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Use of bio-methane for auto motive application: primary energy balance and well to wheel analysis

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Abstract

To promote the development of sustainable energy systems, the biomass represents an interesting renewable source, due to its wide availability (often as waste to be disposed) and the versatility of the technologies and processes which can be employed in its exploitation. In this work, has been examined the use of the bio-methane, i.e. the gas resulting from digestion processes of wet biomass, further treated (by the so called "up-grading" process) to obtain a methane content useful to feed the combustion engines and representing a short-term solution to the dependence on fossil fuels. The study is focused on different scenarios taking into account several parameters affecting the overall efficiency of the process of production and use. The analysis takes into account the possible biomass supply chains, the different types of biomass exploitable as primary source and different technologies for conversion. The different stages from the production, through the up-grading, up to the availability at the tank have been evaluated. The latest Italian regulation in the distribution field is also taken into account. By a Well-To-Wheel analysis an estimation of the primary energy savings and greenhouse gas emissions reduction is performed, in comparison to the use of methane from fossil source.

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Keyswords: bio-methane for automotive application; WTW analysis; primary energy balance.

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1. Introduction

Biomass is an interesting energy source in reason of its wide availability and because it includes both natural resources and waste. For this reason, the biomass provisions can be warranted both by the natural availability from the land (forests, agricultural and woods related activities, conservation of the green spaces, etc.) and by industry activities as animal husbandry and food and wood processing, together with the urban waste, so that it results a source well compatible with the sustainability of energy systems, based on the concept of closed cycle of resources and clean energy vectors [1,2]. The potential varies depending on the morphology of the territory, as well as the use of the land, but taking into account the multiplicity of the biomass sources, it does not poses the geo-political conflicts typically posed by the not homogeneous distribution of fossil sources.

As can be seen in the table 1, which shows without exhaustibility the ell-eraegional distribution in Italy of few biomass residuals [3], the different regions show different level of bio-waste production, but, except few cases, the different voices can compensate each other. It is worth to stress that the exploitation of the "bio-resources" is bounded to the "short chain" (processing no farer than 70km from the production site) as indicated in the Italian regulations (see for example D. Lgs. 3.3.2011) taking into account the low biomass energy density.

The biomass can be exploited by different processes, depending on the chemical features of the biomasses (as for example moisture content, C/N ratio, and so on), offering, apart the heat by direct combustion, a wide range of "products": for example liquid (bio-ethanol; biodiesel) and also gaseous (H_2 rich syngas, CH_4 rich biogas) [4-8]. Usually, the biomasses suitable for the biogas production are wet biomasses and the main process to produce biogas is the anaerobic digestion (AD), which allows to decompose organic matter through a multiplicity of anaerobic microorganisms under oxygen-free condition and goes through three main steps [9]: (i) hydrolysis & acidogenesis, where bacteria break down the complex organic molecules into simple sugars, amino-acids, fatty acids; (ii) acetogenesis, where next decomposition steps produce mainly acetic acid; (iii) methanogenesis, where the intermediate products of the acetogenesis phase are converted into methane, carbon dioxide and water. The whole process can be carried on at different temperatures: this will affect the kind of bacteria and the process time, that can vary from 15 days to a maximum of 2 or 3 months. This technology offer the advantage to reduce the chemical and biological oxygen demand from waste streams and it can produce renewable energy from waste (agro-industrial waste chain, municipal solid waste, wastewater sludge) and it is used to treat more than 10% of organic waste in several European countries [9-19]. It is considered a sustainable option for the management of biomass wastes and recycling of nutrients [20] as the final product of AD includes organic residue rich in nitrogen together to the biogas (60–70% methane). The biogas from the AD needs a cleaning treatment to remove the typical contaminants as halogenates, hydrocarbons, sulphur compounds, ammonia and dust particles. After the contaminants removal, the biogas can be further treated for maximizing the methane content by the CO2 removal (the up-grading process). The upgrading process can be performed by several techniques, as water scrubbing, organic solvents, membrane separation. An interesting technique is the Pressure Swing Adsorption – PSA performed by several steps of pressurization at elevated pressure which facilitates the CO_2 adsorption on molecular sieves. By literature, the methane content of the gas can reach to 95% , whit methane losses below 2%. [21].

Nomenclature

AD	Anaerobic Digestion
BEV	Battery Electric Vehicle
CHP	Combined Heat and Power
NRPE	Non Renewable Primary Energy
OFMSW	Organic Fraction of Municipal Solid Waste
PSA	Pressure Swing Absorption
TTW	Tank-To-Wheel
WTT	Well-To-Tank
WTW	Well-To-Wheel

Table 1: Example of the regional distribution of some kind of biomass (source [22])

	Region	Surface (10^3 km^2)	Forest residuals (10^3 m^3/year)	Grass residuals (10^3 t/year)	Woody residuals (10^3 t/year)	Pig_sewage (10^3 m^3/year)	Pig_manure (10^3 t/year)
North Italy	Piemonte	25.4	670	1475	125	3040	132
	Valle d'Aosta	3.26	109	0.14	1.51	-	-
	Lombardia	23.9	771	1692	44.2	9282	406
	Trentino-Alto Adige	13.6	1158	1.93	66.7	4.01	0.16
	Veneto	18.4	351	1496	148	763	33.5
	Friuli-Venezia Giulia	7.86	262	486	32.1	213	10.6
	Liguria	5.42	257	2.75	20.1	0.49	0.02
	Emilia-Romagna	22.5	384	1138	197	2126	834
Italy Centre	Toscana	23.0	1061	395	226	114	5.16
	Umbria	8.46	271	291	59.3	191	8.40
	Marche	9.37	165	420	43.8	87.9	3.91
	Lazio	17.2	499	250	206	55.7	2.32
South Italy & Islands	Abruzzo	10.8	274	115	113	144	6.27
	Molise	4.43	98.5	101	0.0	39.7	1.67
	Campania	13.6	378	162	230	68.0	3.06
	Puglia	19.4	124	508	776	3.6	0.15
	Basilicata	10.0	294	217	72.6	27.1	1.09
	Calabria	15.1	771	102	324	43.4	1.93
	Sicilia	25.7	259	363	601	70.1	3.06
	Sardegna	24.1	483	139	128	362	16.2

The process of biogas upgrading realizes a carbon negative chain because the bio-methane substitutes the fossil natural gas and the carbon dioxide can be captured and used in industrial processes [22,23] and recently biogas upgrading plants were installed in US and Europe [24,25].

Today, many biogas plants exploit the gas on-farm in combined heat and power engines (CHP), but the electrical power efficiency can be less than 40% when heat cannot be employed [26, 27]. Upgrading the raw biogas and exploiting it in combined large-size heat & power cycles is more efficient, as the generated heat is utilized by customers, such as district or industrial customers [28]; in alternative it can be used also for energy generation and as feedstock for the chemical industry [29].

In the present paper the authors, which studied several kinds of renewable energy systems and processes [30-48], focus the attention on the use bio-methane in the automotive sector. Several scenarios for the biogas production and up-grading have been examined, also taking into account the opportunities of use and distribution offered by the Italian regulations. The energy balance allowed to define the Non Renewable Primary Energy (NRPE) consumption for the production phase and the NRPE saving from the avoided use of fossil methane. The Well – To – Wheel analysis has been performed and the NRPE consumption and the CO2 emissions have been confronted in the case of bio-methane and the other fuels, both traditional (fossil) and nontraditional (bio- fuels and electricity)

2. Methodology description

Different options for the bio-methane production have been considered, taking into account the variables coming from the technological chooses and from the biomasses characteristics. To evaluate the energy expenses in the Well To Tank (WTT) analysis, the production and distribution chain has been schematized in the steps below (and intermediate storage phases). See figure 1.

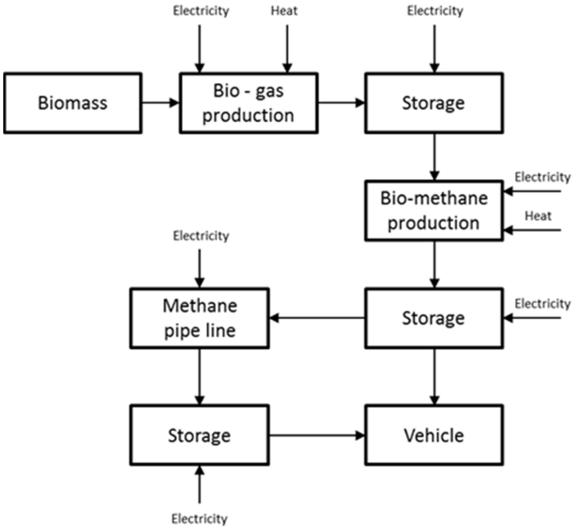

Figure 1: Schematic of the steps for producing and distributing the bio-methane.

- Biogas production by anaerobic digestion of the biomass and cleaning;
- Bio-methane production by upgrading process of the produced biogas (by Pressure Swing Absorption – PSA technique);
- Distribution of the gas to the vehicle filling station (with distribution by Natural Gas (NG) -grid or on-site);
- Gas storage on board (compression at 220 bar).

The steps above can be realized following different strategies which can vary mainly depending on: (i) the methane distribution and (ii) the energy management during the biogas production and biogas upgrading to bio-methane. To define the possible scenarios it has been taken into account that the Italian regulations (see for example D.LGS: 3.3.2011 and DM 5.12.2013) contemplate:

- The use of the bio-methane for co-generation plants;
- The distribution of o the bio-methane by the distribution grid of the natural gas;
- The distribution of the bio-methane on site for automotive purpose.

Being the first option (co-generation plants for power production) out of the purpose of the present work, the second and third options are both pursuable and both have been taken into account. For what concerning the energy management during the biogas and bio-methane production, to supply the heat to the system, any fuel not produced inside the system itself has been excluded. Hence, different options can be adopted for what concerning the amount of energy “auto-produced”, i.e.:

- supplying only the heat by combustion process, whereas the electricity is supplied by the grid;
- supplying electricity and heat by co-generation (i.e. the heat supplied by co-generation is around 85%, whereas the remaining 15% will be supplied by integrative boilers to satisfy the seasonal fluctuations).

Since both biogas and bio-methane could be in principle exploited to supply the “auto-produced” energy to the system, the possible combinations of the above options offer several scenarios, described in the table 2.

Table 2: possible scenarios for producing and distributing the bio-methane.

Scenario	Electricity supply	Heat supply	Bio-methane distribution
1	grid	biogas combustion	on site
2	grid	bio-methane combustion	on site
3	biogas cogeneration	biogas cogeneration	on site
4	bio-methane cogeneration	bio-methane cogeneration	on site
5	grid	biogas combustion	natural gas distribution grid
6	grid	bio-methane combustion	natural gas distribution grid
7	biogas cogeneration	biogas cogeneration	natural gas distribution grid
8	bio-methane cogeneration	bio-methane cogeneration	natural gas distribution grid

Table 3: biogas yield and methane content for the five biomasses examined. Elaboration from [3, 49]

Biomasses	Availability (10^6 t/year)	Percentage	Biogas yield (m^3/t)	CH_4 content (%)
OFMSW	4.81	4%	148	55
Sewage	83.1	77%	59	63
Manure	10.9	10%	205	63
Dedicated energy crops	8.44	8%	133	55
Agro-industrial waste	1.13	1%	266	55

As the energy expense for the bio-methane production is also affected by the biomass type employed in the digestion process, the following five type of biomass widely available in the Italian territory have been considered:

- Organic Fraction of Municipal Solid Waste (OFMSW)
- Sewage
- Manure
- Dedicated energy crops
- Agro-industrial waste

The biogas yield and the methane content vary depending on the different kind of biomass, as shown in table 3. Where required, the biogas properties (specific heat at constant volume/pressure, lower heating value, density, etc) were calculated starting from the data available in literature and considering the biogas composed by the CH_4 content shown in the table 3, 0.5% of hydrogen, 1% of nitrogen and carbon dioxide for the remaining percentage [49]. The biomass influence has been included in the WTT analysis considering the percentage of availability of each biomass, as indicated in the next sections.

2.1. Analysis of the energy requirements

The energy required in the full production & distribution chain to provide methane to the end users (to the car) will be in general depending on: the biomass chosen and the scenario. For what concerning the biogas production and cleaning, it will be affected mainly by the biomass type, which influences the amount of heat required to thermalize the digestion process and the amount of mechanical energy required for feeding and mixing the biomass. The calculated energy required for processing one biomass ton are indicated in the table 4.

For what concerning the biogas upgrading process, i.e. the CO_2 removal for the bio-methane production, it is not influenced by the scenario. In the present study, it has been considered the upgrading process performed by PSA – Pressure Swing Absorption technique, which is carried out at around 10 bars and 700 °C.

Table 4: heat and power expense for processing 1 ton of the five biomasses choosen.

Biomass	Electricity requirement (kWh/t)	Heat (kWh/t)
OFMSW	51	71
Sewage	19	44
Manure	44	165
Dedicated energy crops	27	101
Agro-industrial waste	47	178

Under these hypotheses, for the upgrading process the energy requirements referred to one kg of biogas processed are: 0.20 kWh/kg of electricity and 0.31 kWh/kg of heat. The pressure conditions of this method for the CO_2 removal are favorable for the next distribution step, in fact, starting from 10 bars, the gas inlet into the natural gas distribution grid would not need a compression step after the PSA process. For this reason, the energy requirement for the distribution is only related to the compensation of the pressure drop. The compensation of the pressure drop is performed through compression stations which are fueled by the gas itself. Under the hypotheses that the efficiency of the compression stations is around 40% and that the mean transport distance is around 300 km, the energy requirement for the distribution by the NG grid is around 0.12 kWh/kg.

The last energy expense to be taken into account for the WTT evaluation is related to the storage into the vehicle tank. In fact, for the storage, the gas needs to be compressed at 220 bars. In this case, there is a difference if the distribution is on-site in the place of production or by the NG distribution grid. If the distribution is on-site, the compression up to 220 bars starts from around 10 bars (which is the pressure of the PSA process) and requires less energy in respect to the case of the NG distribution grid, where the initial pressure is around the atmospheric value (around 1 bar): the calculated values are respectively 0.18 $kWh/kg_{biometane}$ and 0. 35 $kWh/kg_{biometane}$.

As told above, the energy balance depends on the biomass, but only in the first phase of the biogas production and on the scenarios for the next steps. For this reason, the OFMSW has been chosen as example for the energy evaluation by scenario shown in the figures 2-5. Each scenario requires a different amount of energy, as detailed in figure 6.

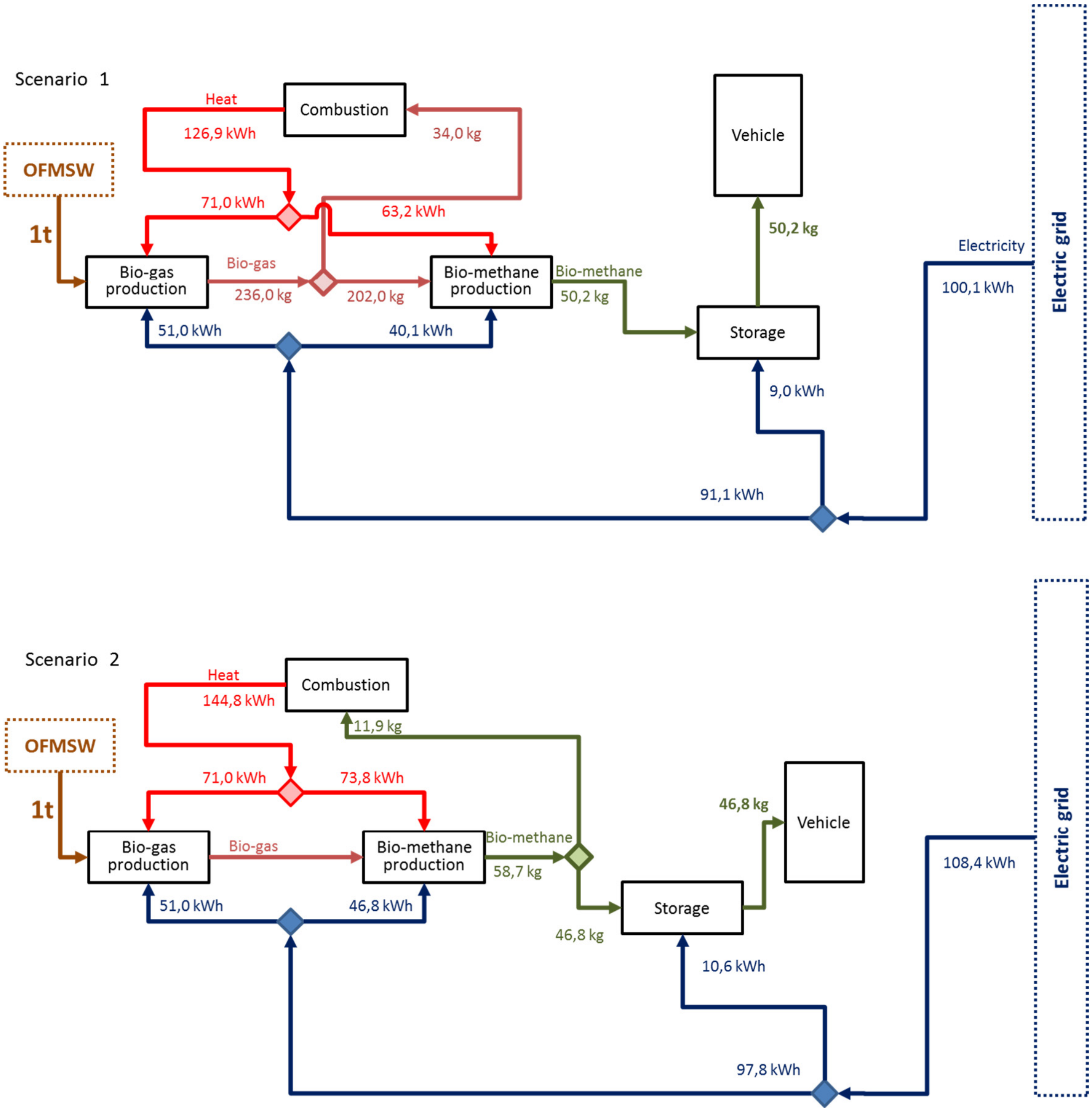

Figure 2: energy balance for scenarios 1 and 2.

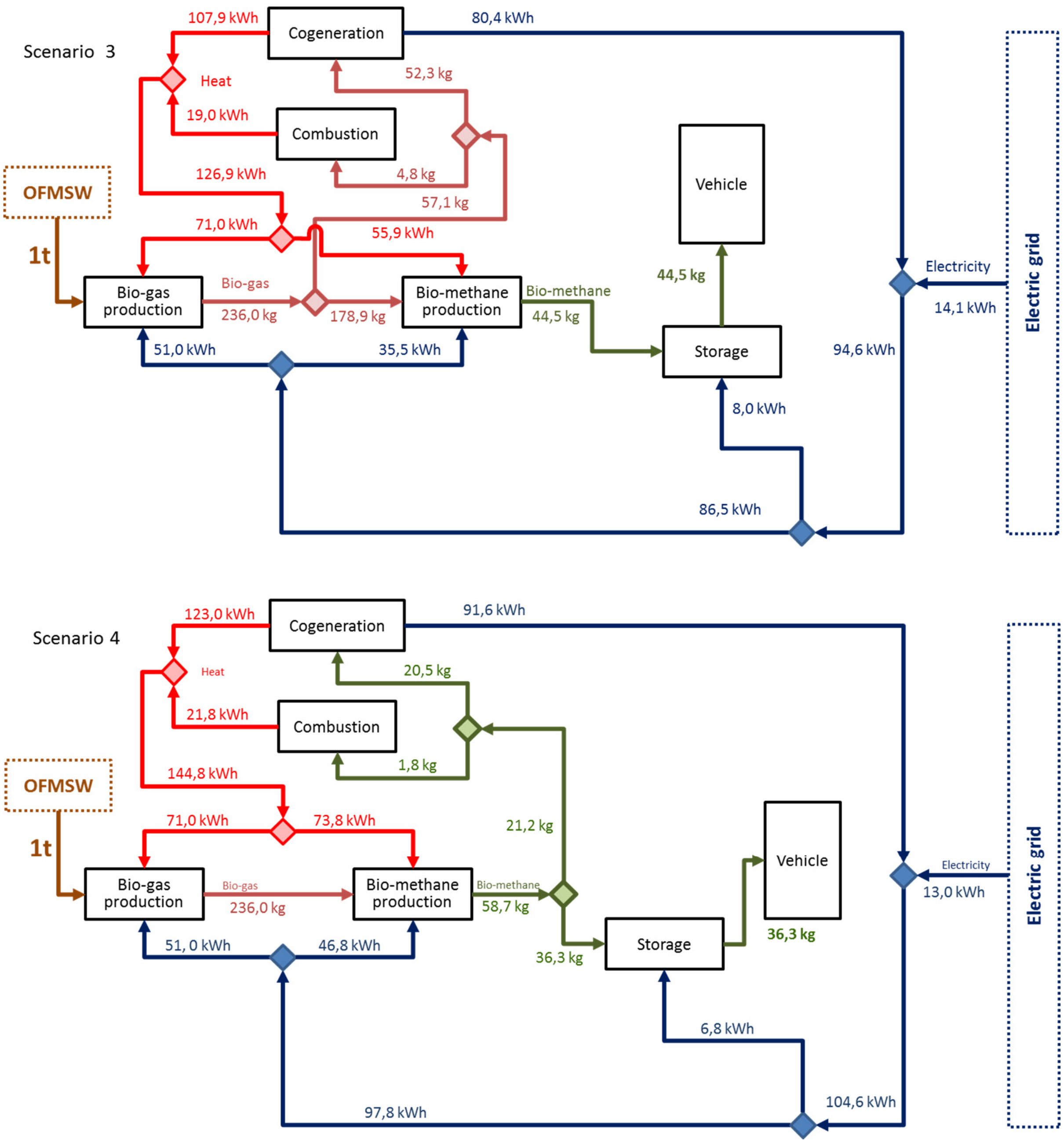

Figure 3: energy balance for scenarios 3 and 4.

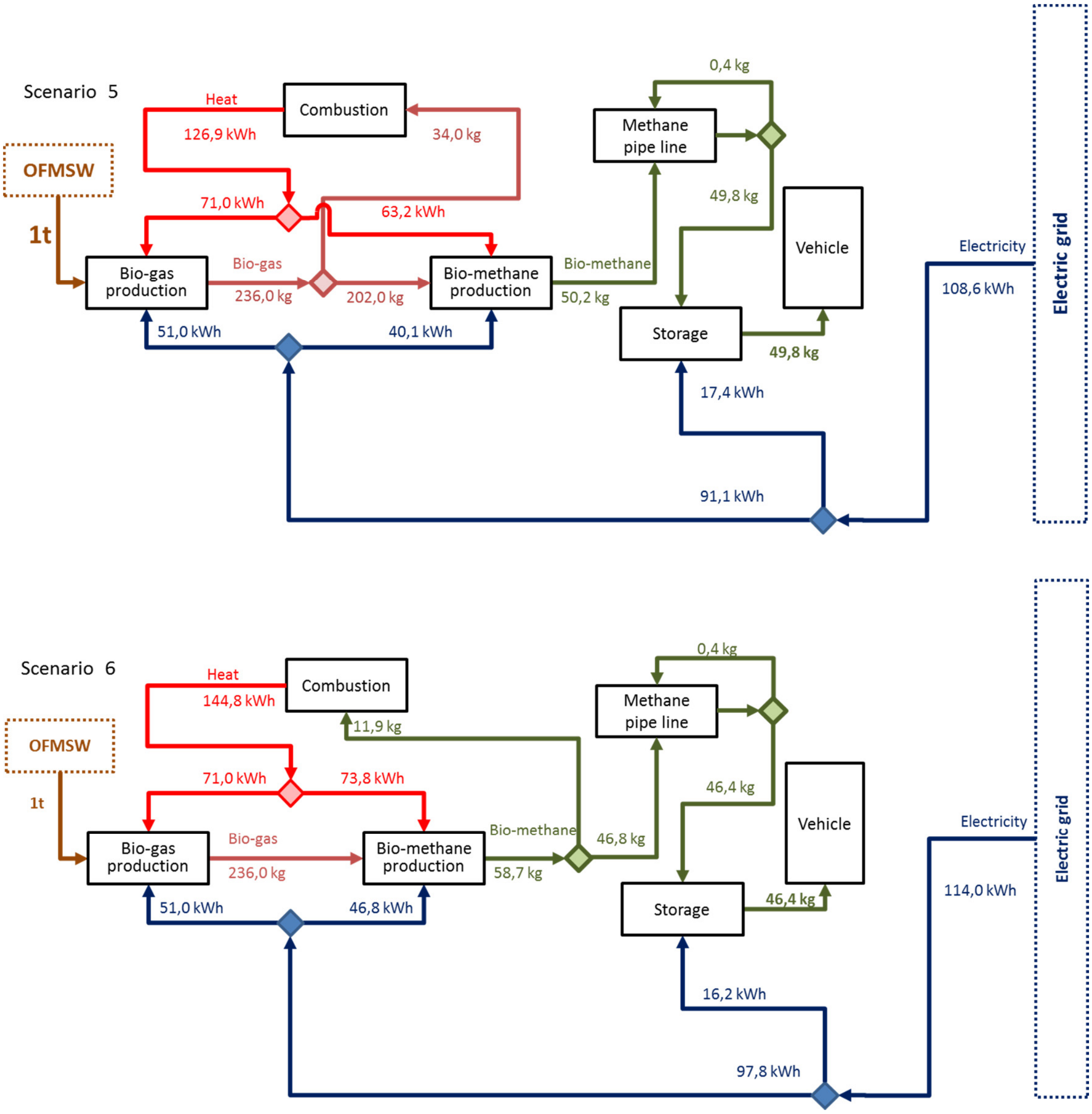

Figure 4: energy balance for scenarios 5 and 6.

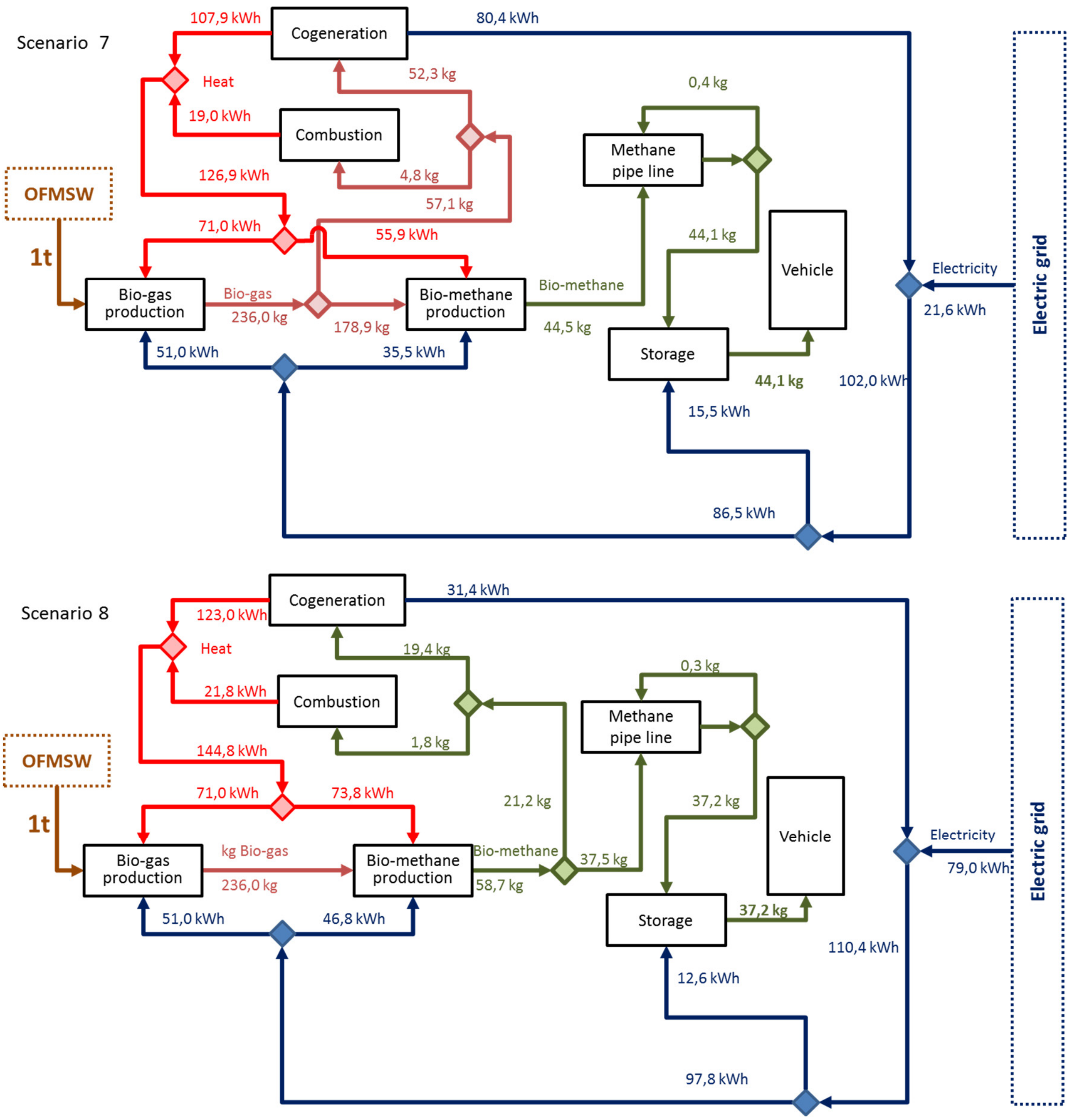

Figure 5: energy balance for scenarios 7 and 8.

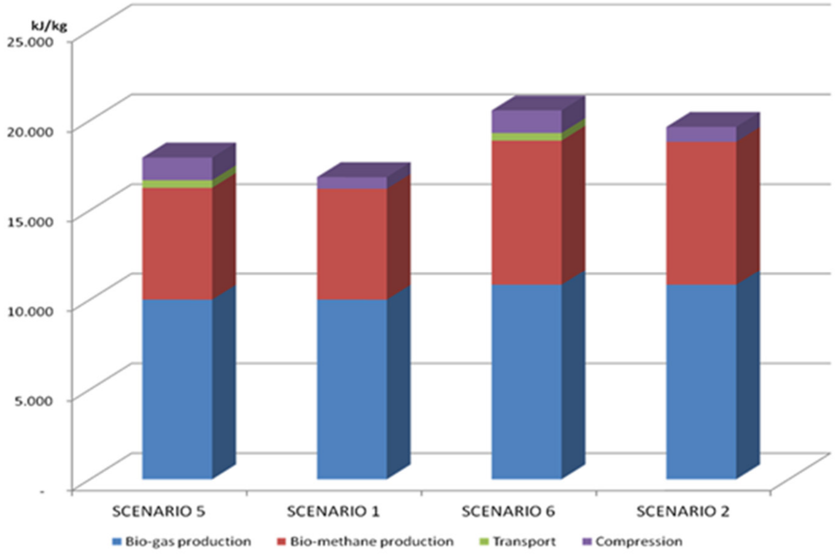

Figure 6: Energy consumption for different scenarios (scenarios without co-generation). It is shown the energy expense for the different phases of the production and distribution chain.

Taking into account that the NRPE consumption and the CO_2 emissions are proportional to the electricity ***e*** taken from the grid depending on the following relations [50-52]:

$$\mathrm{NRPE}=1.85\cdot \boldsymbol{e}\ [\mathrm{kWh}] \quad (1)$$

$$CO_2=585* \boldsymbol{e}\ [\mathrm{g/kWh}] \quad (2)$$

the consumption and the saving of NRPE, and related CO_2 emissions can be evaluated. In general, the amount of required energy increases both in the case of bio-methane distribution by NG grid and in the case of bio-methane use rather than biogas for supplying energy to the process.

2.2. Criteria for the scenarios evaluations

To evaluate the best scenario for the production and distribution of bio-methane for automotive application, different criterion can be adopted: one is the identification of the scenario which minimizes the consumption of NRPE per bio-methane mass unit, whereas another approach can be the identification of the scenario which maximizes the saving of NRPE per biomass unit processing. Adopting the first criterion, the minimum of NRPE consumption is related to the scenarios where the energy is supplied to the system by cogeneration of heat and electricity, exploiting for the cogeneration the biogas rather than the bio-methane. The consumptions are very lower than the other scenarios in both the cases of distribution on site and distribution by the grid (see table 5, column 2^{nd}). On the other hand, adopting the second criterion, the maximum of net NRPE saving (i.e. considering the NRPE saving by substituting the fossil methane minus the energy expense for the bio-methane production) is achieved by the scenario where the electricity is taken from the grid and the heat is supplied by biogas (see table 5, column 4^{th}). The accordance in between these results can be better understood considering the efficiency in the biogas yield. In fact, if on one side the co-generation allows to save NRPE during digestion and upgrading, on the other side the consumption of produced biogas decreases the bio-methane yield at the end of the process. Instead, taking the electricity from the grid, also if increases the NRPE consumption during the process, increases also the amount of bio-methane produced. This increases the global avoided NRPE consumption, increasing the avoided NRPE consumption related to the use of fossil methane by the end users. The analysis can take into account just the efficiency of the process (as the case of the first criterion), or including also the use of the produced resource (as the case of the second criterion): in the case of the present work, which considers the bio-methane production for automotive exploitation, the second criterion is more appropriate.

Table 5: NRPE balance and CO_2 emissions by scenario and by approach (NRPE consumption / NRPE saving). Avoiding the cogeneration (scenarios 1 and 5) the bio-methane yield and the NPRE saving increase.

	Production of 1 kg of methane		Processing of 1 ton of biomass (net values)		bio-methane yield per biomass ton
Scenario	Consumption of NRPE (MJ)	CO_2 emissions (kg)	Saving of NRPE (GJ)	Avoided CO_2 emissions (kg)	mass of bio-methane available at the tank (kg)
1	13,3	1,2	10.471	147,6	50,2
2	15,4	1,4	9.749	128,5	46,8
3	2,1	0,2	9.271	174,2	44,5
4	13,3	1,2	7.820	110,2	37,5
5	14,5	1,3	10.380	140,9	49,8
6	16,4	1,4	9.665	123,6	46,4
7	3,3	0,3	9.191	168,3	44,1
8	14,6	1,3	7.504	105,17	36,0

3. Well-To-Wheel analysis

3.1.1. Well-To-Tank analysis

The considerations above stressed the differences in between the scenarios and what chooses would minimize the energy expense, or the CO_2 emission. Taking into account these considerations, the Well-To-Tank (WTT) analysis will require some extra evaluation related to the real users condition. In particular, regarding the scenarios:

- the on-site distribution is more convenient than the distribution by NG grid. On the other hand, thinking to a large-scale distribution of the bio-methane, the on-site distribution would cover only a fraction of the whole demand. For this reason, the hypothesis of distribution by NG grid would be more realistic and would be a conservative hypothesis (considering the maximum energy expense for the distribution step). Under this hypothesis, the possible scenarios are the 5 – 6 – 7 – 8.
- the cogeneration process is more efficient thinking to the energy expense for producing 1kg of bio-methane, but maximizing the bio-methane yield is more convenient, taking into account the use in the automotive applications. For this reason, in the above scenarios 5 – 6 – 7 – 8, the 7 and 8 can be discarded.
- if the heat alone is provided to the system by combustion of the auto-produced gases, it is more convenient to burn the biogas as produced, rather than the upgraded biogas (bio-methane), as can be seen for example in figures 3 and 5. For this reason, the more convenient scenario results the scenario 5.

Considering that the bio-methane distributed by the grid would be produced exploiting the availability of the different biomasses, and considering that each biomass would require a different energy expense for the biogas production, for evaluating the global energy expense and the global CO_2 emission for 1kg of bio-methane at the tank, the availability of the biomasses has to be taken into account. The calculation refer to the values shown in the table 3 above. Considering the scenario 5 and the mix of biomasses as in tables 3 and 4, for each kg of bio-methane available at the tank, the values of NRPE consumption and CO_2 emission result:

$$NRPE=12.16\ kJ/kg_{\_biomethane} \tag{3}$$

$$CO_2=1.07\ kg_{\_CO2}/kg_{\_biomethane} \tag{4}$$

3.1.2. Tank-To-Wheel analysis

For evaluating the consumptions and the emission on board, the bio-methane is equivalent to the fossil methane. An interesting Tank-To-Wheel (TTW) analysis to confront different power trains is available in literature [53].

Table 6: Energy consumption and specific CO_2 emission by fuel [53].

Power train	Energy consumption (kJ/km)	Fuel consumption (g/km)	Specific CO_2 emission (g/g)
MCI gasoline	2447	55.7	3.143
MCI diesel	2234	52.3	3.143
MCI LPG	2566	55.7	3.000
MCI methane	2447	50.3	2.750
Battery Electric Vehicle (BEV)	540	-	-

3.2. Well-To-Wheel results

The Well-To-Wheel (WTW) analysis in the case of the bio-methane at this point is easily obtained by the results shown in the section 3.1 and 3.2. and it is interesting to confront the case of bio-methane and the cases of the other fuels nowadays available in the automotive field, as the traditional gasoline, diesel, Liquid Petroleum Gas- LPG, fossil methane, but also the less traditional bio-ethanol and bio-diesel.

Table 7: NRPE consumption and CO_2 emissions of traditional fuels [54]

	WTW/WTT	
Fuel	Consumption of NRPE (#)	CO_2 emissions (#)
MCI Gasoline	1.1376	1.1683
MCI diesel	1.1800	1.1915
MCI LPG	1.1193	1.1333
MCI methane	1.1944	1.2436

Known the consumption and emissions of traditional fuels on board (table 6), the global consumption and emissions can be evaluated by the ratios indicated in the table 7 (see [54]). In the same report [54], the WTW values of consumption and emission are expressed also for bio-ethanol and bio-diesel, whereas the data for the electric vehicle are available in [53].

Bio-ethanol

$$NRPE=0.57\cdot NRPE_{\_gasoline} \quad (5)$$

$$CO_2=0.55\cdot CO_{2\_gasoline} \quad (6)$$

Bio-diesel

$$NRPE=0.36\cdot NRPE_{\_diesel} \quad (7)$$

$$CO_2=0.47\cdot CO_{2\_diesel} \quad (8)$$

Electricity

$$NRPE=2.27\cdot BEV_{\_(energy\text{-}consumption)} \quad (9)$$

$$CO2=0.21\cdot kg/kJ_{consumed} \quad (10)$$

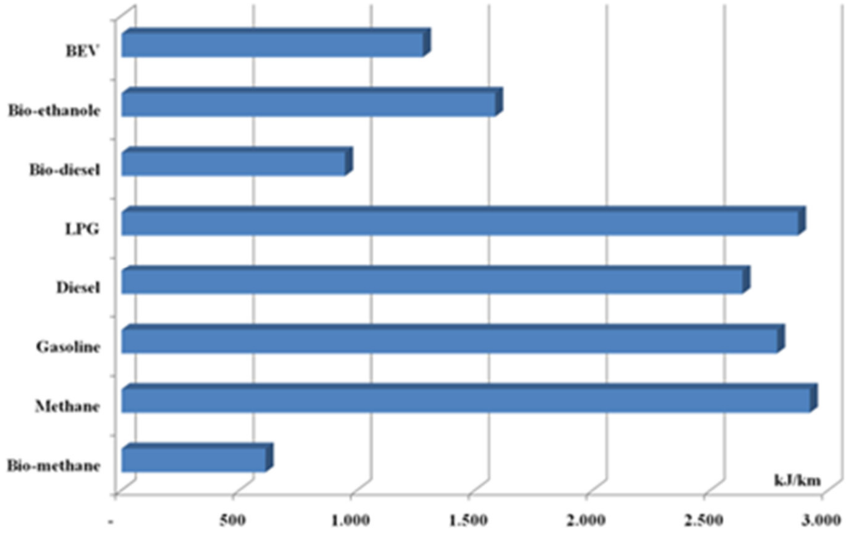

Figure 7: confront of the NRPE consumption in kJ/km for different fuels.

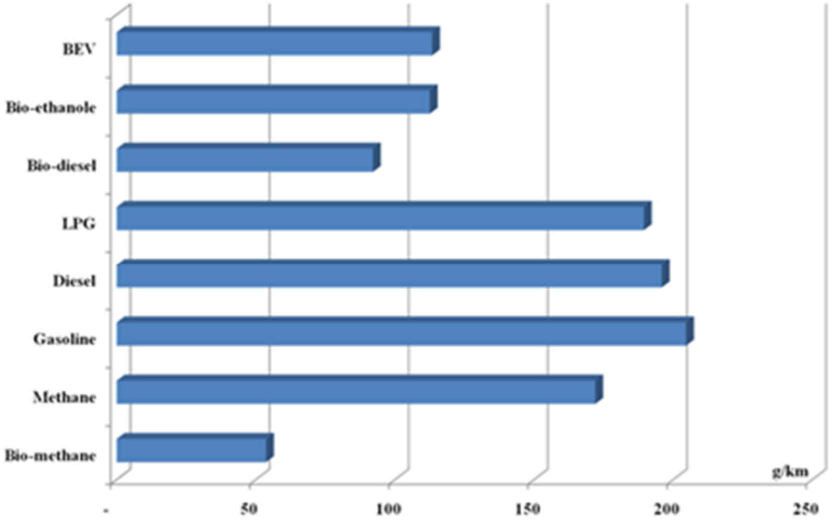

Figure 8: confront of the CO_2 emissions in g/km for different fuels.

Taking into account the values calculated by the help of table 7 and equations 5-10, the NRPE consumption and the CO_2 emission per covered kilometer can be expressed for the fuels described above, see figures 7 and 8.

The bio-methane results the fuel which allows spending less non renewable primary energy and less CO_2 emission per km. The bio-methane is competitive not just in respect to the traditional fuels, but also in respect to the others fuels from biomass, as bio-diesel and bio-ethanol and in respect to the electric vehicles.

4. Conclusions

The use of bio-methane for transport purposes results very interesting for different reasons. By the results of the present work, it is clear the advantage for what concerning the reduction of the CO_2 emissions and the reduction in the consumption of NRPE. But also other aspects can be taken into account, as for example the impact on the public opinion coming from the awareness that such a fuel at the same time has minimal greenhouse gas emission and is made from waste (including the OFMSW produced by the car user itself at his own home).

Another interesting aspect is that the large-scale production of bio-methane would help in reaching the 2020 target which imposes to achieve 10% from renewable energy sources - RES of the energy consumed in the transport field. Up to now, the risk is to come forward the pathway of bio-fuels from dedicated energy crops, which poses doubts in matter of sustainability and conflicts with food crops, apart economical issues. In Italy in 2011 the bio-fuels were produced with 99,9% of imported biomass: to achieve the 2020 target, the cost for the car drivers, to date and not including the increase in the fuels price, would be higher than 3.5 bln [55].

Table 8: evaluation of NRPE saving and CO2 avoided emission by (partial) exploitation of the Italian bio-methane potential.

	Fossil Fuels %	Bio- fuel %	NRPE saving (TJ/year)	CO_2 avoided emissions (Mt/year)
Data by ISPRA at 2012	96	4	-	-
+ 2.5×10^9 m^3/year of bio-methane	87	13	22×10^3	1.08
+ 4×10^9 m^3/year of bio-methane	84	16	79×10^3	11.40

The data from the Observatory of Agro-Energy at 2013 begin [49], indicate that the potential of bio-methane production is around 5.6 bln of cubic meters per year, enough to cover 5-10% of the whole Italian energy demand at 2020. The Italian Consortium for Biogas estimated that such a potential would be able to reach 8 bln of cubic meters per year, without any conflict with the food and pasture production (which is the critical point of the dedicated energy crops). If the bio-methane production would rise up to 8 bln of cubic meters per year, Italy would save 5 bln€ from the reduction in gas importation and the Gross Domestic Product GDP of agriculture would increase 5%, with advantages for employment opportunities.

From data by ISPRA (Superior Institute for Environmental Research and Protection) it is easy to calculate the NRPE saving and the CO_2 emissions avoided, see table 9. If only less than half of the estimated potential will be achieved and 2.5 bln of cubic meters per year would be produced, the 2020 target of 10% would be fully satisfied by the use of biomass alone.

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