MSc Program
Renewable Energy in Central and Eastern Europe

POTENTIAL AND COSTS ESTIMATION OF BIOMETHANE IN CROATIA: URBAN WASTE TO GRID INJECTION AND USE IN TRANSPORT SECTOR

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"Master of Science"

Supervised by
Dr. Dipl.Ing. Amela Ajanovic

Dipl. Ing. Karolina Čegir
ID 1127402

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AFFIDAVIT

I, ***Karolina Čegir***, hereby declare

1. that I am the sole author of the present Master's Thesis, "***Potential and Costs estimation of biomethane in Croatia: Urban waste to grid injection and use in transport sector***", 78 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

A topic of this work is connecting two areas – municipal waste and transport sector. From one side is the need for new energy resources in transport sector and from another - using waste as renewable source which is everywhere available although not desired and has to be solved anyhow. So, why not to consider more closely re-use of municipal waste in the form of energy needed for transport?

The core thesis’ question is how much biomethane can be produced from municipal waste in Croatia and being further used in transport sector or injected into the natural gas grid. To answer to this question, I used available data and estimation when needed. Additional issues under considerations were conditions for natural grid injection and usage by vehicles, as well as costs of biomethane production.

At the end, as a conclusion, it has to be stated that any assessed potential would always stay only theoretical if there are no preconditions for its employment: awareness, the need for use, a proper development strategy and clear economic and social benefits.

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ABBREVIATIONS

AD = Anaerobic Digestion

Bcm = billion cubic meter

EU = European Union

GHG = Green House Gases

IEE = “Intelligent Energy for Europe”

Mmcm = million cubic meter

MSW = Municipal Solid Waste

NGVA = Natural Gas Vehicle Association

OG = Official Gazette of the Republic of Croatia

PJ = Peta Joule, i.e. 10^{15} Joule

RES = renewable energy sources

RES-T = renewable energy sources in transport sector

TS = Total Solids

VS = Volatile Solids

WM = Waste Management

1. INTRODUCTION

1.1 Motivation

Almost 30% of final energy worldwide is consumed in the transport sector, and this energy comes mainly from fossil fuels. The transport sector or more precisely – the tremendous increase of transport services, especially the use of personal vehicles– is the main trigger for oil consumption, which has almost doubled in the last 3 decades. So, not surprisingly, the contribution of transport to climate change is indisputably significant. For example, in the EU, transport causes 25% of GHG emissions.

The demand for transport services is not likely to decrease, but is expected to grow; thus the need to switch to less GHG emission fuels and to introduce different concepts of mobility is obvious. In that context renewable energy sources can play a significant role. Unfortunately, for most people, as well as energy policy makers, renewable energy sources still mean electricity produced using wind, water and sun energy. Thus, choosing the topic related to transport sector is my personal response and, hopefully, contribution to promoting the need for and the potential of RES in the transport sector of Croatia.

In addition, RES in the transport sector is one of my tasks in my current work which has brought me to the MSc Program on Renewable Energy at the Technical University of Vienna in the first place. My working experience in the field of natural gas transmission has lead to the topic which combines old and new knowledge – a comparison of biomethane injected into the natural gas grid and used in the transport sector. Keeping in mind the controversial issues related to biofuels produced from energy crops and the timeline for commercial use of advanced biofuels, I chose waste as a source of biomethane production. And last, but not less important, waste management is one of the challenges in urban municipalities where re-use has to be the leading principle.

1.2 Core question / objective of this work

Croatia became the 28th Member State of the European Union on 1 July 2013 and has had to harmonize its legal framework with the EU acquis, as well as fulfill the related obligations in practice. The following is relevant to this work: waste treatment is defined by Directive 1999/31/EC on the landfill of waste and by Directive 2008/98/EC on waste management, while the share of Renewables in transport, according to Directive 2009/28/EC, has to be a minimum of 10% by 2020. Biomethane could be a part of the solution for obligations in both sectors: as a positive valuable result of organic urban waste treatment and as a fuel contributing to the increase of RES share in transport sector.

There is a legal framework in Croatia of transposing the related directives, as well as strategies and plans for both areas at the state and local levels, including different projects, but a general overview of the potential for biomethane production, particularly from municipal solid waste, is missing. Thus, an assessment of the potential of biomethane for feed into the grid and/or usage in the transport sector is the core task of this work. The focus has been put on municipal solid waste, not taking into account industrial and agricultural waste. Furthermore, costs and benefits for biomethane grid injection and direct use in transport have been elaborated.

1.3 Literature and data

Relevant EU acquis - directives on landfills, waste management and renewables - and official Croatian documents – statistics, strategies, laws, ordinances, rulebooks, action plans and reports in the field of Waste Management and RES - were required for this work.
All technological descriptions – on biogas production and upgrade – were cited from the publications by Professor Wellinger, IEA reports, particularly of Bioenergy Task 37, as well as the reports published within related IEE projects (Urbangas, Biomethane Regions, GreenGasGrids, Civitas/Elan).

1.4 Structure of work

The first step is an assessment of the annual quantity of municipal solid waste produced in Croatia using national statistics, published by the Bureau of Statistics and by the Environment Agency.
The second step is dedicated to a concise elaboration of the relevant technologies of biogas production.

According to the calculated biowaste potential and taking into account the most applicable technologies, a further step is a calculation of potential biogas production, including assessment of relevant costs.

The forth part is an elaboration on biogas upgrade: why and how it can be done – a definition of requirements for gas grid injection and vehicles and upgrade technologies. Furthermore, the potential biomethane has been calculated, based on the correlations between biogas and biomethane production, using the Biomethane Calculator, one of the deliveries within the IEE project “Biomethane Regions”. The costs of upgrade have been included in the calculations.

The requirements, possibilities and barriers for further use of biomethane – directly in the transport sector and in the natural gas grid – have been considered within the fifth part of this work. The characteristics of the transport sector and the natural gas network in Croatia are briefly described.

Further, the Croatian potential for biomethane production from municipal solid waste has been deducted - based on the calculated technical potential, assessed costs and conditions for injection to the natural gas grid and for usage in road transport.
The final part brings conclusions on the possible contribution of biomethane to the fulfillment of the RES transport target by 2020, as well as meeting obligations in regards to waste treatment and landfills.

1.5 Method of approach

The scope of this work is the potential of biomethane production in Croatia from the biodegradable part of municipal solid waste only, i.e. excluding energy crops, agricultural and industrial waste, as well as sewage. Furthermore, the usage side of biomethane is limited to the transport sector and injection to the gas grid, without consideration of electricity and heat production. It has to be noted that this source – MSW - has not been considered so far as a source of biomethane at the state level.

The applied approach is a combination of the use of publicly available data and assessments and calculations, when needed.

All data and assessment were done for 2011, the last year for which real data have been published by the Bureau of Statistics and the Environment Agency.

Data on municipal solid waste produced in Croatia, county by county, are published by the Environment Agency. A certain annual common amount – assessed by the Agency – was further extrapolated among counties, in line with their respective share in the overall MSW production at the state level. The numbers at the county level were needed for further calculation of treatment plant costs, distributed per county and per different groups of counties.

Keeping in mind the fact that the separation of municipal waste is still not very developed in most of the counties and that it has to be introduced to fulfill the obligations imposed by Directive 2008/98/EC, not all amounts of biodegradable MSW were taken into account as potential sources of biomethane production. To be more precise: plastics, paper and cardboard were deducted from the overall MSW quantity.

An exact structure of MSW is publicly available for the City of Zagreb, and this structure was used for the assessment of the MSW structure for other counties. It has been considered as adequate, since the City of Zagreb contributes 20% to the total MSW of Croatia, which corresponds to 18% of the Croatian population living in Zagreb.

According to this assessed MSW structure, 36,1% of municipal solid waste has been considered as a source for biogas production and biomethane production respectively.

The potential of biogas production has been calculated based on the type of waste (as defined according to the MSW structure) and given the correlation between the type of waste and biogas yield (as given by Wellinger (2012)).

Further, using the same correlation (Wellinger (2012)), a share of biomethane in biogas was assessed as of 61%, i.e. 61% of biogas potential has been taken as biomethane potential.

Investment costs were assessed according to the technology (appropriated for this type of waste as input material), quantities of biodegradable waste (as assessed per county for an estimated MSW structure) and investment costs for certain biogas technology and quantity (as given by Kovacevic (2010))

The counties have been grouped in different groups – according to geographical and traffic configurations – to apply the economy of scale principle, i.e. to try to find a more economical solution for biogas production from MSW (not 1 plant in each county, then other configurations downsizing to only 3 plants in the entire country).

Additional costs – to upgrade biogas to biomethane – have been calculated using the results of “Bio-methane Regions” project (Biomethane Calculator) and according to the gas requirements in the case of injection to the natural gas grid and in vehicle use. Those upgrading costs have been added to biogas plant costs, following the same grouping of counties (from one plant per county to the grouping where 3 plants can cover the MSW of entire country).

The data on the existing natural gas network have been found at the Transmission System Operator, Plinacro (for transmission grid) and at the Croatian Gas Association (for distribution grids). Taking into further consideration population data, as given by the Bureau of Statistics after the last Consensus in 2011, an assessment of the population with access to transmission natural gas network and distribution networks respectively, has been done. In other words, it was assessed how much biomethane produced from MSW can be easily injected into the natural gas network – from “the population covered by the natural gas network” point of view.

The data for the transport sector, i.e. vehicles in Croatia using natural gas, were found at NGVA and HSUP. The same sources were used for natural gas prices, in order to make a price comparison of methane produced from MSW and the existing methane (natural gas) on the Croatian market.

The results have been shown mainly by tables and, when appropriate, by diagrams. More comprehensive tables, with detailed calculations, are part of Annexes, not of the main text.

2. BACKGROUND - LEGISLATIVE FRAMEWORK & RELATED PROJECTS

Legislative framework forms an important background to this work. On the one hand, the requirements towards waste in general, including municipal solid waste have been imposed; defining a scope of waste which can and has to be used for energy production, including biomethane. On the other hand, the compulsory targets for Renewables, including the transport sector, have to be fulfilled by 2020.
Croatia transposed the relevant EU acquis into the national legislation, making an obligatory framework which is, in a way, an incentive basic for this thesis.

The second pillar which defines the background of this work includes different projects related to biogas and biomethane at the EU level, most of which include Croatia. The relevant reports and findings were used within this work, but it has to be noted that none of the projects deal exactly with the topic of this thesis – either biomethane in other regions has been elaborated or biomethane produced only in certain parts of Croatia. In that sense, all relevant projects form a background for this work. In the end, the results of this thesis can hopefully contribute in a synergetic way to other finalised and ongoing projects.

2.1 Waste management legislative framework

Waste management is one of the important issues interlinked with environmental protection. Several directives and regulations define the EU framework for waste management, but only the most relevant to municipal waste and, consequently, to this work, have been described within this sub-chapter.

Directive 1999/31/EC[1] stipulates an obligatory decrease of land filled biodegradable waste in all Member States. In concrete terms, for Croatia, the reference year is 1997. Biodegradable waste quantities at landfills have to be reduced to 75% of 1997 values by 31 December 2013, 50% by 31 December 2016 and 35% by 31 December 2020 respectively[2]. Absolute numbers are shown by Table 1:

[1] Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste
[2] Originally for EU MS, the reference year was 1995, and deadline years 2006, 2009 and 2016, while Croatia negotiated a certain postponement (to 2013, 2016 and 2020) during the Accession process to EU

Table 1 – Mandatory decrease of biodegradable waste disposal at landfills in Croatia

1997	by 31.12.2013	by 31.12.2016	by 31.12.2020
100%	75% of 1997' value	50% of 1997' value	35% of 1997' value
756.175 t	567.131 t	378.088 t	264.661 t

(Data source: Law on sustainable waste management, OG 94/13; own creation of table)

Directive 2008/98/EC[3] establishes mayor principles of handling waste in a way that does not have a negative impact on the environment or human health, at the same time imposing certain requirements to product producers and introducing a waste hierarchy and relevant treatment manners.

Figure 1 - Waste hierarchy according Directive 2008/98/EC

(Data source: Directive 2008/98/EC; own creation of figure)

For this work, recovery, i.e. energy recovery, is the most relevant.

Croatia has transposed both directives into its national legislation. A basic primary law, the Law on Waste (OG 178/04, OG 111/06, OG 60/08 and OG 87/09), has been complemented by secondary legislation: the Ordinance on Waste Management (OG 23/07 and OG 111/07); the Rulebook on Register of Environmental Impurity (OG 35/08) and the Rulebook on Manner and Conditions of

[3] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

Waste disposal, categories and work conditions of landfills (OG 117/07 and OG 111/11). A comprehensive Law on sustainable waste management (OG 94/13) was approved in July 2013, comprising definitions and requirements of the previous law and secondary acts.

The legislation defines waste and its categories, as well as the responsibility for waste management. Cities and municipalities are responsible for municipal waste management, which includes waste separation and set up of relevant containers. The counties and the city of Zagreb are responsible for managing all types of waste, except hazardous waste, which is the sole responsibility of the state.

The legislation foresees, in line with the EU acquis, an increase of waste separation and re-use, as well as a decrease of landfills.

The Strategy of Waste Management in the Republic of Croatia (the Strategy in further text) describes the state of play in 2005 as the base line and ways to achieve mandatory goals. Two main issues have to be solved at the same time: the decrease of landfills and re-design of current waste separation and waste management.

Certain goals have been achieved in regard to landfills. In 2005 there were 187 registered official landfills, while the number of illegal landfills was much higher, around 3.000. The Strategy has foreseen the closure of all illegal landfills and the reduction of official landfills, down to 30 by 2020. According to the latest report on the municipal solid waste published by the Environment Agency, 107 official landfills were closed by the end of 2011, while similar activities were ongoing for another 48 sites. In addition, 750 illegal sites were also closed. It is clear that landfill closures can be done only if input waste quantities have been decreased, i.e. if proper waste management – from collection to re-use and disposal –is in place.

The first step required in the direction of proper waste management and reduction of landfills is the separation of municipal solid waste. Only 16,3 % of MSW in Croatia was separated in 2011 (which is an increase in comparison to 10% in 2005). Glass, plastics, metals and paper are target waste parts, although established systems and achieved results vary very much among the cities and counties in Croatia. The biggest shares of separated MSW (25,9 - 21%) have been achieved in Medjimurska County, the City of Zagreb and Primorsko-goranska County, while the lowest share – at the level of 2-3% - belongs to Licko-senjska and Vukovarsko-srijemska County.

According to the Report by the Environment Agency, 212 companies are involved in MSW collection in Croatia. 20 plants for the mechanical treatment of MSW, with a total capacity of 50.000 t/y, are in operation. There are also 3 plants for biological treatment, all of them located in the city of Zagreb. Zagreb is also the location of the single plant for landfill gas, used for further energy production, with the installed capacity of 2 MSW. In any case, the City of Zagreb, as the biggest city in Croatia (18% of population), appropriately has the biggest share of MSW production (19,9%). Composting is organized at 7 sites, with 14.000 t of MSW composted in 2011. Still, in 2011, 91% of municipal biodegradable waste (937.375 t) was deposited at landfills. As described in Table 1, by the end of this year, the amount of deposited biodegradable waste has to be decreased to 75% of the quantity in 1997, i.e. to the level of 567.131 t.

In order to foster better waste management, the Strategy foresees the establishment of waste management centers in almost every county (7-10 by 2015, 10-14 by 2020, and 14-21 by 2025 respectively) and several regional centers (1-2 by 2010, 3 by 2020). So far, the development of the first 3 regional centers has started during 2011 and 2012 (Bikarac in Sibensko-kninska, Kastijun in Istarska County and Marinscina in Primorsko-goranska County). 48% of the total investments costs (cca 100 mln EUR) have been ensured trough IPA funds, while 52% will be covered by the Energy Efficiency and Environment Protection Fund and by the counties concerned.

2.2 Legislative framework of Renewables in transport sector

Whereas municipal solid waste is the first pillar, the transport sector is the second pillar of this work; in particular transport fuels produced from renewable energy sources.

Directive 2003/30/EC[4] on the promotion of biofuels set up a general direction for transport sector – indicative renewable fuel targets (2% in 2005 and 5,75% in 2010), principles of support and promotion measures, as well as obligations on monitoring and reporting. One of the obligations was dedicated to monitoring the effects of the fuel mix with more than 5% biofuels, enabling the set up of a higher target. A higher target – as minimum of 10% fuels from renewable energy sources in transport by

[4] Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport

2020 – has been set up by Directive 2009/28/EC[5] on renewable energy sources. The Directive unifies different sectors – electricity and transport, and recognizes the importance of heating and cooling in terms of energy consumption and consequently as a potential area of usage of renewable energy.

However, the most demanding requirements have been defined for Renewables in the transport sector, in particular towards liquid biofuels. Only biofuels produced in compliance with sustainability criteria, related to the types of land for crops production and CO_2 emission savings, can be calculated towards target fulfillment, regardless of the origin of production (i.e. by a Member State or imported).In addition, the contribution made by biofuels produced from waste, residues and non-food cellulosic material, as well as from ligno-cellulosic material, shall be considered to be twice that made by other biofuels.

Both aspects – more strict requirements towards liquid biofuels than before and double counting of biofuels produced from waste (including municipal solid waste) – are very important for this work, and, in a way, they were the triggers for the chosen topic.

Additional requirements for the transport sector have been defined by Directive 2009/33/EC[6] on clean and efficient road vehicles. Special obligations have been placed on public authorities at state, regional and local levels regarding the general procurement of public vehicles. In this context, biomethane produced from municipal waste can play a significant role.

As well as waste management directives, the directives related to Renewables in the transport sector have been transposed by the Croatian legislation. The main document is the Law on Biofuels for Transport (OG 65/09 and OG 145/10), followed by several rulebooks and decrees, which define in more detail the support measures in production and usage of biofuels, eligibility conditions for support, sustainability criteria and its certification, energy content and fuel quality. The relevant framework was completed by strategic documents, such as the Energy Strategy and the Strategy of Sustainable Development, the National Renewable Energy Action Plan

[5] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

[6] Directive 2009/33/EC of the European Parliament and the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles

and the National Action Plan on incentives for production and usage of biofuels in the transport sector for the period of 2011-2020. Biogas has its place in all of these documents, although not a significant one.

It is important to emphasize that transport in Croatia is the sector with highest share in total final energy consumption since 2005 (30%) and has been growing continuously by 4,69% per year. Keeping in mind the consumption level in 2005 (80,02 PJ in transport sector), as the reference year for RES 2020 targets, the development forecast (128,54 PJ in transport sector in 2020) and the obligation by Directive 2009/28/EC (10% RES-T by 2020), renewable energy sources in transport must reach 10,05 PJ by 2020.

In 2011, bio-liquids contributed only 0,16% of the total consumption of 84,97 PJ in the transport sector. Biogas has not been consummated in transport so far. The contribution of biogas (biomethane) has been foreseen from 2016 on; with 0,37 PJ in 2016, reaching 0,62 PJ by 2020. The National Action Plan on the incentives for production and usage of biofuels elaborates the potential for biomethane production, taking into account only livestock manure (2-2,6 PJ/y) and sewage waters in the 5 largest cities (0,31 PJ/y)[7]. The potential of biodegradable municipal waste, the topic of this work, has not been considered.

2.3 Relevant projects within the EU framework

Biogas production, complementing biomethane to natural gas, in grids and in the transport sector, as well as the need for a redesign of public transport, have been recognised at the EU level as areas which can contribute to changing the energy footprint.

Croatia has been included in several European projects relevant for biogas production and utilisation. Some of them have already been finalised (BiG>East, BiogasIN, CIVITAS), while some are still running (UrbanBiogas, GreenGasGrid, Bio-methane Regions).

[7] Planed achievements in the whole paragraph are according to the National Action Plan on incentives for production and usage biofuels in transport sector in the period 2011-2020 (http://www.mingo.hr/default.aspx?id=3376), while data on actual consumption in 2011 are according to the report “Energy in Croatia 2011” prepared by the Ministry of Economy, (http://www.mingo.hr/default.aspx?id=3258)

They have all been launched within the Intelligent Energy for Europe (IEE) Programme, a part of a wider framework for creating an “energy-intelligent future”. The programme offers a helping hand to organisations willing to improve energy sustainability by simultaneously supporting EU energy efficiency and renewable energy policies. It was launched in 2003 by the European Commission and was open to all EU MS plus Norway, Iceland, Liechtenstein, Croatia and the Former Yugoslav Republic of Macedonia.

2.3.1 BiG>East

The project “Promoting Biogas in Eastern Europe – Mobilization of Decision Makers and Training for Farmers”, called ***BiG>East***, was a project within the framework of the IEE 2007-2010.
Considering the contrast between the significant potential of biogas production and undeveloped biogas markets in Eastern Europe, the general objective of the BiG>East project was to promote the production and use of biogas as an available and sustainable energy source in six target countries of Eastern and Southern Europe: Bulgaria, Croatia, Latvia, Romania, Slovenia, and Greece.

The focus of the project was on building capacities in the agricultural sector by transferring knowledge from project partners from Western Europe with successful, long-term experience in biogas production to farmers, biogas plant operators, and decision makers in Southern and Eastern Europe. This was achieved by the organisation of 13 mobilisation campaigns for decision makers, 19 training courses for farmers, and several study tours.

One of the results of BiG>East is a biogas handbook prepared through the joint efforts of a group of biogas experts from Denmark, Germany, Austria and Greece. The handbook has been translated into national languages of 6 target countries and provides basic information on anaerobic digestion, source of production and biogas technologies, technical components of plants, as well as the utilisation possibilities and safety aspects.

However, BiG>East showed the main obstacles to biogas development in the target countries, including Croatia. On the one hand, there is a lack of capacity for biogas production and use (lack of pilot projects, public awareness, as well as a lack of knowledge and skilled personnel).On the other hand, unsuitable legislative framework (permission procedures, lack of adequate polices and incentives) is still a burden.

2.3.2 BiogasIN

Based on the obstacles defined by the BiG>East project, the European Commission supported within the same framework (IEE programme, but in the following period 2010-2013) a follow up project, the ***BiogasIN*** project called "The Development of sustainable biogas markets in Central and Eastern Europe".

The objective of BiogasIN was to address the main barriers to the development of biogas in 7 target countries: Bulgaria, Croatia, the Czech Republic, Greece, Latvia, Romania and Slovenia. This was done as capacity building trough training courses (for administrative bodies, farmers and biogas investors on permission procedures and financing options) and trough study tours and high level conferences (for decision-makers and stakeholders involved in national biogas policies). The events were supplemented by several studies on framework conditions in CEE compared to the framework conditions in the top 5 EU biogas plant countries (Austria, Germany, Denmark, Italy, the Netherlands), and by a pan-European survey on biogas permission procedures and financing options.

Although both projects, BiG>East and BiogasIN, with their focus on the agricultural sector, are not related to biogas production from municipal organic waste, they are important for raising general awareness of biogas as a sustainable source of energy with various areas of implementation. Thus, both projects have been referred to within this work, in order to illustrate a wider framework for the development of biogas production and utilisation in Croatia.

2.3.3 ELAN/CIVITAS

Contrary to BiG>East and BiogasIN, the ***ELAN*** project, another project within the EU framework as part of the ***CIVITAS*** initiative in the 2007-2012 period, could interrelate directly to this work.

One of the measures within ELAN was to introduce energy efficient vehicles and clean fuels to the public transport fleet in Zagreb. The first 2 buses powered by compressed natural gas (CNG) were introduced as a pilot project in 2007.Currently, 60 CNG buses, together with 100 biodiesel buses, represent a 35% share of clean fuel vehicles in the total ZET fleet[8].

In the case of biomethane production, as the final result of MSW treatment in Zagreb, those 60 buses can switch to biomethane easily; i.e. a sustainable, renewable chain in the city – from households waste to public transport – can be established.

2.3.4 GreenGasGrids

This project is also focused more on the transport sector than biogas production. Similarly to the CIVITAS ELAN project, it could influence the use biogas usage.

"*GreenGasGrids is a 3-year European project funded by the Intelligent Energy for Europe (IEE) programme with the aim to boost the European biomethane market. The project will run until mid-2014 and is co-ordinated by the German Energy Agency Dena. The project's consortium consists of 13 European partners, including national energy agencies, scientific institutions as well as industry associations involved in biomethane, natural gas, and renewable energy. GreenGasGrids aims to substantially contribute to realising a significant contribution of biomethane to the Renewable Energy Directive (RED) targets of 20% renewable energy and 10% renewable energy in transport in 2020 as well as the renewable energy targets set by individual EU Member States in their Renewable Energy Action Plans. The project's objective is to measurably increase the production and use of biomethane for transport, heat and electricity by addressing the most hindering barriers to biomethane deployment in the EU, both in forerunner and starter countries*."[9]

This paper, aiming to asses a potential of MSW for biomethane production in Croatia, could contribute positively to the ongoing GreenGasGrids project, where Croatia is one of the stakeholder countries.

2.3.5 UrbanBiogas

The results of the ***UrbanBiogas*** project can be used for this work.

[8] According to http://www.zet.hr/autobus.aspx

[9] Citation from "Biomethane Market Matrix", Draft Summary Report (April 2013) of GreenGasGrid

Namely, the City of Zagreb, together with Graz, Valmiera, Abrantes and Rzeszów, was included in the IEE project UrbanBiogas which has started in May 2011 and will end by May 2014. The project's goals are the promotion of biomethane production from municipal solid waste and usage in the transport sector and/or injection in to the gas grid; defining the concepts of biomethane production for the 5 cities involved and stimulating the development of relevant biogas plants.

The UrbanBiogas project and this work can achieve a kind of synergetic effect. The project covers the City of Zagreb, the biggest city in Croatia or 18% of the country's population, while this thesis aims to cover all of Croatia, but at the level of potential assessment, without going into the details of development projects as the UrbanBiogas project.

In any case, the concept of biomethane production from municipal waste in Zagreb and its use in the transport sector and injection in the gas grid could serve as an example for other major cities in Croatia.

2.3.6 Bio-methane Regions

Bio-methane Regions is another IEE project whose reports and results were used for this work, especially the Biomethane Calculator.

The project has started in 2011 and will run until 2014. The aim of the project is to promote anaerobic digestion and biogas upgrade technologies, along with the market development of biomethane for grid injection and vehicle use. The intentions are to facilitate new AD plants and biomethane production by providing independent advice to potential developers, regulators, politicians and other stakeholders.

2.3.7 GasHighWay

GasHighWay, finalised in 2012, is another IEE project which falls within the biomethane production framework. Croatia was not included, but the project was aiming to promote biomethane as a vehicle fuel, and from that perspective it is of relevance to this work.

"*The European project called* ***GasHighWay*** *aimed at promoting the uptake of gaseous vehicle fuels, namely biomethane and CNG, and especially the realisation* *of a comprehensive network of refuelling stations for these fuels spanning Europe from the north, Finland and Sweden, to the south, Italy – in other words: the GasHighWay."*[10] The main findings of the project can be summarized as follows: public opinion of gas vehicles and gaseous fuels is very positive; the interest in CNG cars (as well all alternative fuels) is strongly interlinked with the level of gasoline and diesel prices; the role of legislation and regulations is essential when promoting gaseous fuels and cars; a continuous communication between policy makers and local authorities can contribute to the development of gas fuel stations; and a well established co-operation among the entire chain – from biogas production and upgrade, to filling stations and car dealers – is crucial to fostering the use of biomethane in the transport sector.

2.3.8 BioMaster

BioMaster, an IEE project which will run until mid 2014, aims to prove that biomethane for transport is an operational and viable solution.

The 4 regions included (the UK, Sweden, Italy and Poland) are committed to exploit the biomethane potential, as "waste-to-wheel" chain, including possibilities to gas grid injection. This work will refer to the findings achieved thus far, to the extent they are applicable to Croatia.

[10] "GasHighWay" final report

3. AN ASSESSMENT OF MSW AS A SOURCE FOR BIOGAS PRODUCTION

Different wastes with an organic component can be an excellent source of biogas production: agricultural waste, manure, food & beverage industry waste, municipal waste. This work is focused on the biodegradable part of municipal solid waste, as the source whose potential Croatia has not comprehensively tapped yet, particularly not for the transport sector and grid injection.

Since biodegradable waste, disposed at landfills, has to be significantly decreased in the coming years, while fostering waste separation, all biodegradable components of municipal solid waste have not been taken into account as a potential source of biogas production. Only the leftover municipal solid waste, after the separation of plastics, paper and cardboard, has been considered as an input for biogas potential assessment.

Thus, for the assessment of municipal solid waste as a source for biogas production, two items were used: the production of MSW in Croatia as published by the Environment Agency and the assessment of leftover biodegradable components according to the MSW structure for the City of Zagreb.

3.1 Municipal solid waste separation and collection

The Law on waste imposes the responsibility for municipal solid waste management to all administrative units – cities and municipalities. In practical terms, this means that all citizens of Croatia must be covered by organized municipal solid waste management. This is almost achieved in practice – according to the Report on municipal waste by the Environment Agency for the year 2011, 96% of the population has been included in organized waste collection. The goal of including 90% of the population, set up for 2015 by the Strategy on waste management, was achieved in 2007; while the goal of 95% set up for 2020 was reached in 2009. Thus, keeping in mind the legislative obligations on municipal solid waste management for all administrative units and the population targets reached so far, the potential of biogas and biomethane will be calculated based on the entire population, i.e. as municipal solid waste collected from 100% of population.

While good results have been achieved in the scope of population included in organized waste collection, the same cannot be said for waste separation. As described in chapter 2.1, the share of separated MSW is not at a high level – it varies from 2 to 25,9% among the 21 counties in Croatia. The majority (91%) of municipal biodegradable waste still ends up at landfills.

Table 1 shows mandatory maximum quantities of biodegradable waste at landfills by the end of 2013 and further on. However, according to the Environment Agency data , municipal solid waste production and its deposit at landfills was continuously growing until 2008, when a slight decrease started. Biodegradable waste disposed at landfills in 2011 amounted to 937.375 t, or, in other words, 370.604 t above the limit set for the end of 2013 in accordance with Directive 1999/31/EC, which have to be treated in a different manner, not disposed at landfills.

It is clear that paper and plastics still make up a significant part of biodegradable waste at landfills, and their separation in the first stages (collection in households and in municipalities) are the ultimate actions towards landfill deposit decrease as required by national and the EU legislations. Thus, those extra quantities at landfills (with a significant share of paper and plastics) have not been taken as the basis for biogas potential calculation.

The best part of MSW for biogas production would be separated biowaste, and, thus, an ideal source to be considered in further calculations. However, biowaste separation is lagging even behind the very modest separate collection of paper, plastics and metal.

Nevertheless, a few positive examples of biowaste separation in Croatia can be found in Medjimurska County (the leader in MSW separation) and on the biggest island in Croatia, Krk[11], which will be described in more detail.

The island of Krk has a constant population of c. 20.000 people, a number which increases 2,5 times by weekend house owners from March/April to October, and 3 times by all tourists during the two summer months. These variations in population and the relevant waste production, from 20.000 to 120.000 people, were a challenge for designing a separation system and defining emptying dynamics. The implementation started in 2006: containers for mixed municipal solid waste were

[11] Source of information for waste management at island Krk: the presentation of "Ponikve Krk" activities by Mr. Ivan Juresic within the project "UrbanBiogas"

replaced by 5 containers – for paper, glass, plastics, biowaste and the rest (mixed MSW)- at 1500 locations.

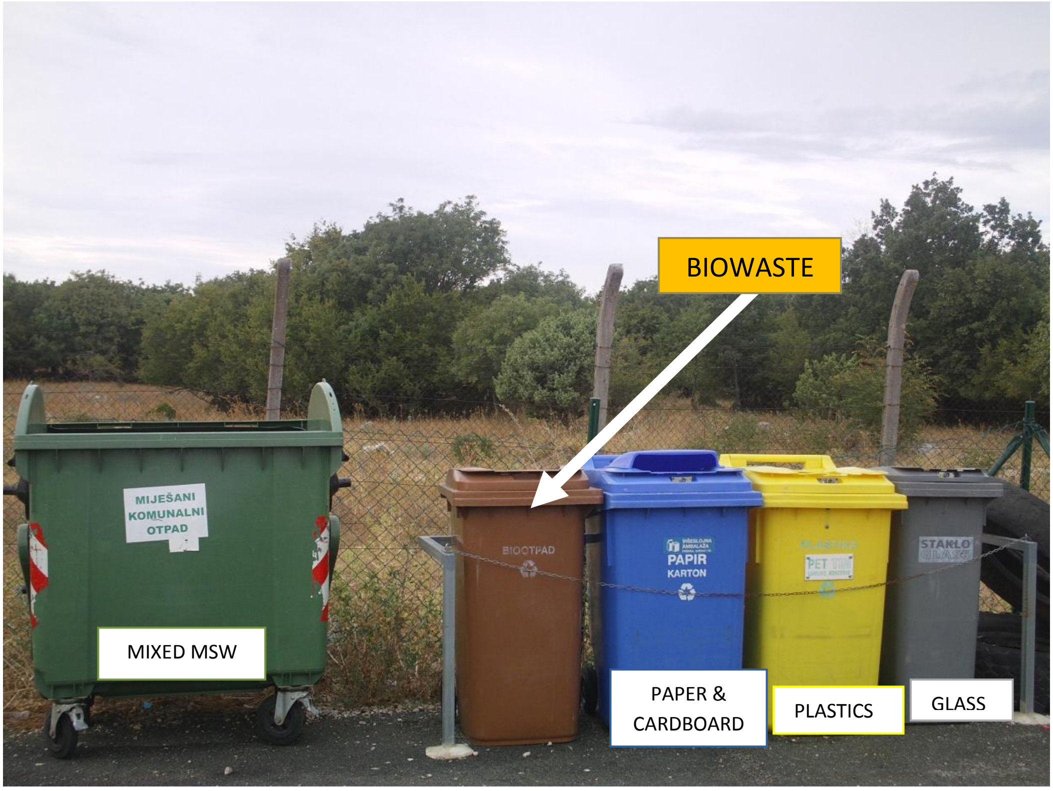


Figure 2 - Example of waste collection point at island Krk

(Source: own photo)

Notable results have been achieved in the 5 years since the implementation of the project "Eco waste management system" – a share of separately collected waste increased from 18,2% in 2006 to 35,3% in 2011. The collected biowaste is used for compost. The "Treskavac" landfill has been arranged and upgraded as part of the same waste management project at the island of Krk.

The City of Cakovec in Medjimurska County with its 27.000 inhabitants, , is well advanced in waste separation and waste management. Waste separation has been ensured at the place of production – the household. Different dustbins and sacks have been distributed by a company responsible for waste collection. Dustbins are dedicated to biodegradable waste and mixed waste, while sacks are used for special parts such as paper, plastics, beverage boxes etc. Upon request, additional waste sacks can be provided – for example, for computer toners & cartridges. Also, a certain number of sacks are free of charge, while additional sacks have to be purchased. Only mixed waste (from one of the dustbins) is disposed at landfills, all other categories are re-used or re-cycled. For biowaste, an adequate solution still has to be found, in the meantime, it is stored at a special deponium. The target is to go beyond the EU standard of 50% and to reach a target of only 30-35% biodegradable waste landfilled.

In the City of Zagreb, biowaste containers have been introduced in a few districts only. The pilot project, covering a big residential area (13 buildings, 3100 inhabitants, MSW at the level of 51t/month), has started in May 2011. The results are encouraging: 56,5 % of separately collected waste in 6 months was biowaste, while the total share of separated waste was between 12 and 18%. Biowaste was disposed for compost.

It can be concluded that biowaste separation has not been widely introduced in Croatia, and those 3 positive examples cover a far too small area to extrapolate results – in terms of biowaste quantity – for the entire country. Thus, an assessment of the biodegradable part of MSW, suitable for biogas production, has been done and elaborated within the further sub-chapters.

3.2 Assessment of Municipal Solid Waste production

Keeping in mind the MSW collection systems in place in Croatia, where separate biowaste collection is not very widely implemented, the author has decided to assess the biogas production potential based on municipal biodegradable waste produced annually in Croatia. For this assessment, national statistics, published by the Statistical Office and by the Environment Agency, have been used.

According to the Bureau of Statistics and the 2011 Census, Croatia has 4.284.889 citizens. For further calculation, data at the level of individual counties have been used.

Figure 3 – Map of Croatia with counties' borders
(Source: http://www.croatia-travel-info.com/maps/croatia-regions-map.htm)

The Environment Agency's Report provides details for each county and indicators at the state level. Since certain obligations for establishing municipal waste management have been imposed on counties, further calculations were carried out for each county and then summarized on the state level, as shown by Table 2.

It has to be noted that the average county' values for the MSW per capita have been calculated by the Environment Agency, based on reported quantities by responsible collecting companies. However, not all of the 212 companies had submitted reports and an additional quantity of 133.657 t has been defined by the Agency, based on landfill data and the assumption that 4% of the population is not yet covered by organized MSW collection. For the purpose of further calculations within this work, those additional quantities of 133.657 t have been distributed among counties according to each county's share in the overall MSW production in Croatia and added to reported quantities for 2011, resulting in the numbers for MSW per county in Table 2. All details - on the county' share of the total MSW, MSW/capita county by county and additional quantities - can be seen in Annex 1.

Table 2 – Production of municipal solid waste in Croatia

County	population	MSW (t/y)
Zagrebačka	317.606	77.822
Krapinsko-zagorska	132.892	29.380
Sisačko-moslavačka	172.439	62.058
Karlovačka	128.899	57.777
Varaždinska	175.951	44.245
Koprivničko-križevačka	115.584	22.541
Bjelovarsko-bilogorska	119.764	39.333
Primorsko-goranska	296.195	136.481
Ličko-senjska	50.927	31.903
Virovitičko-podravska	84.836	32.194
Požeško-slavonska	78.034	17.433
Brodsko-posavska	158.575	51.980
Zadarska	170.017	91.395
Osječko-baranjska	305.032	94.719
Šibensko-kninska	109.375	48.486
Vukovarsko-srijemska	179.521	45.163
Splitsko-dalmatinska	454.798	223.145
Istarska	208.055	125.414
Dubrovačko-neretvanska	122.568	66.883
Međimurska	113.804	20.153
City of Zagreb	790.017	326.789
Total	4.284.889	1.645.295

(Data source: Statistical Office & Environment Agency;
Own calculation of the last column)

Significant differences between the counties, not only in terms of absolute numbers, but as MSW/capita (from 163 to 574 t/capita, as shown by Annex 1), can be explained as results of different major economic activities by different counties (agriculture in the north and east, tourism in the west and south of the country) and of different waste management levels (better organized separation in the north-west counties).

3.3 Assessment of Biowaste production

As explained within 3.1, biowaste separation is not widely spread among counties, thus the next step in this work is an assessment of how much of total municipal solid waste can be taken into account as biowaste, i.e. as a source for biogas production.

This study strictly used the definition within Directive 2008/98/EC: “bio-waste means biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants”.

Collected and deposed biodegradable municipal waste in Croatia still contains plastics, paper, cardboards, wood and textile – materials which have to be separated before disposal. As imposed by Directive 2008/98/EC, re-use and recycling are desirable and required steps before any energy recovery. Having in mind those activities still required to be fulfilled, all biodegradable MSW waste, which is disposed for the time being (still 91%, or 937.375 t), will not be taken into account for biogas production calculation, i.e. only biodegradable parts which could be a leftover after all required separation will be taken into account for potential assessment.

Detail structure of municipal solid waste for all counties is not published, thus a share of biowaste in calculated MSW has been assessed.

An actual data on MSW structure can be found for the City of Zagreb[12], which participates by the biggest share (19,9%) in the total MSW production in Croatia. Thus, if not fully accurate, it is a pretty much approximate to use a pattern of the biggest MSW producer to assess MSW structure of other municipalities.

[12] Report by “Cistoca” within UrbanBiogas project

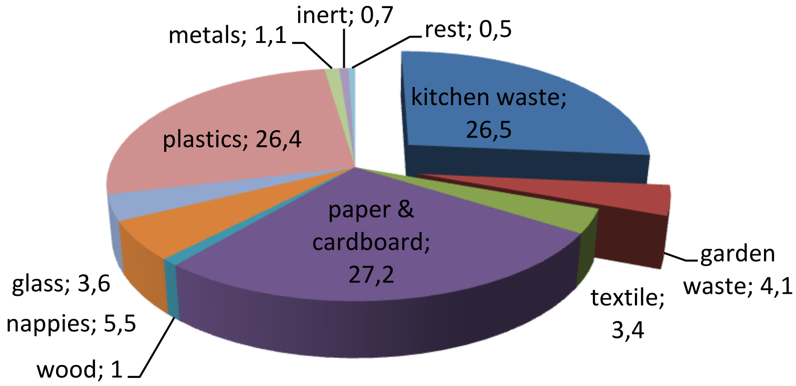


Figure 4 – Structure of municipal solid waste in the city of Zagreb (in %)

(Source:Bojan Ribic, Zagrebacki Holding – Cistoca, based on IPZ Report 2010)

As shown by the figure 4 above, kitchen and garden waste represent 30,6%, and nappies as of 5,5%, as biodegradable material can be add to it; which leads to 36,1% share of biowaste in municipal waste of the City of Zagreb. The same contribution has been used for biowaste calculation of other counties in Croatia.

Table 3 – Assessment of Biowaste production in Croatia

County	MSW t/y	Biowaste t/y
	according Table 2	36,1% of MSW
Zagrebačka	77.822	28.094
Krapinsko-zagorska	29.380	10.606
Sisačko-moslavačka	62.058	22.403
Karlovačka	57.777	20.857
Varaždinska	44.245	15.972
Koprivničko-križevačka	22.541	8.137
Bjelovarsko-bilogorska	39.333	14.199
Primorsko-goranska	136.481	49.270
Ličko-senjska	31.903	11.517

Virovitičko-podravska	32.194	11.622
Požeško-slavonska	17.433	6.293
Brodsko-posavska	51.980	18.765
Zadarska	91.395	32.994
Osječko-baranjska	94.719	34.194
Šibensko-kninska	48.486	17.503
Vukovarsko-srijemska	45.163	16.304
Splitsko-dalmatinska	223.145	80.556
Istarska	125.414	45.274
Dubrovačko-neretvanska	66.883	24.145
Međimurska	20.153	7.275
Grad Zagreb	326.789	117.971
Total	**1.645.295**	**593.952**

(Source: own calculation)

As shown by Table 3, total biowaste produced in Croatia in 2011 has been assessed at the level of almost 600.000 t, or 63,36% of actually deposited biodegradable MSW at landfills in 2011. This quantity is taken further into calculation of biogas and biomethane potential production.

It has to be noted that assessed quantity of biowaste – 593.952 t – is only for 5% above the target as set up by Directive 2008/98/EC by the end of 2013 – 567.131 t (see Table 1). In another words, the target of reducing the biodegradable MSW deposited at landfills could be achieved in the first step, by the end of 2013, if systems of separation and collection of paper & cardboard would be in already introduced all over the country for the time being.

4. AN ASSESMENT OF POTENTIAL BIOGAS PRODUCTION

This chapter elaborates at the first on basics of biogas formation process and relevant technologies. The second part is dedicated to an assessment of potential biogas production, using the result of chapter 3 – assessed biowaste – as input into the process of biogas formation. Further, investment costs needed for such type of biowaste and relevant biogas production have been assessed (using a correlation by Kovacevic, (2010)). At the end, different possibilities have been considered from economic point of view – from 21 biogas plants (i.e. in each of the counties) to 3 biogas plants in entire country.

At the beginning of this chapter, in order to avoid possible misunderstanding, we should distinguish several terms, commonly used:

Natural gas is mainly composed of methane (CH_4), while ***biogas*** is the term used for balanced mixture of methane (CH_4) and carbon dioxide (CO_2). Thus, it is not appropriate to exchange the terms "natural gas" and "biogas" when applicable, as it can be done for example for diesel and biodiesel (equal in regards to composition and different according to the origin). Keeping in mind gas compositions, the link between the terms "***natural gas***" and "***biomethane***" is more accurate.

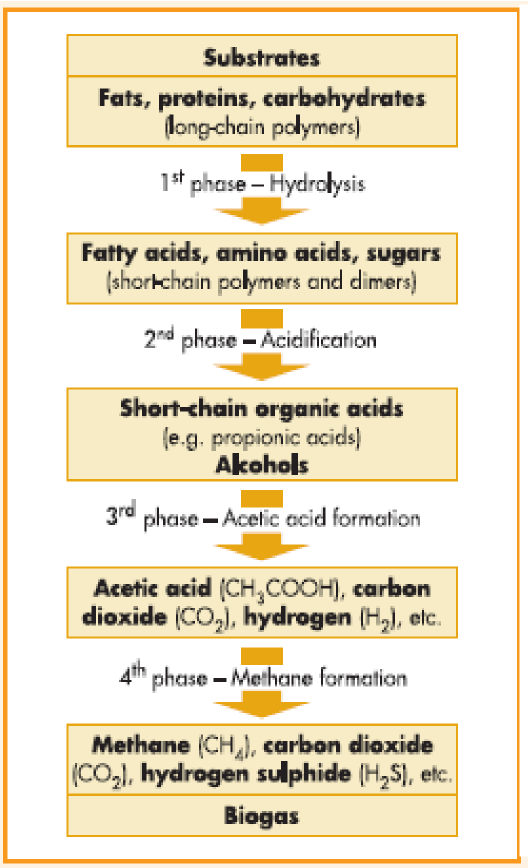
4.1 Introduction – The Basic of biogas formation process

Biogas production is a natural process which takes place when biodegradable matter is fermented by anaerobic bacteria in the absence of oxygen. Biogas is formed solely by bacteria, unlike composting where fungi and some lower organisms are also present in the process of bio material degradation.

In nature, anaerobic digestion occurs in the bottom sediments of lakes, ponds, swamps, peat bogs and hot springs. In our urban world, organic waste ferments into biogas spontaneously at waste disposals. When the process is under control, the product – the resultant biogas – is a significantly higher and more important energy source, which is anyhow needed, produced from waste.

The process, know as anaerobic digestion (AD), and shown in Figure 5, consists of 4 stages: ***hydrolysis***, in which complex molecules are broken down to constituent monomers; ***acidogenesis***, i.e. the forming of acids; ***acetogenesis***, or production of acetates and ***methanogenesis***, the phase in which methane is created from acetate or hydrogen. It has to be noted that each stage has a unique bacteria population and environmental conditions.

All processes occur simultaneously and synergistically, but digestion is complete when one substrate has undergone all 4 phases.



Lipids $\Rightarrow$ Fatty acids, Glycerol
Polysaccharides $\Rightarrow$ Monosaccharides
Proteins $\Rightarrow$ Amino acids

$C_6H_{12}O_6 \leftrightarrow 2\ CH_3CH_2OH + 2\ CO_2$
$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2\ CH_3CH_2OOH + 2\ H_2O$

$CH_3CH_2COO_- + 3H_20 \leftrightarrow CH_3COO^- + H_+ + HCO_3^- + 3H_2$
$C_6H_{12}O_6 + 2H_20 \leftrightarrow 2CH_3COOH + CO_2 + 4H_2$
$CH_3CH_2OH + 2H_20 \leftrightarrow CH_3COO^- + 2H_2 + H^+$
$2HCO_3- + 4H_2 + H_+ \leftrightarrow CH_3COO_- + 4H_20$

Acetate $\Rightarrow CH_4 + CO_2$
$CO_2 + 4H_2 \Rightarrow CH_4 + 2H_20$

Figure 5 – Process of Biogas formation

(Source: FNR (2009) & Wellinger (2012))

Anaerobic degradation, i.e. the formation of biogas, has quite a wide range of occurring conditions in nature: a share of moisture content can vary from 60 to over 99 percent, and temperatures can range from temperatures close to freezing (such as sewage in the arctic[13]) to well over 100 °C (such as the steams of geysers). In technical applications, we can distinguish 3 different temperature ranges:

[13] *McGhee, 1968*

Psychrophilic (or cryophilic) temperature	10° to 25°C
Mesophilic temperature	25° to 42°C
Thermophilic temperature	49° to 60°C

In each temperature range, different types of bacteria are present as participants in the AD process.

The time required for the completion of anaerobic digestion depends on the feedstock complexity and temperature, but, in general, it can be measured in days. Lower temperatures result in longer times needed to complete the AD. The majority of agricultural AD plants work at mesophilic temperatures, while large-scale biogas plants operate at thermophilic temperatures. Biogas yields also depend on feedstock and temperature, as shown by Figure 6 and Annex 2.

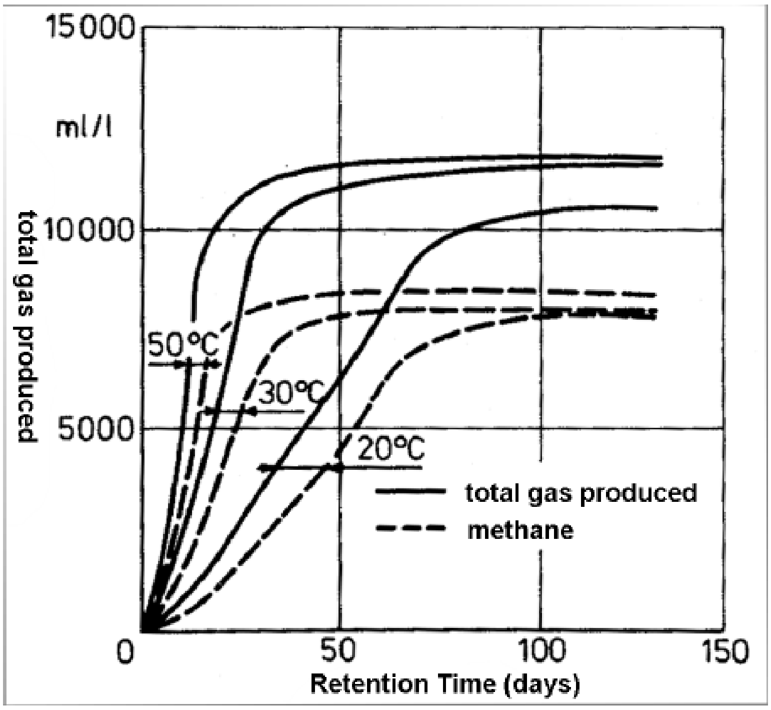


Figure 6 – Biogas yield in function of retention time and temperature

(Source: Wellinger, (2012); Fair&Moore (1934))

Along with biogas, AD has another product – digestate.

Digestate is the generic term for the material remaining after the completion of the anaerobic digestion process, comprising undigested solids (such as nitrogen, phosphorous and potassium) and a liquid fraction, which can vary from 50 to 85%. The liquid fraction can be processed further for additional biogas production, within the same process as waste water treatment. The solid fraction, with its content of valuable nutrients (N, P, K), can be used as soil conditioner, i.e. fertilizer, in agriculture.

4.2 Anaerobic Digestion (AD) Technologies

Anaerobic Digestion is suitable for materials with high carbon content, delivering high energy output during the easily controllable process.

Some evidence indicates that biogas was used to heat bath water more than 3000 years ago – in the 16th century B.C. in Persia and 10th century B.C. in Assyria (Lusk 1997).

However, the science of biogas started in the 18th century by the famous researchers. "*As early as 1764, Benjamin Franklin described his experiment to light a large surface of a shallow muddy lake in New Jersey in a letter to Joseph Priestly in England who published in 1790 his own experiences with the inflammable air. Alexander Volta was the first searcher who described scientifically the formation of inflammable gases in (low-temperature) marshes and lake sediments. His letters on the formation where published in Italy in 1776. In 1804, Dalton gave the correct chemical formula for methane.*"[14]

Fewer than a hundred years were needed from the scientific definition to application in practice: the first biogas digestion plant in Bombay (1859), gas lightening based on sewage treatment in England (1896), waste water treatment plant in Germany (1920), solid waste digester in Algeria (1938). The development started on a wider scale in the second half of the 20th century: liquid agricultural plants (1950), modern sewage digesters (1960), recovery of land fill gas (1975), continuous solid waste digestion (1988)…

In general, there are 2 basic systems: wet and dry digestion (fermentation) systems, depending on the content of total solids (TS) in feedstock. The terms are not strictly defined – wet systems usually operate between 6 and 12% TS, dry systems with TS above 30%, as explained by Wellinger (2012). According to other sources, a division

[14] Wellinger (2012)

can be done at 15% TS[15], or at 25% TS[16]. However, feeding models for both systems can be the same: batch-feed, continuous feeding and accumulation.

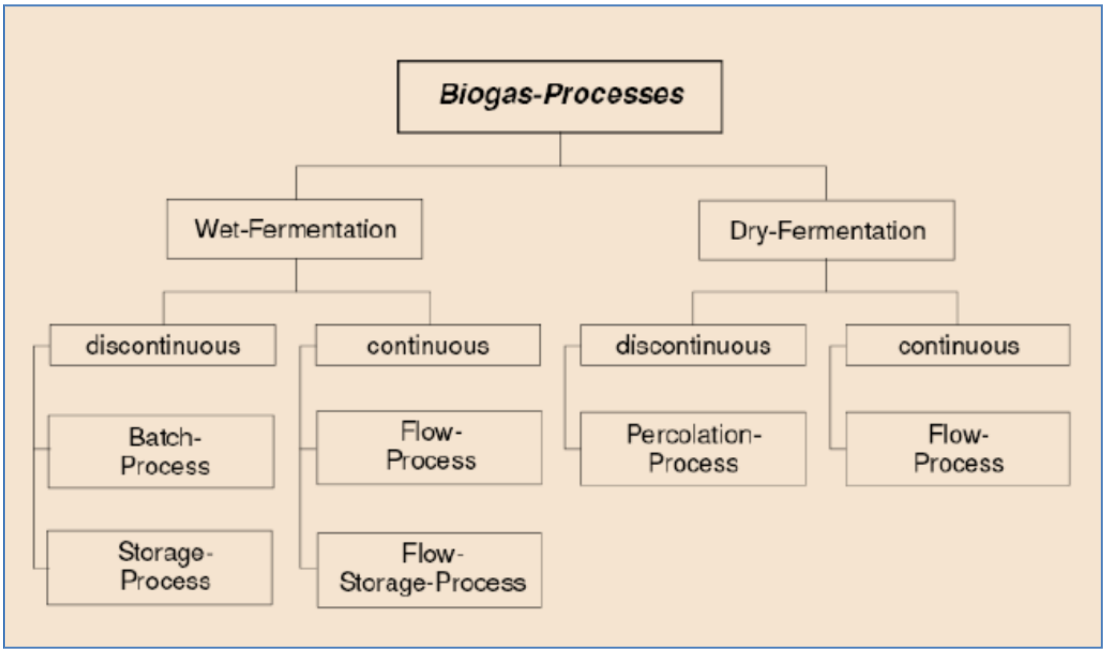


Figure 7 - Biogas processes – wet and dry systems

(Source: Wellinger, (2012))

The selection of technology depends on the share of dry substance which is related to the type of biowaste collected, i.e. if biowaste had been collected together with other municipal waste and then separated on the spot or if biowaste separation had been organized at the beginning of waste disposal.

As it has been described in Chapter 3, the municipal waste collected in Croatia is still mixed, but the implementation of the relevant legislation and obligations within the EU requires source separation to enable re-cycling and re-use, as well as the decrease of biodegradable waste deposits at landfills. Keeping in mind these requirements to change the concept of MSW separation and collection, biowaste structure has been assumed as shown by Figure 3, i.e. waste composition of mainly kitchen waste will be taken into account as feedstock for a biogas plant.
According to Annex 2, kitchen waste has 25% total solids in its content. Thus, the chosen AD system can be both wet and dry digestion, while feeding can be two-fold

[15] UrbanBiogas Report
[16] Kovacevic (2010)

also: continuous feeding or batch system. Sate of the equipment for all systems are present on the market, with proven operation records for more than 20 years.

When designing an optimal system in line with the type of feedstock and expected input flow, two more issues regarding biowaste have to be addressed: pre-treatment and hygienic requirements.

The most common pre-treatment of households waste is ***mechanical separation***. Separation techniques include mechanical and optical processing and handpicking, and should include the removal of iron, non-iron metals, stones and sands, plastics, glass and grids, as well as size reduction and the sorting of the organic fraction.

Households waste is usually categorized as category 3 of animal by-products (ABP) according to Regulation (EC) 1069/2009[17], i.e. ***hygienic requirements*** are defined as:

- Sanitation at temperature ≥ 70°C for 1 hour, and temperature ≥ 37°C in mesophilic digestion
- Minimum 12 days of retention time and temperature ≥ 55°C in thermophilic digestion

The sterilization of biowaste (category 3 ABP) is still required by EU legislation, as a method of classical prevention (30 min at 3 bar and 130°C).

An additional issue which has to be taken into account when designing a biogas plant is digestate. A digestate consists of solid and liquid fractions, both of which require a certain further treatment. The solid part can still contain remainders of plastics or glasses which have to be removed. A fresh digestate has a very unpleased smell and its mitigation has to be one of the parameters when planning a biogas plant. Furthermore, the storage of digestate triggers additional issues to be solved: minimizing losses and the protection of land and water resources.

The liquid part has to be either removed, respecting the protection of land and water resources, or processed further in the waste water treatment plants, when available.

[17] Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation)

All those parameters and requirements have to be considered when planning a biogas production plant. However, the design of biogas production system is not within the scope of this work. What is of relevance is an assessment of potential production, linked to relevant approximate costs.

4.3 Biogas yield assessment

The potential biogas production for all Croatian counties has been calculated according to:

- the potential biowaste production, as assessed within chapter 3.3 and shown by Table 3
- the prevailing component of biowaste as shown by Figure 4, i.e. kitchen waste
- biogas yield for kitchen waste (as prevailing component of biowaste) is calculated according to Annex 2, i.e.:

$$\text{Biowaste (t/y)} \times 0{,}215 \times 123 = \textbf{Biogas (m}^3\textbf{/y)}$$

Table 4 – Assessment of Biogas production in Croatia

County	MSW t/y	Biowaste t/y	Biogas m^3/y
Zagrebačka	77.822	28.094	742.946
Krapinsko-zagorska	29.380	10.606	280.476
Sisačko-moslavačka	62.058	22.403	592.447
Karlovačka	57.777	20.857	551.563
Varaždinska	44.245	15.972	422.380
Koprivničko-križevačka	22.541	8.137	215.183
Bjelovarsko-bilogorska	39.333	14.199	375.493
Primorsko-goranska	136.481	49.270	1.302.945
Ličko-senjska	31.903	11.517	304.567
Virovitičko-podravska	32.194	11.622	307.344
Požeško-slavonska	17.433	6.293	166.418
Brodsko-posavska	51.980	18.765	496.240
Zadarska	91.395	32.994	872.526
Osječko-baranjska	94.719	34.194	904.260

Šibensko-kninska	48.486	17.503	462.867
Vukovarsko-srijemska	45.163	16.304	431.159
Splitsko-dalmatinska	223.145	80.556	2.130.303
Istarska	125.414	45.274	1.197.271
Dubrovačko-neretvanska	66.883	24.145	638.515
Međimurska	20.153	7.275	192.387
Grad Zagreb	326.789	117.971	3.119.743
Total	1.645.295	593.952	15.707.061

(Source: own calculation)

From the total amount of MSW produced in 2011 – 1.645.295 t; 36,1% or 593.952 t can be considered as biowaste, input material which can be then transferred into 15,7 Mmcm of biogas.

As explained earlier, the term “biogas” cannot be mutually exchanged with the term “natural gas”. Thus, to put this quantity of 15,7 Mmcm and the relevant energy into the context of the current natural gas consumption and energy consumption in the transport sector, a further step – biogas upgrade to biomethane – has to be elaborated. This will be done within chapter 5.

4.4 Estimation - Investment costs of biogas production

The focus of this work is the potential and cost assessments, with a general costs overview, not concrete biogas plants with detailed input and technological parameters.

In order to make such a general investment cost assessment, the results of „Comparative economical analysis of biogas production costs between standard wet anaerobic digestion and dry fermentation of biodegradable fraction of municipal solid waste” by V-M. Kovacevic have been used.

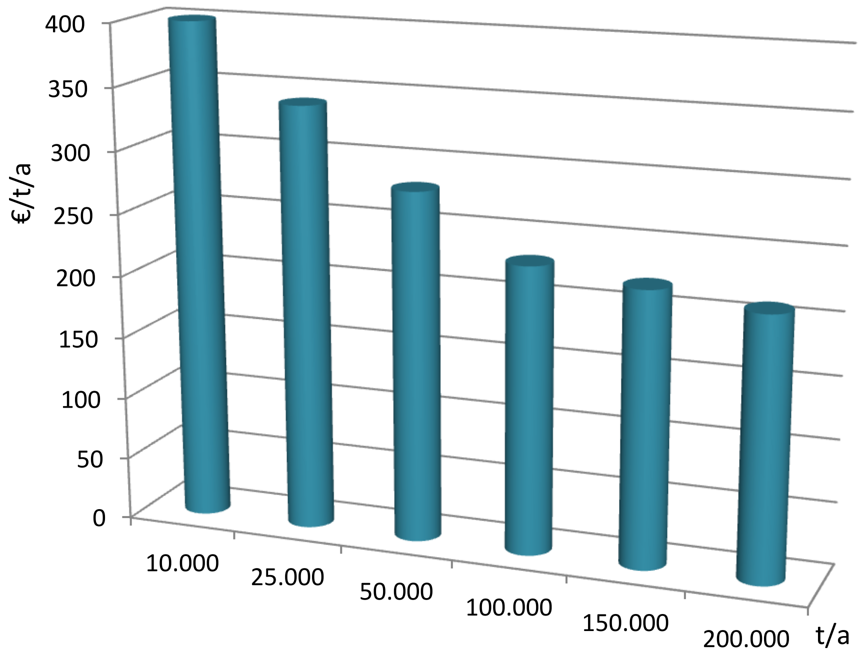


Figure 8 – Investment costs of biogas plant per unit of input waste capacity

(Data source: Kovacevic, (2010); own creation of figure)

By using approximate costs per t of input waste, as shown in Figure 8 and the quantities of biowaste, as assessed within the previous chapter, investment costs can be calculated on county by county basis.

Investment costs are at the level of 230 EUR/t/a only for the City of Zagreb and Splitsko-dalmatinska County, the two counties with the biggest annual biowaste quantities, , followed by 280 EUR/t/a for Istarska and Primorsko-goranska County, whereas the investment costs are 340 EUR/t/a and 400 EUR/t/a for all other counties, respectively.

Table 5 – Estimation of investment costs for biogas production plant / County by county

County	Biowaste	Investments	Biogas	Specific investment
	t/y	€	m^3/y	€/m^3
Zagrebačka	28.094	9.551.884	742.946	12,86
Krapinsko-zagorska	10.606	4.242.462	280.476	15,13
Sisačko-moslavačka	22.403	7.617.019	592.447	12,86
Karlovačka	20.857	7.091.496	551.563	12,86
Varaždinska	15.972	6.388.917	422.380	15,13
Koprivničko-križevačka	8.137	3.254.991	215.183	15,13

Bjelovarsko-bilogorska	14.199	5.679.675	375.493	15,13
Primorsko-goranska	49.270	13.795.505	1.302.945	10,59
Ličko-senjska	11.517	4.606.856	304.567	15,13
Virovitičko-podravska	11.622	4.648.852	307.344	15,13
Požeško-slavonska	6.293	2.517.350	166.418	15,13
Brodsko-posavska	18.765	7.505.942	496.240	15,13
Zadarska	32.994	11.217.853	872.526	12,86
Osječko-baranjska	34.194	11.625.798	904.260	12,86
Šibensko-kninska	17.503	7.001.355	462.867	15,13
Vukovarsko-srijemska	16.304	6.521.577	431.159	15,13
Splitsko-dalmatinska	80.556	18.527.766	2.130.303	8,70
Istarska	45.274	12.676.803	1.197.271	10,59
Dubrovačko-neretvanska	24.145	8.209.197	638.515	12,86
Međimurska	7.275	2.910.072	192.387	15,13
Grad Zagreb	117.971	27.133.323	3.119.743	8,70
Total	**593.952**	**182.724.693**	**15.707.061**	**11,63**

(Source: own calculation)

Most of the counties have the annual input of biowaste bellow 50.000 t. Only the City of Zagreb has an input that is higher than 100.000 t. Since specific costs are lower for bigger plants, i.e. for larger waste input, it would make sense to use the economics of scale. In other words, it would be better to build several regional plants rather than a MSW biogas plant in each of the counties.

The author has decided to group counties based on their geographical position, traffic connections and their quantity contribution. The different groupings have been shown by Figures 9 to 13:

Figure 9 - Grouping A of counties (source: own creation)

Figure 10 - Grouping B of counties (Source: own creation)

Figure 11 - Grouping C of counties (Source: own creation)

Figure 12 - Grouping D of counties (Source: own creation)

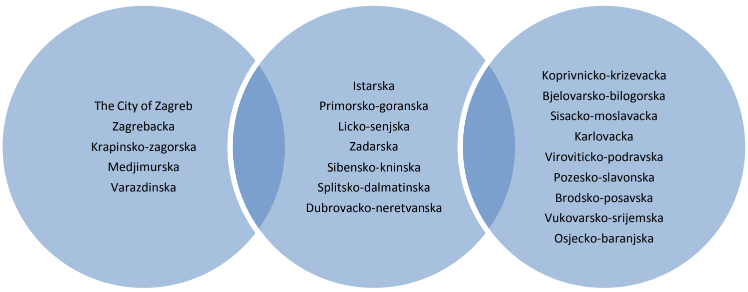


Figure 13 - Grouping E of counties (Source: own creation)

With these different groupings, the annual biowaste input for individual plants increases, decreasing investments costs. The resultant approach of organizing biogas production in one plant for several counties, allows us to decrease investment costs. For Grouping A, annual investments costs would be decreased from 340 EUR/t down to 220 EUR/t, for Grouping B they from 280 to 220 EUR/t, for Grouping C and D investments costs would be 220-230 EUR/t/a, while Grouping E (i.e. having 3 biogas plants to service the entire country) reduces investments costs to 200-220 EUR/t/a.

An overview of the estimated investment costs for different grouping of counties has been shown in Table 6.

Table 6 – Estimation of investment costs for biogas production plant / Different grouping of counties

Grouping	Biowaste	Investments	Biogas	Specific investment
	t/y	€	m^3/y	€/m^3
21 plants	593.952	182.724.693	15.707.061	11,63
8 plants (grouping A)	593.952	149.355.799	15.707.061	9,51
6 plants (grouping B)	593.952	136.092.252	15.707.061	8,66
5 plants (grouping C)	593.952	133.375.009	15.707.061	8,49
5 plants (grouping D)	593.952	132.486.564	15.707.061	8,43
3 plants (grouping E)	593.952	123.644.995	15.707.061	7,87

(Source: own calculation)

It is clearly shown that lower investments costs can be achieved by constructing fewer plants with bigger input capacity. However, the exact combination and final design would depend on the development strategies of waste management, administrative settlements and, at the end of the day, further usage of biogas – all issues out of the scope of this work.

More detailed calculations for different combinations – grouping of counties - have been shown in Annex 7.

5. AN ASSESSMENT OF POTENTIAL BIOMETHANE PRODUCTION

This chapter elaborates the potential of biomethane production to be produced from biodegradable components of municipal solid waste, as defined within previous chapters.

Biomethane production is the separation of biomethane from biogas, i.e. biogas upgrade. Different technologies of upgrading biogas are briefly explained, as well as the requirements for gas to be injected into the natural gas grid or used by vehicles. The share or biomethane in biogas has been estimated based on the type of biowaste, which leads to the assessment of biomethane potential production. For the assessed production, upgrade costs have been estimated using the Biomethane Calculator and the groupings of counties shown in Figures 9 to 13.

As explained at the beginning of Chapter 4, biogas is a mixture of methane and carbon dioxide. Biogas produced from the AD process is composed of methane (50-70%) and carbon dioxide (30-50%), with smaller amounts of hydrogen sulphide and ammonia, while traces of hydrogen, nitrogen, carbon monoxide and oxygen can be present occasionally. The typical composition has been shown in Table 5.

Table 7 – Characteristics of biogas produced by AD

Methane (CH_4)	53 -70	%
Higher hydrocarbons	0	%
Carbon dioxide (CO_2)	30-47	%
Carbon oxide (CO)	0	%
Nitrogen (N_2)	0	%
Hydrogen (H_2)	0	%
Oxygen (O_2)	0	%
Hydrogen sulphide (H_2S)	<1000	ppm
Total sulphur (S_2)	0-10000	ppm
Ammonia (NH_3)	<100	ppm
Total chlorine (Cl^-)	0-5	mg/m^3
Lower heating value	23	MJ/m^3
Higher Wobbe index	27	MJ/m^3
Methane number	>135	

(Data source: Wellinger (2012); own creation of table)

In order to be injected into the gas network or used by vehicles, gas has to fulfill technical standards. In other words, biogas cannot be directly used, it has to be cleaned of organic and inorganic impurities and upgraded to the characteristics which meet the requirements for natural gas grid injection and for use by vehicles.

5.1 Requirements for natural gas grid injection

Unlike the electricity produced from renewable sources, the EU acquis puts very general requirements regarding the acceptance of biogas by natural gas grids: "*Member States should ensure that, taking into account the necessary quality requirements, **biogas and gas from biomass or other types of gas** are granted non-discriminatory access to the gas system, provided such access is permanently compatible with the relevant technical rules and safety standards. These rules and standards should ensure, that these gases can technically and safely be injected into, and transported through the natural gas system and should also address the chemical characteristics of these gases.*" This was stated by Directive 2003/55/EC[18] and it has been repeated by the third energy package, i.e. Directive 2009/73/EC[19].
Further, the Renewable Energy Directive, Directive 2009/28/EC, refers to biogas in terms of non discriminatory tariffs for access and connection, necessary extensions of network infrastructure to facilitate the integration of gas from renewable energy sources, and network connection rules that include gas quality, gas odoration and gas pressure requirements.

Croatia has transposed relevant provisions on its national legislation, i.e. through the Energy Act (OG 120/12) and the Gas Market Act (OG 28/13). In addition to the technical requirements for connection, a composition of gas which can be injected into the grid is one of the biogas requirements. The General Conditions of Gas Supply (OG 43/09) define chemical properties of gas which can be supplied trough the gas network as shown by Table 8.

[18] Directive 2003/55/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in natural gas and repealing Directive 98/30/EC
[19] Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC

Table 8 – Characteristics of gas which is allowed for injection into gas network in Croatia

Methane (CH_4)	**85%**	**min**
Ethane (C_2H_6)	7%	max
Propane (C_3H_8) and other hydrocarbons (C4H_{10}, C_5H_{12} etc)	6%	max
Nitrogen (N_2), **carbon dioxide (CO_2)** and other inert gases	**7%**	**max**
Hydrogen sulphide (H_2S)	7,0 mg/m^3	max
Total sulphur (S_2)	100 mg/m^3	max
Lower heating value	33,1-40,2	MJ/m^3
Higher Wobbe index	45,1-55,0	MJ/m^3

(Data source: the General Conditions of Gas Supply (OG 43/09); own creation of table)

5.2 Requirements for usage by vehicles

A definition of the quality of biomethane for usage by vehicles is closely related to the definition of the quality of natural gas, i.e. the defined quality has to be the same. The problem is that there is no such unique standard for vehicle gas fuel. Most of the European countries have gas standards for injection into the grid (as does Croatia, shown in Table 8), and those standards have become the standards for vehicle gas fuel as well, since vehicles have been fed from natural gas grids.

An additional problem is that those gas grid injection standards have not been unified on the European level. The differences in standards are the result of differences in gas composition across Europe: domestic production (particularly in the Netherlands and the North Sea), pipeline import (Russian gas), and LNG import (different sources and different gas – from Algeria to Qatar).

The issue of natural gas grid standards, as well as vehicle gas fuel standards, is the focus of several EU organisations and it has been tackled trough different platforms and projects. ENTSOG, European Transmission System Operators for Gas, has considered the issue of natural gas quality trough a Network Code under preparation. One of the technical committees within the CEN, the European Committee for Standardization, CEN TC 408 has the task of bringing a European Standard for quality specification of biomethane to be used as a fuel for vehicles. An Expert group within the project “Green Gas Grid” has focus on standards for vehicle gas fuels. Hopefully, in a few years, a European standard will be in place, with common efforts of all stakeholders.

But, for the time being, a reference for biomethane quality as a vehicle fuel in Croatia are the same characteristics as those defined for grid injection (see Table 8), since the same conditions are valid for compressed natural gas (CNG) used by vehicles.

Furthermore, there are specifications defined by individual car producers.

The requirements for gas characteristics are usually lower than those for grid injection. For example, an Otto engine requires at least 85% of methane and allows 14% of nitrogen. The car producers specifications are more oriented to additional components (such as hydrogen sulphide, siloxanes, oxygen) than the share of methane as such. Additional important characteristics are methane numbers (in relation to methane content, of course) and water dew point (in function of water content and pressure).

Table 9 – Vehicle' gas fuel characteristics
defined or proposed by different stakeholders

Hydrogen sulphide (H_2S)		
	Max 23 mg/m^3	ECE R110
	Max 7 mg/kg	DIN 51624
	3,5-7 mg/kg	Bosch
	Max 10 ppm	Volkswagen
	20 mg/m^3	TC234/WG11
	<5 mg/m^3	the Netherlands
	Max 6,6 mg/m^3	Italy
	>10 ppm	Biogas producers
	5-10 ppm	TC 408 proposal
Siloxanes	0,05 mg/m^3	max
Oxygen	0,1-2%	TC 234 proposal
Methane number	70	ACEA, car industry proposal
	65-75	North Sea gas
	80-100	Euromot proposal

(Data source: Wellinger, GreenGasGrids (2013); own creation of table)

Further requirements come from the output side, i.e. the requirements for fuel quality in regard to GHG emissions, as defined by Directive 2009/30/EC.[20]. However, this is not problematic for biomethane and natural gas. Gas vehicles reduce CO_2 emissions by 95% compared to diesel and petrol engines. NOx concentration has to be monitored, but, generally, they are also lower than gas (57% of NOx produced by gasoline).

In conclusion, since there is no unique standard for biomethane for vehicles, either in the EU or Croatia, the same requirements for biogas upgrades as defined for gas grid injection by the General Conditions of Gas Supply (Table 8), have been considered for vehicle usage.

5.3 Biogas Upgrade & Cleaning Technologies

In order to be used by vehicles or injected into the gas grid, biogas has to be enriched in methane (from 53-70% to a minimum of 85% in Croatia), while the share of carbon dioxide has to be decreased (from 47-30% down to 7% max, according to Table 8). The removal of CO_2 at the same time means enrichment in CH_4, and increasing energy value.

There are various methods of carbon dioxide removal, based on the absorption (water, polyethylene glycol, mono- and di-ethanolamine) or adsorption processes (carbon molecular sieves or pressure swing adsorption) and on membrane separation (low pressure and high pressure).

Along with the upgrade, i.e. the removal of carbon dioxide, biogas also has to be cleaned of hydrogen sulphide. Hydrogen sulphide is a hazardous and very corrosive gas, thus it has to be removed before any further application of gas, including any upgrading processes.
Available technologies include sulphide precipitation, biological scrubbing, chemical-oxidative scrubbing, and adsorption of metal oxides or activated carbon. All of those technologies add a bit to the overall investment costs of biomethane production.

[20] Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC

Water or polyethylene scrubbing, upgrade methods, while removing carbon dioxide, at the same time remove hydrogen sulphide.

As technologies for biogas production, biogas upgrade technologies are also state of the art. Table 10 shows set of parameters for different methods.

Table 10 – Comparison of different biogas upgrading technologies

		Absorption		*Adsorption*	*Membrane separation*
Parameter	**Water scrubbing**	**Organic physical scrubbing**	**Amine scrubbing**	**PSA** *	**Membrane technology**
typical methane content in biomethane [vol%]	95-99	95-99	>99	95-99	95-99
methane recovery [%]	98	96	99.96	98	80-99.5
methane slip [%]	2.0	4.0	0.04	2.0	20-0.5
typical delivery pressure [bar(g)]	4-8	4-8	0	4-7	4-7
electric energy demand [kWhel/m^3 biomethane]	0.46	0.49-0.67	0.27	0.46	0.25-0.43
heating demand and temperature level	-	medium 70-80°C	high 120-160°C	-	-
desulphurisation requirements	process dependent	yes	yes	yes	yes
consumables demand	antifouling agent, drying agent	organic solvent (non-hazardous)	amine solution (hazardous, corrosive)	activated carbon (non-hazardous)	
partial load range [%]	50-100	50-100	50-100	85-115	50-105
number of reference plants	high	low	medium	high	low
typical investment costs [€/(m^3/h) biomethane]					
for 100m^3/h biomethane	10,100	9,500	9,500	10,400	7,300-7,600
for 250m^3/h biomethane	5,500	5,000	5,000	5,400	4,700-4,900
for 500m^3/h biomethane	3,500	3,500	3,500	3,700	3,500-3,700
typical operational costs [ct/m^3 biomethane]					
for 100m^3/h biomethane	14.0	13.8	14.4	12.8	10.8-15.8
for 250m^3/h biomethane	10.3	10.2	12.0	10.1	7.7-11.6
for 500m^3/h biomethane	9.1	9.0	11.2	9.2	6.5-10.1

(Source: IEE project "Bio-methane regions", Technology Review, 2012)

*PSA=pressure swing adsorption

Additional issues which have to be solved are the removal of trace components (such us water, ammonia, siloxanes and particulates) and the reduction of methane slips in offgas.

Methane is a green gas 23 times stronger than carbon dioxide, thus, small slips of methane in the offgas can annualte all benefites in GHG emissions reduction achieved trough biogas production and use. Methane slips of different technologies has been shown by Table 10. There are two most common methods to remove methane from offgas – combustion (or oxidation) and heat generation. Heat can be used in the AD process, contributing to the decrease of outside energy required and contributing to the economic vialbility of the plant.

All those issues have to be considered carefully when planning biomethane production. However, the design of a concrete plant is not within the scope of this work and for costs assessment, approximate values have been used.

5.4 Biomethane yield assessment

Biomethane potential production from MSW in Croatia has been calculated taking into account the potential biogas production (as assessed in chapter 4.3 and shown by Table 4), the composition of biowaste (as explained in Chapter 3.3) and the content of methane in biogas, adequate for the type of waste (which is 61%, as shown in Annex 2).

Table 11 – Assessment of Biomethane production in Croatia

County	MSW t/y according to Table 2	Biowaste t/y according to Table 3	Biogas m^3/y according to Table 4	Biomethane m^3/y 0,61 x Biogas
Zagrebačka	77.822	28.094	742.946	453.197
Krapinsko-zagorska	29.380	10.606	280.476	171.090
Sisačko-moslavačka	62.058	22.403	592.447	361.393
Karlovačka	57.777	20.857	551.563	336.453
Varaždinska	44.245	15.972	422.380	257.652
Koprivničko-križevačka	22.541	8.137	215.183	131.262
Bjelovarsko-bilogorska	39.333	14.199	375.493	229.051
Primorsko-goranska	136.481	49.270	1.302.945	794.796

Ličko-senjska	31.903	11.517	304.567	185.786
Virovitičko-podravska	32.194	11.622	307.344	187.480
Požeško-slavonska	17.433	6.293	166.418	101.515
Brodsko-posavska	51.980	18.765	496.240	302.706
Zadarska	91.395	32.994	872.526	532.241
Osječko-baranjska	94.719	34.194	904.260	551.599
Šibensko-kninska	48.486	17.503	462.867	282.349
Vukovarsko-srijemska	45.163	16.304	431.159	263.007
Splitsko-dalmatinska	223.145	80.556	2.130.303	1.299.485
Istarska	125.414	45.274	1.197.271	730.335
Dubrovačko-neretvanska	66.883	24.145	638.515	389.494
Međimurska	20.153	7.275	192.387	117.356
Grad Zagreb	326.789	117.971	3.119.743	1.903.043
Total	**1.645.295**	**593.952**	**15.707.061**	**9.581.307**

(Source: own calculation)

Of the MSW produced in Croatia (as reported for 2011 - 1.645.295 t), as assessed by this work, 36,1% is biowaste, i.e. a source which can be used for biogas production. In other words, from 593.952 t of biodegradable MSW, 15,7 Mmcm of biogas can be produced. After the upgrade of biogas, i.e. the removal of CO_2 and other forbidden components, 9,6 Mmcm of biomethane is potentially available, on an annual basis, for injection into the gas network and/or usage by vehicles.

To illustrate, this is only 0,3% of the actual annual consumption of natural gas in the entire country (3,2 Bcm), but it is comparable to the yearly demand of cities with 8 to 13 thousands inhabitants, such as Djurdjevac, Daruvar and Krapina. This is also the total consumption of Karlovacka County in 2011, one of the counties in the initial stages of gasification[21].

Furthermore, those 9,6 Mmcm are 10 times more than the current consumption of CNG in the transport sector. (The data on primary energy consumption and natural gas in transport sector in Croatia are shown in Annexes 3 and 4.)

According to the General Conditions on Gas Supply (OG 43/09), the lower heating value of natural gas in the grid has to be between 33,100 and 40,200 MJ/m^3. Taking

[21] http://www.hsup.hr/dokumenti/hr/PGH%202012.pdf

into account composition of gas in the network (domestic production + import from Russian sources), the standard value is 33,33835 MJ/m^3.

Thus, this potential biomethane quantity of 9,6 Mmcm represents 0,319 PJ of energy, i.e. 0,639 PJ when double counting biofuels produced from waste. This is equal to the quantity of biomethane in the transport sector predicted to be used annually from 2017 to 2020, as defined by the "National Action Plan on incentives for production and usage biofuels in the transport sector for the period 2011-2020". It has to be noted that the Plan does not include the biomethane produced from municipal waste, instead, it focuses on potential production from agricultural, industrial and sewage waste, as described by Chapter 2.

5.5 Estimation - Investment costs of biomethane production

As explained by chapter 5.3, different methods can be used to upgrade biogas to biomethane. Their specific costs vary for smaller input capacities, and come to the same values for larger input, as shown by Figure 14.

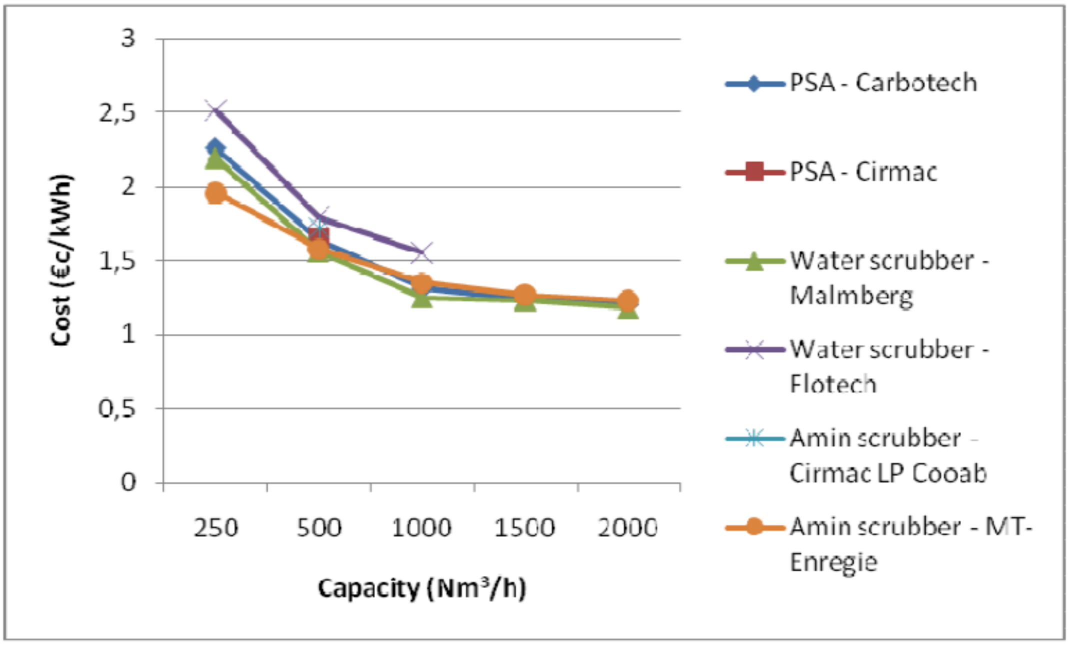


Figure 14 - Estimated cost of biogas upgrading plants using different technologies

(Source: Wellinger, (2012) / Urban et al, (2008))

For a more detailed calculation, the Biomethane Calculator, the publicly available result of the IEE project "Bio-methane Regions", has been used. According to the estimated biogas production, relevant biogas composition and required characteristics for injection into the Croatian gas grid, the investment costs of the biogas upgrade have been calculated using the same grouping of counties, i.e. same combination of biogas plant numbers.

Comprehensive calculations can be found in Annex 7, while a short summary has been shown in Table 12.

Table 12 – Estimation of biogas upgrading costs for different county' groupings (A-E)

Grouping	Biowaste	Biogas	Specific Upgrade costs to transmission network	Specific Upgrade costs to distribution network
	t/y	m^3/y	ct€/m^3 biogas	ct€/m^3 biogas
21 plants	593.952	15.707.061	17,99	13,59
8 plants (grouping A)	593.952	15.707.061	13,33	9,53
6 plants (grouping B)	593.952	15.707.061	11,79	8,20
5 plants (grouping C)	593.952	15.707.061	11,24	7,74
5 plants (grouping D)	593.952	15.707.061	11,14	7,65
3 plants (grouping E)	593.952	15.707.061	9,86	6,58

(Source: own calculation + Biomethane Calculator)

The principle of the economy of scale is also valid for biogas upgrade, as the bigger the biogas plant capacity, the lower the specific investment costs for upgrade.

As a summary, the estimation of investment costs for biomethane production from MSW (biogas production + upgrade to biomethane) – is shown in Table 13.

Table 13: Estimation of investment costs

Grouping	Biowaste	Biogas	Biomethane	Specific investment costs /to transmission network	Specific investment costs / to distribution network	Total Investments /injection in transmission network	Total Investments /injection in distribution network
	t/y	m^3/y	m^3/y	€/m^3 biogas	€/m^3 biogas	€	€
21 plants	593.952	15.707.061	9.581.307	11,81	11,77	185.550.392	184.859.281
8 plants (grouping A)	593.952	15.707.061	9.581.307	9,64	9,60	151.450.138	150.853.270
6 plants (grouping B)	593.952	15.707.061	9.581.307	8,78	8,75	137.944.637	137.380.754
5 plants (grouping C)	593.952	15.707.061	9.581.307	8,60	8,57	135.141.110	134.590.421
5 plants (grouping D)	593.952	15.707.061	9.581.307	8,55	8,51	134.236.958	133.688.154
3 plants (grouping E)	593.952	15.707.061	9.581.307	7,97	7,94	125.194.234	124.677.996

(Source: own calculation + Biomethane Calculator)

6. NATURAL GAS NETWORK OF CROATIA

To be able to assess the potential biomethane for grid injection, a configuration of the existing natural gas network – both, transmission and distribution – has to be known, and this is an aim of this chapter.

The natural gas market has a long tradition in Croatia. In 1863 city gas was introduced in Zagreb. In 1959 the first transmission pipeline (98 km pipeline Janja Lipa – Zagreb) was put into operation. During the 1960s, ‘70s and ‘80s the development of the transmission network followed gas fields discovered and exploited in the Eastern part of the country. During this period, the imports of Russian gas through Slovenia along the main European route Ukraine – Slovakia – Austria had also begun.

At the beginning of the 21st century, the gas market was re-organized in line with the EU processes of internal energy markets. A transmission system operator has been established, transmission tariffs defined and the development of the network was spread to the non-gasified counties in the west and south of the country. As of May 2013, after putting into operation the pipeline ending in Split, the transmission network comprises of 2,140 km of pipelines, operating at the 50 and 75 bar. The transmission network has been shown by Figure 15.

Figure 15 – Natural gas transmission network of Croatia
(source: Plinacro, 2013)

Among the 21 counties, only Dubrovacko-neretvanska County is not covered by the natural gas transmission network. In practical terms, this means that 97% of the population has access to the transmission network, i.e. from the network accessibility point of view, biomethane produced from municipal waste of 97% of the population can be injected into the transmission network. If we would like to be more precise, and to exclude those municipalities in Splitsko-dalmatinska County which have not yet been passed by the transmission pipeline, the scope of the population is 93%. The relevant calculations of the scope have been shown by Annex 5.

However, the injection of biomethane in the transmission network has to fulfill technical standards, in the first place, an adequate pressure. The transmission network in Croatia is projected to operate at 50 bar and 75 bar and according to the

Transmission Network Code (OG 50/09 and 88/12), the minimum input pressure is 70 bar and 45 bar respectively. This means that, in order to be injected in the transmission grid, biomethane must first be compressed to 45 or 70 bar.
Such a compression would increase by 30 to 50% specific investment costs per m^3, as can be seen in Table 12. It would make sense if all biomethane were produced in a few regional waste treatment centers, collecting available biowaste from several counties. But then storage in municipalities and the transport of biowaste to centers have to be organized – which can be very impractical, environmentally unfriendly and challenging.

An additional question is the question of price, i.e. if biomethane produced from MSW can compete with natural gas prices. From estimations done for biogas and biomethane production, as shown in Tables 6 and 12, specific investment costs for 1 m^3 of biomethane which can be injected into the grid range from 7,94 to 11,77 EUR, while the prices of natural gas, at the distribution level, were from 0,4 to 0,8 EUR for 1 m^3.

From technical and economical points of view, injection of biomethane into natural gas distribution network is easier and more frequently applied by those Member States who have some experience with biomethane injection into the gas grid. In Croatia that has not been the practice so far. All produced biogas has so far been used directly for heat and electricity production.

However, distribution networks have been well developed in Northern and Eastern Croatia, while in Istria, Lika and Dalmatia only some cities have gas distribution. Nevertheless, approximately 52% of the population is covered by the gas distribution network, i.e. biomethane produced from municipal waste of 52% of the population could be easily injected into distribution network from the network accessibility point of view. For detailed calculation see Annex 6.

7. USAGE OF NATURAL GAS IN TRANSPORT IN CROATIA

Despite the relatively developed natural gas network and the long existence of the gas market in Croatia, the usage of natural gas in the transport sector is very low. As shown by Annex 3, the total quantity of CNG used in 2011 was only 906.206 m^3, which represents 0,03 PJ of the 85 PJ consumed in the transport sector[22]. Compressed natural gas is mainly used in the city of Zagreb and this mainly by CNG buses in public transport. The total CNG fleet counts 143 vehicles or 0,01% of total number of vehicles in the country.[23]. Nevertheless, the price of CNG in transport is at the level of 1,16 EUR per m^3.

The situation is a bit different with cars run on liquefied petroleum gas (LPG). LPG contributes 2,02 PJ of the total energy consumption in the transport sector – 67 times more than CNG. A network of more than 100 LPG filling stations is spread around the country (unlikely only two CNG stations in the entire Croatia) and a growing number of personal vehicles is retrofitted with a gas tank and gas supply system in addition to the original liquid fuel system. This might be a sound basis for further development of CNG as a vehicle fuel.

[22] According to the report "Energy in Croatia in 2011", published by the Ministry of Economy
[23] According to NVGA statistics for 2011

8. DESCRIPTION OF RESULTS

The first step in the assessment of biomethane potential form urban waste in Croatia was the estimation of municipal waste produced in Croatia. This was done at a very accurate level, since good data were available – population data from the 2011 Census and the 2011 MSW production figures reported by the responsible companies and summarized by the Environment Agency.

Total **MSW** produced in Croatia was **1.645.295 t** in 2011 (Table 2).

The next step was to estimate how much of the produced MSW could be used for biogas production. This was not so straight forward – taking into account all the obligations set by the legislation on waste separation, re-cycling and re-using on the one hand, and on the reduction of landfilled biodegradable waste on the other. The decrease of landfill deposit and separation and re-cycling go hand in hand, thus only the left-over biodegradable waste has been counted, i.e. only what can remain after the pre-separation of paper and cardboard. More or less, this remainder corresponds with kitchen and garden waste. The MSW structure has been assessed according to the available structure for the City of Zagreb.

Total **Biowaste**, produced in 2011 in Croatia, was estimated at the level of **593.952 t** and this quantity was basis for further estimations of biogas potential (Table 3).

A further step was the estimation of how much biogas, and biomethane, respectively, can be produced. This was done using the relationship between biogas yields and methane content for concrete types of waste.

Biogas production was estimated at **15.707.061 m^3** (Table 4), and expecting a methane content of 61%, **biomethane** production was estimated at **9.581.307 m^3** (Table 11).

In order to ensure such biomethane production, **investment costs** in the range from **8 to 12 EUR/m^3 of biogas** are needed. In absolute terms, that would be between 124 and 186 millions EUR (Table 13). **The costs depend on the number of biogas plants –** one in each of the counties, or 8, 6, 5 or 3 bigger regional centres, and on injection into the distribution or transmission natural gas network.
For a comparison, the Strategy of waste management in the Republic of Croatia (2005) foresees 460 millions EUR for establishment of regional centres for waste management.

Injection into the natural gas grid, from pure point of availability of the network, would not be a problem.

Since the **natural gas transmission network** covers a significant area of the country, most or even all the biomethane can be injected into the grid if we consider a regional biogas plant for the entire Dalmatia. An injection into the transmission grid would require an increase of pressure at 45 or 70 bar, which would cause an increase of the total investments costs by 3-4% (as shown in Table 13).
More than half of the Croatian population is covered by a **natural gas distribution network –** which means the possibility to inject a half of biomethane into the distribution network without any problems, regardless of the number of biogas plants. The numbers of plants, i.e. possible load hours and biogas flow, have a more significant impact on investment costs.
However, it has to be noted that the price of natural gas in Croatia at the distribution level is between 0,4 and 0,8 EUR/m^3, i.e. 10-20 times lower that specific investment costs needed for 1 m^3 of biomethane produced from MSW.

The usage of **biomethane by vehicles** is strongly interlinked with the usage of methane by vehicles (Biomethane is methane; the difference is only in source of production). CNG consumption in the transport sector in Croatia is at a very low level and in limited areas.
Additionally, the price of CNG as vehicle fuel is at level of 1,16 EUR/m^3, i.e. 7 to 10 times lower than specific investment costs needed for 1 m^3 of biomethane produced from MSW.

9. CONCLUSIONS

The potential of biogas from biowaste is significant. It can be used for producing energy by re-using waste and as a solution for the required redesign of waste management.

The preamble of Directive 2008/98/EC says “The first objective of any waste policy should be to minimise the negative effects of the generation and management of waste on human health and the environment. Waste policy should also aim at reducing the use of resources, and favour the practical application of the waste hierarchy.”

In conclusion, biodegradable waste, disposed at landfills, has to be significantly reduced in the coming years. Tapping into its potential can be one of the steps towards the required landfill decrease and re-use.

Despite Croatia’s widespread natural gas network, the potential for injection into the gas grid is rather low. Biomethane is methane, and it has to be competitive the same market. This is by far not the case – for the time being, gas prices in the retail market are 0,4-0,8 EUR/m^3. Unlike the electricity produced from renewable sources, biogas (biomethane) injection to the gas grid is not supported by feed in tariffs, which compensate the differences in production costs.

Biomethane application in the transport sector would make more sense, from the aspects of RES targets and conditions set up for the transport sector. In the first place, energy of biofuels produced from waste count double towards the target, and in a way biomethane for MSW is feasible. Furthermore, all available renewable sources for transport fuels will play a more significant role after the proposal of the European Commission on limits for 1st generation biofuels at 6% has been accepted by the European Parliament. In practical terms, this means that the RES-T target by 2020 remains 10%, but only 6% can be achieved by 1st generation biodiesel and bioethanol which meet sustainability criteria. For Croatia, this does not seem as a significant problem – only 0,91% in the transport sector in 2011 was met by bio-liquids and it still has a long way to go to reach 6%. But, nevertheless, the remaining 4% also have to be achieved from other sources. And again, biomethane from MSW is feasible, much closer than 2nd and 3rd generation biofuels.

Biomethane from MSW makes the most sense for municipalities as such. They have to deal with their own waste and organise their own public transport. Biomethane can be a good answer to both issues. The example of the city of Zagreb shows a good direction, so far only half a picture – CNG buses in the public transport. The examples of the city of Cakovec and the island of Krk show another part of the picture: a well organised MSW separation and collection system. Biomethane potential – the topic of this work – makes a bridge between both required actions: waste management and the introduction of a greener public transport.

In the end, the sum of many small contributions in waste management and the decrease of GHG emissions become apparent on the bigger, state-level scale.

For the comprehensive biogas and biomethane potential to be reached in Croatia, all other potential sources have to be considered: sewage water, food industry, agriculture, food markets and hotel food waste etc. Also, costs and benefits of usage of biogas in electricity and heat production and in the transport sector have to be elaborated further, in order to have a comprehensive waste to energy potential analysis for Croatia.

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- Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC
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Annex 1

Municipal Solid Waste produced in Croatia in 2011

County	Total MSW (t)	Average (kg/capita)	County share in total MSW
Županija	**Ukupna količina proizvedenog komunalnog otpada (t)**	**Količina otpada po stanovniku (kg/stan)**	**Udio županije u ukupno skupljenom komunalnom otpadu (%)**
Zagrebačka	74 859	224	5,0
Krapinsko-zagorska	23 955	205	1,6
Sisačko-moslavačka	55 068	332	3,6
Karlovačka	51 879	413	3,4
Varaždinska	35 041	234	2,3
Koprivničko-križevačka	20 406	180	1,3
Bjelovarsko-bilogorska	31 871	305	2,1
Primorsko-goranska	129 513	422	8,6
Ličko-senjska	30 041	574	2,0
Virovitičko-podravska	29 668	348	2,0
Požeško-slavonska	14 040	208	0,9
Brodsko-posavska	50 514	300	3,3
Zadarska	87 242	492	5,8
Osječko-baranjska	83 947	286	5,6
Šibensko-kninska	50 543	403	3,3
Vukovarsko-srijemska	43 142	230	2,9
Splitsko-dalmatinska	204 025	451	13,5
Istarska	115 124	554	7,6
Dubrovačko-neretvanska	61 333	501	4,1
Međimurska	18 258	163	1,2
Grad Zagreb	301 170	386	19,9
Dodatno utvrđene količine:	**133 657**		
Ukupno:	**1 645 295**	**371**	**100**

Source: Environment Agency, February 2013

Annex 2

Biogas yield in function of substrate composition

Substrates

Agricultural wastes and energy crops	**TS [%]**	**VS [% TS]**	**NH4-N [% TS]**	**Biogas yield**		**CH4 [%]**
				Nm3/t FM	**Nm3/t VS**	
Cattle manure	8 to 11	75 to 82	1 to 3	20 to 30	230 to 450	62
Pig manure	2.5 to 7	75 to 86	3 to 8	2 to 10	300 to 700	68
Cattle waste	18 to 25	68 to 76	0.2 to 2	35 to 55	200 to 350	60
Pig waste	20 to 25	75 to 80	0.9 to 1.8	55 to 65	270 to 450	63
Poultry wste	32	63 to 80	0.4	70 to 90	250 to 450	60
Corn silage	20 to 35	85 to 95	0.15 to 0.3	170 to 200	450 to 700	50 to 55
Rye whole plant silage	30 to 35	92 to 98	0.57 to 0.71	170 to 220	550 to 680	55
sugar beet	23	90 to 95	0.2	170 to 180	800 to 860	54
Sugar beet leafs	11	91		103	1020	54
Grass silage	25 to 35	70 to 95	0.5 to 0.62	170 to 220	550 to 620	55
Lawn cuttings	12	83 to 92	1.5 to 2	150 to 200	550 to 680	55 to 65
Grains (wheat, Triticale)	87	89 to 97	-	700 to 770	587 to 598	53
Agro-industrial wastes						
Beer stillage	20 to 25	70 to 80	1.5	105 to 130	580 to 750	60
Vinasse from Grains	6 to 8	83 to 88	3.6 to 6	430 to 700	580 to 700	58 to 65
Vinasse from potato	6 to 7	85 to 95	0.9	36 to 42	400 to 700	58 to 65
Vinasse from fruits	2 to 3	95	0.73	10 to 20	300 to 650	58 to 65
Molasses	80 to 90	85 to 90	0.3	290 to 340	360 to 490	70 to 75
Grape skins	40 to 50	50 to 70	0.2 to 0.8	80 to 120	150 to 600	58 to 65
Whey	5	86	0.5	29.5	730	53
Used animal oil and fat	99	99	-	1200	1210	67
Used plant oil	99	99	-	1200	1210	67
Municipal wastes						
Source separated biowaste	25 to 40	50 to 70	0.05 to 0.2	80 to 140	400 to 600	55 to 62
Outdated vegetable food	9 to 37	80 to 97	0.3 to 1.5	50 to 480	200 to 500	45 to 61
Vegetable waste	13	83		83	550	52
Fat from separators	5 to 20	80 to 95	0.01 to 0.06	35 to 280	900 to 1200	65 to 72
Paunch manure	11 to 19	80 to 90	1.1. to 1.6	20 to 60	200 to 600	58 to 72
Kitchen waste	25	86	-	570	123	61

(Source: Wellinger (2012))

ANNEX 3

Total primary energy consumption in Croatia

Ukupna potrošnja energije

Total primary energy consumption

PJ	2008.	2009.	2010.	2011.
prirodni plin / *natural gas*	110,22	102,15	111,37	108,60
ugljen / *coal*	34,65	24,66	30,92	31,66
obnovljivi izvori / *renewables*	14,35	15,85	18,29	22,07
el. energija (uvoz) / *electricity (import)*	23,68	20,46	17,15	27,71
tekuća goriva / *liquid fuels*	180,15	178,04	152,54	149,30
vodne snage / *hydropower*	50,19	65,77	79,71	42,59
ukupno / *total*	413,24	406,93	409,98	381,93

Source: Croatian Gas Association (HSUP), Gas Industry in Croatia 2012, publication 2013, according to Energy Institute "Hrvoje Pozar" (EIHP)

ANNEX 4

Usage of CNG by vehicles in Croatia

Prirodni plin za vozila

Natural gas vehicles

9.299 BROJ PUNJENJA *filling number*

1 STANICA ZA PUNJENJE PRIRODNIM PLINOM (ZAGREB) *CNG filling station*

ISPORUČENO KUPCIMA cijena: 6,00 kn/kg — 906.206 m^3 (625.282 kg) — *CNG delivered price: 6,00 HRK/kg*

ZET *Zagreb-public transport* — 877.717 m^3 (605.625 kg)

28.489 m^3 (19.657 kg) — ostali *others*

Source: Croatian Gas Association (HSUP),

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Note: the second CNG filling station was open in the city of Rijeka in 2013

ANNEX 5

Population with access to existing gas transmission network in Croatia

County	Population
Zagrebačka	317.606
Krapinsko-zagorska	132.892
Sisačko-moslavačka	172.439
Karlovačka	128.899
Varaždinska	175.951
Koprivničko-križevačka	115.584
Bjelovarsko-bilogorska	119.764
Primorsko-goranska	296.195
Ličko-senjska	50.927
Virovitičko-podravska	84.836
Požeško-slavonska	78.034
Brodsko-posavska	158.575
Zadarska	170.017
Osječko-baranjska	305.032
Šibensko-kninska	109.375
Vukovarsko-srijemska	179.521
Istarska	208.055
Međimurska	113.804
Grad Zagreb	790.017
Splitsko-dalmatinska	278.713
Total population hold by gas transmission network (B)	3.986.236
Total population (A)	4.284.889
B/A	0,93030088
non gasified county	
Dubrovacko-neretvantska	122.568

(Data source for population Statistical office; own calculation and creation of table)

ANNEX 6

Population with access to gas distribution network in Croatia

County	City	Population
Zagrebačka	Dugo Selo	17.466
Zagrebačka	Ivanić-Grad	14.548
Zagrebačka	Jastrebarsko	15.866
Zagrebačka	Samobor	37.633
Zagrebačka	Sveta Nedelja	18.059
Zagrebačka	Sveti Ivan Zelina	15.959
Zagrebačka	Velika Gorica	63.517
Zagrebačka	Vrbovec	14.797
Zagrebačka	Zaprešić	25.223
TOTAL		**223.068**
Krapinsko-zagorska	Donja Stubica	5.680
Krapinsko-zagorska	Klanjec	2.915
Krapinsko-zagorska	Krapina	12.480
Krapinsko-zagorska	Oroslavje	6.138
Krapinsko-zagorska	Pregrada	6.594
Krapinsko-zagorska	Zabok	8.994
Krapinsko-zagorska	Zlatar	6.096
TOTAL		**48.897**
Sisačko-moslavačka	Kutina	22.760
Sisačko-moslavačka	Novska	13.518
Sisačko-moslavačka	Sisak	47.768
TOTAL		**84.046**
Karlovačka	Duga Resa	11.180
Karlovačka	Karlovac	55.705
TOTAL		**66.885**
Varaždinska	Ivanec	13.758
Varaždinska	Lepoglava	8.283
Varaždinska	Ludbreg	8.478
Varaždinska	Novi Marof	13.246
Varaždinska	Varaždin	46.946
Varaždinska	Varaždinske Toplice	6.364
TOTAL		**97.075**
Koprivničko-križevačka	Đurđevac	8.264
Koprivničko-križevačka	Koprivnica	30.854
Koprivničko-križevačka	Križevci	21.122
TOTAL		**60.240**
Bjelovarsko-bilogorska	Bjelovar	40.276
Bjelovarsko-bilogorska	Čazma	8.077

Bjelovarsko-bilogorska	Daruvar	11.633
Bjelovarsko-bilogorska	Garešnica	10.472
Bjelovarsko-bilogorska	Grubišno Polje	6.478
TOTAL		**76.936**
Primorsko-goranska	Delnice	5.952
Primorsko-goranska	Rijeka	128.624
TOTAL		**134.576**
Ličko-senjska	Gospić	12.745
Ličko-senjska	Otočac	9.778
TOTAL		**22.523**
Virovitičko-podravska	Orahovica	5.304
Virovitičko-podravska	Slatina	13.686
Virovitičko-podravska	Virovitica	21.291
TOTAL		**40.281**
Požeško-slavonska	Kutjevo	6.247
Požeško-slavonska	Lipik	6.170
Požeško-slavonska	Pakrac	8.460
Požeško-slavonska	Pleternica	11.323
Požeško-slavonska	Požega	26.248
TOTAL		**58.448**
Brodsko-posavska	Nova Gradiška	14.229
Brodsko-posavska	Slavonski Brod	59.141
TOTAL		**73.370**
Zadarska	Benkovac	11.026
Zadarska	Zadar	75.062
TOTAL		**86.088**
Osječko-baranjska	Beli Manastir	10.068
Osječko-baranjska	Belišće	10.825
Osječko-baranjska	Donji Miholjac	9.491
Osječko-baranjska	Đakovo	27.745
Osječko-baranjska	Našice	16.224
Osječko-baranjska	Osijek	108.048
Osječko-baranjska	Valpovo	11.563
TOTAL		**193.964**
Vukovarsko-srijemska	Ilok	6.767
Vukovarsko-srijemska	Otok	6.343
Vukovarsko-srijemska	Vinkovci	35.312
Vukovarsko-srijemska	Vukovar	27.683
Vukovarsko-srijemska	Županja	12.090
TOTAL		**88.195**
Istarska	Pula - Pola	57.460
TOTAL		**57.460**
Međimurska	Čakovec	27.104
Međimurska	Mursko Središće	6.307

Međimurska	Prelog	7.815
TOTAL		**41.226**
Grad Zagreb		**790.017**
TOTAL with access to distribution network (B)		**2.243.295**
Total population (A)		**4.284.889**
B/A		**0.523536**

(Data source for population Statistical office; own calculation and creation of table)

A calculation is based on total population of the cities with existing off-take stations from the transmission network, not on actual number of gas consumers or actual gas distribution network

ANNEX 7

Estimations of investment costs for biogas production and upgrade plant

Estimation of investment costs for biogas production & upgrade plant / Grouping A

County	Biowaste	Investments	Biogas	Specific investment costs	Biogas	Specific Upgrade costs to transmission network	Specific Upgrade costs to distribution network
	t/y	€	m^3/y	€/m^3	m^3/h	ct€/m^3 biogas	ct€/m^3 biogas
Grad Zagreb	117.971	27.133.323	3.119.743	8,70	390	11,00	7,53
Istarska	45.274	12.676.803	1.197.271	10,59	150	14,81	10,80
Primorsko-goranska	49.270	13.795.505	1.302.945	10,59	163	14,37	10,42
Sisačko-moslavačka	22.403		592.447				
Karlovačka	20.857		551.563				
Ličko-senjska	11.517		304.567				
	54.777	15.337.694	1.448.577	10,59	181	13,84	9,96
Međimurska	7.275		192.387				
Varaždinska	15.972		422.380				
Krapinsko-zagorska	10.606		280.476				
Zagrebačka	28.094		742.946				
	61.947	17.345.273	1.638.189	10,59	205	13,27	9,47
Koprivničko-križevačka	8.137		215.183				
Bjelovarsko-bilogorska	14.199		375.493				
Virovitičko-podravska	11.622		307.344				
	33.959	11.545.991	898.020	12,86	112	16,62	12,38
Zadarska	32.994		872.526				
Šibensko-kninska	17.503		462.867				
Splitsko-dalmatinska	80.556		2.130.303				
Dubrovačko-neretvanska	24.145		638.515				
	155.197	34.143.400	4.104.211	8,32	513	10,30	6,94
Požeško-slavonska	6.293		166.418				
Brodsko-posavska	18.765		496.240				
Vukovarsko-srijemska	16.304		431.159				

Osječko-baranjska	34.194		904.260				
	75.556	17.377.811	1.998.077	8,70	250	12,46	8,77
TOTAL	593.952	149.355.799	15.707.061	9,51	245	13,33	9,53

(Source: Own calculation + Biomethane Calculator)

Estimation of investment costs for biogas production & upgrade plant / Grouping B

County	Biowaste	Investments	Biogas	Specific investment	Biogas	Specific Upgrade costs to transmission network	Specific Upgrade costs to distribution network
	t/y	€	m^3/y	€/m^3	m^3/h	ct€/m^3 biogas	ct€/m^3 biogas
Grad Zagreb	117.971	27.133.323	3.119.743	8,70	390	11,00	7,53
Istarska	45.274		1.197.271				
Primorsko-goranska	49.270		1.302.945				
	94.544	20.799.670	2.500.216	8,32	313	11,67	8,09
Zagrebačka	28.094		742.946				
Sisačko-moslavačka	22.403		592.447				
Karlovačka	20.857		551.563				
Ličko-senjska	11.517		304.563				
	82.871	18.231.676	2.191.519	8,32	274	12,12	8,48
Međimurska	7.275		192.387				
Varaždinska	15.972		422.380				
Krapinsko-zagorska	10.606		280.476				
Koprivničko-križevačka	8.137		215.183				
Bjelovarsko-bilogorska	14.199		375.493				
	56.190	15.733.282	1.485.919	10,59	186	13,72	9,85
Zadarska	32.994		872.526				
Šibensko-kninska	17.503		462.867				
Splitsko-dalmatinska	80.556		2.130.303				
Dubrovačko-neretvanska	24.145		638.515				
	155.197	34.143.400	4.104.211	8,32	513	10,30	6,94

Virovitičko-podravska	11.622		307.344				
Požeško-slavonska	6.293		166.418				
Brodsko-posavska	18.765		496.240				
Vukovarsko-srijemska	16.304		431.159				
Osječko-baranjska	34.194		904.260				
	87.178	20.050.901	2.305.421	8,70	288	11,95	8,33
TOTAL	593.952	136.092.252	15.707.061	8,66	327	11,79	8,20

(Source: Own calculation + Biomethane Calculator)

Estimation of investment costs for biogas production & upgrade plant / Grouping C

County	Biowaste	Investments	Biogas	Specific investment	Biogas	Specific Upgrade costs to transmission network	Specific Upgrade costs to distribution network
	t/y	€	m^3/y	€/m^3	m^3/h	ct€/m^3 biogas	ct€/m^3 biogas
Grad Zagreb	117.971		3.119.743				
Zagrebačka	28.094		742.946				
Krapinsko-zagorska	10.606		280.476				
	156.671	34.467.599	4.143.165	8,32	518	10,28	6,92
Istarska	45.274		1.197.271				
Primorsko-goranska	49.270		1.302.945				
Karlovačka	20.857		551.563				
	115.401	26.542.298	3.051.779	8,70	381	11,07	7,58
Međimurska	7.275		192.387				
Varaždinska	15.972		422.380				
Koprivničko-križevačka	8.137		215.183				
Bjelovarsko-bilogorska	14.199		375.493				
Sisačko-moslavačka	22.403		592.447				
Virovitičko-podravska	11.622		307.344				
	79.609	18.310.131	2.105.234	8,70	263	12,27	8,61
Ličko-senjska	11.517		304.567				
Zadarska	32.994		872.526				
Šibensko-kninska	17.503		462.867				

Splitsko-dalmatinska	80.556		2.130.303				
Dubrovačko-neretvanska	24.145		638.515				
	166.714	36.677.171	4.408.778	8,32	551	10,14	6,81
Požeško-slavonska	6.293		166.418				
Brodsko-posavska	18.765		496.240				
Vukovarsko-srijemska	16.304		431.159				
Osječko-baranjska	34.194		904.260				
	75.556	17.377.811	1.998.077	8,70	250	12,46	8,77
TOTAL	593.952	133.375.009	15.707.061	8,49	393	11,24	7,74

(Source: Own calculation + Biomethane Calculator)

Estimation of investment costs for biogas production & upgrade plant / Grouping D

County	Biowaste	Investments	Biogas	Specific investment	Biogas	Specific Upgrade costs to transmission network	Specific Upgrade costs to distribution network
	t/y	€	m^3/y	€/m^3	m^3/h	ct€/m^3 biogas	ct€/m^3 biogas
Grad Zagreb	117.971		3.119.743				
Zagrebačka	28.094		742.946				
	146.065	32.134.244	3.862.689	8,32	483	10,45	7,06
Istarska	45.274		1.197.271				
Primorsko-goranska	49.270		1.302.945				
	94.544	21.745.110	2.500.216	8,70	313	11,67	8,09
Međimurska	7.275		192.387				
Varaždinska	15.972		422.380				
Krapinsko-zagorska	10.606		280.476				
Koprivničko-križevačka	8.137		215.183				
Bjelovarsko-bilogorska	14.199		375.493				
Sisačko-moslavačka	22.403		592.447				
Karlovačka	20.857		551.563				
	99.451	21.879.138	2.629.929	8,32	329	11,51	7,96

Ličko-senjska	11.517		304.567				
Zadarska	32.994		872.526				
Šibensko-kninska	17.503		462.867				
Splitsko-dalmatinska	80.556		2.130.303				
Dubrovačko-neretvanska	24.145		638.515				
	166.714	36.677.171	4.408.778	8,32	551	10,14	6,81
Virovitičko-podravska	11.622		307.344				
Požeško-slavonska	6.293		166.418				
Brodsko-posavska	18.765		496.240				
Vukovarsko-srijemska	16.304		431.159				
Osječko-baranjska	34.194		904.260				
	87.178	20.050.901	2.305.421	8,70	288	11,95	8,33
TOTAL	593.952	132.486.564	15.707.061	8,43	393	11,14	7,65

(Source: Own calculation + Biomethane Calculator)

Estimation of investment costs for biogas production & upgrade plant / Grouping E

County	Biowaste	Investments	Biogas	Specific investment	Biogas	Specific Upgrade costs to transmission network	Specific Upgrade costs to distribution network
	t/y	€	m^3/y	€/m^3	m^3/h	ct€/m^3 biogas	ct€/m^3 biogas
Grad Zagreb	117.971		3.119.743				
Zagrebačka	28.094		742.946				
Međimurska	7.275		192.387				
Varaždinska	15.972		422.380				
Krapinsko-zagorska	10.606		280.476				
	179.918	37.782.859	4.757.932	7,94	595	9,97	6,67
Istarska	45.274		1.197.271				
Primorsko-goranska	49.270		1.302.945				
Ličko-senjska	11.517		304.567				
Zadarska	32.994		872.526				
Šibensko-kninska	17.503		462.867				
Splitsko-dalmatinska	80.556		2.130.303				

Dubrovačko-neretvanska	24.145		638.515				
	261.258	52.251.674	6.908.994	7,56	864	9,28	6,09
Koprivničko-križevačka	8.137		215.183				
Bjelovarsko-bilogorska	14.199		375.493				
Sisačko-moslavačka	22.403		592.447				
Karlovačka	20.857		551.563				
Virovitičko-podravska	11.622		307.344				
Požeško-slavonska	6.293		166.418				
Brodsko-posavska	18.765		496.240				
Vukovarsko-srijemska	16.304		431.159				
Osječko-baranjska	34.194		904.260				
	152.775	33.610.463	4.040.107	8,32	505	10,34	6,97
TOTAL	593.952	123.644.995	15.707.061	7,87	654	9,86	6,58

(Source: Own calculation + Biomethane Calculator)