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# Profitability Analysis for Biomethane: A Strategic Role in the Italian Transport Sector

**Federica Cucchiella, Idiano D'Adamo*, Massimo Gastaldi**

Department of Industrial Engineering and Information and Economy, Via G. Gronchi 18, 67100 L'Aquila, University of L'Aquila, Italy. *Email: idiano.dadamo@univaq.it

**ABSTRACT**

Biomethane is an interesting source for sustainable energy systems, featuring great flexibility that translates into multiple possible applications (vehicle fuel, combined production of thermal and electrical energy, injection in the gas grid). Compared to biogas, biomethane permits greater efficiency. Its use is not limited to the immediate area of the plant and purification of the raw methane means greater lifespans for the equipment. This paper analyses its use in the transport sector in light of recent statutory changes that introduce incentives. Net present value and discounted payback time are applied for the evaluation of profitability of biomethane plants, and are calculated in function of the feedstocks used, the plant dimensions and the firm configuration (producer and distributor combined; separate firms). Environmental considerations and a high number of natural gas vehicles define its strategic role in the Italian transport sector.

**Keywords:** Biomethane, Economic Development, Sustainability
**JEL Classifications:** 018, Q2

## 1. INTRODUCTION

Renewable sources have a determining role in the development of sustainable energy systems (assoRinnovabili, 2013; Cerović et al., 2014; Cucchiella and D'Adamo, 2015). The enhancement of biogas through production of biomethane offers a series of advantages, and can play important roles in the transport and cogeneration sectors. In fact the methane obtained from biogas is an equal substitute to that from fossil sources, and can thus contribute to reduction of greenhouse gases (Carchesio et al., 2014) and reduce dependence on imports (Poggi-Varaldo et al., 2014). At the same time, it favours development of the local economy through creation of new employment (Pantaleo et al., 2014). Biogas and biomethane production are continuous throughout the year and so can compensate for interruptions in non-programmable energy sources such as wind and photovoltaic (Cucchiella et al., 2014a). The use of feedstocks such as livestock manure, agricultural waste, energy crops, organic wastes and the organic fraction of solid urban (FORSU) waste, permits the closing of the production chain through reuse of inputs. The production chain is also shortened if the feedstocks are sourced near the plants (Cucchiella and D'Adamo, 2013; Negri et al., 2014). Biomethane is much more flexible than biogas: it can be mixed with methane as vehicle fuel, where it assists in attaining the overall correct fuel mix; it can be injected into the gas grid, and can be used in heat and electrical-energy production (Hahn et al., 2014).

Although use of biomass is undergoing strong growth, its correct application requires both evaluation of its effective sustainability (Cucchiella et al., 2014b) and correct placement within a national development plan (Cucchiella et al., 2014c). In virtually all nations, the problems surrounding sustainability are one of the major challenges in the transport sector (Bekhet and Ivy-Yap, 2014; Sukarno et al., 2015). The use of electric vehicles (Yuan and Zhang, 2014) and biofuels (Emodi et al., 2015) are certainly among the appropriate solutions.

The current study departs from previous studies that examine the financial feasibility of the development of biomethane plants, in several ways (Bortoluzzi et al., 2014; Forgács et al., 2014; Teghammar et al., 2014): the paper considers different types of feedstocks and different plant sizes, and the destination for final use is considered as vehicle fuel, given recent Italian legislation that introduces valid forms of incentivization. Other European nations (Germany, Sweden, Switzerland, Netherlands) have already invested substantially in biomethane as vehicle fuel. The Italian case presents a national population of 846,523 natural gas vehicles (NGVs) and a well-developed distribution system for automotive natural gas, as well as the continent's third largest biogas-biomethane production sector, however, there is as yet no use of biomethane in the automotive sector.

The next section of the paper describes the strategic advantages of biogas-biomethane production chains, the presence of production systems in Europe, and the technical aspects and environmental advantages of this renewable source. Section 3 begins the case study, considering the feedstocks: (i) Energy crops, (ii) organic FORSU waste, (iii) a mix of substrates consisting primarily of livestock wastes. We calculate the potential producible biomethane given a unit quantity of each of these feedstocks. Beginning from the plant dimensions considered (100 $m^3$/h, 250 $m^3$/h, 500 $m^3$/h, 1000 $m^3$/h) we then quantify the costs associated with the different biomethane production stages. We describe the incentivizing structure recently established in Italy and consider two potential business structures: (i) The firm as both a producer and distributor of biomethane, (ii) the firm as only active in production. Section 4 presents the results of the analyses using discounted cash flow (DCF), and in Section 5 we consider the role of biomethane in the transport sector. Section 6 presents the summary conclusions and offers further considerations.

## 2. STRATEGIC, TECHNOLOGICAL AND ENVIRONMENTAL CONTEXT

The development of biomethane as a fuel source offers significant advantages for achievement of national energy objectives (Smyth et al., 2011). The biogas-biomethane production chain achieves the following benefits (Goulding and Power, 2013; Hahn et al., 2014):

- Substitution of fossil fuels
- Programmability (vs. non-programmable renewable sources)
- Potential for storage (as for natural gas)
- Ease of integration with non-programmable and intermittent sources
- Usability at distance from the production points (unlike biogas)
- Can be developed in a decentralized manner, and permits "biomethane islands" where biogas is present but not the natural gas grid.

The following three subsections illustrate the status of production systems in nations that have already implemented biomethane as an energy source, followed by descriptions of its technological and environmental characteristics.

### 2.1. Global Market

In 2013 there were 247 biomethane plants in operation, worldwide. As seen in Table 1, 57% of these are situated in Germany and 19% are in Sweden (GreenGasGrids, 2014). The European region has been the most active in developing biomethane as a fuel source, while the USA also has significant experience. There are a total of 12 production plants in the USA, although biomethane is not used on a large scale and the coverage of the related natural gas grid is incomplete. Concerning raw biogas, it is Germany and Italy that have the highest number of active plants (EurObserv'ER, 2014).

**Table 1: Leading nations in biomethane production - European Union**

| Nation | Total TWh produced by biogas | Nation | Biomethane plants |
|---|---|---|---|
| Germany | 58.9 | Germany | 140 |
| United Kingdom | 20.5 | Sweden | 47 |
| Italy | 12.7 | Netherlands | 23 |
| France | 4.1 | Switzerland | 17 |
| The Netherlands | 3.4 | Austria | 10 |

Source: (EurObserv'ER, 2014)

The following paragraphs examine the experiences and systems of the four leading nations for number of active biomethane plants (DENA, 2014; Energigas Sverige, 2014; IEA, 2014).

#### *2.1.1. Germany*

The national policy objective is to achieve yearly injection of 6 bcm in the gas grid by 2020, for motives of reducing dependence on foreign energy supplies. Statutory incentives are exclusively for the use of biomethane in cogeneration, and recent changes in incentivization impose limits on the use of corn in its production. Objectives in the area of vehicle fuels are to increase the vehicle population using methane; in this context, natural gas (liquefied natural gas [LNG]) providers have adhered to a non-binding agreement to inject biomethane in the grid in order to achieve up to 20% of total consumption of LNG as vehicle fuel. The sizes of current biogas-biomethane upgrading plants are in the range of 250-750 $m^3$/h, while the substrates most commonly used are crop biomass and livestock wastes.

#### *2.1.2. Sweden*

Sweden has activated an energy policy with strong concentration on the use of biomethane as vehicle fuel, including in public transport. In fact given the current national emphasis on nuclear and hydroelectric power, policies have not included incentives for cogeneration. The dimension of biomethane plants is less than in Germany (generally not more than 250 $m^3$/h) and the substrates most commonly used are sewage sludges and FORSU.

#### *2.1.3. Switzerland*

The majority of plants were implemented shortly after the year 2000, and were developed without incentives. The plants belong to municipal corporations and are of very limited dimension (usually <160 $m^3$/h). The substrates used are exclusively urban and biomass wastes.

#### *2.1.4. Netherlands*

This nation is the European leader in LNG production and intends to exploit its excellent infrastructure to become the continental focal point for gas exchanges. The principle uses of LNG are in heating and electrical generation. Current objectives are to increase the role of biomethane, including its use as vehicle fuel, supported by financing from higher tariffs on energy consumption. As in Germany, the dimension of plants is generally 250-750 $m^3/h$, however there is greater incidence at the lower end of this scale. The substrates used are agro-food wastes and FORSU.

## 2.2. Technological Evaluation

Biogas is primarily composed of methane ($CH_4$, 45-70% of total volume) and a lesser quantity of inert carbonic gas ($CO_2$) with small percentages (together <10%) of hydrogen sulphate ($H_2S$), ammonia ($NH_3$) and water vapour ($H_2O$). It is produced by anaerobic digestion beginning from a range of inputs, particularly livestock waste, crop waste, energy crops, organic waste and the organic fraction of urban solid waste (Di Maria et al., 2014; McEniry et al., 2014).

Fossil-fuel natural gas contains 85-98% methane by volume, depending on the source. To achieve biomethane with the qualities necessary for the natural gas grid, the percentage of $CH_4$ in raw biogas must be increased while other compounds are reduced. This is done through combined purification processes and "upgrading" that remove the $CO_2$, achieving energy characteristics similar to that of natural gas (Asam et al., 2011; Ryckebosch et al., 2011). The most common upgrading technologies are pressure washer systems (PWS; 37% of total production) and pressure swing adsorption (PSA; 24% of total production) (IEA, 2014).

Figure 1 provides a flow-chart comparing the biomethane and biogas production and consumption chains. Although the final uses as energy and heat appear similar, biomethane has a different, more flexible chain. It can be used both near the production site and at a distance, meaning that it can be injected in the natural gas grid and used in different ways over time and space, including its use as vehicle fuel.

## 2.3. Environmental Impact

The biogas-biomethane chain serves as a carbon-negative substitute for consumption of fossil gas (Buratti et al., 2013). Firstly, combustion of fossil fuels emits new $CO_2$, while the $CO_2$ emissions from biogas are equal to the amounts fixed and accumulated by plant substrates, or acquired indirectly from plants via the animals that consume them. The use of biogas also reroutes the natural emissions of $CH_4$ resulting from decomposition of vegetable and animal matter, with the captured $CH_4$ ultimately being burned in and released as $CO_2$ and $H_2O$. This is an improvement over outright release in the atmosphere, since $CH_4$ is itself a potent greenhouse gas: over a 100 year span, the initial emission of 1 kg of $CH_4$ is equivalent to the emission of 21 kg of $CO_2$ (Rehl et al., 2012). Given this context, a life-cycle assessment of a biomethane plant in Einbeck, Germany, demonstrated that the use of biomethane as an alternative to natural gas achieves a reduction of greenhouse gases amounting to the equivalent of 200 g of $CO_2$ per kWh of generation (200 g $CO_2$ eq/kWh) (Adelt et al., 2011).

In the transport sector, the use of methane as fuel for a given vehicle currently achieves emissions savings of 21-24% compared to diesel and petrol (Table 2). A mixture with 20% biomethane would provide further reductions of 19%. Using 100% biomethane as the fuel source, the vehicle would emit only 5 g $CO_2$ eq/km (DENA, 2014).

Given the above general context we now present the Italian case study, in which the aim of the analysis is to define the profitability of biomethane production for purposes as vehicle fuel.

# 3. CASE STUDY

From data reported as of June 2013 (NGVA Europe, 2014), we observe that a number of European nations distribute biomethane mixed with fossil natural gas. We can subdivide these in three categories:

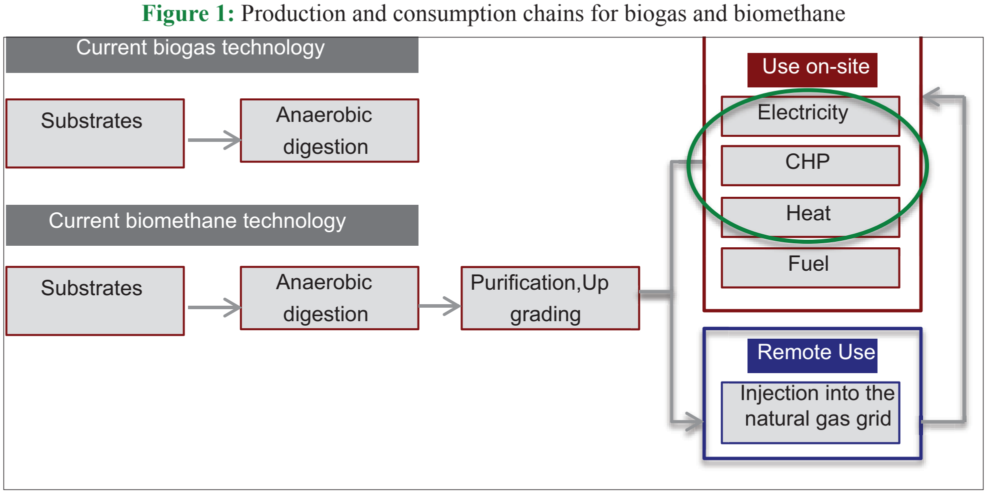
- High market share - Iceland (100%), Sweden (60%), Netherlands (50%)

**Table 2: GHG emissions per fuel source, data in $CO_2$ eq/km**

| Fossil fuels | GHG | Biofuels | GHG | Electric drive | GHG |
|---|---|---|---|---|---|
| Gasoline | 164 | Methane (biomethane 20%) | 100 | Electric (current energy mix) | 75 |
| Diesel | 156 | Biomethane 100% | 5 | Electric (100% wind) | 5 |
| LPG | 141 | Ethanol | 111 | | |
| Natural gas (methane) | 124 | Biodiesel | 95 | | |

Source: (DENA, 2011), GHG: Greenhouse gas

**Figure 1:** Production and consumption chains for biogas and biomethane



- Medium share - Finland (25%), Switzerland (23%), Germany (20%), Norway (10%)
- Low share - France (3%), Hungary (2%).

The remaining nations, including Italy, have no distribution. However, in terms of NGVs, the ordering of nations is remarkably different, and Italy shows as having a significant vehicle population (46% of the European total):

- High NGV population - Italy (846,523), Ukraine (388,000), Armenia (244,000)
- Medium NGV population - Germany (96,349), Russia (90,050), Bulgaria (61,270), Sweden (44,321)
- Low NGV population - France (13,538), Switzerland (11,058), Austria (7717), the Netherlands (6680) and other countries.

Following the above considerations of general context, these data provide the motivation for choosing Italy for the case study: there is a significant population of vehicles on the territory; there is a developed biogas-biomethane production chain; there is a well-established natural gas distribution network in the automotive sector; yet in spite of all these stimulating aspects, there is no use of biomethane vehicle fuel. The case study will include an investigation of these aspects, as well as the question of the sustainability of biomethane as a renewable fuel source. Recent researchers have indicated that this issue is particularly important (Liew et al., 2014; Patterson et al., 2013).

In 2012, Italian consumption of methane as fuel for vehicles increased 2.4% over 2011, from 884 to 905 million $m^3$ (Ministry of Economic Development). The increase could appear modest however at the same time, consumption of gasoline and diesel fuels decreased 19.8% and 10.4% respectively.

This contrast results in part from a continuing year-on-year boom in registration of methane-powered vehicles. The diffusion of gas fuels is also linked to public policies driven by environmental considerations, which impose fiscal structures with lower excise rates.

The environmental advantages have been reviewed above; hence the core objective of the study is investigating the economic feasibility of biomethane as vehicle fuel. For this, we next define the various inputs necessary in terms of: the biomethane potential for three feedstocks; the costs of production plants using different feedstocks; the incomes associated with biomethane production.

### 3.1. Potential Producible Biomethane

The quantities of biomethane producible are calculated by integrating the total potential solids of the relative feedstocks with the percent component of volatile solids they contain (Bacenetti et al., 2014). The feedstocks analysed in Table 3 are chosen on the basis of indications from operators already active in the sector (Scaglia et al., 2010), as follows:

- FORSU
- Energy crops (volatiles content considered as the average of the different crops)
- Mixed (a mix of 30% energy crops and 70% of cattle and pig manure slurries).

The quantity of biomethane producible from a given feedstock depends on the methane content of the raw biogas, which is variable. For this reason we consider a base scenario and two further scenarios in which we lower and raise the percentage methane content by 10% (%$CH_4$ base, %$CH_4$ low; %$CH_4$ high).

The maximum potential biomethane production from a single ton of input is from corn (≈ 123 $m^3$), which has a yield roughly a third higher than FORSU (≈ 85 $m^3$). However, in Table 3 we see that energy crops actually show a lower yield than FORSU, given the composition of the combined crops. The "mixed" plant has a still lower yield, given the production from the additions of pig slurry (≈ 9 $m^3$) and cattle slurry (≈ 18 $m^3$).

### 3.2. Plant Size

The profitability of biofuel plant investment is strongly influenced by the plant dimension (Abbasi and Diwekar, 2014), which must in turn be linked to the market request, particularly the propensity of consumers to opt for less polluting vehicles (Profillidis et al., 2014). As proposed in previous literature (Delzeit and Kellner, 2013) we thus consider the yields from small, medium and large plants, specifically 200 kW, 500 kW, 1 MW and 2 MW capacities. However the planning for biogas plants is usually in terms of kW, with further conversion to $m^3$/h, thus for the plant dimensions we consider:

- 100 $m^3$/h
- 250 $m^3$/h
- 500 $m^3$/h
- 1000 $m^3$/h.

### 3.3. Costs of Biomethane Production

Table 4 illustrates the costs of biomethane production per substrate and plant dimension, subdivided per production stage:

**Table 3: Potential biomethane per feedstock**

| Resources | Mixed | FORSU | Energy crops |
|---|---|---|---|
| Potential biogas ($m^3$/t) | 47.09 | 141.54 | 102.39 |
| Feedstock (t) | 1 | 1 | 1 |
| Biogas ($m^3$) | 47.09 | 141.54 | 102.39 |
| % $CH_4$ in biogas (base scenario) | 57 | 60 | 58 |
| Biomethane ($m^3$) - low % $CH_4$ | 24.43 | 76.43 | 53.44 |
| Biomethane ($m^3$) - base % $CH_4$ | 27.15 | 84.92 | 59.38 |
| Biomethane ($m^3$) - high % $CH_4$ | 29.86 | 93.41 | 65.32 |

Source: (Scaglia et al., 2010), FORSU: Organic fraction of solid urban

**Table 4: Costs of biomethane production (€/$m^3$)**

| Substrate | Plant size ($m^3$/h) | 100 | 250 | 500 | 1000 |
|---|---|---|---|---|---|
| Energy crops | Biogas production | 1.00 | 0.83 | 0.68 | 0.58 |
| | Upgrading | 0.27 | 0.22 | 0.16 | 0.12 |
| | Compression and distribution | 0.15 | 0.15 | 0.15 | 0.15 |
| | Biomethane production | 1.42 | 1.20 | 0.99 | 0.85 |
| Mixed subtstrate (30% energy crops, 70% livestock slurries) | Biogas production | 0.89 | 0.74 | 0.52 | 0.44 |
| | Upgrading | 0.27 | 0.22 | 0.16 | 0.12 |
| | Compression and distribution | 0.15 | 0.15 | 0.15 | 0.15 |
| | Biomethane production | 1.31 | 1.11 | 0.83 | 0.71 |
| FORSU | Biogas production | 0.97 | 0.81 | 0.59 | 0.50 |
| | Upgrading | 0.27 | 0.22 | 0.16 | 0.12 |
| | Compression and distribution | 0.15 | 0.15 | 0.15 | 0.15 |
| | Biomethane production | 1.39 | 1.18 | 0.90 | 0.77 |

FORSU: Organic fraction of solid urban

- Cost of biogas production
- Cost of upgrading
- Cost of compression and distribution.

The cost of the biogas production stage are heavily influenced by the type of substrate used, and it emerges that in Italy this cost is higher than in other EU nations (Browne et al., 2011; Schievano et al., 2009; Walla and Schneeberger, 2008). On the other hand, costs for upgrading do not show significant differences among the different nations (Browne et al., 2011). Among the various technologies, PSA shows lower costs than PWS (Hahn, 2011). Although the differences are limited, for the current study we consider the use of PSA technology. Compression is necessary to pressurise the product from the upgrading stage to a value higher than that of the distribution grid. For this work we hypothesise a level of roughly twice that for the transmission system (Amiri et al., 2013; Murphy and Power, 2009). The investment costs for pipeline systems are high (roughly 70 k€/km), therefore where the proposed production location is far from the distribution grid this new projects inadvisable (Börjesson and Ahlgren, 2012). In calculating Table 4, for the aspect of the relative costs of investment and operation, we define these as in the existing literature (Heffels et al., 2014) (Amiri et al., 2013; Deutsche Gesellschaft für Internationale Zusammenarbeit, 2012; Dzene et al., 2014; Murphy and Power, 2009; Uusitalo et al., 2013). It is relevant to highlight:

- The range of total costs for production is: for FORSU plants 0.77-1.39 €/$m^3$; for mixed crop-slurry plants 0.71-1.31 €/$m^3$; for energy-crops plants 0.85-1.42 €/$m^3$.
- The most significant component cost is the biogas production stage, and for smaller plants this cost becomes even more significant compared to that for the other two stages. For example in the mixed plant at dimension 100 $m^3$/h, biogas production represents 68% of total costs, while at dimension 1000 $m^3$/h the cost drops to 62%. The same occurs for the FORSU plant, where with the same plant sizes these component costs are respectively 70% and 65% of total. In the case of energy-crops plants the variation is less, with the same costs respectively at 70% and 68%.

Next we quantify the costs associated with a plant for distribution of vehicle-fuel methane. For a distributor marketing methane from a 500 $m^3$/h capacity plant, the estimated investment cost is €500,000 (Browne et al., 2011).

Economies of scale for the production plant are estimated at 5% for a doubling capacity. Operating costs are as follows (Johnson, 2010):

- For smaller plants (100 $m^3$/h and 250 $m^3$/h) we hypothesise maintenance costs at 8% of initial investment, with operating costs (e.g. labour) at 100,000 €/y.
- For larger plants (500 $m^3$/h and 1000 $m^3$/h), we hypothesise these same costs as 5% and 150,000 €/y.

### 3.4. Incentivizing Structure, Sales Income

The income from production and sales of biomethane consists of two main components:

- Incentives
- The price of biomethane to a vehicle-fuel distribution plant; or the pump price to consumer in the case where the producer firm is also the methane distributor.

For the sales price to a distribution plant we assume the average sales price of natural gas for the year 2012, which is 0.27 €/$m^3$. For the pump price to end user we again assume the average 2012 market value, net of excise taxes, which results as 0.66 €/$m^3$.

In a decree dated December 5, 2013, the Italian Ministry of Economic Development has established means of incentivization for use of biomethane in place of methane for vehicle fuels. The instrument for release of incentives is the issuance of 20-year Certificates of Immission of Biofuel in Consumption (CICs), with the producer's immission of 10 Gcal of biofuel energy generally giving rights to one CIC. Given the heat power of biomethane (at 11.945 Gcal/t), it follows that one CIC corresponds to 0.8372 t of biomethane, meaning 1231 $m^3$ of $CH_4$ (1 $m^3$ $CH_4$=0.68 kg). The value of the incentives obtained per CIC is still to be determined and will be in the range of €300-€800 as seen in Table 5, however, the current expectation is a value under 600 € (Mezzadri, 2014).

Further, the incentives will vary with the type of substrate used, and there will be a premium in the case that the title-holding biomethane producer implements a new vehicle-fuel methane distribution plant at their own expense (Table 6). For example in the scenario that a biofuel producer is also a methane distributor and the plant is built new, then for the first 10 years the value of the CIC increases by the coefficient "2*1.5" if the feedstock is FORSU. The coefficient is reduced to "2" for the subsequent 10-year period. However, where the distributor and producer are not the same, the producer simply receives a coefficient of "2" for the entire 20 years, thus not obtaining the 50% premium over the first 10 years.

Where FORSU is used as the feedstock, the associated processing of urban waste is a paid service and thus in this case the feedstock is a source of income for biogas production plants, rather than a cost. Accompanying the income there are counter-balancing costs for pre-treatment to obtain the solid organic fraction. The net value of income is considered as 0.27 €/$m^3$ (Cucchiella et al., 2013).

With the inputs thus defined, in the next section we calculate the financial performance results from the various investments and evaluate the criticalities of several variables (choice of feedstocks; plant size; sales of biomethane through own distribution plant or by third parties).

## 4. RESULTS

The profitability of an investment measures the economic suitability of undertaking the plant project. We assume the useful life-span of the plant as 20 years, meaning equivalent to the time-

**Table 5: Incentives per 1 $m^3$ of biomethane in function of value of CIC**

| CIC (€) | 300 | 400 | 500 | 600 | 700 | 800 |
|---|---|---|---|---|---|---|
| (€/$m^3$) | 0.24 | 0.32 | 0.41 | 0.49 | 0.57 | 0.65 |

Source: (Mezzadri, 2014)

span of the incentives. We assume that capital financing is by third parties. Under these terms, the weighted average capital cost is thus fixed at 5% (Cucchiella et al., 2014a).

Tables 7-9 present the results from 24 investment scenarios obtained considering the four plant dimensions (100 $m^3$/h, 250 $m^3$/h, 500 $m^3$/h, 1000 $m^3$/h), three feedstocks (energy crops, mixed and FORSU), and the two business configurations (sales to third parties, meaning the producer of biomethane sells the product to a distributor; sales to the end client, meaning the biomethane producer is also the distributor). The analysis considers only new plants, not those already in existence.

Considering the recent statutory stipulations on incentivization, we conduct a profitability analysis for these scenarios through application of DCF analysis. The indicators used are net present value (NPV) and discounted payback time (DPBT). The financial feasibility of the investment is made to function in variation of the incentives, for which we conduct a sensibility analysis with the consideration of a range of CIC values between €300 and €800.

The analysis of the results indicates that the profitability of the biomethane plants is only verified under certain scenarios, and the condition necessary for this to occur is the presence of

**Table 6: Corrective coefficients applied for the use of biomethane as vehicle fuel**

| Substrate | New plants | | | | Existing plants | | | |
|---|---|---|---|---|---|---|---|---|
| Sales | To third parties | | To end client | | To third parties | | To end client | |
| Energy crops | 1 | 1-20 y | 1*1.5 | 1-10 y | 1*0.7 | 1-20 y | 1*1.5*0.7 | 1-10 y |
| | | | 1 | 11-20 y | | | 1*0.7 | 11-20 y |
| Mixed substrate | 1.7 | 1-20 y | 1.7*1.5 | 1-10 y | 1.7*0.7 | 1-20 y | 1.7*1.5*0.7 | 1-10 y |
| | | | 1.7 | 11-20 y | | | 1.7*0.7 | 11-20 y |
| FORSU | 2 | 1-20 y | 2*1.5 | 1-10 y | 2*0.7 | 1-20 y | 2*1.5*0.7 | 1-10 y |
| | | | 2 | 11-20 y | | | 2*0.7 | 11-20 y |

FORSU: Organic fraction of solid urban

**Table 7: Profitability of biomethane plants using energy crop feedstock**

| CIC (€) | 100 $m^3$/h | | 250 $m^3$/h | | 500 $m^3$/h | | 1000 $m^3$/h | |
|---|---|---|---|---|---|---|---|---|
| | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) |
| New plants (sales to third parties) | | | | | | | | |
| 300 | −12,218 | >20 | −23,936 | >20 | −35,183 | >20 | −53,419 | >20 |
| 400 | −11,421 | >20 | −21,943 | >20 | −31,195 | >20 | −45,443 | >20 |
| 500 | −10,523 | >20 | −19,699 | >20 | −26,708 | >20 | −36,470 | >20 |
| 600 | −9726 | >20 | −17,705 | >20 | −22,721 | >20 | −28,494 | >20 |
| 700 | −8928 | >20 | −15,711 | >20 | −18,733 | >20 | −20,519 | >20 |
| 800 | −8131 | >20 | −13,717 | >20 | −14,745 | >20 | −12,543 | >20 |
| New plants (sales to end client) | | | | | | | | |
| 300 | −11,119 | >20 | −17,497 | >20 | −19,843 | >20 | −20,278 | >20 |
| 400 | −10,075 | >20 | −14,885 | >20 | −14,619 | >20 | −9831 | >20 |
| 500 | −8899 | >20 | −11,947 | >20 | −8743 | >20 | 1922 | 19 |
| 600 | −7855 | >20 | −9336 | >20 | −3520 | >20 | 12,368 | 12 |
| 700 | −6810 | >20 | −6724 | >20 | 1704 | 18 | 22,815 | 9 |
| 800 | −5765 | >20 | −4112 | >20 | 6927 | 13 | 33,262 | 5 |

NPV: Net present value, DPBT: Discounted payback time

**Table 8: Profitability of biomethane plants using mixed substrates (30% energy crops, 70% livestock slurries)**

| CIC (€) | 100 $m^3$/h | | 250 $m^3$/h | | 500 $m^3$/h | | 1000 $m^3$/h | |
|---|---|---|---|---|---|---|---|---|
| | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) |
| New plants (sales to third parties) | | | | | | | | |
| 300 | −12,124 | >20 | −24,230 | >20 | −31,961 | >20 | −49,175 | >20 |
| 400 | −10,768 | >20 | −20,841 | >20 | −25,182 | >20 | −35,616 | >20 |
| 500 | −9242 | >20 | −17,027 | >20 | −17,555 | >20 | −20,363 | >20 |
| 600 | −7887 | >20 | −13,638 | >20 | −10,775 | >20 | −6804 | >20 |
| 700 | −6531 | >20 | −10,248 | >20 | −3996 | >20 | 6755 | 16 |
| 800 | −5175 | >20 | −6858 | >20 | 2783 | 17 | 20,314 | 12 |
| New plants (sales to end client) | | | | | | | | |
| 300 | −9546 | >20 | −16,404 | >20 | −19,784 | >20 | −27,185 | >20 |
| 400 | −7770 | >20 | −11,964 | >20 | −10,905 | >20 | −9426 | >20 |
| 500 | −5772 | >20 | −6969 | >20 | −915 | >20 | 10,554 | 10 |
| 600 | −3996 | >20 | −2530 | >20 | 7965 | 10 | 28,313 | 3 |
| 700 | −2220 | >20 | 1910 | 16 | 16,845 | 4 | 46,073 | 1 |
| 800 | −444 | >20 | 6350 | 10 | 25,724 | 2 | 63,832 | 1 |

NPV: Net present value, DPBT: Discounted payback time

**Table 9: Profitability of biomethane plants using FORSU feedstock**

| CIC (€) | 100 m³/h | | 250 m³/h | | 500 m³/h | | 1000 m³/h | |
|---|---|---|---|---|---|---|---|---|
| | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) | NPV (k€) | DPBT (y) |
| New plants (sales to third parties) | | | | | | | | |
| 300 | −7642 | >20 | −12,735 | >20 | −8935 | >20 | −1984 | >20 |
| 400 | −6047 | >20 | −8747 | >20 | −959 | >20 | 13,968 | 14 |
| 500 | −4252 | >20 | −4260 | >20 | 8014 | 14 | 31,913 | 10 |
| 600 | −2657 | >20 | −272 | >20 | 15,989 | 11 | 47,865 | 4 |
| 700 | −1062 | >20 | 3716 | 15 | 23,965 | 7 | 63,817 | 3 |
| 800 | 533 | 19 | 7703 | 12 | 31,941 | 4 | 79,768 | 2 |
| New plants (sales to end client) | | | | | | | | |
| 300 | −5802 | >20 | −4442 | >20 | 10,111 | 11 | 38,570 | 4 |
| 400 | −3713 | >20 | 781 | 19 | 20,558 | 5 | 59,464 | 2 |
| 500 | −1362 | >20 | 6658 | 11 | 32,311 | 3 | 82,969 | 2 |
| 600 | 727 | 17 | 11,881 | 6 | 42,758 | 2 | 103,862 | 1 |
| 700 | 2817 | 11 | 17,104 | 3 | 53,204 | 2 | 124,756 | 1 |
| 800 | 4906 | 8 | 22,328 | 2 | 63,651 | 1 | 145,650 | 1 |

NPV: Net present value, DPBT: Discounted payback time

incentives. In fact when the CIC value is equal to zero, even with consideration of the largest plants (1000 m³/h) the NPV is negative with all feedstocks: equal to −240,110 k€ with FORSU, −80,464 k€ with mixed substrates, and −77,346 k€ with energy crops in business configuration "sales to third parties." While it is equal to −49,839 k€, −89,852 k€ and −51,618 k€ with FORSU, mixed substrates and energy crops in business configuration "saled to the end client" respectively.

The NPV of a 1000 m³/h plant has a positive range from 13,968 to 145,650 k€ if the feedstock is FORSU, while with mixed substrates and energy crops the maximum profits obtainable are respectively 63,832 k€ and 33,262 k€. The DPBT results in six scenarios as equal to 1 year, and in seven scenarios as 2 years. These are decidedly low values, a fact deriving from the limited investment costs. In fact these "weigh" less in the DPBT than either the costs of operations or the hypothetical consideration of third-party financing, which spreads the payment over multiple years rather than concentrating the entire investment received in the 1st year of operations. Where DPBT is indicated as >20 this means that even fixing the cut-off period equal to the 20-year useful lifespan of the plant (pessimistic hypothesis), the investment cannot be recovered within this date. The NPV and DPBT analyses thus provide results that are consistent between each other.

The plant is profitable under the following scenarios:

- In 11%, 25%, 44% and 58% of cases, respectively for plants of size 100 m³/h, 250 m³/h, 500 m³/h and 1000 m³/h
- In 679% of cases using FORSU, in 25% using mixed substrates and in 13% using energy crops
- In 49% and 21% of cases respectively, where the producer is the same or not the same as the distributor
- In 8%, 17%, 29%, 38%, 54% and 63% of cases, respectively where the CIC value equals 300 €, 400 €, 500 €, 600 €, 700 € and 800 €.

The definition of the optimal plant dimension depends in part on economic questions (initial capital available, economies of scale), but must also take into account other evaluations:

- Of technical issues (i.e., the material injected in the grid must meet precise technical standards)
- Of environmental questions (e.g. an increased geographic basin for collection of raw material also requires more transport)
- Of social issues (e.g. not in my back yard, not in my term of office).

It emerges that Italian statute for the vehicle fuels sector has been designed unlike the regulation for biofuels injected in the grid, where there are greater incentives for plants of smaller dimensions. The objective is in fact to maximise the arrival of quantities of biomethane for use as vehicle fuel, given the observation of the very strong market request and the relative environmental advantages. The nation would also achieve a reduction of fuel risks, since growth in the biomethane supply implies reductions of gas imports. This result would not be definitive but still pursues less dependence on foreign energy, particularly from suppliers at high geopolitical risk.

The development of biogas in Italy has largely depended on heavy use of energy crops, particularly corn, which has a high index of producibility. However this development clearly withdraws agricultural land from the primary sector and thus, as in other nations, Italian legislators have attempted to favour the use of other non-crop feedstocks. The results in terms of NPV confirm that the planned incentivization achieves the desired aims: the profitability associated with the other feedstocks considered is higher. It is for FORSU in particular that we observe the highest values of profitability under the different scenarios, a result that is influenced by the incomes obtained through waste treatment. Together with "waste-to-energy" power and heat generation, the new provisions could in fact move Italy towards parity with other European nations in reducing and ultimately minimizing the quantity of urban waste routed to landfills. The choice of FORSU feedstocks for the production of biomethane also avoids the costs associated with the disposal of waste residues and by-products, which otherwise require specific treatment.

The diffusion of methane-powered vehicles has pushed many distributors to install compressed natural gas pumps, and led towards a competitive market model. This situation is well known to provide a greater general surplus (consumers and distributors), compared to a monopolistic model. The Italian decree moves still further in this direction, with incentives favouring the opening of new distribution points by the biogas producer. The financial results obtained define how the profitability of these scenarios is more favourable than those where biomethane producer and distributor are different firms. The analyses demonstrate in particular that some new operators in the distribution market succeed in practicing decidedly advantageous pricing (0.82 €/kg compared to the average 1 €/kg).

Higher values of CICs would clearly permit greater profitability, however the management of public funds requires cautious and targeted management. The proper balance could be determined by the effective sustainability of the specific renewable source; however, the current literature does not appear to examine this issue. In any case the value of the CICs is expected to be <€600, thus at the moment we note that in the example of a €500 value, the scenarios with positive NPV are:

- A 1000 $m^3$/h plant in the scenario of a producer-distributor firm with sales to the client, independent of the feedstock used
- 250 $m^3$/h and 500 $m^3$/h plants with sales to the end client for FORSU
- The scenarios of sales to third parties for FORSU plants of 500 $m^3$/h and 1000 $m^3$/h size.

## 5. ROLE OF BIOMETHANE IN THE TRANSPORT SECTOR

In evaluating the potential for biomethane it is indispensible that we consider both of the principle biogas production chains, meaning from agriculture and from FORSU, and their sustainability relative to the demand. The North-East Italian Agro-Energy Cluster estimates the gross potential biogas yield from the two sources at 10.3 billion $m^3$/y (Mattirolo, 2013), meaning potential gross biomethane of 5.6 billion $m^3$/y. However, in evaluating the potential production of biomethane we must account for the quantities of biogas currently used in cogeneration. After this, the net potentials are 7.6 billion $m^3$/y of biogas and 4.1 billion $m^3$/y of biomethane (Table 10).

Given current Italian consumption of natural gas at 70 billion $m^3$/y, the net potential for biomethane production represents 6% of gross consumption. This adds to the present domestic production of fossil gas at 9 billion $m^3$/y. Analysing the potential biomethane consumption specific to the transport sector, it emerges that NGVs are currently 2% of total vehicle population. Hypothesising that the annual NGV's consumption is equal to 1100 $m^3$ (792 kg) of methane and all current NGVs use biomethane in partial substitution for natural gas we can define the demand, or resource need, as 0.93 billion $m^3$/y.

The environmental benefits associated to this choice would lead to savings equal to 30.2 $MtCO_2$eq during 20 years (Table 11). This value is obtained by two following considerations: (i) a NGV travels 15,000 km/y, (ii) a NGV powered by biomethane saves 119 g $CO_2$ eq/km compared to the one powered by fossil fuel (Table 2), (iii) the number of vehicles is equal to 846,523 units.

In a mid to long-term perspective we can imagine that the penetration of NGVs will either show moderate growth arriving at 5%, or accelerated growth arriving at 9% (which would correspond to total potential net biomethane). In Table 12 we proposed these scenarios as objectives, identify the number of vehicles necessary (new or converted), and define the relative consumption of biomethane, seen as either 2.25 or 4.1 billion $m^3$/y.

Biomethane plays a strategic role in the transport sector, thus many actors benefit from the Italian incentivising policy:

- The agro-foods industry, where actors diversify their portfolios and increase their income by using their available primary resources
- Plant-engineering and related manufacturing sectors, where Italy is among European leaders in the production of biogas-production systems and natural gas treatment-transport systems
- Automotive industries, given that Italy has the highest number of NGVs in Europe and is the European leader in their production
- Public utilities, particularly those active in environmental services; these can invest in projects for satisfactory yields and control of risks, and create virtuous cycles where their own vehicles are fed by biomethane from refuse collection
- The general population, which perceives new employment opportunities and reduction atmospheric pollution.

The authors' future research objectives include the evaluation of the most profitable conditions for biomethane under the various scenarios of its end use. Thus we intend to compare the results from the current work with those from investments where the biomethane produced is used in the methane grid and in cogeneration.

## 6. CONCLUSIONS

Biomethane is a programmable, renewable fuel source that can serve to balance the intermittent production of other renewables, reduce fuel risks, reduce pollution and favour local economic development. Finally, it permits efficient use of resources, in that it uses territorially-available raw materials and offers wide flexibility in final uses.

**Table 10: Net potential for biomethane in Italy (million $m^3$)**

| Substrate | Biogas | Biomethane | Substrate | Biogas | Biomethane |
|---|---|---|---|---|---|
| Livestock waste | 1827 | 1005 | Energy crops | 3000 | 1590 |
| Butchery waste | 43 | 24 | Sewage sludges | 900 | 477 |
| FORSU | 1330 | 732 | Gross potential | 10,300 | 5588 |
| Crop-waste biomass | 3200 | 1760 | Net potential | 7612 | 4110 |

Source: (Mattirolo, 2013), FORSU: Organic fraction of solid urban

**Table 11: Environmental benefits**

| Reduction of GHG | Methane (biomethane 20%) | Biomethane 100% |
|---|---|---|
| ΔGHG (g $CO_2$ eq/km) | 24 | 119 |
| KmNGV/y | 15.000 | 15.000 |
| 1 vehicle | | |
| ΔGHG (kg$CO_2$eq/y) | 360 | 1.785 |
| ΔGHG (t$CO_2$eq) | 7.2 | 35.7 |
| 846,523 vehicles | | |
| ΔGHG (kt$CO_2$eq/y) | 305 | 1511 |
| ΔGHG (Mt$CO_2$eq) | 6.1 | 30.2 |

GHG: Greenhouse gas

**Table 12: Objectives for biomethane consumption as vehicle fuel**

| Scenario | As is | Future (moderate growth) | Future (accelerated growth) |
|---|---|---|---|
| % NGVs/total vehicles | 2 | 5 | 9 |
| NGVs (current population) | 846,523 | 846,523 | 846,523 |
| ΔNGVs (total) | 0 | 1,200,000 | 2,880,000 |
| Biomethane (million $m^3$) | 0.93 | 2.25 | 4.10 |

NGV: Natural gas vehicles

The data reported in the literature and the processes of development in many nations indicate both the opportunity and the relevance of the theme. The results of the paper have illustrated following the introduction of incentives there are now various scenarios where the profitability of biomethane is verified. This is particularly true for those sub-products where double counting is recognised. Thus the treatment of FORSU, usually managed by companies active in environmental services, can be used to feed the relative vehicle fleets, obtaining an optimal model of sustainability. The same occurs for agricultural operations, which can now adopt a mixed-substrate plant strategy that reduces reliance on feedstocks with low biomethane yields (livestock waste), but which still accesses rewarding that resembles that from double counting. The economies of scale and the absence of contrary normative inventions push towards development of large plants, thus a favourable strategy would be the adoption of consortium structures. The adoption of the incentives is determining: without them there is no investment that would produce profits and the sensibility analysis quantifies how the financial profitability varies in a significant manner. The legislator has also favoured the establishment of new biomethane distributors. This addresses the current situation of insufficient distributors, particularly as seen along the nation's motorways. We conclude that biomethane can take on a strategic role in renewable energy policies, with interesting environmental, social and economic implications.

## REFERENCES


Abbasi, S., Diwekar, U. (2014), Characterization and stochastic modeling of uncertainties in the biodiesel production. Clean Technologies and Environmental Policy, 16, 79-94.

Adelt, M., Wolf, D., Vogel, A. (2011), LCA of biomethane. Journal of Natural Gas Science and Engineering, 3, 646-650.

Amiri, S., Henning, D., Karlsson, B.G. (2013), Simulation and introduction of a CHP plant in a Swedish biogas system. Renewable Energy, 49, 242-249.

Asam, Z.Z., Poulsen, T.G., Nizami, A.S., Rafique, R., Kiely, G., Murphy, J.D. (2011), How can we improve biomethane production per unit of feedstock in biogas plants? Applied Energy, 88(6), 2013-2018.

assoRinnovabili. (2013), Aper: azioni per lo sviluppo delle rinnovabili elettriche in Italia. Available from: http://www.assorinnovabili.it/.

Bacenetti, J., Fusi, A., Negri, M., Guidetti, R., Fiala, M. (2014), Environmental assessment of two different crop systems in terms of biomethane potential production. Science of the Total Environment, 466-467, 1066-1077.

Bekhet, H.A., Ivy-Yap, L.L. (2014), Highlighting energy policies and strategies for the residential sector in Malaysia. International Journal of Energy Economics and Policy, 4, 448-456.

Börjesson, M., Ahlgren, E.O. (2012), Cost-effective biogas utilisation – A modelling assessment of gas infrastructural options in a regional energy system. Energy, 48, 212-226.

Bortoluzzi, G., Gattia, M., Sognia, A., Consonnia, S. (2014), Biomethane production from agricultural resources in the Italian scenario: techno-economic analysis of water wash. Chemical Engineering, 37, 259-264.

Browne, J., Nizami, A.S., Thamsiriroj, T., Murphy, J.D. (2011), Assessing the cost of biofuel production with increasing penetration of the transport fuel market: a case study of gaseous biomethane in Ireland. Renewable and Sustainable Energy Reviews, 15, 4537-4547.

Buratti, C., Barbanera, M., Fantozzi, F. (2013), Assessment of GHG emissions of biomethane from energy cereal crops in Umbria, Italy. Applied Energy, 108, 128-136.

Carchesio, M., Tatàno, F., Lancellotti, I., Taurino, R., Colombo, E., Barbieri, L. (2014), Comparison of biomethane production and digestate characterization for selected agricultural substrates in Italy. Environmental Technology, 35, 2212-2226.

Cerović, L., Maradin, D., Čegar, S. (2014), From the restructuring of the power sector to diversification of renewable energy sources: preconditions for efficient and sustainable electricity market. International Journal of Energy Economics and Policy, 4, 599-609.

Cucchiella, F., D'Adamo, I. (2013), Issue on supply chain of renewable energy. Energy Conversion and Management, 76, 774-780.

Cucchiella, F., D'Adamo, I. (2015), Residential photovoltaic plant: environmental and economical implications from renewable support policies. Clean Technologies and Environmental Policy, 1-16. doi: 10.1007/s10098-015-0913-1.

Cucchiella, F., D'Adamo, I., Gastaldi, M. (2014a), Financial analysis for investment and policy decisions in the renewable energy sector. Clean Technologies and Environmental Policy, 1-18. doi: 10.1007/s10098-014-0839-z.

Cucchiella, F., D'Adamo, I., Gastaldi, M. (2014b), Strategic municipal solid waste management: a quantitative model for Italian regions. Energy Conversion and Management, 77, 709-720.

Cucchiella, F., D'Adamo, I., Gastaldi, M. (2014c), Sustainable management of waste-to-energy facilities. Renewable and Sustainable Energy Reviews, 33, 719-728.

Cucchiella, F., D'Adamo, I., Gastaldi, M. (2013), A multi-objective optimization strategy for energy plants in Italy. Science of The Total Environment, 443, 955-964.

Delzeit, R., Kellner, U. (2013), The impact of plant size and location on profitability of biogas plants in Germany under consideration of processing digestates. Biomass and Bioenergy, 52, 43-53.

DENA. (2011), The role of natural gas and biomethane in the fuel mix of the future in Germany.

DENA. (2014), Publications. Available from: http://www.dena.de/en.

Deutsche Gesellschaft für Internationale Zusammenarbeit. (2012), Guide to Biogas–From Production to Use. Fachagentur Nachwachsende Rohstoffe e. V. (FNR).

Di Maria, F., Micale, C., Sordi, A. (2014), Electrical energy production from the integrated aerobic-anaerobic treatment of organic waste by

ORC. Renewable Energy, 66, 461-467.
Dzene, I., Romagnoli, F., Seile, G., Blumberga, D. (2014), Comparison of different biogas use pathways for Latvia: biogas use in CHP vs. biogas upgrading, 9th International Conference on Environmental Engineering, Vilnius, Lithuania.
Emodi, N.V., Bayaraa, Z., Yusuf, S.D. (2015), Energy technology innovation in Brazil. International Journal of Energy Economics and Policy, 5, 263-287.
Energigas Sverige. (2014), Publikationer. Available from: http://www.energigas.se/.
EurObserv'ER. (2014), 13th Annual Overview Barometer. In: Observ'ER (FR), R.D., Institute for Renewable Energy (IEO/EC BREC, PL) Jozef Stefan Institute (SI), ECN (NL), Frankfurt School of Finance & Management (DE), editors. Available from http://www.eurobserv-er.org/downloads.asp.
Forgács, G., Niklasson, C., Horváth, I.S., Taherzadeh, M.J. (2014), Methane production from feather Waste pretreated with Ca (OH) 2: process development and economical analysis. Waste and Biomass Valorization, 5, 65-73.
Goulding, D., Power, N. (2013), Which is the preferable biogas utilisation technology for anaerobic digestion of agricultural crops in Ireland: biogas to CHP or biomethane as a transport fuel? Renewable Energy, 53, 121-131.
GreenGasGrids. (2014), Analysis and results. Available from: http://www.greengasgrids.eu/.
Hahn, H. (2011), Good practice projects for biogas production from waste, upgrading and utilization. Available from: http://www.urbanbiogas.eu/.
Hahn, H., Krautkremer, B., Hartmann, K., Wachendorf, M. (2014), Review of concepts for a demand-driven biogas supply for flexible power generation. Renewable and Sustainable Energy Reviews, 29, 383-393.
Heffels, T., McKenna, R., Fichtner, W. (2014). An ecological and economic assessment of absorption-enhanced-reforming (AER) biomass gasification. Energy Conversion and Management, 77, 535-544.
IEA. (2014), Statistics. Available from: http://www.iea.org/.
Johnson, C. (2010), Business case for compressed natural gas in municipal fleets. National Renewable Energy Laboratory.
Liew, W.H., Hassim, M.H., Ng, D.K.S. (2014), Review of evolution, technology and sustainability assessments of biofuel production. Journal of Cleaner Production, 71, 11-29.
Mattirolo, P. (2013), Il biometano – Modelli di impianti sostenibili in Italia. Available from: http://www.admil.com/index.php/it/pubblicazioni.
McEniry, J., Allen, E., Murphy, J.D., O'Kiely, P. (2014), Grass for biogas production: the impact of silage fermentation characteristics on methane yield in two contrasting biomethane potential test systems. Renewable Energy, 63, 524-530.
Mezzadri, M. 2014, Sistema incentivante e aspetti tecnici del biometano. Available from: http://www.aiel.cia.it/.
Murphy, J.D., Power, N. (2009), Technical and economic analysis of biogas production in Ireland utilising three different crop rotations. Applied Energy, 86, 25-36.
Negri, M., Bacenetti, J., Brambilla, M., Manfredini, A., Cantore, A., Bocchi, S. (2014), Biomethane production from different crop systems of cereals in Northern Italy. Biomass and Bioenergy, 63, 321-329.
NGVA Europe. (2014), Markets & Statistics. Available from: http://www.ngvaeurope.eu/.
Pantaleo, A., Candelise, C., Bauen, A., Shah, N. (2014), ESCO business models for biomass heating and CHP: Profitability of ESCO operations in Italy and key factors assessment. Renewable and Sustainable Energy Reviews, 30, 237-253.
Patterson, T., Esteves, S., Dinsdale, R., Guwy, A., Maddy, J. (2013), Life cycle assessment of biohydrogen and biomethane production and utilisation as a vehicle fuel. Bioresource Technology, 131, 235-245.
Poggi-Varaldo, H.M., Muñoz-Páez, K.M., Escamilla-Alvarado, C., Robledo-Narváez, P.N., Ponce-Noyola, M.T., Calva-Calva, G., Ríos-Leal, E., Galíndez-Mayer, J., Estrada-Vázquez, C., Ortega-Clemente, A. (2014), Biohydrogen, biomethane and bioelectricity as crucial components of biorefinery of organic wastes: a review. Waste Management and Research, doi: 0734242X14529178.
Profillidis, V.A., Botzoris, G.N., Galanis, A.T. (2014), Environmental Effects and externalities from the transport sector and sustainable transportation planning – A review. International Journal of Energy Economics and Policy, 4, 647-661.
Rehl, T., Lansche, J., Müller, J. (2012), Life cycle assessment of energy generation from biogas-attributional vs. consequential approach. Renewable and Sustainable Energy Reviews, 16, 3766-3775.
Ryckebosch, E., Drouillon, M., Vervaeren, H. (2011), Techniques for transformation of biogas to biomethane. Biomass and Bioenergy, 35, 1633-1645.
Scaglia, B., Confalonieri, R., D'Imporzano, G., Adani, F. (2010), Estimating biogas production of biologically treated municipal solid waste. Bioresource Technol, 101, 945-952.
Schievano, A., D'Imporzano, G., Adani, F. (2009), Substituting energy crops with organic wastes and agro-industrial residues for biogas production. Journal of Environmental Management, 90, 2537-2541.
Smyth, B.M., Smyth, H., Murphy, J.D. (2011), Determining the regional potential for a grass biomethane industry. Applied Energy, 88, 2037-2049.
Sukarno, I., Matsumoto, H., Susanti, L., Kimura, R. (2015), Urban energy consumption in a city of Indonesia: general overview. International Journal of Energy Economics and Policy, 5, 360-373.
Teghammar, A., Forgács, G., Sárvári Horváth, I., Taherzadeh, M.J. (2014), Techno-economic study of NMMO pretreatment and biogas production from forest residues. Applied Energy, 116, 125-133.
Uusitalo, V., Soukka, R., Horttanainen, M., Niskanen, A., Havukainen, J. (2013), Economics and greenhouse gas balance of biogas use systems in the Finnish transportation sector. Renewable Energy, 51, 132-140.
Walla, C., Schneeberger, W. (2008), The optimal size for biogas plants. Biomass and Bioenergy, 32, 551-557.
Yuan, X., Zhang, J. (2014), An analysis of development mechanism of china's smart grid. International Journal of Energy Economics and Policy, 4, 198-207.