peat land and forests, thus causing additional greenhouse gas emissions [6].

In order to diminish this negative environmental impact, residual resources are expected to have increased utilization due to lower environmental impact [7]. In 2018, the revised Renewable Energy Directive [8] has set minimum GHG savings, which biogas used for electricity, heat and cooling production has to compile, and limits the use of maize silage. It has been proven by researchers that alternative substrates like industrial by-products yield better prospects and lower production costs [9]. In addition, Korberg et al. [10] concluded that free feedstock for biogas generation brings significant energy system cost reductions.

Besides the contribution of biogas to renewable energy generation, biogas generation from wastes must be viewed from the standpoint of bio circular economy and sustainable development. While generating renewable energy and minimising environmental impacts of various types of waste materials, biogas generation through anaerobic digestion technology (AD) meets requirements related to waste treatment. In addition, digestate obtained through

AD technology is suitable as agricultural fertiliser, due to the high ammonium-N/total N ratio [11]. Residues and by-products which occur in some industries for food and beverage production, such as industries for sugar, wine, olive oil and vegetable production, are noted as feasible feedstock for biogas generation. This has been proven in various experimental studies, such as the study [12] where Al Afif et al. concluded that the quality of biogas produced from olive mill solid waste was sufficient for all experiments. Furthermore, Duarte et al [13] concluded in their experimental research that industrial residues such as residues from vegetable and fruit industry are promising co-digestion substrates due to the positive synergetic effect demonstrated in increased biogas yield.
In this context, the assessment of biogas potential of residues and by-products captivates the attention of many researchers. Moreda et al. [14] calculated the yearly methane potential of numerous agricultural residues and by-products from agro-industrial production in Uruguay. In this review work, Moreda et al detected residues and by-products from a brewery, dairy, fish, malting, poultry, rice, sausage, slaughterhouse, tannery, wine and wool scouring industry as viable for biogas production and assessed respective annual potential on the national level. Similar to this, Kythreotou et al. [15] assessed the annual biogas potential of several potential sources for biogas production, such as biodegradable fractions of municipal solid waste, residues from food and beverage industry and sewage sludge. Assessment of the biogas potential from manure and slaughterhouse by-products was conducted in the work [16]. In this work, Mahmoud Ali et al. used the GIS tool to present the distribution of annual biogas potential from the above-mentioned feedstocks, between Mauritania's provinces. In another work [17], Pereira et al. calculated the economic potential for electricity generation from vinasse in accordance with the annual potential of biogas from vinasse, obtained from sugarcane processing. The economic potential was calculated with a GIS tool, for each municipality of the state of São Paulo. Höhn et al. [18] developed GIS-based methods for the analysis of suitable biogas plant location considering the spatial variation of annual biogas potential from numerous agricultural residues, industrial by-products, municipal biowaste, wastewater sludge and energy crops. In the work [19], the annual potential of biogas and second-generation biomethane was calculated for the territory of Sicily, for numerous feedstocks: pomace, olive residue, slaughter, waste, pulp, cattle slurry, pig slurry, straw from cereal crops and many other agricultural residues and industrial by-products, within the territory of Sicily. In accordance with the annual potential of residues from palm oil industry, Loong Lam et al. [20] developed an environmental strategy for a sustainable supply chain.

As can be seen from the literature review, application of the GIS tool has been recognised as very beneficial for biomass potential mapping, as it can give valuable insights into the spatial distribution of the biomass potential and provide input data for identification of the optimal location for new biogas plant sites, sustainability assessment, techno-economic studies of biomass supply chains and supply risks management. Furthermore, interest in the utilization of novel feedstock for biogas production, such as industrial by-products for biogas production is increasing, due to several environmental and economic benefits.
Up until now, biogas potential from industrial residues and by-products was assessed on an annual basis. However, industrial production of some commodities, such as wine, sugar, mashed tomatoes and olive oil is not continuous during the year. This represents an additional challenge in the utilization of those feedstocks, as it brings several constraints in energy

planning. The contribution of this work is to develop a method that would enable the integration of seasonal and spatial assessment, developed to be used with a GIS tool.
The hypothesis of this research is that the assessment of the spatial and seasonal variation of biogas potential from industrial by-products could give better insight into the economic viability and feasibility of its utilization. This approach will be presented and validated in the following sections.

METHOD

The approach presented in this work exploits the spatial distribution of biogas potential from industrial residues and by-products and integrates seasonal (monthly) variation of potential generation. A part of this method is based on previously published work [21] by authors, in which spatial and seasonal assessment was conducted for agricultural residues.

This work aims to present an integrated approach for assessment of the spatial and seasonal variation of the potential of the industrial residues and by-products, but also prove its value through the calculation of seasonality and its influence on the economic viability of biogas plant operation. Here, it is important to mention that the scope of this research is set from feedstock determination/production to the assessment of biogas production potential. However, in real-life applications, the final disposal of residues and by-products does not end with the potential production of biogas, as this problem is much more complex.

The method used in this work contains several steps, which are presented in Figure 1. Each step is described in more detail in the sections below.

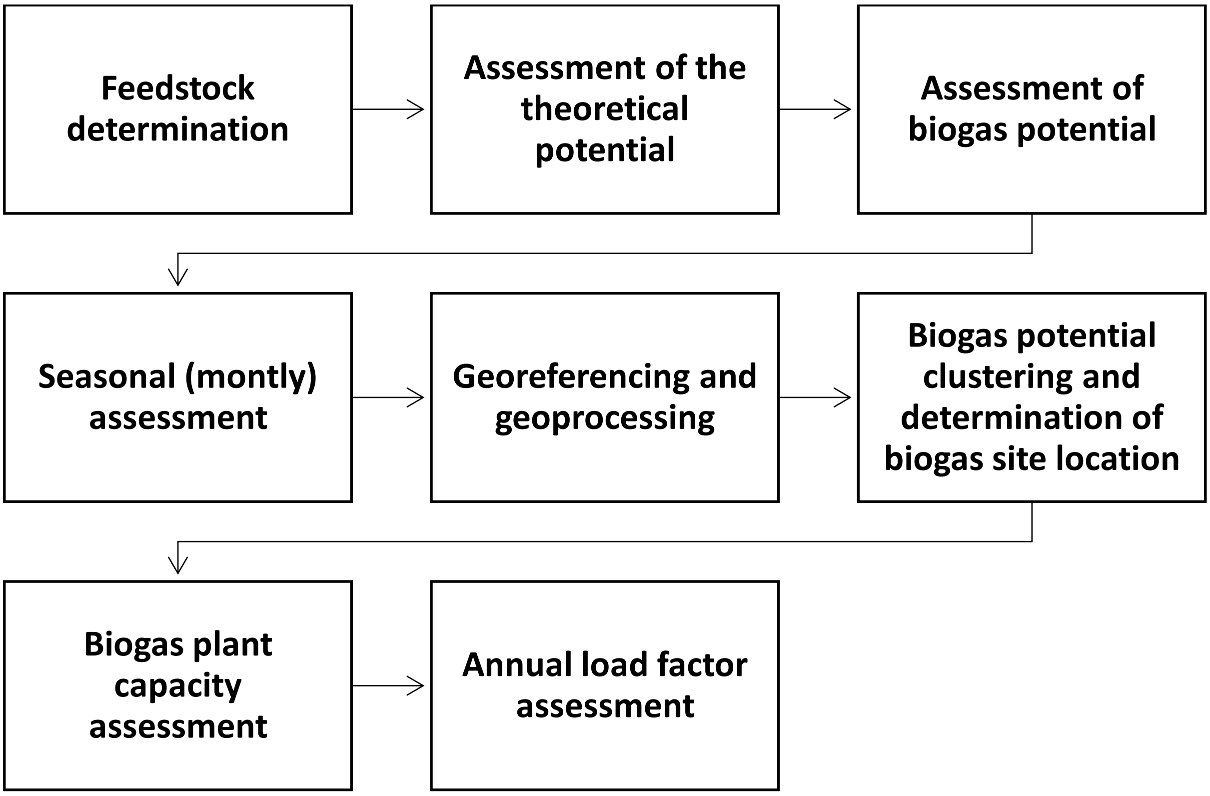

Figure 1 Steps of the method

Feedstock determination

The feedstocks considered in this work are industrial residues and by-products, which occur in sugar refineries, wineries, tomato and olive oil industry (olive oil mills).

Grape pressings occur during the grape crushing and pressing. This step is done after the collection of grapes in vineyards, in order to separate a liquid from grape marc. Grape pressings include the skins and pulp, seeds and stems.

Sugar beet pulp is the fibrous by-product obtained after water extraction of sugar contained in the root of the sugar beet [22]. Sugar beet is a vegetable cultivated for the extraction of crystallized sugar.

Oliva pomace and olive mill wastewater (OMW) are residue and by-product which occur as a result of olive milling for olive oil production. Olive pomace is the solid residue obtained during pressing or centrifugation [23].

Residues and by-products which occur during olive oil production are suitable for biogas production due to relative high biogas yield. Those residues are high-strength organic effluents whose disposal can degrade soil and water quality [24]. Thus, biogas production via AD technology is beneficial from the point of waste management, in addition to energy recovery. However, there are certain negative features for anaerobic digestion, as OMW are deficient in nitrogen, and inhibitory effects due to low pH could create problems in anaerobic digestion [25]. Therefore, there is a need for pre-treatments and the share of OMW should be low in co-digestion with other feedstocks for biogas production.

Tomato waste is a residue that occurs during the industrial processing of fresh tomatoes into mashed tomatoes, juice, sauces, food additives, etc.

Assessment of the theoretical potential of considered feedstocks

The theoretical potential of by-products is defined as the annual production of industrial by-products and residues. As can be seen from equation (1), it is a function of the amount of processed commodities and residue to the processed commodity ratio:

$$P_{ind} = M_{p.com} * RPPC \quad (1)$$

where P_{ind} stands for the theoretical potential of residues and by-products from industrial production (t), $M_{p.com}$ for the amount of processed commodities (t) and $RPPC$ for the residue to processed commodity ratio for a specific commodity (t/t). RPPC factors for the considered commodities are presented in Table 1.

Table 1 RPPC factors for the considered commodities

Industry	**Processed commodity**	**By-product**	**RPPC** (t/t)	**Reference**
Sugar	Sugar beet	Sugar beet pulp	0.25	[26]
Wine	Grape	Grape pressings	0.22	[27]
Olive oil production	Olive	Olive mill wastewater	1.25	[28]
		Olive pomace	0.55	[29]
Tomato	Tomato	Tomato residues	0.15	[29]

Assessment of biogas and methane potential

Biogas potential of the considered feedstocks is based on theoretical potential of fresh feedstocks, specific biogas yield from fresh feedstock and methane content of biogas, according to equation (2):

$$E_{ind} = P_{ind} * y_{com} * s_{CH_4} \quad (2)$$

where E_{ind} stands for a methane potential of residues and by-products from industrial production (m^3), y_{com} for a specific biogas yield of specific industrial by-product (m^3/t) and s_{CH_4} for a share of the methane contained in biogas (%). Specific biogas yield and share of the methane contained in the biogas obtained from the specific industrial by-products are given in Table 2. It is important to note here that those parameters are not obtained from the same basis of anaerobic digestion conditions, as can be seen in Table 2.

Table 2 Specific values for the calculation of biogas and methane potential from industrial by-products

By-product	y_{com} (m^3/t*)	s_{CH_4} (%)	**Anaerobic digestion conditions**			**Reference**
			pH (-)	**Temperature** (°C)	**Retention time** (days)	
Sugar beet pulp	96	50	5.18 ± 0.07	ND	ND	[30]
Grape pressings	160	80	ND	ND	21	[31]
Olive pomace	121	71	ND	ND	27	[32]
Olive mil wastewater	57.1**	**	ND	35	ND	[25]
Tomato residues	94	53	ND	ND	32	[33]

ND- not defined in the referenced literature

*values of specific biogas yield, y_{com}, are given per 1 tone of fresh matter.

** In literature, the value of biogas yield is given in specific methane yield (m^3 CH_4/t)

Seasonal assessment

Seasonality of the biogas potential of grape pressings, sugar beet pulp, olive pomace, OMW and tomato residues is determined in accordance with the month(s) of processing. In the case of tomato, olive and sugar industry, in which the production season lasts several months, the assumption is used that production is equally distributed during those months. Months of occurring and respective potential is determined for each industry and written as an additional set of attributes, where each attribute presents one month in a year and includes information of biogas potential in a specific month. Those attributes can be written and calculated in csv documents since GIS tools enable adding layers written in csv format. Furthermore, those attributes can be added and calculated directly in GIS tools by using the Field calculator.

Geocoding and geoprocessing

The economic feasibility of residues and by-products utilization is often constrained by the geographical distribution of the potential and the distance to potential biogas plants. This especially relates to smaller industries, with a small amount of by-products and residues available for biogas production. The prior step to geoprocessing is geocoding, which is the process of converting addresses into geographic coordinates. Geoprocessing enables visualisation of sources of the biogas potential, distance determination between several points, density analysis etc. GIS tools are used for geospatial information processing (geoprocessing) and can be applied to a wide range of various problems. One of the main advantages provided by GIS tools is the possibility to link non-spatial attributes with spatial information. When using a GIS tool for seasonal and spatial assessment of the biogas potential, the following information is required:

- Coordinates of the industries in which considered residues and by-products occur (in a case when respective industries are not pre-defined in the map);
- Biogas potential in a specific month;
- Months of processing commodities.

Biogas potential clustering and determination of biogas site location

GIS tools enable assessment of the areas with high concertation of biogas potential. The prior step (Geocoding and geoprocessing) will result in a point vector layer, where each point represents one industry site and includes attributes listed in the subsection Geocoding and geoprocessing. This spatial and non-spatial information are used in defining the biogas plant location. Those biogas plant locations can be understood as the centralised processing sites, which use residues and by-products from nearby industries to produce biogas. When defining the biogas plant location, the objective is to maximise the biogas potential which can be utilised and to minimise the transportation distance. For the purpose of this research, we used the assumption that the maximum air distance from the industrial site to the biogas plant is 20 kilometres. Therefore, the first step was to define the area within a radius of 20 kilometres from the industrial site. This was done in the GIS tool, with the Vector Spatial Analysis tool, by performing a "Buffer" spatial query, which resulted in buffered polygons, with a radius of 20 kilometres. The next step is to define biogas plant location, which can utilise maximal potential but is also close enough to each industrial site. Suitable areas for locating biogas sites are defined as intersections of buffered polygons, by performing the "Intersection" spatial query. As those intersections are representing area (and not a point) suitable for locating biogas sites, the final step was to define optimal locations, which are close to the industries with the greatest biogas potential, in order to minimise transportation cost and related greenhouse gas emissions. This was performed with the "Mean coordinate" spatial query. Once the potential site locations are determined, industrial sites within a radius of 20 kilometres from potential biogas site are considered viable to provide their by-products and residues for biogas production. As described in the "Geocoding and geoprocessing" sub-section, for each industrial site is defined the biogas potential and months of occurrence. Therefore, this approach integrates spatial and seasonal distribution, as the final map presents geo-location of biogas potential in each month of the year.

Biogas plant capacity assessment

In this work, the capacity of biogas plants is defined in accordance with feedstock supply. More precise, biogas potential is determined as it is a function of biogas potential of the specific cluster and time duration in which specific feedstock should be utilised, as described in equation (3):

$$P_{biogas} = \frac{E_{ind} * H_{d,CH4}}{N_{hours}} \quad (3)$$

Where P_{biogas} stands for a capacity of biogas plant (kW), E_{ind} for methane potential of residues and by-products from industrial production (m^3), $H_{d,CH4}$ for the specific lower heating value of methane (kWh/m^3) and N_{hours} for a number of hours (time duration) in which specific feedstock should be utilised (h).

Time duration in which specific feedstock should be utilised, N_{hours}, is limited by two constraints:

- Available storage capacity;
- The time period in which feedstock can be stored (storability of feedstock).

It is important to mention that industrial residues and by-products are more challenging to store, in comparison with some other conventional feedstocks for biogas production (such as maize silage). Improper storage of grape pressings, sugar beet pulp, tomato and olive mill residues may lead to degradation of feedstock: deterioration, mould formation and pests occurrence. Furthermore, it has been noted, that storage of olive pomace for 7 months causes an increase in triterpenic acids and other bioactive compounds [34]. Since biogas production is very sensitive to pH change, the assumption was used that considered residues and by-products can be stored for up to six months.

In this work, capacity was assessed for two scenarios, which present two extremes. In the first scenario, the assumption is used that there is no feedstock storage capacity and therefore feedstock for biogas production has to be utilised in the month of its occurrence. Thus, the potential of the biogas plant is determined by the maximal biogas potential in a specific month. In the second scenario, the assumption is used that feedstock for biogas production can be stored for up to six months. Those two scenarios are selected to have two extreme cases-the first in which there is no possibility to store feedstock and the second in which feedstock is stored for as long as possible, prior to a change of the bioactive compounds. The latter scenario will give a maximum annual load factor, which can be obtained by the utilisation of the considered feedstocks. For the purpose of this research, those two extremes will present the annual load factor ranges, as a function of the storage time. However, in a real-life application, the selected storage time may be in between, as the investment cost of the 6-month storage can offset the financial benefits of the produced biogas.

Annual load factor assessment

Annual load factor is a measure of the utilisation rate. In this work, annual load factor is used as a measure of utilisation of biogas plants which use industrial residues and by-products as feedstock for biogas production. This factor determines to a great extent the payback period of the specific plant. Thus, it is used in this work for the calculation of the influence of the seasonality of the industrial residues and by-products on the economic viability of biogas plant operation.

Annual load factor is a ratio of average load factor and peak load. In the case of a biogas plant, it can be considered as the ratio of biogas produced in one year and maximal amount of biogas that could be produced in one year, if a biogas plant operated at full capacity all 8,760 hours of the year, as described in equation (4):

$$f_{an.load} = \frac{E_{ind} * H_{d,CH4})}{P_{biogas} * 8760\ h} \tag{4}$$

Where $f_{an.load}$ stands for annual load factor (-), E_{ind} for methane potential of residues and by-products from industrial production (m^3), $H_{d,CH4}$ for the specific lower heating value of methane (kWh/m^3), for a number of hours (time duration) in which specific feedstock should be utilised (h) and P_{biogas} stands for a capacity of biogas plant (kW).

Annual load factor can be also represented by annual full load hours.

CASE STUDY

The presented method was demonstrated in the case study of Istria county and Osijek- Baranja county, which are presented in Figure 2. Istria County is the westernmost county of the Republic of Croatia and the largest peninsula of the Adriatic. Osijek-Baranja county is a county situated in the north-eastern part of the country. Those counties are selected to give diversity in industrial production. Both counties have intensive use of land for agricultural production.

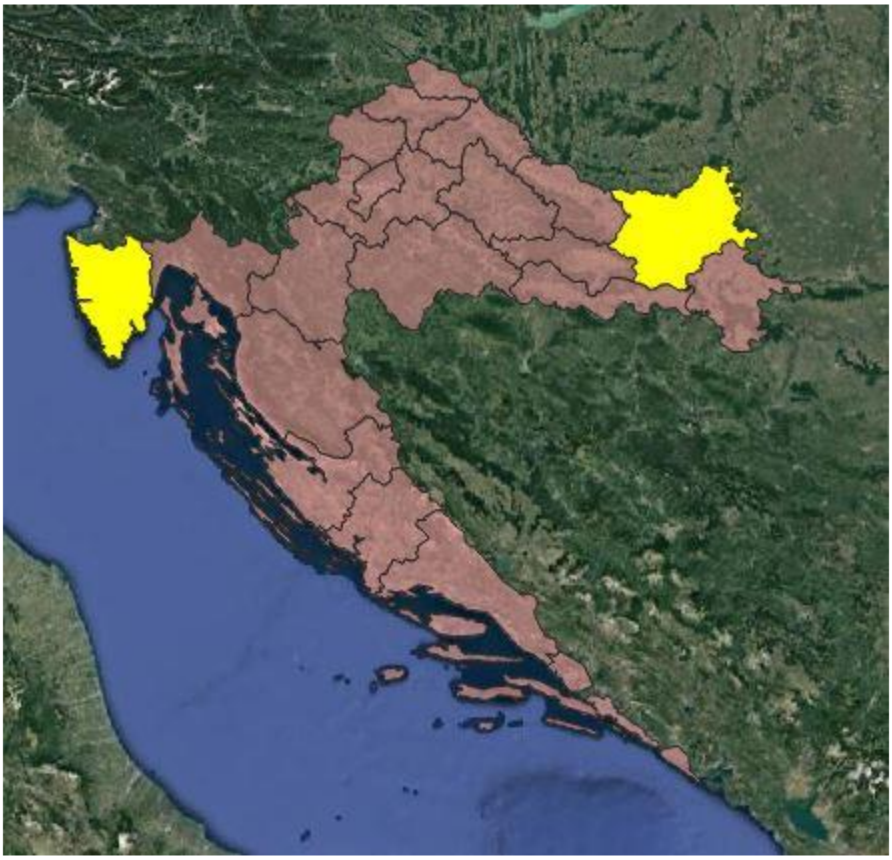

Figure 2 Case study area- Istria county (left) and Osijek- Baranja county (right)

Istria County

Istria County has a Mediterranean climate, suitable for olive oil and wine production. For the case study, nine wineries, six olive oil mills and one vegetable factory, which process tomatoes, were selected. Those industries are listed in Table 3, with respective annual processing amounts and respective commodity production.

Table 3 Annual grape processing in selected wineries, olive oil mills and vegetable industry[35], [36]

Industry	**Processed commodity**	**Annual processed commodity** (t)	**Final product**	**Annual final product production** (l)
Oil mill 1	Olive	7,140	Olive oil	1,000,000
Oil mill 2		43		6,000
Oil mill 3		464		65,000
Oil mill 4		21		3,000
Oil mill 5		200		-*

Oil mill 7		200		28,000
Vegetable factory 1	Tomato	12,000	Mashed tomato, juice, sauces	-*
Winery 1	Grape	108	Wine	70,000
Winery 2		92		60,000
Winery 3		138		90,000
Winery 4		54		35,000
Winery 5		7		4,500
Winery 6		154		100,000
Winery 7		770		500,000
Winery 8		58		37,500
Winery 9		154		100,000

*no data available

Since in the publicly open reports there are no data on the annual grape processing in each of the selected wineries, the assumption was used that one litre of wine requires 1.54 kilograms of grapes. Similar to this for olive oil production, the assumption was used that one litre of olive oil requires 7.14 kilograms of olives [37].

Osijek-Baranja County

Due to favourable climate and soil conditions, wine production is among the most represented economic activities in Osijek-Baranja county. For the case study, nineteen wineries have been selected. Those wineries are listed in Table 4, with respective annual wine production and annual grape processing amount. Grape harvesting and processing are done in September.

Table 4 Annual grape processing in selected wineries [36]

Industry	**Annual wine Production** (l)	**Annual grape processing** (kg)
Winery 10	30,000	46,150
Winery 11	300,0000	4,615,400
Winery 12	150,000	230,770
Winery 13	6,000	9,230
Winery 14	133,000	204,600
Winery 15	60,000	92,300
Winery 16	14,000	21,550
Winery 17	15,000	23,075
Winery 18	10,000	15,383
Winery 19	3,500,000	5,384,167
Winery 20	30,000	46,150
Winery 21	37,500	57,688
Winery 22	20,000	30,767
Winery 23	900,000	1,384,500

Winery 24	35,000	53,842
Winery 25	150,000	230,750
Winery 26	60,000	92,300
Winery 27	50,000	76,917
Winery 28	350,000	538,417

One of two Croatian sugar refineries is situated in the capital city of Osijek- Baranja county. This sugar refinery produces 70,000 tons of sugar annually by processing 550,000 tons of sugar beet [38]. The average sugar production campaign length in Croatia is three months [39].

RESULTS

The biogas potential from grape pressings, sugar beet pulp, olive pomace, OMW and tomato residues was calculated for the considered wineries, sugar refinery, olive oil mills and vegetable industry as described in the Method section.

Istria county

The results of the calculations of biogas potential from industrial by-products and residues in Istria County are presented in Table 5.

Table 5 Biogas potential from industrial residues and by-products in Istria County

Industry	Industrial by-product	Biogas potential (m^3 CH_4)			
		August	September	October	November
Oil mill 1	Olive pomace	-	-	168,684	168,684
	OMW	-	-	286,180	286,180
Oil mill 2	Olive pomace	-	-	786	786
	OMW	-	-	1,717	1,717
Oil mill 3	Olive pomace	-	-	8,518	8,518
	OMW	-	-	18,602	18,602
Oil mill 4	Olive pomace	-	-	393	393
	OMW	-	-	859	859
Oil mill 5	Olive pomace	-	-	3,671	3,671
	OMW	-	-	8,016	8,016
Oil mill 6	Olive pomace	-	-	3,669	3,669
	OMW	-	-	8,013	8,013
Vegetable factory 1	Tomato residues	59,784	29,892	-	-
Winery 1	Grape pressings	-	3,032		-
Winery 2	Grape pressings	-	2,599	-	-
Winery 3	Grape pressings	-	3,899	-	-
Winery 4	Grape pressings	-	1,516	-	-

Winery 5	Grape pressings	-	195	-	-
Winery 6	Grape pressings	-	4,332	-	-
Winery 7	Grape pressings	-	21,660	-	-
Winery 8	Grape pressings	-	1,624	-	-
Winery 9	Grape pressings	-	4,332	-	-

As can be seen from Table 5, the vegetable factory, as well as several olive oil mills and wineries have a significant potential for biogas production. The considered by-products from the vegetable industry (tomato processing) occur in August and September, from wineries occur in September, while from the olive oil industry residues and by-products occur in October and November. The spatial and seasonal distribution of biogas potential is presented in Figure 3.

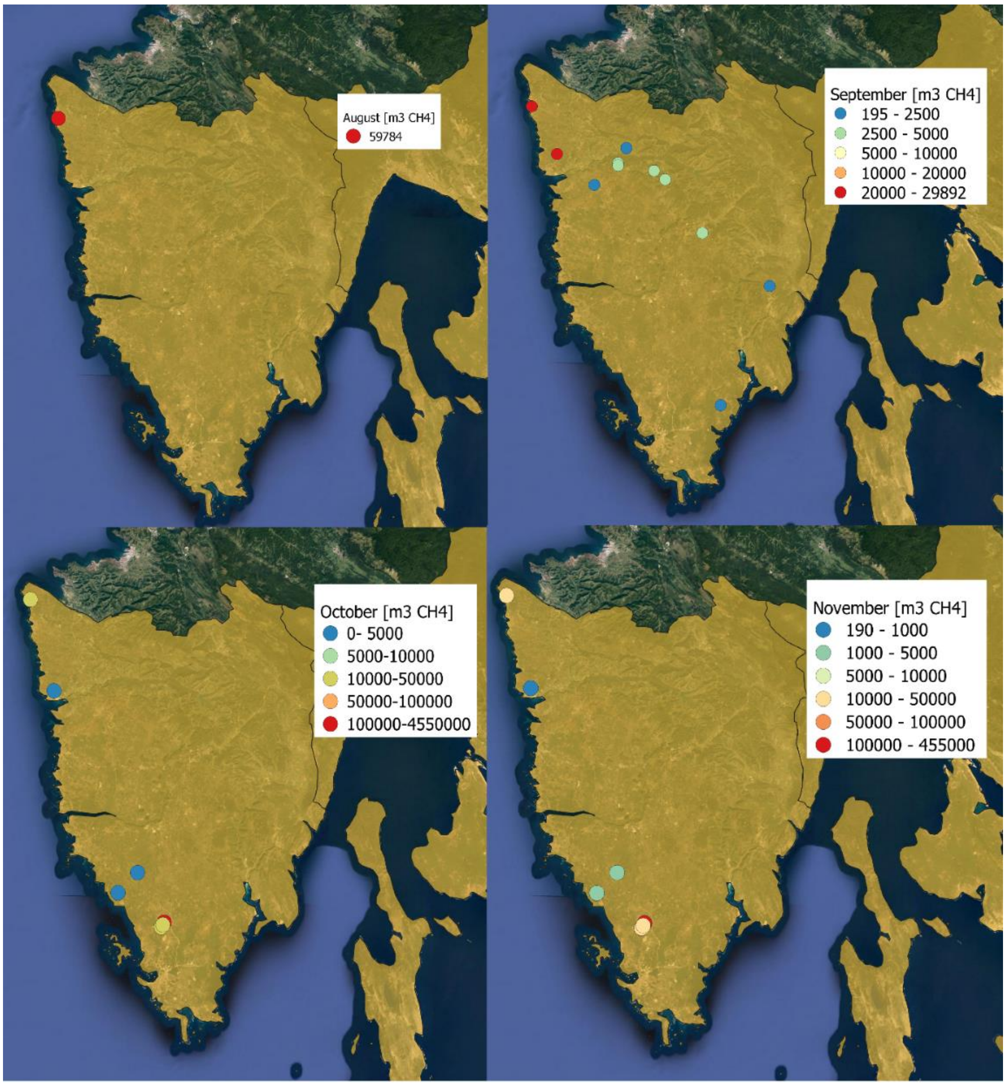

Figure 3 Biogas potential from wineries, olive mills and tomato industry in August, September, October and November

Based on the annual biogas potential and locations of industries with the greatest biogas potential, locations of potential biogas sites were determined. The determined biogas site locations for Istria County are represented in Figure 4, together with the annual biogas potential of considered industries. As described in the Method section, the GIS tool was used to define optimal biogas sites. When defining the biogas sites, suitable locations for biogas plant installations were those which are in the radius of 20 kilometres from the industrial site, which can utilise the maximum potential and where the transport distance was minimised. Figure 4 also clearly depict which industries are considered as viable to provide their residues and by-products as feedstocks for biogas production.

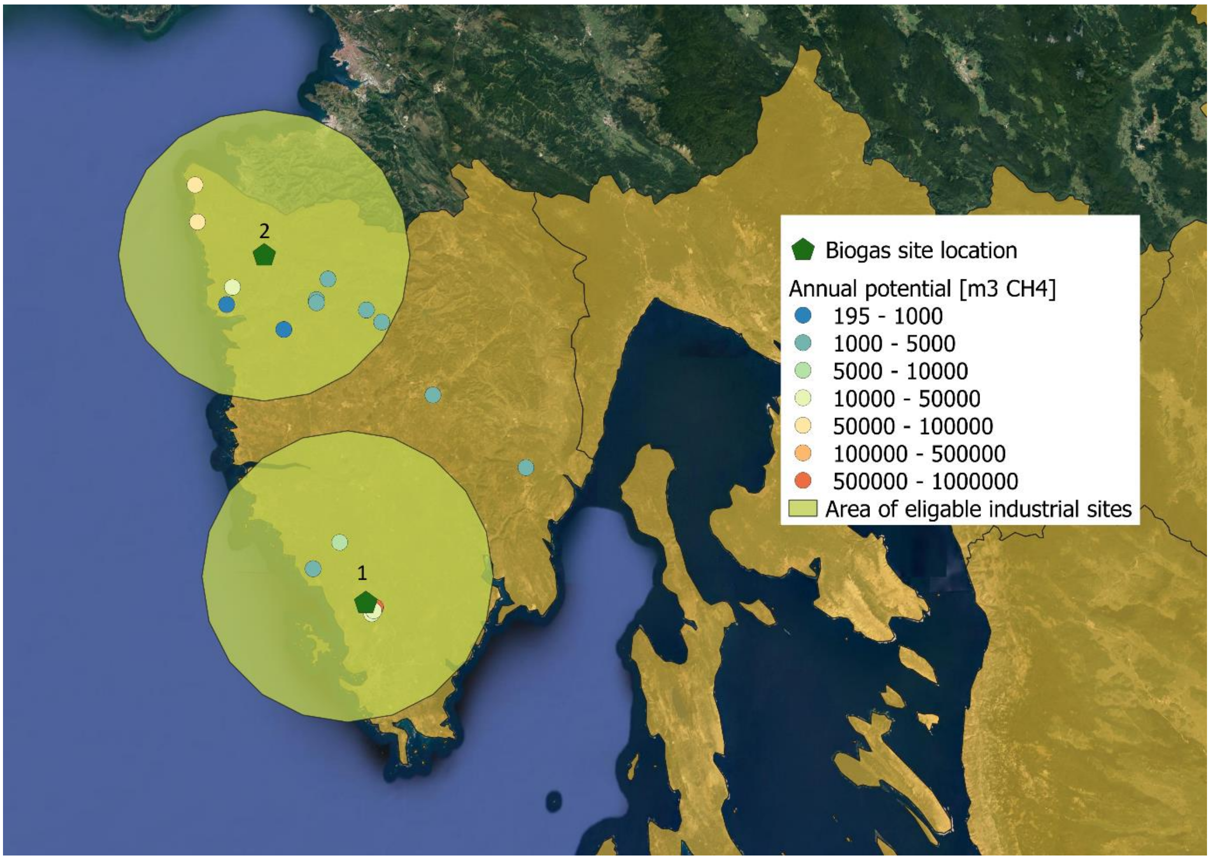

Figure 4 Annual biogas potential and potential biogas sites

Osijek Baranja County

The results of the biogas potential assessment from industrial residues and by-products in Osijek-Baranja county are presented in Table 6.

Table 6 Biogas potential from industrial residues and by-products in Osijek-Baranja county

Industry	**Industrial by-product**	**Biogas potential** (m^3 CH_4)		
		September	**October**	**November**
Winery 10	Grape pressings	1,300	-	-
Winery 11	Grape pressings	129,969	-	-
Winery 12	Grape pressings	6,498	-	-
Winery 13	Grape pressings	260	-	-

Winery 14	Grape pressings	5,762	-	-
Winery 15	Grape pressings	2,599	-	-
Winery 16	Grape pressings	607	-	-
Winery 17	Grape pressings	650		
Winery 18	Grape pressings	433		
Winery 19	Grape pressings	151,618		
Winery 20	Grape pressings	1,300		
Winery 21	Grape pressings	1,624		
Winery 22	Grape pressings	866		
Winery 23	Grape pressings	38,988		
Winery 24	Grape pressings	1,516		
Winery 25	Grape pressings	6,498		
Winery 26	Grape pressings	2,599		
Winery 27	Grape pressings	2,166		
Winery 28	Grape pressings	15,162		
Sugar refinery	Sugar beet pulp	2,200,000	2,200,000	2,200,000

As can be seen from Table 6, the sugar refinery and some of the wineries have a significant potential for biogas production. As expected, winery 11 has by far the highest potential for biogas production from grape pressings. The considered by-products from the wine industry occur in September and from the sugar industry in September, October and November.
The spatial and seasonal distribution of biogas potential is presented in Figure 5. The left part of Figure 5 presents the spatial distribution of biogas potential from by-products that occur in September (grape pressings and sugar beet pulp). Since the biogas potential from sugar beet pulp is equal in November and October, this potential is presented in one figure (right part of Figure 5).

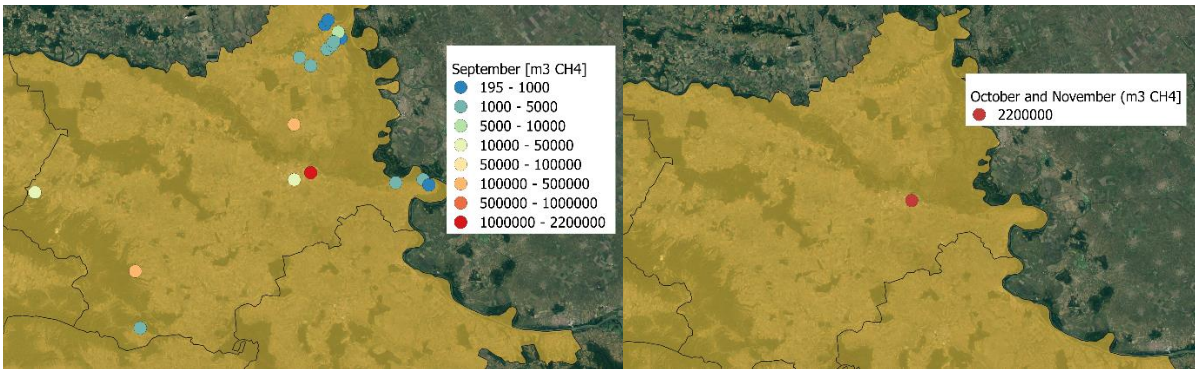

Figure 5 Biogas prom from sugar refinery and wineries in September (left) and from sugar refinery in October and November (right)

Based on the annual biogas potential and locations of industries with the greatest biogas potential, locations of potential biogas sites were determined. The determined biogas site locations for Osijek-Baranja county are represented in Figure 6, together with the annual biogas potential of considered industries. Figure 6 also clearly depict which industries are considered as viable to provide their residues and by-products as feedstocks for biogas production.

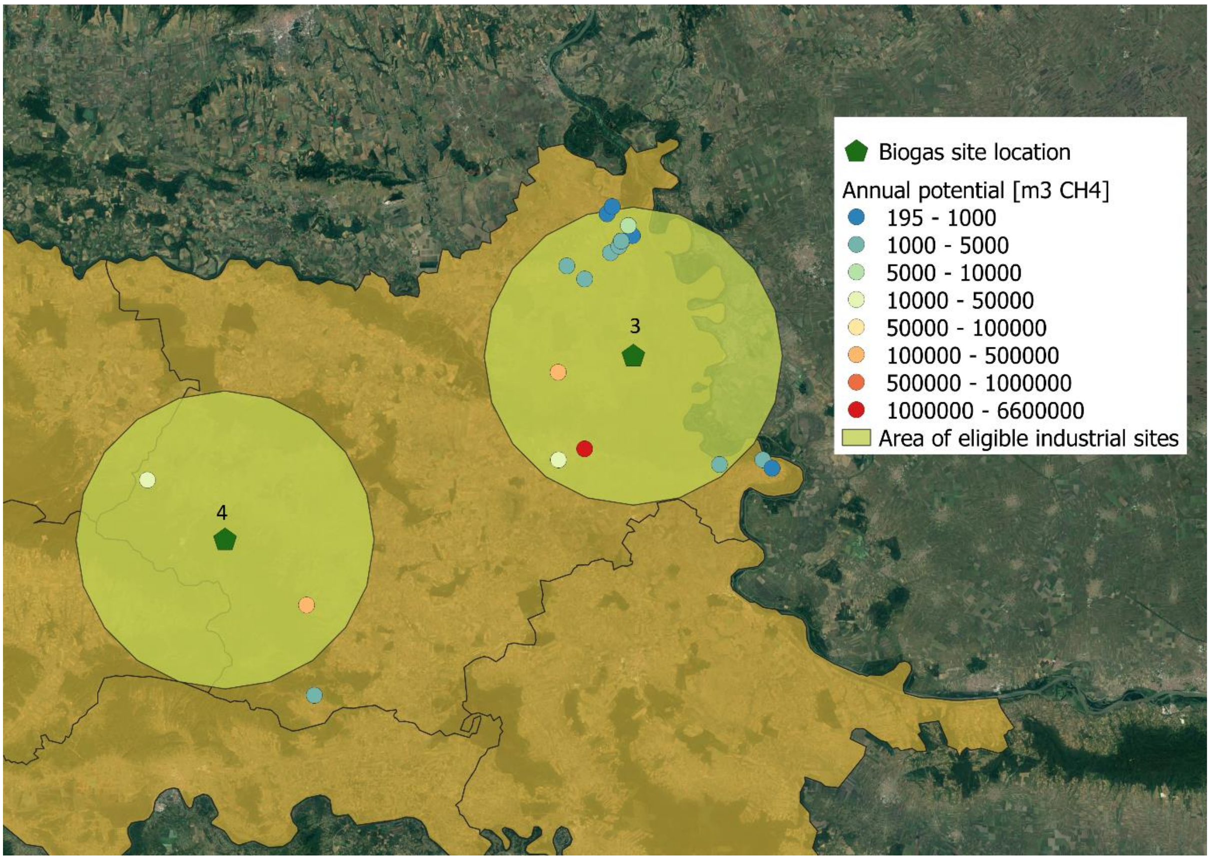

Figure 6 Annual biogas potential and potential biogas sites

Buffered layers presented in Figure 4 and Figure 6 and are used to assess the seasonal variation of each biogas site. The final results are aggregated and presented in Table 7. Here, seasonal variation is represented for biogas sites which are presented in Figure 4 and Figure 6.

Table 7 Seasonal variation of biogas potential in four potential biogas sites

Biogas site	**Industry**	**Annual biogas potential** (m^3 CH_4)	**August** (m^3 CH_4)	**September** (m^3 CH_4)	**October** (m^3 CH_4)	**November** (m^3 CH_4)
1	Olive oil mills	964,172	-	-	482,060	482,060
2	Wineries, olive oil mils, vegetable industry	187,946	59,784	72,988	27,587	27,587
3	Wineries, sugar refinery	6,776,560	-	2,376,560	2,200,000	2,200,000
4	Wineries	190,605	-	190,605	-	-

As can be seen in Table 7, the seasonal variation of biogas potential differs for each considered biogas site.

Biogas plant capacity and annual load factor

As described in the Method section, biogas plant capacity and annual load factors were calculated for two scenarios. For the first scenario assumption was used that there is no feedstock storage capacity and therefore feedstock for biogas production has to be utilised in the month of its occurrence. For the second scenario, the assumption was used that there is feedstock storage that enables storage of feedstocks for up to six months. The results are given in Table 8.

Table 8 Biogas plant capacity and load factor for two scenarios (without feedstock storage and with 6-month feedstock storage)

Biogas plant (cluster)	**Industry**	P_{biogas} (kW)		$f_{an.load}$ (-)	
		Without storage	**6-month storage**	**Without storage**	**6-month storage**
1	Olive oil mills, wineries	6,658	1,665	0.16	0.66
2	Wineries, olive oil mils, vegetable industry	1,008	185	0.18	0.82
3	Wineries, sugar refinery	32,824	10,400	0.24	0.74
4	Wineries	2,633	376	0.1	0.58

DISCUSSION

This research presented a method based on an integrated GIS approach for the assessment of the seasonal and spatial distribution of biogas potential from industrial residues and by-products. As can be seen from the results conducted for the case studies, industrial residues and by-products have significant potential to be utilised for biogas production. Total biogas potential, which could be used in 4 potential biogas sites, equals 8,119,280 m^3 CH_4. The potential biogas sites are determined in accordance with the methodology elaborated in the section above. It is important to note that localisation of biogas plant is very complex, not only due to technical reasons, which are addressed in this research (maximisation of the potential, minimisation of the transport distance), but also due to social reasons, such as "not in my back yard" (NIMBY) phenomenon. This phenomenon refers to individuals who recognize the greater benefits of a facility but show a protectionist attitude when the object is proposed in their “neighbourhood”.

Potential of industrial residues and by-products was studied in numerous papers, such as the work [40], in which Francesca et al. calculated the annual potential of olive pomace available for biogas production on a municipal level. Based on annual feedstock potential, some of the authors calculated electrical and thermal energy which could be produced from biogas generated from industrial residues and by-products. Ulusoy et al. [33] calculated that on an annual basis, 14,175,000 kWh of electrical energy and 150,660,000 kWh of thermal energy can be produced from biogas generated from 90,000 tonnes of tomato waste. Similar to this, Ulosoy et al. [24] calculated that on an annual basis, 74,959,780 kWh of electrical energy and 71,961,390 kWh of thermal energy could be produced from biogas generated from 1,260,000 tons of OMW. Results of this research prove that feedstocks which are nowadays regarded as waste can significantly contribute to an increase of renewable energy production.

However, as can be seen in Figure 3 and Figure 5 those feedstocks occur only in a few months of the year. Based on the results presented in Figure 3 and Figure 5, the question which arises is whether it would be economically viable to use this feedstock for biogas production, as recommended in many studies.

To give better insight into the influence of seasonality on the economic viability of industrial residues and by-products utilisation in biogas sites, annual load factors are assessed for each potential biogas cluster. As it can be seen in Table 8, load factors for case study biogas sites, for the case where there is no feedstock storage capacity, are ranging from 0.1-0.24. These values indicate that case study biogas sites will be operating at full load from 720-2,100 hours. It is worth mentioning that the biogas plants which are nowadays in operation have a high annual load factor. In the work [41], Stürmer et al. conducted research on 291 biogas plants with different capacities and from different European countries and concluded that those biogas plants operate on an annual basis from 6,096 to 8,421 full load hours. In addition, Hublin et al. [42] calculated on a Croatian case study, that a biogas plant with an annual load factor of 0.82, that use cow manure and whey as biogas feedstock has a payback period of 9.9 years.

One of the possibilities to increase the number of full load hours is to include feedstock storage. As can be seen from Table 8, 6-month storage would in the case of pilot biogas sites lead to load factors from 0.58-0.82 (5,080-7,180 hours). However, it must be noted here that investment in 6-month storage leads to additional investments cost, which could strongly affect a payback period. Furthermore, storage of considered feedstock requires special attention, as improper storage may lead to deterioration, mould formation and pests occurrence.

Another possibility to increase load factor is to use feedstock from diverse industries and from those in which feedstock for biogas production is generated in a longer period, as it can be seen on example for biogas site 2 and 3 (Table 8).

To investigate the influence of the seasonality on the payback period of biogas plants that use industrial by-products and residues for biogas production, the payback period is calculated for five different load factors:0.1, 0.24, 0,58, 0.82 and 0.9. For this purpose, we selected as a referent a biogas plant with 1 MW_{el}, which sells net electricity to the electric grid and net thermal energy to the district heating grid.

For payback period calculation, which refers to a number of years it takes to recover the cost of an investment, we used the following equation (5) [42] :

$$I = \sum_{t=1}^{PB} C_t \tag{5}$$

Where I is a capital investment (€), C_t is a net annual cash flow in year t (€) and PB is a payback period of the investment.

For the calculation of the initial investment, we used the following assumptions:

- Biogas CHP engine cost- 1,000,000 €;
- Feedstock preparation equipment costs-600,000 €;

- Civil works-500,000 €;
- Plant's regulation system cost-300,000 €;
- Cost of connecting the plant to the local district heating network-750,000 €;

Net annual cash flow, C_t is the difference between annual income and annual expense. When calculating the annual income, we assumed that the income is generated by selling electricity to an electric grid and by selling heat to a district heating grid. The annual expenses consist of operation and maintenance costs, as well as corporate tax.

More precisely, the following assumptions were used:

- Electrical efficiency, η_{el} is 40 % and heat efficiency, η_{el} is 43%;
- The electrical energy is sold to the grid at the referent price of 140 €/MWh_{el} [43] and the thermal energy is sold to the district heating system at the price of 20 €/MW_{h};
- The cost of feedstock is neglected, as those feedstocks are nowadays regarded as waste;
- Digestate will not be sold and the cost of thermal treatments, required before digestate utilisation in agriculture is not included;
- Operations and maintenance (O&M) cost 6% of the total investment. In the case of load factor <0.5, O&M cost is 4% of the total investment;
- 10% of produced electrical energy and 15% of produced thermal energy is used for biogas plant operation;
- Depreciation of the equipment, connection to the district heating plant and civil work is 15 years;
- Corporate tax is 20%.

The payback periods, for each considered load factor, are presented in Table 9.

Table 9 Payback period dependence on the load factor

Load factor, $f_{an.load}$ (-)	0.9	0.82	0.58	0.24	0.1
Payback period (year)	3.9	4.4	6.5	15	44.1

The results presented above confirm that seasonality of biogas potential from industrial by-products and residues has a significant influence on the economic viability of biogas utilization and therefore it is beneficial to include this aspect in the potential assessment.

CONCLUSION

The approach presented in this work exploits the spatial distribution of biogas potential from industrial residues and by-products and integrates seasonal (monthly) variation of potential generation. The developed method demonstrates how seasonal assessment can be integrated into GIS assessment of biogas potential from industrial residues and by-products.

The presented approach was applied to the wine, sugar, vegetable and olive oil industry and tested at two case study area-Istria and Osijek-Baranja County. The presented method contains eight steps and was used for defining biogas potential available to be utilised in potential biogas sites, whose locations are set in areas with a higher concentration of biogas potential.

The results show that considered industries generate a substantial amount of residues and by-products (grape pressings, sugar beet pulp, tomato waste, olive pomace and OMW) suitable for biogas production. For the industries located nearby potential biogas sites (in a radius of 20 km), total biogas potential equals 8,119,280 m^3CH_4. Feedstock considered in potential assessment occurs from one (grape pressings) to three months (sugar beet pulp).

The influence of seasonality on the economic viability of industrial residues and by-products utilisation for biogas production was assessed in the case biogas sites, through assessment of annual load factors for two scenarios- the scenario without feedstock storage and the scenario with 6-month case storage. For the first scenario, annual load factors for case study biogas sites are ranging from 0.1-0.24. As biogas sites are operating at multiple higher load factor, it can be concluded that seasonality highly affects the economic viability of biogas site operation. For the scenario where 6-month feedstock storage is available, the annual load factors increase to 0.58-0.82. However, it should be noted that those storages may highly affect total investment and require special attention, due to possible issues which occur in case of improper feedstock storage.

The results presented in this work confirm the hypothesis that the integrated assessment of the spatial and seasonal variation of biogas potential from industrial by-products and residues give better insight into the economic viability and feasibility of its utilization.

ACKNOWLEDGEMENT

This work has been financially supported by the Croatian Science Foundation and the Slovenia-Croatia bilateral project Interdisciplinary Research on Variable Renewable Energy Source and Biomass in Clean and Circular Economy (BIOVARES).

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