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*Research Article*

# Feasibility of a Dual-Fuel Engine Fuelled with Waste Vegetable Oil and Municipal Organic Fraction for Power Generation in Urban Areas

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Biomass, in form of residues and waste, can be used to produce energy with low environmental impact. It is important to use the feedstock close to the places where waste are available, and with the shortest conversion pathway, to maximize the process efficiency. In particular waste vegetable oil and the organic fraction of municipal solid waste represent a good source for fuel production in urban areas. Dual fuel engines could be taken into consideration for an efficient management of these wastes. In fact, the dual fuel technology can achieve overall efficiencies typical of diesel engines with a cleaner exhaust emission. In this paper the feasibility of a cogeneration system fuelled with waste vegetable oil and biogas is discussed and the evaluation of performance and emissions is reported on the base of experimental activities on dual fuel heavy duty engine in comparison with diesel and spark ignition engines. The ratio of biogas potential from MSW and biodiesel potential from waste vegetable oil was estimated and it results suitable for dual fuel fuelling. An electric power installation of 70 kW every 10,000 people could be achieved.

## 1. Introduction

The increasing costs and climate changing related to fossil fuels exploitation require a major share of the energy production from alternative sources, in particular from waste or renewable sources. Recently, great attention is given to the use of biomass to produce fuels, especially for transport as alternative to petrol. Biofuels production is a way to use solar energy. However, the low conversion efficiency of the global process can create land competition between food and energy production. From this consideration derives that dedicated energy crops cannot be seen as the solution of the energetic and environmental issues. Biofuels production becomes extremely interesting when obtained from waste or residual of others human activities, but, in this case, the limited feedstock could contribute only with a small impact on the reduction of the fossil fuel demand. Furthermore, the efficient energy use of waste could contribute strongly to control the questions of waste disposal. While, in the case of biofuel production from dedicated energy crops, it is important to support those with the best "biomass to energy" global efficiency, in order to minimize land use competition, [1], for "waste to energy" conversion, it could be important to collect the feedstock near the places where waste is available and achieve the shortest conversion pathway, to maximize the process efficiency.

Considering wastes produced in urban areas, after an appropriate selective collection, it could be possible to use the organic fraction of municipal solid waste (MSW) and waste vegetable oils (WVOs) and fats for energy production. The per capita potential of these feedstock, as will be discussed, could reach (in particular in Italy, but the average value will be not so different in Europe) a theoretical value of about 10 kg of methane equivalent per year. Considering a per capita annual electricity consumption (in Italy) of about 5500 kWh/year [2] and assuming to produce this energy with an efficient natural gas (NG) plant (combined cycle), the per capita fuel requirements per year, as regard the only amount for electricity consumption, are about 800 kg of methane equivalent per year. So a rate close to 1% of this demand can be met with fuels derived from organic fraction of MSW and WVO. Nowadays, the larger part of

WVO produced is discharged into the local sewage network, while the collected part is often used to produce biodiesel blended with conventional diesel oil in refinery. Instead the MSW organic fraction is increasingly selective collected and composted or converted in biogas with digester plant. This management seems to be not very efficient; in fact, the two wastes have to be processed separately in few places far away from the production areas.

In this paper, a more efficient utilization of this renewable source is proposed. A dual-fuel engine fuelled with biogas from MSW and biodiesel from WVO has been taken into consideration for a realization of a more efficient waste to energy conversion pathway. In addition, it is opportune to consider that, due to the limited feedstock amount, a combined heat and power (CHP) production with an internal combustion engine (ICE) could be more appropriate than other systems (turbines) or than the production of biofuels suitable for transport sector. The dual-fuel technology represents the optimal solution offering possibility to manage both the two-waste typology in the same plant as gaseous and a liquid fuel allowing their utilization in an engine with a global efficiency typical of diesel engines but with cleaner exhaust emissions and so suitable for urban areas.

## 2. Biogas Potential from Organic Fraction of MSW

The capture and use of biomethane derived from organic waste matter decomposition process allow a significant reduction of greenhouse gas emissions in the atmosphere. A biogas production plant represents an attractive way, alternative to simple composting, to reduce organic material landfill disposal, as required by the European Union.

Biogas is produced during process of anaerobic fermentation (also called digestion) that consists in a biological breakdown of organic matter in absence of oxygen activated by means of anaerobic microorganisms (bacteria). Biodegradable organic materials are converted into a mixture of methane ($CH_4$) and carbon dioxide ($CO_2$) with smaller amounts of hydrogen sulphide ($H_2S$). Trace of hydrogen ($H_2$), nitrogen ($N_2$), ammonia ($NH_3$), and oxygen ($O_2$) could be present in biogas. Usually, the mixture is saturated with water vapour and may contain dust particles and siloxanes.

The typical composition of biogas is reported in Table 1 [3].

Some biogas proprieties, calculated in dependence of methane content, are shown in Figures 1 and 2.

Biological decomposition of organic waste without oxygen is a process that occurs spontaneously in nature and in particular in old landfills at ambient temperature. Thus, uncontrolled and open air landfills are responsible for biogas escape into the atmosphere. Since methane has a higher greenhouse effect than carbon dioxide (more than 20 times), capturing and burning $CH_4$ from organic matter decomposition contribute to the reduction of global earth warming. In controlled landfill, it is possible to capture part of biogas generated. The use of closed reactors (digesters), to produce biogas, optimizing all factors involved in biological processes (temperature, pH, feedstocks, retention time in the system, and solid content), leads to a higher yield of methane in biogas drastically lowering escape into atmosphere. A certain amount of heat is necessary to keep the temperature at optimum levels in the digester. Heat is generated by burning part of produced biogas. In particular the share of biogas consumed for its production is usually around 25% in conventional plants.

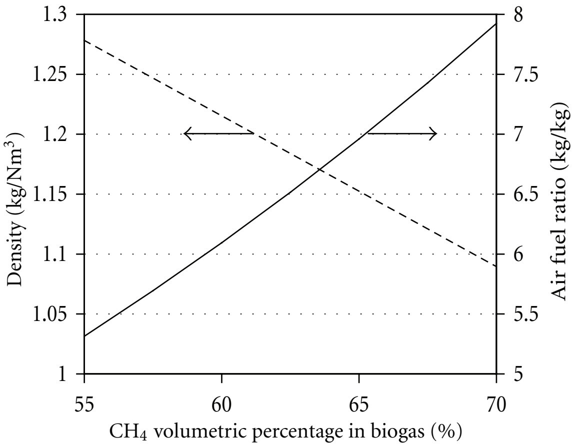

Figure 1: Biogas density and stoichiometric air fuel ratio.

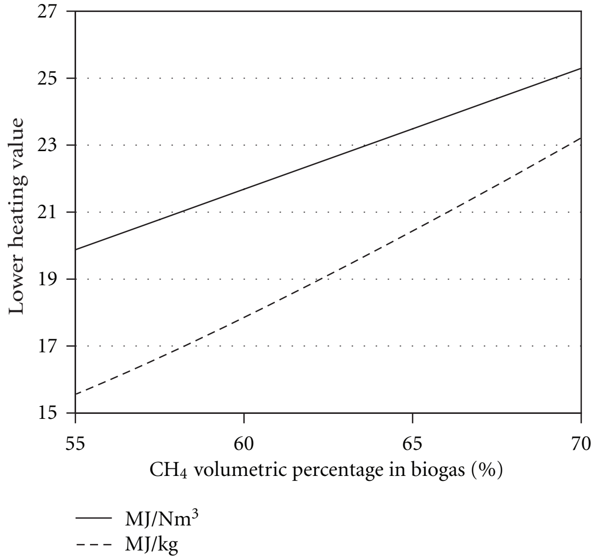

Figure 2: Biogas lower heating value on mass and volume basis.

Table 1: Typical composition of biogas.

| Compound | Volumetric percentage, (%) |
|---|---|
| $CH_4$ | 55∼70 |
| $CO_2$ | 30∼45 |
| $H_2S$ | 0.02∼0.2 |
| Water dew point | Saturated |
| $H_2$, $NH_3$, $O_2$, $N_2$ | Traces |

Feedstocks suitable for the production of biogas are all the putrescible biomass: manure or sewage, organic fraction of MSW, and plants from energy crops, taking into account that the higher the content of lignin the lower the amount of biogas obtainable. In Table 2 is reported the quantity of biogas producible (after a couple of weeks in a digester) from anaerobic fermentation of different feedstocks. Biogas yield is expressed as a percentage by mass of dry or wet material. Biogas yield data, as tonnes of oil equivalent, were taken from [4] together with the feedstock dry matter content. Then biogas yield was expressed as percentage in mass of the feedstock considering an average lower heating value of 19 MJ/kg (obtained as the mean value of Figure 2).

Although biogas can be directly utilized with the maximum efficiency in a CHP plant, the biogas upgrading to biomethane is the best alternative to use it as vehicle biofuel or to replace fossil NG in the existing network. The process increases the energy content by removing $CO_2$, raising methane content, and meanwhile removes dust particles, $H_2S$, siloxanes, and other impurities to prevent pollution and formation of dangerous compounds during combustion. The energy cost necessary for the upgrading process is roughly 10% of produced biomethane, estimated from the energetic consumptions necessary in the process [5]. When the technology for second generation biofuels production will become available, it will be also possible to obtain biomethane from biomass gasification by methanation of syngas.

The principal source of organic waste in urban areas is the organic wet fraction (almost 30%) of MSW (roughly 1.5 kg per capita per day, in Europe).

The steps to estimate per capita daily biomethane potential production from 450 g wet organic fraction of MSW (1500 g per capita daily) are shown in Figure 3 [6]. Almost 68 g of biogas that could be upgraded 22 g of biomethane could be obtained every day from the waste produced by each people.

Therefore, on an annual basis, almost 8 kg of biomethane (or about 9 kg of biomethane equivalent in the form of biogas) could be derived per capita from the organic fraction of MSW.

## 3. Biodiesel Potential from WVO and Fats

Waste vegetable oils are constituted of used cooking oils or other vegetable and animal oils and fat.

In several Europe member states, some consortia are currently active for the WVO collection. The waste collected and recovered for industrial use by the consortia is mainly oil from fried food production, both industry and households. Used oil for frying, while not dangerous in itself, should be collected and treated separately from other types of waste. In reality, only a small amount is collected separately. Most of this oil, particularly waste oil and fats from households that are disposed through the sewerage, reaches sewage treatment plants with a high increasing of the economics and energetic cost of the sewage treatment process.

In Italy, currently, it is estimated that the amount of waste consisting of vegetable and animal oils and fats produced in a year is 280,000 tons, of which 50% derived from households. This quantity corresponds approximately to 5 kg per person per year, while a consumption of about 30 kg per person per year is estimated. Similar amounts can be found in other European countries [7] and in the United States [8]. As for the catering industry, the production of vegetable and animal oils and fats is estimated to be between 55,000 and 60,000 tons per year of which a fraction of 60% was collected and recycled in 2007, [9].

It is unthinkable to recycle the entire annual production per capita, but the need to increase the share of recycled waste vegetable oil rather than dispersed is the basis of studies for the development of appropriate methodologies [10, 11]. It is important an effective public education and communication to improve the percentage of recycled waste oils. In fact, the large number of holders of oils and their dispersal is one of the main difficulties for the collection.

The waste oil collected is usually converted, with high added value, in vegetable lubricants, biodiesel, glycerine, or fuel, for energy recovery.

The main application of waste oil collected in Italy is the production of biodiesel.

The process of biodiesel production involves several stages of processing and chemical treatment to which waste oils or fats are subjected. In particular, roughly it is possible to obtain 100 g of biodiesel and 10 g of glycerine from 100 g of vegetable oil using 10 g of methanol [12]. The transesterification process uses a quantity of energy equal to about 25–35% of available energy in the biodiesel produced [13]. Most of this energy is used to produce methanol.

Therefore, assuming that the per capita share of recyclable waste food oils and fats effectively collectible could be close to 3 kg/year (in Italy was 0.65 kg in 2007), the same amount of biodiesel could be produced annually per capita from waste oils and fats. However, only a 65–75% of this fuel could be considered effectively produced from waste due to the fossil fuel consumption of the transesterification process.

## 4. Maximum Efficiency of Energy Conversion

Given the small amount of fuel obtainable from waste oils and organic MSW, compared to typical average consumption, it should be important to maximize the energy efficiency in order to obtain at least the maximum $CO_2$ reduction. Therefore, the distance from where the wastes are produced to where the wastes are treated should be reduced together with the number of the steps for refining the fuel. The recycling of WVO and MSW organic fraction aimed at the production of biofuels for the transport sector appears to be not the best solution. In fact, in this case, it is necessary to obtain a fuel with high purity characteristics and have a centralized production for the blending with conventional fuels (especially for biodiesel). It would be preferable to use these wastes to produce electricity and heat with a cogeneration system close to the urban areas of waste production.

The technologies nowadays most adopted on a small-scale basis are the microturbines (MT) and the ICE. For low powers involved, cogeneration systems with internal combustion engines would be preferred. In fact, ICE performs

Table 2: Biogas yields from some feedstocks (toe: tonnes of oil equivalent − 1 toe = 42 GJ).

| Feedstock | Estim. dry matter [4] (%) | Biogas yield [4] (toe/dry tonne) | Biogas yield (%) of feedstock dry mass | Biogas yield (%) of feedstock wet mass |
|---|---|---|---|---|
| Manure (cow-pig) | 8 | 0.16 | 35 | 3 |
| Straw | 82 | 0.17 | 38 | 31 |
| Slaughter waste | 17 | 0.23 | 51 | 9 |
| Tops and leaves of sugar beet | 19 | 0.25 | 55 | 11 |
| Ley crops | 23 | 0.25 | 55 | 13 |
| MSW, organic fraction | 30 | 0.30 | 66 | 20 |

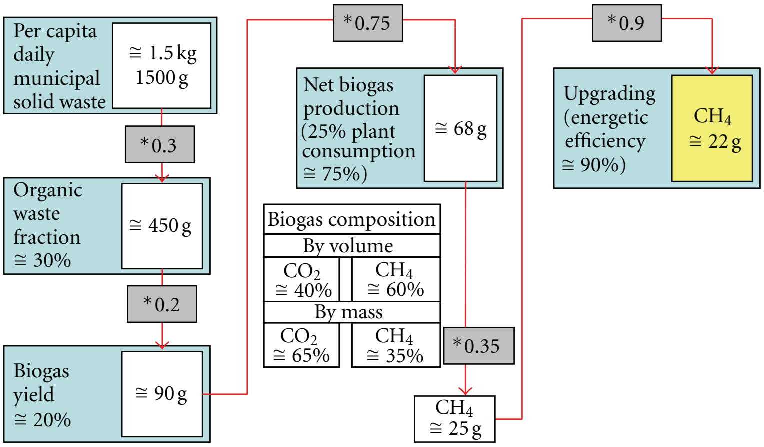

Figure 3: Per capita daily biomethane potential production from anaerobic fermentation of wet organic fraction of MSW.

better than the MT due to a higher electrical (and often also overall) efficiency [14].

In a CHP plant, unlike the case of transports, it would be possible to adapt the fuel feeding system and the combustion mode to the available fuel achieving an increasing in the energy output.

In fact, due to the absence of the autonomy problem and to the possibility of using directly biogas in the existing engine, it could be possible to remove the phase of biogas upgrading to biomethane and then to reach a potential of about 25 kg/year per capita of biogas (energy equivalent to about 9 kg/year biomethane) with a gain of almost 10% in the overall "waste to energy" conversion efficiency.

As regard conversion of WVO into biofuels, while there is a large number of experiences in literature with engines fuelled by pure plant oil (PPO) from dedicated energy crops, experiences have not been found with not esterified waste vegetable oil.

Biodiesel is chemically treated vegetable oil. The advantage of PPO is that the production process is easy: cold pressing the oil out of the seeds; oil filter to remove solid particles. Therefore, the possibility of using directly vegetable oils as fuel for engines without the need for an additional transesterification process would increase the overall efficiency and $CO_2$ reduction. However, the use of nonesterified oils involves some problems due to high viscosity. Kinematic viscosity ranges from 50 to 90 $mm^2/s$ for PPO versus 4 to 6 $mm^2/s$ for conventional diesel. Modern diesel engines have fuel-injection systems that with a high viscosity may lead to coking of the fuel injectors, to ring carbonization, and to the accumulation of fuel in the lubricating fuels [15]. A very high viscosity elevates the pumping work and increases the size of the droplets that are formed by the injector in the jet resulting in a faulty mixture, a reduction of thermodynamic efficiency, and an increase of soot emissions and particles. With esterified oil, the engine performance and emission are quite not affected, and any operational and durability problem is eliminated [16, 17]. However, PPO can be used safely and advantageously in the diesel engine, at least in small blending ratios with normal diesel fuel [18]. Preheating of the oil is necessary. Viscosity measurements indicate a required preheating to adjust the temperature of the fuel before injection into the combustion chamber of about 90° or more [19, 20]. This operation has to be done in the engine, so the engine has to be wormed. This could be a complication, certainly in the case of application in the transport but also for CHP plant, because of the needs of such a double tank: one for PPO and one for diesel oil for cold starts and engine heating.

However, the use of WVO in substitution of PPO is not immediate, in fact, the large quantity of impurities present in the used oil (free fatty acids, polymers, chlorides, and phospholipids) cannot be adequately removed through a simple cleaning process. For waste oil, there is the additional problem of high acidity. The transesterification process should be performed to obtain the methylester fraction, while the impurities are enriched in the glycerine fraction [21]. Once esterified as biodiesel, there are no substantial differences in terms of engine performance and emissions, [22].

## 5. Feasibility of Using a CHP Dual-Fuel Engine Fuelled with Biogas and WVO Methylester

Due to the availability of a gas and a liquid fuel that could be produced in the same cogeneration plant, as a facility for the disposal of organic waste and waste oil, the possibility of using a dual-fuel (DF) engine for the energy conversion seems to be favoured.

In a diesel-NG DF engine, a carburetted air NG mixture enters the cylinder and is ignited by means of pilot diesel oil injection, as in a compression ignition engine. Then, the combustion propagates by means of different flame fronts in almost homogeneous air fuel mixture. At light and medium load, the lean mixture does not allow a quick flame fronts propagation [23]. On the other hand, at high load, knock could occur, caused by autoignition of the end gas and favourite by high intake temperatures and high levels of gas substitution [24]. The vantage of the DF technologies is the possibility of achieving an overall efficiency typical of a diesel engine, higher than a full NG spark ignition (SI) engine, but with exhaust emission cleaner than a diesel engine, especially for the particulate matter emission. To obtain these results, at least in stationary condition, different devices, such as a throttle valve, an EGR system, and a three-way catalyst, have to be implemented and optimized, [25].

In the following, data taken from experimental activity carried out, in stationary condition, in Istituto Motori, on two slightly different six cylinder heavy duty engines for bus application are reported. The two engines are a EURO II diesel engine and a EURO V NG SI engine. The EURO II diesel engine was fuelled in full diesel (FD) and in DF mode. Even if “Euro engines” refer to engines that meet emission standards, the comparison between a SI EURO V engine, a FD EURO II engine, and a DF engine is useful to highlight the potentiality of a DF engine. In fact, the SI EURO V engine, stoichiometric and with a three-way catalyst, represents the best technology for emission reducing. Instead, a FD engine represents the best technology for high efficiency. The main characteristics of the a EURO II diesel engine and the NG SI EURO V engine are reported in Tables 3 and 4, respectively. Both the two engines were equipped with a three-way catalyst.

For the EURO II engine, a Borghi & Saveri FE 350S eddy currents dynamometric brake was used. A laminar flow meter was utilised for air flow measurement; a Micro Motion RFT 9739 Coriolì mass flow meter was used for NG consumption, while diesel fuel consumption was measured by an electronic integrated gravimetric system AVL MOD 730. Instead, for the EURO IV engine, a 315 kW APA asynchronous dynamometer controlled by a AVL PUMA system and a Sensyflow hot film anemometer for air mass flow meter were used. The exhaust emissions were measured using the following analysers: Beckmann HFID MOD 404 for THC, Beckmann HCLA MOD 955 for NO$_x$, Beckmann NDIR MOD 880 for CO low concentration, Hartmann & Braun Uras 10E for NO, CO$_2$, O$_2$, and CO high concentration. The accuracy of the measures is about ±0.1% for torque and speed, ±1% for NO$_x$, CO$_2$, O$_2$, CO, and THC emission, and ±1% for air and fuel flow rate.

Table 3: Main characteristics of IVECO 8360.46R EURO II engine.

| 6 cylinder inline turbocharged | |
|---|---|
| Displacement | 7.8 l |
| Bore × stroke | 112 × 130 mm |
| Compression ratio | 17.6 : 1 |
| Rated power | 166 kW at 2050 rpm in full diesel |
| Maximum torque | 965 Nm at 1250 rpm in full diesel |
| Specific power | 21 kW/l of swept volume |

Table 4: Main characteristics of IVECO CURSOR 8 CNG EURO V engine.

| 6 cylinder inline turbocharged | |
|---|---|
| Displacement | 7.8 l |
| Bore × stroke | 115 × 125 mm |
| Compression ratio | 11.0 : 1 |
| Rated power | 200 kW at 2100 rpm |
| Maximum torque | 1100 Nm at 1250 ÷ 1650 rpm |
| Specific power | 26 kW/l swept volume |

In Figure 4, the tested points are represented for the three (FD-DF-NG) studied cases. The test points were chosen throughout the whole operating range of the SI engine and of the diesel engine in FD mode. Instead, in DF mode, the engine working area was limited not including very low and maximum loads, respectively, due to high total unburned hydrocarbon (THC) and to knock risk. Since the two engines have a slight difference in maximum speed and maximum brake mean effective pressure (BMEP), in Figure 4, the tested points are normalized with the rated speed (SPEED/SPEEDmax) and the rated load (BMEP/BMEPmax) of each engine. In the figure, the DF working area (hatched area) is clearly smaller than the diesel one (dotted area).

From Figures 5, 6, 7, and 8, it could be seen that with a DF engine, obtained from a diesel EURO II engine, it is possible to reach a low level of engine emission, CO$_2$ included, similar to the SI EURO V engine. The THC, CO, and NO$_x$ emissions reported were measured downstream the three-way catalyst for all the three cases. As regard the particulate matter emission, the reduction respect the original FD engine is in average about 70 ÷ 80%, [25]. The experimental values are reported versus BMEP/BMEPmax, but they are referred to the same conditions of speed and load of Figure 4. This choice justifies itself by the fact that specific emissions and thermal efficiency are more influenced by load rather than by speed.

Figure 9 shows that also an engine efficiency higher than a SI engine, in stationary condition, could be achieved with a DF engine.

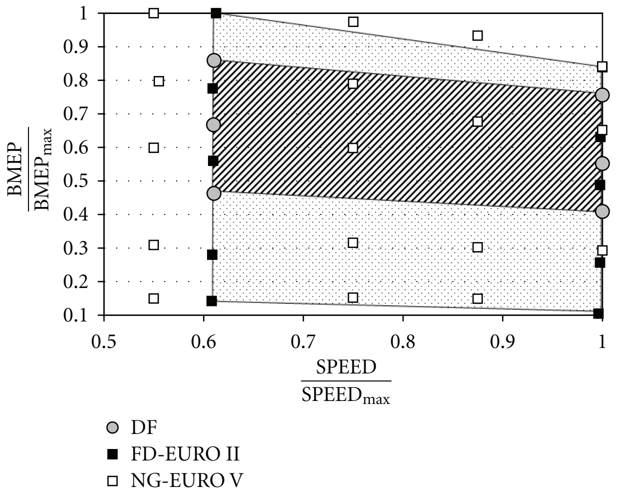

Figure 4: Tested points in FD, DF and full NG on the normalized engine map of the two engines.

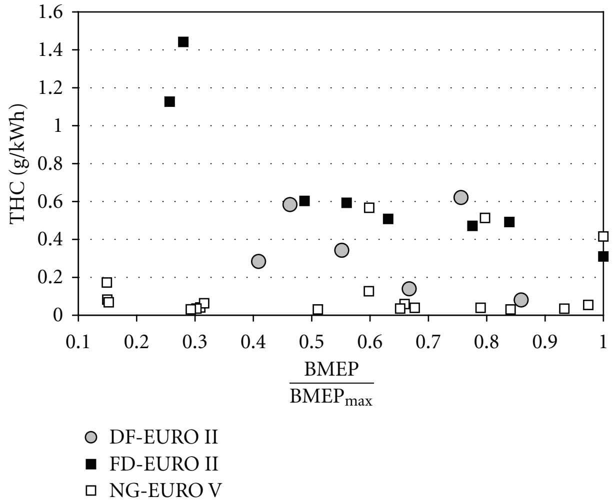

Figure 5: THC emission for DF, FD and full NG engines measured in the condition of Figure 4.

In Figure 10 is shown the NG mass fraction achieved in DF mode. High percentage of NG (85~90%) has been used to maintain high-quality combustion and low emissions.

Considering a potential from organic waste available in urban areas of 9 kg/year per capita of biomethane equivalent and 3 kg/year per capita of biodiesel, the fraction of gaseous fuel is about 75%, and so compatible with a DF engine. Therefore, it would be possible to treat all solid and oil organic waste in the same CHP plant with a DF engine. In addiction, a DF engine could be very suitable for a CHP plant in urban areas; in fact,

(i) as the cogenerator will be connected to the electricity grid it will be not necessary to run it at low loads or rapidly change the load;

(ii) as the engine having to work 24 hours a day, it cannot operate at rated power, but it should work for most of the time at an output of about 20% less. So it could be possible to maintain the operation of diesel only at full peak power. In addiction, it may be possible to reach a maximum power of about 10% less than the nominal FD, without knocking, by delaying the pilot injection advance.

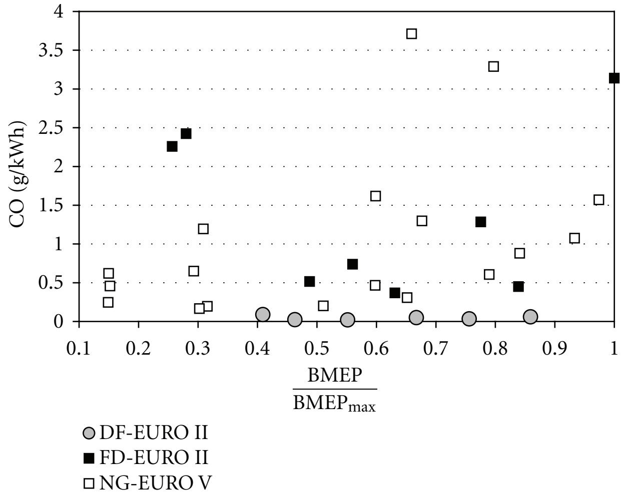

Figure 6: CO emission for DF, FD and full NG engines measured in the condition of Figure 4.

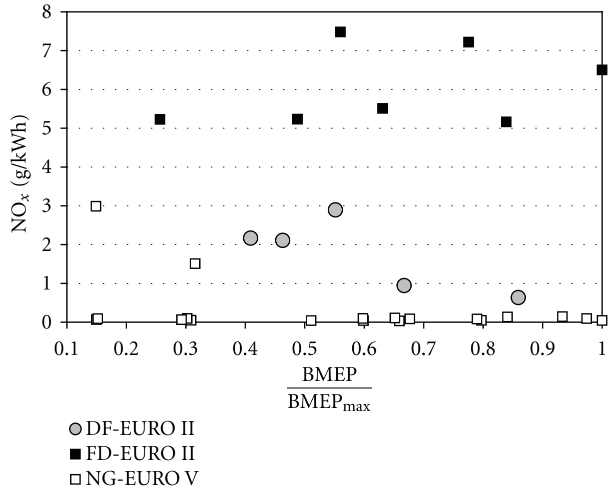

Figure 7: $NO_x$ emission for DF, FD and full NG engines measured in the condition of Figure 4.

In Table 5, the possible performance in terms of electric energy produced and $CO_2$ avoided of a DF engine fuelled with biogas from MSW and biodiesel from WVO are reported. It could be noted that, roughly, the tested engines could be suitable for an urban areas of almost 25,000 ÷ 30,000 peoples.

## 6. Conclusions

Biomass, in form of residues and waste, can be managed in order to produce energy and reduce the environmental

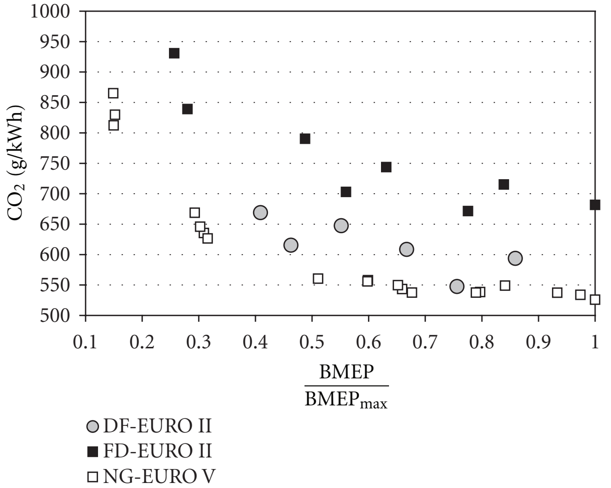

Figure 8: $CO_2$ emission for DF, FD, and full NG engines measured in the condition of Figure 4.

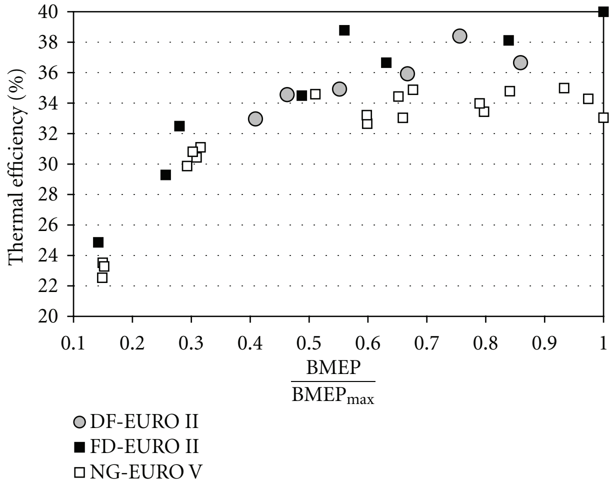

Figure 9: Thermal efficiency for DF, FD, and full NG engines measured in the condition of Figure 4.

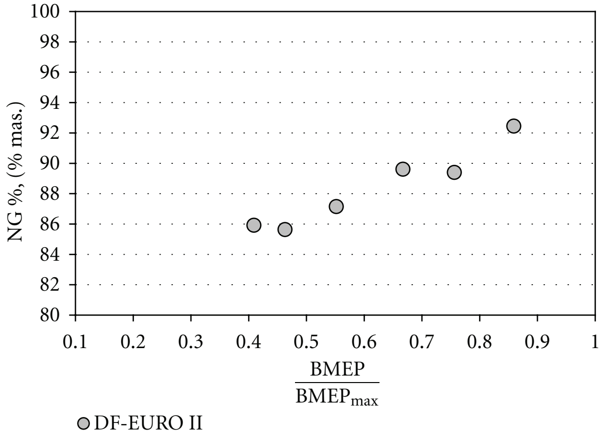

Figure 10: Natural gas fraction for DF engines measured in the condition of Figure 4.

Table 5: Potential electric performance of a CHP plant with a DF engine considering the waste from 10,000 people (CC: combined cycle, EE: electric energy).

| Potential electric performance of a CHP with a DF engine considering the waste from 10,000 people | |
|---|---|
| Biomethane from organic MSW | ≅90 tonne/year |
| Biodiesel from WVO | ≅30 tonne/year |
| EE production with a DF ICE | ≅550,000 kWh/year |
| Engine continuous power | ≅70 kW |
| $CO_2$ avoided from EE produced in a NG CC plant | ≅200 tonne/year |
| $CO_2$ avoided from biogas escape in atmosphere | ≅1,800 tonne/year |

impact at the same time. In urban areas, WVO and the organic fraction of MSW represent a feedstock for biofuel production. However, the electric energy recoverable compared to the average consumption is close to 1%. So it should be important to maximize the energy efficiency in order to obtain at least the maximum $CO_2$ reduction.

In this paper, the performance of a DF engine, a FD engine, and a full NG engine has been compared in stationary condition to evaluate the potential of using in the same waste conversion/cogeneration plant both organic fraction of MSW and WVO. The dual-fuel technology can achieve overall efficiencies typical of diesel engines with a cleaner exhaust emission. The ratio of biogas from MSW and biodiesel from WVO is suitable for DF fuelling. An electric power installation of 70 kW every 10,000 people could be achieved. This data represent an estimation of the problem. In fact, the amount of energy that can be produced by the utilization of waste vegetable oil and municipal organic fraction is not so linear and depends of many factors that have been excluded from this work. At the same time, the problem of associated system costs and of the revenue of the electric energy sale has not been evaluated.

## Nomenclature

| | |
|---|---|
| BMEP: | Brake mean effective pressure |
| CHP: | Combined heat and power |
| DF: | Dual fuel |
| EGR: | Exhaust gas recycling |
| FD: | Full diesel |
| ICE: | Internal combustion engine |
| LHV: | Lower heating value |
| MSW: | Municipal solid waste |
| NG: | Natural gas |
| PPO: | Pure plant oil |
| THC: | Total unburned hydrocarbon |
| WVO: | Waste vegetable oils. |

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