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Net Electricity and Heat Generated by Reusing Mediterranean Agro-Industrial By-Products

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Abstract: The necessity to investigate suitable alternatives to conventional fossil fuels has increased interest in several renewable energy resources, especially in biomasses that are widely available and make it possible to reach environmental and socio-economic improvements. Among solutions for bioenergy production, anaerobic digestion technology allows biogas production by reusing agricultural residues and agro-industrial by-products. By considering the basic concepts of the Biogasdoneright® method, the objective of this study was to estimate the theoretical potential net electricity and heat production from anaerobic digestion of citrus pulp and olive pomace highly available worldwide. A model was developed and applied in a study area of the Mediterranean basin, where the biogas sector is still very limited despite the importance of both agricultural and agro-industrial activities, especially with regard to citrus and olive cultivation processing. Firstly, the application of a geographical information system (GIS) software tool allowed the estimation of the biogas potentially produced from citrus pulp and olive pomace re-use. Then, the development of a technical assessment demonstrated that 15.9 GWh electricity and 88,000 GJ heat per year could be generated from these by-products, satisfying approximate 17% of the electricity demand of the agricultural sector of the study area (90.2 GWh y^{-1}). The achieved results could be relevant with regard to the intervention priorities established by the European Union related to the planning activities supported by the European Structural and Investment Funds within the Smart Specialisation Strategy.

Keywords: citrus pulp; olive pomace; by-products; anaerobic digestion; biogas; GIS

1. Introduction

The fast acceleration of industrialisation, combined with increased growth of population and urbanisation, has dramatically changed the world and the continuous climatic changes are signs of concern for the future of the planet [1]. Carbon dioxide emissions are continuously increasing [2], mainly due to high fossil fuel consumption [3,4]. Approximately 85% of current energy consumption is based on fossil fuels, which are the most responsible source of greenhouse gas (GHG) emissions and have a relevant role in global warming. According to the estimated world energy requirement, the energy demand would increase approximately by 36% between 2008 and 2035 [5]. According to the Kyoto protocol [6,7], a sustainable way to satisfy this demand is the implementation of renewable energy technologies in order to reduce the use of fossil fuels and, therefore, reduce CO_2 and other GHG emissions [8].

Several technologies for renewable energy (i.e., solar, wind, hydro, geothermal, and biomass) have been widely analyzed, and by considering the cost-effectiveness and the positive externalities, bioenergy from biomasses could offer a versatile solution, mainly for rural communities where relevant quantities of agricultural biomasses are produced [9,10]. In rural areas, the harnessing of biomass for energy production could trigger environmental improvement and socio-economic development of local communities. In fact, with regard to the economic sectors of agriculture, forestry, and industry [11], new agro-energy supply chains could involve several impacts at a local level, such as, protection of the associated agricultural activities, crop diversification, start-up of businesses specialized in the collection and transfer of biomasses, and "active" management of forest areas [8,12].

Recently, among the technological solutions for bioenergy production, such as pyrolysis, liquefaction, and gasification, anaerobic digestion technology to treat agricultural residues and agro-industrial by-products for biogas production have attracted attention due to potential achievements in terms of waste management, reduction of carbon dioxide emissions, and production of clean energy from renewable sources. Biogas can be produced from nearly all kinds of biological feedstocks and it can be converted into different forms of energy (electricity or heat, but also mechanical energy in engines). Therefore, biogas production is currently widely investigated [13–15] and many research studies have already been conducted to improve co-digestion efficiency and enhance its economic performance. This research field has mainly focused on new reactor configuration for improving co-digestion performance [16] in terms of increasing biogas production [17] or on how to improve the efficiency of biogas upgrading for capturing CO_2, by applying Carbon Capture and Sequestration (CCS) to renewable fuels, also known as Bio-CCS or Bioenergy with CCS (BECCS) [18].

In the last twenty years the biogas sector has been continuously increasing worldwide, with more than 8000 new biogas plants installed in Europe, mainly in Germany [19], which has nowadays, four times the number of United States biogas plants, although the US sector is developing, particularly in the State of California [20].

The objective of the study reported in this paper was to assess theoretical potential net electricity and heat generated from biogas obtained by two agro-industrial by-products, citrus pulp and olive pomace, instead of dedicated energy crops, as suggested by the new Biogasdoneright® concept of biogas production. Data acquisition, analyses, and computation were carried out in a study area relevant for the Mediterranean basin that can be followed for analogous studies in other countries. The motivation of this study was inspired by environmental, social, and economic concerns which arise when dedicated energy crops are used for biogas production [21]. Since they derive mainly from food vs. fuel competition, there is a need to analyze the possibility of using alternative biomass sources (non-food sources) for the production of biogas by anaerobic digestion [22]. The Biogasdoneright® method integrates sustainable intensification of crop rotation and the use of agro-industrial wastes to produce biogas [23–25]. The adoption of this new system would reduce both environmental, economic, and social impacts related to dedicated energy crop cultivation and the amount of waste from agro-industrial activities [26].

Since the application of the Biogasdoneright® method requires the assessment of feedstocks availability, geographical information systems (GIS) are relevant tools for investigating both biomass availability and sustainable biogas plant locations. Due to the application of Information and Communication Technology (ICT) in agriculture research fields, GIS tools have been adopted to provide decision support information for spatially-related issues [27–30]. In this context, GIS tools have been used at a local, regional, and national level [31,32] for assessing potential biomasses for biogas production [33–35] and for site-location analyses over the world, by analysing several types of biomasses. Batzias et al. developed a GIS-based model to estimate biogas production potential from livestock manure [33]. Sliz-Szkliniarz and Vogt took a GIS-based approach to determine suitable locations for biogas production from livestock manure and crops at regional scale [36]. Zubaryeva et al. applied GIS to assess local biomass availability for distributed biogas production in Lecce, Italy [37]. Karaj et al., by considering three types of biomass energy sources, i.e., dedicated bioenergy crops, and agricultural and forestry residues and waste, investigated the technical electrical energy by two converting techniques, the combustion of the feedstock directly in an incinerator and then driving a steam generator for producing electrical energy, and the production of biogas from anaerobic digestion and running a turbine for electrical energy generation [38].

Hohn et al. used GIS data to analyze the spatial distribution and amount of potential biomass feedstock for biomethane production and optimal locations, and also the size and number of biogas plants in southern Finland [34]. Franco et al. applied a fuzzy weighted overlap dominance procedure to integrate GIS data and multiple social, technical, and environmental criteria to identify the most suitable biogas production locations [39]. Roberts et al. assessed the residual biomass (herbaceous and vegetable residues) availability and its energy potential in Argentina, by adopting statistical information [40].

Brahma et al. used a GIS-based planning approach to identify an optimized agricultural residues supply network for a specified biogas plant location in India [41].

Among these case studies, only few have reported a spatial assessment of by-products availability in view of improving co-digestion of different organic feedstocks [37].

The results achieved in the study proposed in this paper could be considered an advancement of knowledge in research fields that aim at the valorization of agro-industrial residues [42–45], because they show the contribution of net electricity and heat obtained from citrus pulp and olive pomace re-use to the energy demand of the agricultural sector in the study area. Moreover, the amount of theoretical potential net electricity and heat generated from these by-products should be considered within strategic energy plans for several positive externalities such as: limitation of biogas-related land use [46]; decrement of the competition with food and feed, as well as associated environmental impacts [47] and feeding costs [48]; decrement of fossil fuel dependence [49]; improvement of waste management; and creation of new value chains from agricultural resource [50].

2. Citrus Pulp and Olive Pomace Production

While the spread of biogas plants has earlier and continuously increased worldwide, its spread is more recent in Italy where the biogas sector registered the highest development after 2009. More than 1000 new biogas plants were installed at the end of 2012, particularly in Northern Italy with the objective of producing biogas from anaerobic co-digestion of dedicated energy crops and animal wastes [51]. The spread of biogas plants was not uniform in all Italian regions, especially in the south where the development of the biogas sector is really limited, especially in Sicily, the largest island in the Mediterranean basin. This backwardness could be considered a point of strength for the development of the biogas sector according to the new model of Biogasdoneright ® since the actual land use of the region is not characterized by dedicated energy crops. This specific condition, combined with the relevant quantities of agricultural residues and agro-industrial by-products whose disposal arises environmental concerns, led to the choice of Sicily as the study area of the research reported in this paper. Sicily, a Region of Southern Italy composed of nine provinces (Figure 1), leads in cereal and orange production, which are around 52% of the national production [52]. The national institute of statistics (ISTAT) [53] indicates that Sicily has the highest concentration of growing areas, which equals about 231,000 ha. Furthermore, just considering the agricultural sector, cultivation of olive and citrus represents about 90% of whole orchards in Sicily.

Citrus production and processing play a key role in the economic sector of USA and also in most of the countries of the Mediterranean area [28]. Citrus pulp is the main by-product of citrus processing and its composition changes based on the orange variety, the cultivation process, as well as the climate conditions [28,54].

Data gathered from the 2010 Agricultural Census highlighted that approximately half (46%) of Italian citrus farms are located in Sicily whereas the other regions have no more than 8%, except for Calabria at 26% [55,56]. In detail, there are about 79,500 citrus farms in Italy, which are mostly located in Sicily and Calabria. In Sicily, the province of Catania and Syracuse are the provinces with the highest concentration of citrus production [28].

By considering olive cultivation for olive oil production, this has a key role for the economy in many Mediterranean countries, especially Spain, Italy, Greece, and Portugal which produce more than 98% of the world's olive oil, with an estimated value of 2.5 million tons/year [57,58].

Olive oil consumption is increasing worldwide by promoting intensive olive tree cultivation, which causes several environmental impacts in terms of resource depletion, land degradation, pollutant emissions, and waste generation [59,60]. The production of olive oil is characterised by significant amounts of residues, both solid (olive pomace) and liquid (olive mill wastewater), and their management is a challenge for the olive mill operators from both an economic and an environmental perspective [61–63].

By analysing the situation in Europe, Italy is the second most important producer of olive oil (after Spain) [57,64]. Data gathered from the VI Agriculture General Census 2010 [65] confirms that Sicily, Apulia, and Calabria are the main regions in Italy for olive oil production [66–69]. In Sicily, olive oil production, which accounts for about 45,000 t y^{-1}, is mainly located in the province of Palermo, followed by the provinces of Catania, Agrigento, and Trapani [28]. When considering olive pomace and citrus pulp as by-products suitable for biogas production, the province of Catania is the highest producing area since it has a wide surface of citrus and olive-growing areas [28] and a relevant number of processing facilities.

Only recently, citrus pulp and olive pomace have been considered as a resource for producing renewable energy by anaerobic digestion.

Lack of official data related to the amount, and spatial localization of both citrus pulp and olive pomace have limited their re-use, exploitation, and valorization. Therefore, in previous studies the availability of citrus pulp and olive pomace at a local level was investigated with the final aim of developing the biogas sector [28,66,70,71].

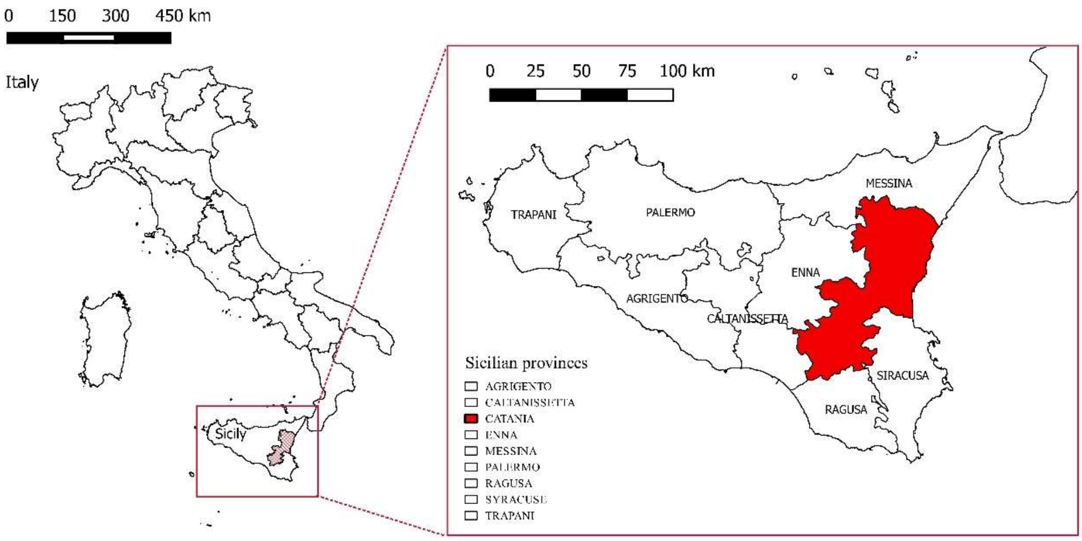


Figure 1. Geographic position of Sicily (Italy).

3. Materials and Methods

3.1. Study Area

In order to assess the theoretical potential net electricity and heat generated from citrus pulp and olive pomace, data acquisition, analyses, and computation were carried out in Catania province (Figure 1). Firstly, the estimation of biogas potentially produced from reusing citrus pulp and olive pomace was obtained by applying a GIS-based model. Then, by using the GIS-based model outcomes, technical assessments were carried out to estimate theoretical potential net electricity and heat generated from a number of theoretical biogas plants.

3.2. The Model for Net Electricity and Heat Computation

In this study, a model for estimating theoretical potential net electricity and heat generated from anaerobic digestion of citrus pulp and olive pomace through the computation of spatial indices was proposed.

The model required the use of indices, which describe the citrus pulp and olive pomace availability at territorial level, and can be executed by using GIS software tools, such as the open source Quantum GIS (QGIS 2.16.2 version) utilised in this study.

The territorial area of Catania was discretized by using administrative boundary subdivisions (municipalities) in view of obtaining data of agricultural production from official databases or other supports such as regional technical maps and ortho-photo images. In this context, automated image processing of high-resolution satellite images could be used to obtain further detailed information on agricultural land use [72,73].

A first phase of the model regarded the computation of the spatial indices $i_{cp\_a_i}$ and $i_{op\_a_i}$, which were defined in previous studies to describe the level of availability for biogas production of citrus pulp and olive pomace, respectively [66,70].

The spatial index i_{cp_a}, for each i-th municipality of the province of Catania (i = 1 to 58), was computed by the following relation:

$$i_{cp\_a_i} = \frac{Cp_{average\ \%} \times P_{processed\_citrus\_i}}{Cp_{tot}} \quad (1)$$

where $Cp_{average\ \%}$, equal to 57.5%, was obtained for each citrus processing industry by the ratio between the amount of citrus processed and the amount of citrus pulp produced, $P_{processed\_citrus\_i}$ was the amount of processed citrus among the total amount of citrus produced, and Cp_{tot} was the amount of citrus pulp produced in Catania province. Then, the obtained index $i_{cp\_a_i}$ was reported on a GIS map to highlight areas with the highest citrus pulp potential production suitable to produce biogas.

With regard to the spatial index $i_{op\_a_i}$, for each i-th municipality of the province of Catania (i = 1 to 58), it was computed by using the following relation:

$$i_{op\_a_i} = \frac{Op_{average\ \%} \times P_{processed\_olive\_i}}{Op_{tot}} \quad (2)$$

where $Op_{average\ \%}$, equal to 44.92% [66], was computed for each olive processing industry by the ratio between the amount of olives processed and the amount of olive pomace produced, $P_{processed\_olive\_i}$ was the amount of processed olives among the total amount of olives produced, and Op_{tot} was the amount of olive pomace measured in tons, produced in Catania province. Then, the obtained index $i_{op\_a_i}$ was reported on a GIS map to obtain areas with the highest olive pomace potential production.

Two GIS maps, i.e., those reporting the indices $i_{op\_a_i}$ and $i_{cp\_a_i}$, were overlaid with the aim of selecting the municipalities with the highest availability of both by-products, i.e., citrus pulp and olive pomace. This operation allowed the selection of geographical areas where transportation costs for feedstock supply and logistics of new biogas plants could be minimized.

A further elaboration made it possible to compute the potential biogas production (B_{tot_i}) related to citrus pulp Cp_i and olive pomace Op_i estimated for each municipality of the study area. To this end Equation (3) was computed for each municipality:

$$B_{tot\_i} = i_{cp\_a_i} \times Cp_{tot} \times Y_{biogas\_CP} + i_{op\_a_i} \times Op_{tot} \times Y_{biogas\_OP} \quad (3)$$

where Y_{biogas_CP} is the citrus pulp biogas potential, equal to 89.3 00 $Nm^3\ t^{-1}$, as reported in Cerruto et al. [74]; and Y_{biogas_OP} is the olive pomace biogas potential, assumed by Reale et al. [75] to be equal to 131.00 $Nm^3\ t^{-1}$.

A second phase of the model was the technical assessment. Energy balance analyses were carried out according to the outcomes of the GIS analyses. After the estimation of the theoretical biogas potential associated with the total amount of citrus pulp and olive pomace, the sizes of the engines for biogas utilization were calculated by considering methane low heating value, biogas engine efficiency, and assuming biogas to contain 50% (v/v) methane, as reported below:

$$E_{GasEngine} = \frac{B \times \%\text{CH}_4 \times LHV_{CH_4} \times \text{Eff}_{Electricity} \times F}{\text{op}_{hours}} \quad (4)$$

where $E_{GasEngine}$ is the electricity output of the engine of gas engine on biogas, B is the biogas production (B, Nm^3 y^{-1}) obtained by considering the theoretical biogas production from literature [74,75]; $\%CH_4$ is the volumetric methane content in the biogas, which was set equal to 50% [76]; LHV_{CH_4} is a lower heating value for methane (LHV_{CH_4} = 36 MJ m^{-3}); $\text{Eff}_{Electricity}$ is the electricity efficiency average of gas engine to convert methane heating value to electricity energy, and was set equal to 0.3 [77]; F is the conversion factor of MJ to kWh, and was set equal to 0.2778; and op_{hours} is the operational hours of the gas engine in a year considering the recommended top-end overhaul maintenance for the Combined Heat and Power (CHP) unit, and was set equal to 7000 [77].

By considering both electricity and thermal efficiencies of gas-engine CHP, the net annual electricity ($E_{Electricity}$, kWh y^{-1}) and heat (E_{Heat}, GJ y^{-1}) generated from a biogas plant were calculated as follows:

$$E_{Electricity} = B \times \%\text{CH}_4 \times LHV_{CH_4} \times F \times \text{Eff}_{Electricity} \times \left(100 - \%_{Electricity}\right)\% \quad (5)$$

$$E_{Heat} = B \times \%\text{CH}_4 \times LHV_{CH_4} \times F \times \text{Eff}_{Heat} \times (100 - \%_{Heat})\% \quad (6)$$

where $\%_{Electricity}$ and $\%_{Heat}$ in Equations (6) and (7) are the percentages of electricity and heat, equal to 9 and 30 respectively, that are used within the biogas plant, and thus are not available for export to the larger society [36]; and $\text{Eff}_{Electricity}$ and Eff_{Heat} are set as electricity and thermal efficiencies, equal to 0.3 and 0.6, respectively [77].

4. Results

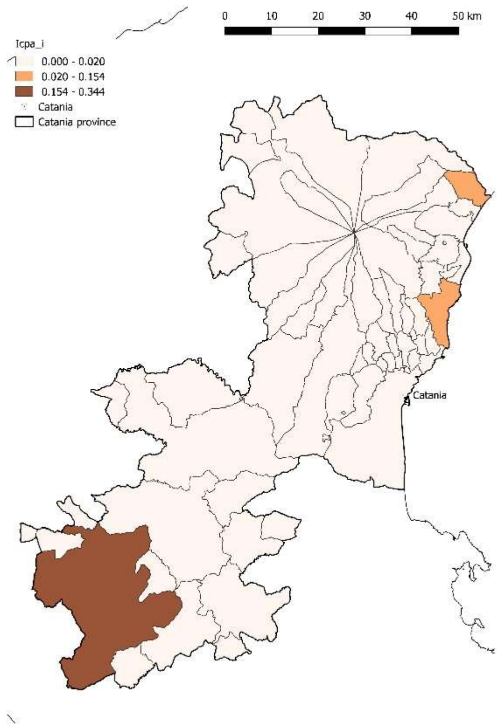
By following Equations (1) and (2), the indices $i_{cp\_a_i}$ and $i_{op\_a_i}$ for each municipality of the province of Catania were computed (Table 1) and reported in GIS maps (Figure 2). With regard to citrus pulp availability index, $i_{cp\_a_i}$, its territorial spreading reflects the citrus processing industries locations (Figure 2a). In fact, the highest values of the computed index $i_{cp\_a_i}$ were obtained for the municipalities of Caltagirone, Calatabiano, and Acireale, where the citrus processing industries are mainly located as reported by Valenti et al. [29,71]. Otherwise, as shown in Figure 2b, the index $i_{op\_a_i}$ highlights several areas with high and homogeneous level of availability of olive pomace for biogas production. As explained in a previous research study by Valenti et al. [67], this result was given by the uniform distribution of both olive oil processing industries and olive orchards within the study area.

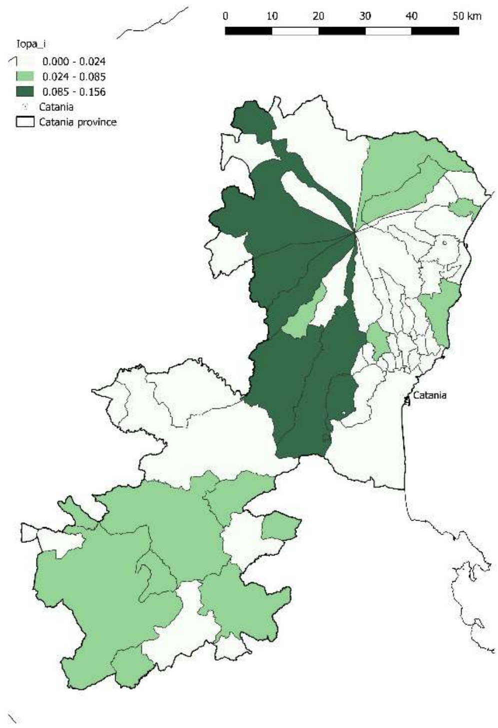
With the aim of obtaining areas with the highest availability of both citrus pulp and olive pomace, the GIS maps of Figure 2 were overlaid, and the results were reported in a new GIS map. The outcomes of this further analysis highlighted that the geographical areas reported in Figure 3a could be used to locate new biogas plants (Figure 3b) in order to minimize transportation costs due to logistics and supply phase of the considered biomasses. These factors are crucial for the sustainable development of biogas plants [39]. These geographical areas were located in the south (Area 1), in the middle (Area 2), and the north (Area 3) of Catania province. Among municipalities included in the Area 1, Caltagirone is characterized by the highest potential production of both citrus pulp and olive pomace (Figure 3a) [71].

Table 1. Computation at municipal level of the indices, $i_{cp\_a_i}$ and $i_{op\_a_i}$, which describe the level of availability for biogas production of citrus pulp and olive pomace.

Municipality	$P_{processed\_olive\_i}$ * (t)	Op_i (t)	$i_{cp\_a_i}$	$P_{processed\_citrus\_i}$ * (t)	Cp_i (t)	$i_{op\_a_i}$
Aci Bonaccorsi	3.11	1.40	0.00	-	-	-
Aci Castello	51.75	23.25	0.07	575.54	330.94	0.17
Aci Catena	8.27	3.72	0.01	-	-	-
Aci Sant'antonio	18.50	8.31	0.03	-	-	-
Acireale	175.06	78.64	0.24	-	-	-
Adrano	1486.05	667.53	2.02	-	-	-
Belpasso	2750.83	1235.67	3.73	20,622.18	11,857.75	6.27
Biancavilla	1029.85	462.61	1.40	-	-	-
Bronte	2063.45	926.90	2.80	316.49	181.98	0.10
Calatabiano	351.40	157.85	0.48	167.85	96.51	0.05
Caltagirone	4333.26	1946.50	5.88	3164.02	1819.31	0.96
Camporotondo Etneo	134.94	60.62	0.18	-	-	-
Castel Di Iudica	775.20	348.22	1.05	2315.63	1331.48	0.70
Castiglione Di Sicilia	1297.18	582.69	1.76	-	-	-
Catania	812.30	364.89	1.10	22,181.20	12,754.19	6.74
Fiumefreddo Di Sicilia	39.15	17.59	0.05	2845.59	1636.21	0.86
Giarre	65.50	29.42	0.09	6291.87	3617.83	1.91
Grammichele	330.90	148.64	0.45	2353.16	1353.07	0.71
Gravina Di Catania	-	-	-	-	-	-
Licodia Eubea	706.93	317.55	0.96	473.95	272.52	0.14
Linguaglossa	359.64	161.55	0.49	15.41	8.86	0.00
Maletto	161.78	72.67	0.22	31.15	17.91	0.01
Maniace	680.31	305.60	0.92	11.07	6.36	0.00
Mascali	94.86	42.61	0.13	6859.22	3944.05	2.08
Mascalucia	55.20	24.80	0.07	-	-	-
Mazzarrone	481.61	216.34	0.65	243.56	140.04	0.07
Militello In Val Di Catania	764.50	343.41	1.04	4095.68	2355.02	1.24
Milo	13.75	6.17	0.02	205.63	118.24	0.06
Mineo	2776.05	1247.00	3.77	17,922.16	10,305.24	5.45
Mirabella Imbaccari	372.52	167.33	0.51	-	-	-
Misterbianco	314.95	141.48	0.43	7381.34	4244.27	2.24
Motta Sant'anastasia	635.75	285.58	0.86	5605.42	3223.12	1.70
Nicolosi	44.78	20.12	0.06	-	-	-
Palagonia	377.46	169.56	0.51	18,711.86	10,759.32	5.68
Paterno'	1928.51	866.29	2.62	16,588.60	9538.45	5.04
Pedara	10.01	4.50	0.01	-	-	-
Piedimonte Etneo	282.33	126.82	0.38	1032.53	593.70	0.31
Raddusa	138.74	62.32	0.19	19.45	11.18	0.01
Ragalna	453.84	203.87	0.62	-	-	-
Ramacca	2154.73	967.91	2.92	40,378.26	23,217.50	12.27
Randazzo	1024.96	460.41	1.39	-	-	-
Riposto	16.02	7.19	0.02	2713.18	1560.08	0.82
San Cono	52.15	23.43	0.07	-	-	-
San Giovanni La Punta	50.16	22.53	0.07	14.82	8.52	0.00
San Gregorio Di Catania	10.23	4.60	0.01	154.93	89.08	0.05
San Michele Di Ganzaria	512.68	230.30	0.70	42.41	24.39	0.01
San Pietro Clarenza	64.87	29.14	0.09	-	-	-
Santa Maria Di Licodia	1192.90	535.85	1.62	-	-	-
Santa Venerina	139.42	62.63	0.19	582.95	335.20	0.18
Sant'agata Li Battiati	6.22	2.79	0.01	68.10	39.16	0.02
Sant'alfio	45.44	20.41	0.06	1384.89	796.31	0.42
Scordia	307.95	138.33	0.42	3762.82	2163.62	1.14
Trecastagni	27.15	12.20	0.04	-	-	-
Tremestieri Etneo	11.23	5.04	0.02	-	-	-
Valverde	11.32	5.09	0.02	-	-	-
Viagrande	57.38	25.77	0.08	-	-	-
Vizzini	900.16	404.35	1.22	114.27	65.71	0.03
Zafferana Etnea	134.48	60.41	0.18	13.41	7.71	0.00

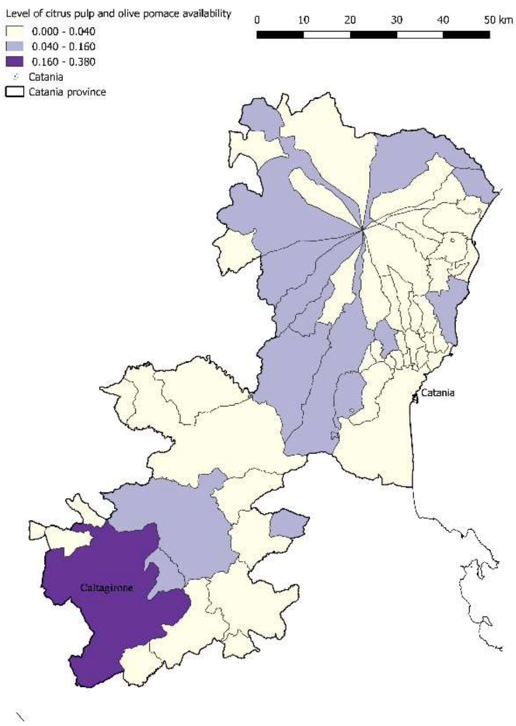
(*) Source: Agricultural statistical database, ISTAT [53,65].

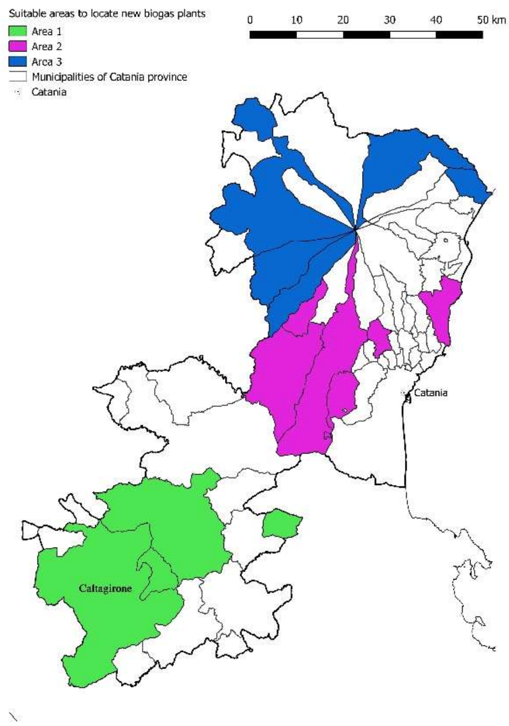




(**a**) $i_{cp\_a_i}$ (**b**) $i_{op\_a_i}$

Figure 2. Territorial distribution of the $i_{cp\_a_i}$ index (**a**) and $i_{op\_a_i}$ index (**b**) in the municipalities of Catania province.





(**a**) (**b**)

Figure 3. (**a**) Territorial distribution of the combined levels of citrus pulp and olive pomace availabilities. (**b**) Areas suitable to locate cooperative biogas plants.

With the aim of estimating the potential biogas availability B_{tot_i} by adopting the Equation (3) (Table 2), the total amount of citrus pulp and olive pomace was computed for Area 1, Area 2, and Area 3.

Based on both the quantity of biogas potentially produced by the two by-products available in Catania province, and the sizes of hypothetical cooperative biogas plants computed by using Equation (4) to be located in Area 1, Area 2, and Area 3, the corresponding amounts of net electricity and heat generated from the anaerobic digestion process were estimated by using Equations (5) and (6) (Table 2).

Table 2. Electricity and heat generated by reusing citrus pulp and olive pomace for biogas production.

By-Products	Potential Biogas Production	Engine Power Size	Net Electricity Generation	Net Heat Generation
	(Nm^3)	(kW)	(kWh y^{-1})	(GJ y^{-1})
		Catania province		
Citrus pulp	9,718,056	2082	13,266,208	73,474
Olive pomace	1,947,758	417	2,658,902	14,726
Total	11,665,815	2500	15,925,111	88,200
		Area 1		
Citrus pulp	1,396,762	299	1,906,733	10,560
Olive pomace	455,942	97	622,410	3447
Total	1,852,704	397	2,529,144	14,007
		Area 2		
Citrus pulp	1,910,680	409	2,608,287	14,449
Olive pomace	359,103	76	490,214	2715
Total	2,269,783	486	3,098,502	17,160
		Area 3		
Citrus pulp	24,869	5	33,949	188
Olive pomace	366,483	78	500,290	2770
Total	391,353	83	534,239	2958

By considering the total amount of citrus pulp and olive pomace available in Catania province, cooperative biogas plants could have a net electricity capacity estimated to be about 2.5 MW (Table 1). The biogas potentially produced by reusing citrus pulp and olive pomace could generate 15.9 GWh net electricity and 88,000 GJ heat per year.

As reported by Terna Group, the annual electricity required in Catania province is 3560.1 GWh y^{-1} for 2016, subdivided into the agricultural sector (90.2 GWh y^{-1}), industrial sector (1040.8 GWh y^{-1}), service sector (1311.7 GWh y^{-1}), and household sectors (1117.3 GWh y^{-1}) [78]. Based on these data, the biogas obtainable from the anaerobic co-digestion of citrus pulp and olive pomace could satisfy approximate 17% of the annual electricity demand of the agricultural sector (90.2 GWh y^{-1}) in Catania province. This net electricity could be produced mainly by cooperative biogas plants located in Area 1 and Area 2 (Table 2).

This could be considered an interesting result because the annual electricity obtainable from anaerobic digestion of the two by-products examined in this study could be improved by enlarging the number of possible feedstocks coming from other agricultural residues and/or agro-industrial by-products [79,80]. Furthermore, in view of a growing development of the biogas sector in Southern Italy, this study could contribute to planning a sustainable localization of biogas plants in the three geographical areas where transportation cost due to logistic and supply phase of the two by-products could be minimized.

With regard to net heat produced by the biogas plants, it could be re-used by local farms located in the considered areas, after an improvement of the existing rural infrastructures. Nowadays, the heat obtained from the biogas plants located in Sicily is re-used on farm for heating agricultural facilities such as, greenhouses, farmhouses, biogas plants office, and some livestock buildings.

Though the engine sizes computed for the biogas plants locatable in the areas obtained in this study are quite small, these results could be relevant within research studies regarding the application of anaerobic digestion for biogas production by following the new concept of the Biogasdoneright®. In fact, other research studies aiming at localizing and quantifying further by-products could be fostered by the awareness that at today a large amount of net electricity could be generated from the anaerobic digestion of citrus pulp and olive pomace. By re-using other agricultural by-products, anaerobic digestion could reduce problems related to both national dependences on imported fossil fuels and agricultural waste disposal. In this context, Algieri et al. analyzed the possible energy conversion in a combined heat and power (CHP) system by demonstrating that the co-digestion of multiple agricultural residues from fruit trees and cereal crops, livestock sewage, waste, and by-products of the agro-food industry could ensure a high electric production between 466 and 669 GWh y^{-1} in Calabria region [81].

In terms of agricultural waste disposal, the study could aid the application at the local level of the European policy and planning strategies close to the Horizon2020 which aim at exploitation, re-use, and valorization of biomass, by-products, and agro-industrial wastes in view of a circular economy process. In recent years, the circular economy has attracted a great deal of attention, and within the Horizon2020 strategies, many projects were funded from the European Union by transcending both geographical and scientific borders. The major thrust areas of these projects were the development of green production routes for (bio)commodities and products through waste valorization. Initiatives have been taken by the European Union to fund research and innovation networks across Europe [82]. The launch of specific COST actions such as FP1303, FP1003, FP0602 (BIOBIO), and TD1203 (EuBis) [83] are a few examples of the recent efforts in promoting the development and evaluation of bio- or waste-based products [84].

Moreover, the Smart Specialization Strategy related to the topic "Re-use and valorization of by-products and agro-industrial waste" aims to develop industrialization processes for both valorizing waste and by-products, coming from all food processing operations, and reusing for non-food production. In this context, the results achieved in this work could be relevant with regard to the new intervention priorities established by the European Union, supported by the European Structural and Investment Funds for developing next planning activities [85].

5. Conclusions

The objective of this study was the estimation of the theoretical potential net electricity and heat production from anaerobic digestion of citrus pulp and olive pomace, two agricultural by-products highly available worldwide. A model was proposed and applied in a study area of southern Italy, representative of the Mediterranean basin for citrus pulp and olive pomace production. In the first phase of the model, a GIS software tool was used to compute indices which describe the level of availability of citrus pulp and olive pomace, respectively, in the study area. The outcome of these analyses made it possible to find the most suitable areas for biogas production by re-using the two by-products. In detail, three different areas were obtained for planning the sustainable development of new biogas plants with regard to the minimization of transportation costs for feedstock supply and logistics, in terms of economic, social, and environmental impacts.

Based on the amount of biogas potentially produced by a number of hypothetical cooperative biogas plants, theoretical potential net electricity and heat production were computed for both the three areas and the whole study area. It was demonstrated that it is possible to provide approximately 17% of the total electricity demand of the agricultural sector (90.2 GWh y^{-1}) in the study area. This result is relevant in view of using other biomasses for carrying out similar research studies. With regard heat power generation, these results could be considered a starting point for future development of adequate infrastructure which, currently, are not available within the study area.

Information on other biomasses required for improving biogas production by anaerobic digestion within each selected area could be useful for a more precise localization of new biogas plants based on their potential availability. In fact, the availability of biomass in the area is of primary importance, as it represents a distinctive element of the supply chain. In fact, the use of off-site biomass (i.e., biomass supplied by external areas) would increase the negative externalities of the investment with an economic impact related to transportation (costs and energy).

Nowadays, the sustainability of energy production is one of the main challenges for Europe. In this regard, the European Union and the Member States need to address the challenges which derive from the high dependence on energy imports, from the scarcity of energy resources, as well as the necessity to limit climate change and overcome the economic crisis. On the one hand, the potential reduction of energy consumption and, on the other hand, the increase in energy production by using renewable energy sources could generate economic benefits for all the involved European partners.

Based on the actual framework, the achieved results could help the development of a sustainable biogas sector by solving problems related to by-products disposal and reducing environmental and economic concern related to the national dependence on imported fossil fuels. In detail, producing bioenergy from residual biomass could significantly reduce CO_2 emissions and even could tend toward Bioenergy Carbon Capture and Storage (BECCS).

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