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Development and Governance of Renewable Methane Use in Transport

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Abstract

Renewable methane is promoted in many countries as a sustainable alternative to fossil fuels in all types of transport applications. This article examines development, governance and motives for the use of biogas, synthetic biogas, wind methane and other types of renewable methane in transport. Fossil methane fuels, such as natural gas, shale gas and synthetic natural gas, are included as a comparison. Compressed town gas played an important role in the adoption of methane for traffic use, so its history is also examined. Three waves of development in the use of traffic biogas are identified: the Second World War, the 1970s oil crises, and the present day quest for sustainability. While biogas has been used in transport since the 1930s, the other renewable methane fuels are now emerging in the commercial market with only a few years of history. The article looks at the use of renewable methane in a global perspective, although most of the examples are from Europe, as the majority of the technological and political advances have been European.

***Keywords**: biogas, renewable methane, renewable energy, transport, history of technology, governance, transformation of energy systems, sustainability, climate change, energy security, crude oil independence*

Contents

Preface

Large part of the material in this publication was published in the journal Finnish Quarterly for the History of Technology in September 2013 (Lampinen 2013a). This new publication includes more text, pictures and sources. It also includes one more empirical study: the use of traffic biogas in Stockholm in the 1940's is for the first time compiled and published here. Updates have been made to reflect the current situation and the format of presentation is different.

1. Introduction

For environmental and energy security reasons there is currently a lot of political interest globally in transforming transport energy systems from crude oil based fuels to crude oil independent sustainable energy systems based on renewable energy sources. Liquid biofuels are almost always used as blends with crude oil based fuels. This enables reduction of crude oil use, but retains dependency on crude oil and dependence on vehicles designed for crude oil based fuels. There are a rather limited amount of technological alternatives that offer complete crude oil independence. Of these, electric cars have received most media attention and in many countries most political attention as well. However, they can only substitute crude oil based vehicles in a very small share of total transport needs, due to limitations in electricity storage and charging. Hydrogen economy has been discussed for a very long time. Energy needs

in all types of transport can be fulfilled with hydrogen, but there are a lot of practical technological and economic obstacles in all parts of the fuel chain. Thus, the use of hydrogen in transport is so far very rare.

The third alternative, which enables complete crude oil independence in all types of transport needs (Table 2), is methane. Although it receives much less media attention than hydrogen and electric cars, it is the only alternative fuel, which has already proved that crude oil dependency can be broken: in Pakistan over 80 per cent of road transport has been transferred to methane (Table 6). Use of methane in transport is mature technology in all parts of the fuel chain and there are almost 20 million methane vehicles in use today globally[1]. Waste based biogas is already available in almost 1000 filling stations in Europe enabling European wide transport by sustainable renewable energy.

Methane (CH_4) can be produced from all types of renewable energy sources (Fig. 1) as well as fossil energy sources (Fig. 2). The available resources are much larger than the global total energy consumption and can easily fulfil all transport energy needs[2]. The ability to use the largest and the most sustainable energy resources, solar and wind energy, is a common feature of methane, hydrogen and electric vehicles. In January 2013 the European Commission published a proposal for a Directive of the European Parliament and of the Council on the deployment of alternative fuels infrastructure (COM(2013)18), which requires a certain minimum filling station and charging network for these three, potentially the most sustainable technologies, to be established in member countries.

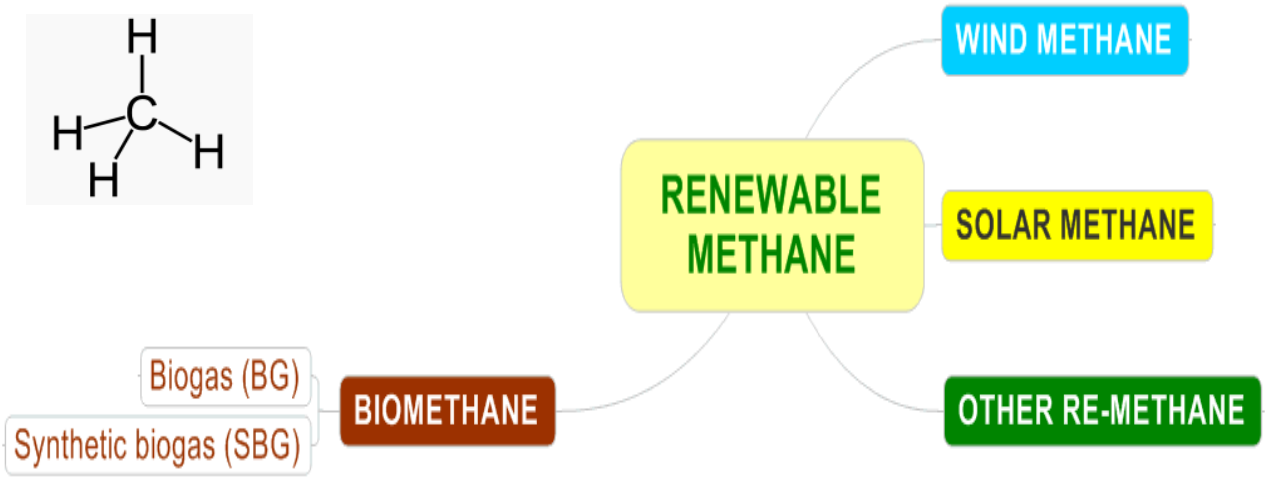

Figure 1. Types of renewable methane.

[1] Methane vehicle statistics are published monthly in the magazine Gas Vehicle Report. In the October 2013 issue the total number of vehicles was 17.8 million. This is not the situation in October 2013, but a sum of national situations reported between March 2006 and July 2013 from 85 countries in all continents. Also, these statistics do not include all types of methane vehicles, e.g. most of methane powered ships. Therefore, the total fleet in October 2013 was much more than 17.8 million. It is about 100 times more than the global fleets of electric and hydrogen vehicles combined.

[2] Biomethane resources in Western and Central Europe are estimated to be up to 6000 TWh annually (FTF 2011, 73), which is more than the total transport energy use in those countries. This includes only terrestrial potential. Not included are algae, which have very high potential (biogas technology is the easiest way of utilizing algae for fuel production). Seaweed and other marine bioresources are also not included. The total renewable methane potential is orders of magnitude larger, because all renewable energy resources can be utilized and bioenergy constitutes only a marginal share (0.002 %) of the total (the global potential of all renewable energy forms is found in the United Nations publication (UN 2000, 166-168)). On the other hand, fossil methane resources are much larger than the resources of all other fossil energy sources combined (IPCC 2001, 315).

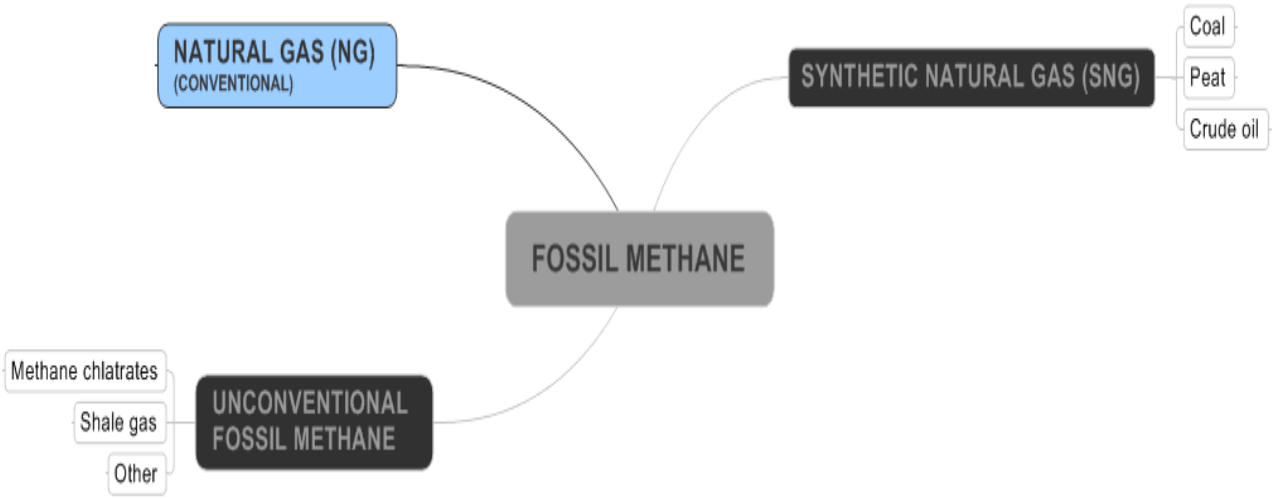

Figure 2. Types of fossil methane.

A methane transport system is the easiest of these three technologies to implement in practice for covering all types of transport. Sustainability issues place limitations on the use of fossil methane sources, especially unconventional fossil methane and synthetic natural gas (SNG), which may yield much larger lifecycle greenhouse gas emissions than crude oil based fuels[3]. Sustainability issues also limit the use of energy crops for production of biomethane[4]. Until the 1990s, all biogas used for transport was produced from biowastes, mostly municipal sewage. Since then some energy crops have also been utilized, but almost all traffic biogas is still produced from waste materials globally. Biogas and other renewable methane are important from a climate policy perspective; they offer especially large lifecycle greenhouse gas reductions compared to crude oil based fuels. Waste based biogas may even reduce lifecycle greenhouse gas emissions by more than 100 per cent[5].

This paper gives a review of the historical development of methane based transport systems, the governance of such systems and the motives behind building such systems. Emphasis is on renewable methane for sustainability reasons. The early days of methane use in transport are poorly known due to the lack of modern literature on the topic and almost complete disappearance of early hardware, museums

[3] For example the European Commission news service warned that shale gas use may have much higher lifecycle greenhouse gas emissions than crude oil and even coal based transport fuels (EC 2011). In addition, shale gas production has many other environmental hazards. For methane clathrates, which are the largest fossil methane resource, the emissions are likely to be even higher.

[4] There are examples globally of energy crop based biofuel production chains, which lead to higher lifecycle greenhouse gas emissions than crude oil based production chains. In addition, ecological, land use and indirect land use effects of energy crop based fuel chains may be very negative. These problems have so far been limited to bioethanol and biodiesel production, but also biomethane can be so produced. To limit energy crop use in traffic biofuel production and to demand the use of best environmental practices, the European Commission proposed in October 2012 a Directive (COM(2012)595) that introduces a cap on the use of energy crops in fulfilling the mandate for each Member State on the share of renewable energy in transport energy consumption. This creates a market for waste based fuels, such as biowaste based biogas and wood waste based synthetic biogas.

[5] Biowaste based biogas is the only fuel, which may offer over 100 % reductions in greenhouse gas emissions during the lifecycle of the fuel compared to gasoline and diesel oil. This is possible, when methane emissions are avoided. See e.g. the study published by the European Commission Joint Research Center together with vehicle and fuel industry (JEC 2011) and the study on Swedish traffic biofuels (Börjesson et al. 2010).

included. Biogas and other renewable methane fuels are now gaining popularity. They have great technical and practical benefits compared to manufactured gas and hydrogen vehicles and even more when comparing to electric vehicles[6].

A review is also given of the use of manufactured gas in transport, because it paved the way for methane fuels. The transport use of manufactured gas has been almost forgotten, with the exception of producer gas vehicles. The use of manufactured gas in gas bag vehicles and in compressed town gas vehicles ended in the 1940s and those vehicles are very rare in museums of today. Modern literature on these technologies does not exist. Manufactured gas is no longer used in transport except for a small amount of producer gas vehicles built by wood gas enthusiasts. There are clear technical and practical reasons for ending the use of these technologies, but they have historical importance and they contributed to the development of methane vehicle technology.

Part 2 of this paper contains a description of global technological development of gaseous fuels used in motorised transport since the first demonstration in 1809 until present time. This review focuses on methane fuels and manufactured gases, but hydrogen, LPG and DME also receive some attention. The technological development of biogas systems for transport reached a commercially mature state in the 1940s and many technological choices made then later became standards that are still valid today. The 1940s is interesting also because of the especially high diversity of gaseous fuel use. For these reasons more space in this paper is devoted to the 1940s than to other time periods.

Part 3 contains an analysis of the governance and motivations behind setting up renewable methane systems for transport. Three distinct waves of development are identified: the Second World War in the 1940s, the oil crises in the 1970s and the present sustainable development policy era since the Rio summit in 1992. Most of the examples are from European countries, since most of the innovations and development took place in Europe. However, the perspective is global and several examples and statistics from other continents are also presented.

2. Technological pathways towards transport use of methane

Gaseous fuels have a longer history than liquid fuels as power sources of engines for mechanical transport. Hydrogen (H_2) was the fuel of choice in the first ever demonstration of an internal combustion engine powered car in 1809 in Switzerland by François Isaac de Rivaz[7] (Fig. 3).

[6] E.g. the biogas van in Fig. 46 has a range of 600 km on gas, which is much more than other gas vehicles and electric vehicles achieve. By increasing storage pressure or using liquefied instead of compressed methane, the range could be extended to 2000 km without additional storage space use. Such a van costs about the same as a corresponding diesel van, but the fuel is significantly cheaper as are vehicle taxes in most countries. There are hundreds of manufacturers of factory made methane gas vehicles (MGVs) and almost 2000 models are available in the global market (Lampinen 2012c). In addition, any other vehicle, whatever the engine, original fuel and transport mode are, can be converted to methane use. Globally about 22,000 filling stations are already operating and the growth rate is high. For these and many other reasons, which are beyond the scope of this paper, MGVs offer technical and sociological potential for replacing gasoline and diesel vehicles. However, today crude oil based fuels still dominate: globally there are 153 vehicles per 1000 people and only 2 (1.3 %) are MGVs. Historical development of the global MGV fleet since 1986 is shown in Fig. 43.

[7] Echerman (2001, 18-19).

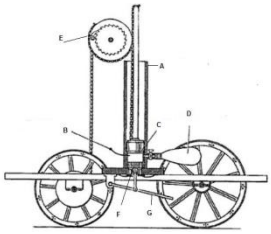

Figure 3. Patent drawing of de Rivaz from 1807 of the first internal combustion engine powered car in the world, fueled by hydrogen.

Hydrogen did not achieve commercial success as an automotive fuel, but manufactured gas did, and the technological development of the transport use of manufactured gas was crucial for the later introduction of methane in transport applications. Figure 4 depicts technological pathways leading to the use of methane in transport. Both biogas and natural gas utilization have millennia long history, but their transport applications emerged only a few decades ago.

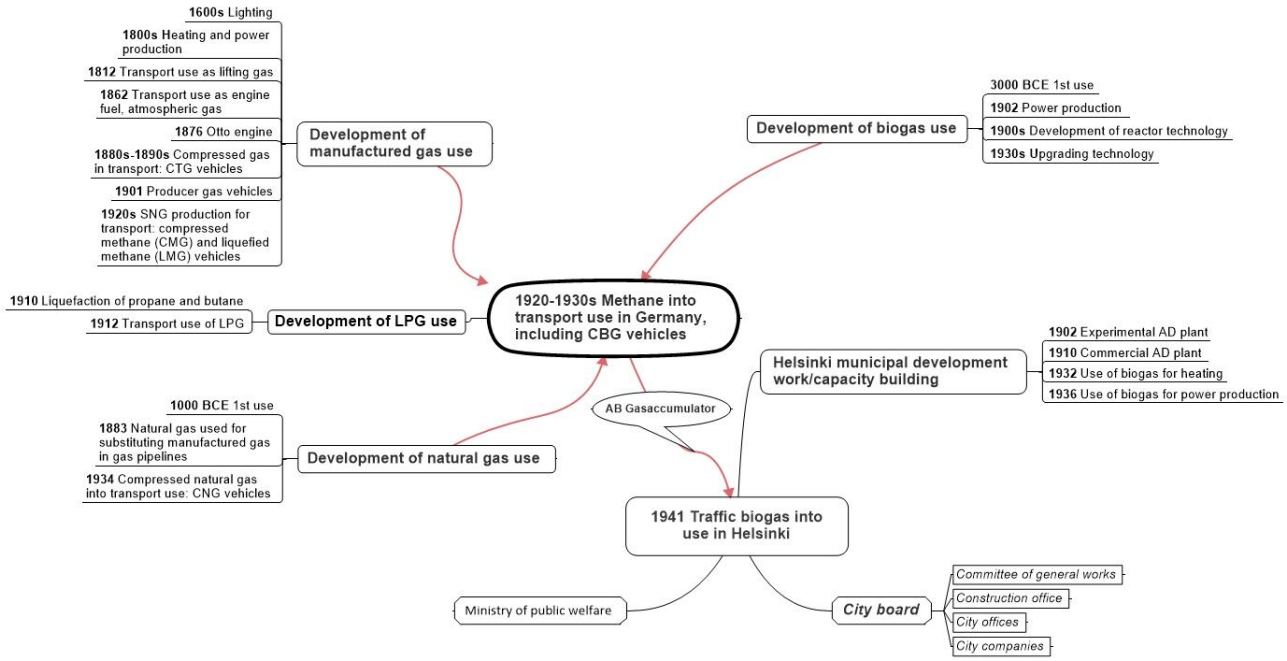

Figure 4. Technological pathways leading to the introduction of methane as transport fuel in Germany and governance of City of Helsinki in the introduction of biogas as transport fuel.

Table 1 shows the energy contents of several gaseous fuels that were used in transport in the 1940s. The high energy content of methane is attractive for vehicle applications, where on-board energy storage is a critical factor.

Table 1. Lower heating values (LHV) of selected energy gases in the 1940s.[8]

Energy gas	LHV [kcal/Nm^3]
Upgraded natural gas / methane	8000-9000
Upgraded biogas (Stockholm) / methane	8000-9000
Purified but not upgraded biogas (Helsinki) / methane	7000
Town gas (Helsinki) / carbon monoxide+hydrogen+methane	4000-4500
Carbon monoxide	3020
Hydrogen	2570
Producer gas / carbon monoxide+hydrogen+methane	1200-1300

[8] Adapted from Talvitie (1944, 140 and 176).

2.1. Manufactured gas

Manufactured gas, most often historically used in the form of town gas, means a heterogeneous mixture of gases, where the main energy gas components are carbon monoxide (CO), hydrogen (H_2) and methane (CH_4). In addition, it contains small amounts of other energy gases. Methane content can be significant (up to 40 per cent), but it may also be present in only trace quantities. The inert gases nitrogen (N_2) and carbon dioxide (CO_2) form a significant part of the gas mixture, sometimes (especially in producer gas) over 50 per cent of the volume. These gas mixtures are manufactured by many types of thermochemical processes from various bioenergy and fossil energy sources. The most common primary resources have been coal and wood. In these cases the gas is often called coal gas or wood gas. Since lighting was the original and main application of town gas in many cities, the gas is frequently called illuminating gas. It also has many other names derived from types of manufacturing processes.[9]

The first transport use of manufactured gas was not as a fuel, but as a lifting gas, first in gas balloons and later also in airships. It was used because its availability was good, although hydrogen and helium, which was discovered in natural gas in 1876, are lighter and therefore have better lifting properties.

Transport fuel use began in the 1860s. Manufactured gas was demonstrated in the Hippomobile car of Jean Joseph Étienne Lenoir of Luxembourg in 1863[10] (Fig. 5a). Manufactured gas was also the original fuel of Nicolaus Otto's engine in 1876 in Germany (Fig. 5b). Otto's engine became the most commonly used engine in transport applications, a status it still holds today. The first car operated by the Otto engine was made by Carl Benz in 1885 (Fig. 5c): manufactured gas was the fuel specified in the name of its patent "Fahrzeug mit Gasmotorenbetrieb" in 1886 (in addition, ligroin was mentioned in the patent as a possible fuel).

Figure 5. Pioneers of manufactured gas vehicles: a) Lenoir's car from 1863[11]. b) Otto's engine from 1876 at Deutsches Museum in Munich. c) Benz's car from 1885 at Deutsches Museum Verkehrszentrum in Munich.

Manufactured gas has been used in road vehicles, off-road mobile machinery, locomotives, boats, ships, airships and airplanes. Technically there are three distinct ways of using it in vehicles (Fig. 6). The essential differences are in the fuel storage and the site of gas manufacture. From an engine point of view these do not differ. In principle, liquefied manufactured gas would be a fourth way, but in practice liquefaction of manufactured gas is used for production of liquefied hydrogen and liquefied methane, both of which have superior characteristics over manufactured gas.

[9] Large amount of literature exist of the basics of manufactured gas, see e.g. Higman & van der Burgt (2003).
[10] This was witnessed by Jules Verne, who chose manufactured gas powered Lenoir engine as the power source of cars in his vision of Paris in the 1960s (Verne 1863).
[11] This is a contemporary depiction taken from Wikimedia Commons. Author and original source are unknown.

Figure 6. The three types of manufactured gas vehicles: a) on-board producer gas system, b) atmospheric storage (gas bag) with centralized production and refilling, and c) compressed storage (CTG) with centralized production and refilling[12].

2.1.1. Producer gas vehicles

Manufactured gas has low volumetric energy density (Table 1). One way of solving this problem is to include a gasifier in the vehicle and store fuel in a solid form. Wood, charcoal, coal, coke and peat have been the most common choices, but any solid biomass and any solid fossil fuels are possible. In this application the synthesised gas is called producer gas. Producer gas vehicles have been the most common way of using manufactured gas in transport. Producer gas was most popular in road vehicles. But it was also used in tractors and other mobile machinery, tanks and other war machines, ships, locomotives and it was even demonstrated in an airplane, where the weight of the gasifier is an especially prohibitive property.

Producer gas was first used in transport in 1901-1903 by the English inventor J.W. Parker for fuelling 2.5 and 25 horsepower cars[13]. Producer gas vehicle use peaked during the Second World War, when it was one of the main alternative fuel vehicle technologies in many countries on all continents[14]. As more than a million were built, they are still found in many automotive museums and a lot of literature is available. It is the only manufactured gas vehicle technology still in use today, by wood gas hobbyists worldwide. In addition, Sweden, the United States and some other governments have included preservation of producer gas vehicle technology knowhow in their national crisis preparation policies (most often called defence policies), because of the excellent availability of local fuel for them even in crisis situations, when trade is interrupted.

Figure 6a is from the Finnish national railway museum in Hyvinkää showing a Finnish railway company owned Ford AA truck model 1929 fitted with a producer gas system for charcoal use. This truck was used to transport logs for wood operated steam locomotives until 1947. Mounting a producer gas generator on the vehicle, like in this example, was the most common practice, but trailer based systems were also applied. Figure 7 shows two types of trailer mounted producer gas generators, powered by charcoal and wood. They were used in Stockholm city buses and are now exhibited at Stockholm Spårvägsmuseet. They were interchangeable in buses with each other and also with biogas trailers, which contained compressed biogas. The biogas originated from a municipal sewage treatment plant.

[12] This photo of a compressed town gas operated Citroën Traction 11 Légère gas d'éclairage from 1940s in France is taken from De Decker's (2011) article. The origin of the photo is unknown.
[13] Cash & Cash (1942).
[14] Already in 1942 more than 920,000 were used in selected 17 countries in Europe (743,000), 3 countries in Asia (111,000), 2 countries in Oceania (47,000), 2 countries in South America (23,000), 1 country in Africa (100) and 2 countries in North America (7) (Egloff & Arsdell 1943). Such vehicles were also used in many other countries than those 27, meaning that their total number exceeded a million.

Figure 7. Three types of energy gas trailers used in city buses in Stockholm in the 1940s. From left to right: charcoal producer gas generator, wood producer gas generator and compressed biogas stored in 150 bar cylinders.

2.1.2. Gas bag vehicles

Figure 8. First World War era advertisements of Lyon-Spencer gas bag kits in London[15]. It was possible to refill gas bag cars at homes, which were connected to town gas network just like today it is possible to refill biogas cars at homes, which are connected to biogas network. It offers independence from commercial filling stations.

[15] Collections of Imperial War Museum, London (© IVM).

Atmospheric gas storage with centralised production and refuelling was the original way of using manufactured gas. This technology was most frequently used during the First World War, but also during the Second World War in Europe. Gas was stored in flexible bags either on the roof of the vehicle or on a trailer[16]. Sometimes a rigid wooden storage cover was constructed. An example of this is a town gas operated Paris city bus Renault TN4F at Musée des Transports Urbains in Paris shown in Figure 6b. During the Second World War 500 such buses were operated in Paris, with a range of 25 km.

The use of gas bag vehicles peaked during the First World War, when about 5000 were in use in Great Britain alone[17] (Fig. 8). But there were still 80 filling stations in London in 1940[18]. The gas bag technology had improved to use up to 10 bar low pressure gas[19]. However, the use of manufactured gas in gas bag vehicles ended in the 1940s.

2.1.3. Compressed town gas (CTG) vehicles

Compression is another way, besides housing the gas generator in vehicle, of solving the problem of the low energy density of manufactured gas. Compressed manufactured gas was used in road vehicles, heavy mobile machinery, trams and locomotives. These vehicles are called CTG (compressed town gas) vehicles, because town gas was the most common fuel choice – however, other types of manufactured gases were also utilized. A CTG vehicle example is shown in Figure 6c. This Citroën car has three 200 bar storage cylinders, each 50 litres in volume, enabling storing 30 cubic metres of town gas for a range of 150 km.

The first CTG vehicles were trams. Gas trams were introduced in the 1880s in the United States and Australia[20]. For example, in San Francisco a gas tram was demonstrated in 1886. It was a hybrid tram including electric motors for assisting in starts and steep grades. Electricity, generated on board by a gas engine, was also used for lighting. Consumption of gas was 1000 cubic feet per day and it was sufficient to fill the tanks once a day.[21] In Australia, one gas tram was operated in Melbourne in 1886-1888[22].

In Europe compressed manufactured gas was used in trams from 1893 until 1920. CTG trams were introduced in 1893 with technology provided by the German company Lührig using 8-10 bar storage pressure and Otto engine[23]. CTG trams were used in Germany, Great Britain and Switzerland. Figure 9 shows a CTG tram in Blackpool, England in 1896.

Figure 9. CTG tram for 40 passengers introduced in Blackpool, England in 1896. They were in use until 1903.[24]

It has a 15 horsepower Otto engine and compressed gas storage for a range of 8 miles. An 8 horsepower compressor at the filling station could fill the tank with town gas in 1 minute. Top speed of the 7 ton tram was 14 miles per hour. Total costs per mile for

[16] See e.g. De Decker's (2011) article: it includes many historical photos of such vehicles.
[17] Simola (1940).
[18] Egloff & Arsdell (1942).
[19] Walter (1940, 421).
[20] Bourcier (1941, 165).
[21] Argus (1886, 5).
[22] Isaacs (2011).
[23] Klapper (1974, 52-53), Hermann (2013).
[24] Photo is from BNL (1896).

> CTG trams were less than half of the cost of horse driven trams and 30 % less than the cost of electric trams. Large improvements were achieved compared to steam trams in soot, smoke, smell and noise emissions and vibration.[25]

One early CTG tram, in use from 1899, has survived and is exhibited at Cefn Coed Colliery Museum in Wales. This technology was used in Neath, Wales between 1896 and 1920.

In the 1910s storage pressures of only a few bars were still used due to technological, especially metallurgical, limitations. During the First World War in Great Britain gas bag cars had a range of 12-20 miles and CTG cars 50 miles[26]. The development of compressor and gas cylinder technology allowed for increasing storage pressure to over 300 bars by the early 1930s and up to 400 bars in early 1940s[27]. Vehicle use of manufactured gas was a major driver for the storage cylinder development.

Figure 10 shows a mobile gas compression unit capable of compressing up to 350 bars. This was the maximum pressure used in the storage cylinders at filling stations in the 1930s, whereas in the vehicles maximum pressure varied between 150 and 275 bars. The first 350 bar CTG station in Great Britain was opened in Chesterfield in 1933 by the Chesterfield Tube Company, a manufacturer of high pressure storage cylinders[28]. The filling time for CTG vehicles in such stations was 3 minutes[29], which corresponds to the filling time of methane (CMG) vehicles today. In Germany there were 41 CTG filling stations and 1000 vehicles using them in 1937[30]. France also introduced CTG road vehicles early, in the 1920s[31] (Fig. 6c).

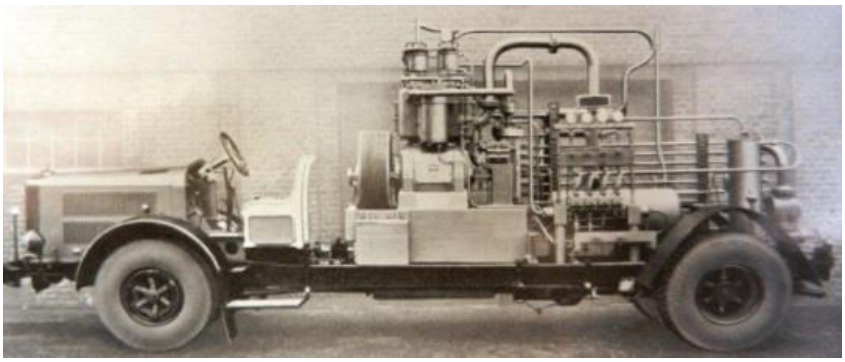

Figure 10. German mobile gas compression unit by Messr. Rheinmetall-Borsig exhibited at Leipzig fair in 1936. It can compress manufactured gas and methane up to 350 bars.[32]

CTG vehicles were not factory made, but converted from gasoline vehicles (Fig. 11). Because gasoline vehicles have Otto engines, which are gas engines, additional technology is needed for using them with liquid fuels. Therefore, modifying from liquid to gas use is actually a reverse-conversion. The changes needed were adding gas storage cylinders with necessary piping, reducing valve and air-gas mixer, and

[25] BNL (1896).
[26] This applied specifically to cars and vans used by medical doctors, as explained by Buist (1917).
[27] Marsh (1932), Bourcier (1941, 173). If 400 bars had been used in the cylinders of the car in Fig. 6c instead of 200 bars, the range would have doubled to 300 km. Further doubling to 600 km was achievable by filling in methane instead of town gas (Table 1).
[28] Engineer (1933).
[29] Engineering (1934).
[30] Simola (1940).
[31] Engineering (1932b), Bourcier (1941, 165).
[32] This photo was published in Engineering magazine, April 10, 1936, in connection with a report on machinery exhibits at the Leipzig fair. The compressor is driven by a gas engine.

adjustment of ignition timing – increase of compression ratio by replacing cylinder heads was an optional change[33].

Figure 11. Advertisement of CTG components for vehicle conversion on page 9 of Technica journal, published in Lyon, November 1943 issue.

Both monofuel and bifuel CTG vehicles were in use. In monofuel vehicles only CTG could be utilized, but bifuel CTG vehicles also could run on gasoline. In some of the bifuel vehicles CTG and gasoline could be used either separately or together (this practice has sometimes also been applied in producer gas bifuel vehicles). The reason for this is the higher energy content of gasoline, making it possible to increase power when necessary, especially in steep uphill climbing, by mixing gasoline with gas. In current bifuel methane vehicles the situation is different. In these vehicles, whether factory made or converted, methane and gasoline can only be used separately, because gasoline does not offer higher power potential than methane. Actually the reverse is true, because the octane number of methane is 130, i.e. substantially higher than gasoline can achieve[34].

CTG vehicles usually experienced about 15 per cent power loss (in producer gas vehicles it was about 50 per cent) compared to gasoline in the normal Otto engines with compression ratio of 6:1. However, CTG could be used in dualfuel Diesel engines with a compression ratio of 16:1, giving slightly higher power compared with diesel oil used in monofuel Diesel engines.[35]

2.2. Propane and butane (LPG)

Propane (C_3H_8) and butane (C_4H_{10}) are gaseous components of crude oil. They were first liquefied in 1910 and became known as liquefied petroleum gas (LPG). This name has prevailed although LPG has also been produced by separation from raw natural gas and by thermochemical synthesis from coal. LPG was the first liquefied gas used in transport. The first demonstration of an LPG car took place in 1912 in the United States, but it took until the 1940s when it became popular there, mostly as a tractor fuel[36]. In Europe LPG was first manufactured synthetically from coal in Germany, as a side product in liquid fuel manufacturing (Bergius synthesis and Fischer-Tropsch synthesis plants) and as a side product of synthetic methane manufacturing. The latter product, originated from manufactured gas, was called “Ruhrgasol”. In Berlin LPG was used in 320 buses in 1940[37].

From an engine point of view the use of LPG is similar to the use of manufactured gas and methane, although ignition timing and air requirements differ slightly between these fuels. The main difference is the liquefied storage system (it is always stored in liquid form). Currently LPG is a significant alternative

[33] Engineering (1932b).
[34] Carbon dioxide in upgraded biogas increases the octane number above 130, whereas ethane and propane in upgraded natural gas decreases the octane number below 130. For gasoline the highest octane number is 102. This is used in race vehicles only due to its high cost compared to the gasoline types sold for the general public, with octane numbers between 95 and 99. The octane numbers here refer to the so-called research octane number.
[35] Walter (1940, 424).
[36] Leffingfwell (1995).
[37] Simola (1940).

transport fuel: it is used in over 17 million vehicles globally. Large majority of these are cars. LPG use in heavier vehicles is rare. In Figure 26a an LPG filling unit ("Autogas") is shown on the right.

LPG has also been synthesised from biomass, but renewable LPG has not yet been produced for transport. Therefore, LPG in transport applications during all of its history has been fossil energy based.

2.3. Methane

The use of methane (CH_4) in transport started with the use of manufactured gas, of which methane makes a minor part. However, in this part we will deal with the so-called methane fuels. They are mixtures of gases, where most of the energy is in the form of methane, but not necessarily all of it. Some methane fuels contain significant share of ethane (C_2H_6). Ethane is an important energy gas especially within natural gas in the United States, but in Russian natural gas ethane content is low. Some methane fuels also contain small quantities of other energy gases, such as propane and hydrogen. Pure methane is never used as a fuel, because it is not necessary to separate methane from other gases present in methane fuels for any engine types[38]. Therefore, whenever methane is mentioned in this paper, it stands for methane fuel, not pure methane.

Vehicles manufactured for methane fuels (MGVs) can also use hydrogen, ethane and LPG (propane and butane) in vehicle dependent percentage of total volume of fuel. For hydrogen this may be up to 20 per cent, which means that the large current global fleet of almost 20 million MGVs is ready to utilize a significant amount of hydrogen, without the need to manufacture specific vehicles for it and without the need for the very high purity hydrogen that fuel cell vehicles demand (Fig. 12).

Figure 12. Filling wind hydrogen into a biogas car in Malmö, Sweden.

Methane cannot be made in on-board systems like manufactured gas in producer gas vehicles. It must be produced in centralised facilities and filled into on-board storage in filling stations. Atmospheric storage (gas bags) is possible, but very rare due to low energy density: it was adopted in the 1940s but has virtually disappeared. Methane is usually stored in compressed gaseous form (CMG) or liquefied form (LMG), both of which were first demonstrated in the 1920s. Solid storage via adsorption (AMG) is a new alternative, which is coming into the market. These offer 100-700 times higher energy density than atmospheric storage, and ranges that are near to those reached by gasoline and diesel vehicles. Methane can be stored in a much more energy dense form than hydrogen and electricity. Therefore, ranges of MGVs may be substantially more than hydrogen and battery electric vehicles can achieve. Methane is a suitable fuel for all transport applications (Table 2).

[38] It is enough to have 84 % methane (although it also depends on what the other gases in the mixture are). Usually in CBG methane content is 95-99 %. Situation is different for hydrogen, since fuel cells require 99.9 – 99.9999 % purity.

Table 2. Suitability of methane in different transport modes.

	Road/passengers			Road/freight			Off-road	Rail	Water			Air	Space
	short	medium	long	short	medium	long			inland	short-sea shipping	maritime		
CMG	X	X	X	X	X		X	X	X	X			
LMG	X	X	X	X	X	X	X	X	X	X	X	X	X

Methane is the only fuel that can be used in all transport engine types, i.e. Otto, Diesel, 2-stroke, Wankel, steam, hot bulb, jet and rocket engines, gas and steam turbines and fuel cells, and in hybrid vehicles it can provide power for electric motors. CMG and LMG vehicles are factory made by hundreds of manufacturers, but they are also produced by converting gasoline, diesel and LPG vehicles. Figure 13 shows a plug-in hybrid biogas car owned by City of Malmö in Sweden. It can be run on wind and solar electricity in short distance city traffic and on waste based biogas and synthetic biogas in longer distance road traffic. This combination of the best features of both electric and gas vehicles has especially low environmental impact making it a vehicle technology for the future.

Figure 13. Plug-in hybrid biogas car exhibited at the NGV Gothenburg 2013 fair.

Methane is the third most important transport fuel globally after gasoline and diesel oil and its share is expected to grow rapidly. The International Energy Agency of the OECD has estimated in one of their scenarios the number of MGVs to grow to 186 million by 2035[39]. The shares of renewable versus fossil methane sources will depend mostly on environmental policies. The resource base for both is significant.

A MGV database published in 2012 has information of 1850 MGV models, including 1290 CMG, 556 LMG, 1 AMG and 1 atmospheric vehicles. Two vehicles are able to use both CMG and LMG. Use of different engine types in this database is presented in Table 3.

[39] IEA (2011, 119).

Table 3. Engine types of MGV models available globally in 2012.[40]

	Light vehicles	Cars	Vans	Heavy trucks	Buses	Mobile machinery	Rail vehicles	Water vehicles	Aircraft	Spacecraft	**TOTAL**
2-stroke	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
Otto engine total	**389**	**274**	**180**	**146**	**258**	**51**	**11**	**20**	**1**	**0**	**1330**
-monofuel	3	35	70	146	243	50	11	20	1		579
-monofuel hybrid	0	3	0	0	9	0	0	0	0		12
-plug-in hybrid	0	0	0	0	1	0	0	0	0		1
-bifuel	386	216	106	0	5	1	0	0	0		714
-bifuel hybrid	0	5	1	0	0	0	0	0	0		6
-multifuel	0	15	3	0	0	0	0	0	0		18
-hythane[1]	0	1	1	0	1	0	0	0	0		3
Diesel engine total	**0**	**3**	**3**	**33**	**5**	**7**	**8**	**130**	**0**	**0**	**189**
-monofuel		0	1	0	0	0	0	0			1
-dualfuel		3	2	33	5	7	8	130			188
Gas turbine (GT) total	**0**	**2**	**1**	**1**	**5**	**0**	**2**	**2**	**1**	**0**	**14**
-monofuel		0	0	0	0		2	2	1		5
-hybrid		2	1	0	5		0	0	0		8
-plug-in hybrid		0	0	1	0		0	0	0		1
Jet engine	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**2**
Steam turbine	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**317**	**0**	**0**	**317**
Rocket engine	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**2**
Methane fuel cell	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**
Electric motor[2] total	**0**	**10**	**2**	**1**	**15**	**0**	**0**	**1**	**0**	**0**	**29**
-otto hybrid		8	1	0	9			0			18
-GT hybrid		2	1	0	5			0			8
-plug-in otto hybrid		0	0	0	1			0			1
-plug-in GT hybrid		0	0	1	0			0			1
-methane fuel cell		0	0	0	0			1			1
Other	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**2**

[1]Hythane vehicles have been listed twice: on hythane, monofuel and bifuel rows.
[2]Electric motors have been listed twice: in addition to own section, in hybrid and fuel cell rows.

2.3.1. Synthetic natural gas (SNG)

The first methane fuel adopted for transport use was coal based synthetic natural gas (SNG). SNG is a fossil methane fuel manufactured by thermochemical methods from coal, peat, crude oil or other fossil fuels. The most common method currently is methane synthesis, where manufactured gas is purified to syngas (CO + H_2) and methane is synthesised by catalytic reaction of CO and H_2 in high temperature and pressure. The method, also called methanation, was first proven in 1902[41]. This method can also be applied to wood or other biomass, in which case the product is synthetic biogas (SBG).

However, a different method was used when SNG was first taken into transport use in Germany in the early 1920s. Methane was separated from coal gas by a cryogenic process called Bronn-Concordia-Linde

[40] This table is translated from an MGV database published in Finnish (Lampinen 2012c).
[41] Sabatier & Senderens (1902). This was one contribution towards the Nobel Prize in chemistry Paul Sabatier received in 1912 (Sabatier 1912).

process[42]. It means that temperature of coal gas was lowered down to -190 ºC to liquefy methane and leave hydrogen, carbon monoxide and nitrogen in gas state (hydrogen was needed in the Bergius synthesis plants for production of synthetic liquid fuels, and in Haber-Bosch synthesis plants for manufacturing ammonia). SNG can also be made using many other thermochemical methods than those discussed above. They include coke hydrogenation, which was available in the 1930s[43]. Similarly, SBG could be made of charcoal.

Liquefied methane (LMG, or in this case LSNG) was regasified and pressurised for transport use in compressed methane gas (CMG) vehicles. In the Ruhr region alone, 3 billion cubic meters of methane could have been produced annually this way from coal gas[44]. It corresponds to 3 TWh of energy, enough for about 300,000 modern cars, which is three times the amount of CMG vehicles currently in use in Germany. This technology was launched for public commercial use in 1932 after over 10 years of experiments and demonstrations by Concordia mining company in Oberhausen, Germany. Demonstrations included using SNG compressed to 150 bars in Liberty and Büssing CMG trucks owned by the Concordia Company as well as a bus and a street sweeper owned by Oberhausen municipal agencies.

The first transport use of LMG was also based on SNG. Several mining companies demonstrated its use in road vehicles since 1927[45]. LMG was also used together with liquid oxygen by Johannes Winkler in 1931 in the first gaseous fuel rocket launch in the world (Fig. 14).

Later liquefied gas fueled (hydrogen) rockets have been applied to some of the most important space vehicles in the history of space travel: the NASA Saturn V Moon rockets and the NASA Space Shuttles.

Figure 14. Johannes Winkler and the LSNG powered HW-1 rocket in 1931.[46]

2.3.2. Natural gas (NG)

Natural gas is a heterogeneous mixture of fossil gases, of which methane usually has largest share. The methane content varies from 44 per cent (Forties field in the North Sea) to 98 per cent (Urengoi field in Russia). In addition, natural gas contains many other energy gases, like ethane, and inert gases, like carbon dioxide and nitrogen. Natural gas has been used for 3000 years, but it started to grow towards a globally significant industrial energy source, a role it has today, only 130 years ago. In 1883 Pittsburgh became the first city where natural gas was used to substitute manufactured gas in the town gas network[47]. Its name originates from this substitution: unlike manufactured gas, which is man-made, natural gas is available (almost) ready for use directly from nature.

In principle, LPG separated from raw natural gas could also be called natural, but all other energy gases (including manufactured gas, biogas, synthetic biogas and hydrogen) are synthetic, man-made,

[42] Engineering (1932a).
[43] See Engineering (1938) for British experiences. Coke hydrogenation for methane production is a version of coal hydrogenation. Coal hydrogenation is used for synthesising liquid fuels. It is also called Bergius synthesis, since Friedrich Bergius proved the process in 1913 and received Nobel Prize in chemistry for it in 1931. A few percent (weight) of methane is produced in coal hydrogenation as a side product (Bergius 1932, 274).
[44] Roth (1932).
[45] This is based on information given by Professor Fritz Frank (Walter 1940, 443-444).
[46] Photo was taken from http://weebau.com/history/winkler.htm. Its origin is unknown.
[47] Yergin (1991, 92).

and cannot be called natural gases. Although natural gas is readily available from nature and could be used in its raw form in crisis situations, substantial purification, upgrading, separation and other processing is needed before it is fed into pipelines for delivery to consumers. These plants are about the same scale as crude oil refining plants (Fig. 15).

Figure 15. Kårstø natural gas processing plant north of Stavanger, Norway.

Compressed natural gas (CNG) was first taken in a vehicle use in 1935 in Italy (Fig. 16a) and in the 1930s also in Australia, Japan, Soviet Union and the United States. In Italy CNG buses had 250 bar storage pressure for a range of 200-400 km and 300 bar storage pressure was used in locomotives[48]. Most of the CNG vehicles today are road vehicles, but CNG is commercially used also in mobile machinery, locomotives, boats and ships. And it has been demonstrated in light airplanes.

Figure 16. Historical natural gas cars: a) Fiat 508C Balilla model 1939 converted to CNG by Tartarini company, as exhibited at the NGV 2012 Fair in Bologna, Italy. b) LNG rocket car "Blue Flame" driven by Gary Gabelich became in 1970 the first car to reach over 1000 km/h speed. It kept the world land speed record for 13 years. It is exhibited at Auto- und Technikmuseum Sinsheim in Germany.

Liquefaction of methane was first demonstrated by Michael Faraday in the mid-nineteenth century. The first commercial liquefied natural gas (LNG) production plant was opened in 1941 in Cleveland. In transport applications LNG has been used since 1964: the first use was in the British steam turbine ship Methane Princess, which was the first purpose-built vessel for ocean shipments of LNG. Currently LNG is used in about 500 ships, of which most are LNG carriers (Fig. 24a). Many other types of ships have recently been launched as a result of United Nations (International Maritime Organization) level air pollution control requirements. LNG is also used in heavy road vehicles and locomotives. It has been demonstrated in jet airplanes and planned for in future space flights. One of the oldest natural gas vehicles exhibited in museums is an LNG rocket engine powered car from 1970 (Fig. 16b).

2.3.3. Unconventional fossil methane

Shale gas was the first unconventional fossil methane type (Fig. 2) adopted for transport use, in the United States a few years ago. Unconventional fossil methane resources are substantially larger than the resources

[48] Buses: Sansone (1936) and Bourcier (1941, 201), locomotives: Egloff & Arsdell (1942).

of natural gas, but they also pose far greater environmental risks[49]. These resources are available in more countries than any other fossil fuels and it is possible to transport these fuels in liquefied form globally. Currently LNG terminals are being planned and constructed in many countries. These may be used to import not only natural gas but also unconventional fossil methane and SNG. In addition to direct environmental hazards, the utilization of these resources may impede implementation of renewable energy policies, as has been warned for example by the OECD International Energy Agency[50].

2.3.4. Biogas (BG)

Biogas is a renewable methane fuel produced microbiologically from biomass, usually biowaste, by microbial metabolism[51]. Traditions of biogas utilisation go back thousands of years. The earliest references are from Sumeria 3000 BCE[52]. China is currently the leading country with over 40 million biogas reactors. There the earliest references are from 1500 BCE[53]. Biogas was first used for city lighting in Exeter, England in 1895 and for electricity production in Matunga, India in 1902[54].

The Otto engine made the use of biogas possible first in power production and later in transport applications. There are uncertainties as to when the transport use of biogas began and where. Germany was technologically ready for it in the 1930s, but the exact date is unknown[55]. In 1945 the situation was the following, according to Karl Imhoff:

> "*In most of the large sewage treatment plants of Germany, the digester gas is collected and compressed into steel cylinders for use as fuel in municipally operated automobiles*."[56]

He names Munich, Essen, Stuttgart, Halle and Berlin as locations for such plants. There are several examples in the literature, where it is mentioned that this technology would have been used in the early 1940s in several countries. One example is the following text:

> "*Probably the most outstanding development of a fuel gas source has been the utilization of methane derived from fermentation of city sewage. In Sweden, as well as in other countries, there has been development in this line.*"[57]

Author has data of traffic biogas use in the 1940s in only three European cities outside Germany: Borås (from 1941) and Stockholm (from 1942) in Sweden and Helsinki (from 1941) in Finland, but it was possibly used also in Italy[58]. Outside Europe, biogas was used in transport in Johannesburg (from 1940) in South

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[49] IPCC (2001, 315).
[50] IEA (2011, 9).
[51] Biogas is produced in biogas reactors. It is also produced in landfills in which case the gas is also called landfill gas. Wood and other biomass with high lignin content can not directly be used for biogas production. Their use requires preprocessing, which is not commercial level technology even today. However, paper can be used because lignin has been removed in pulp production process.
[52] Deublein & Steinhauser (2008, 27).
[53] He (2010).
[54] Fuhrman (1940, 1096).
[55] Deublein & Steinhauser (2008, 29) give 1930 as the approximate year of first demonstration of biogas use in automobiles. It means that biogas was taken into transport use before natural gas. According to Simola (1940, 73), sewage treatment based biogas was used in internal combustion engines 180,000 m^3 in 1935 and 1.25 million m^3 in 1937 in Germany. However, it is not mentioned whether all or part of this was in transport.
[56] Imhoff (1946, 17).
[57] Egloff and Arsdell (1942, 654).
[58] In an Italian documentary film from 1940 it is implied that sewage treatment plant based biogas was also used in transport in Italy, in addition to natural gas; however, no details are given (IWM 1940).

Africa[59]. All of these cities utilised biogas in compressed form (CBG) based on compression and vehicle technologies developed originally for manufactured gas and SNG. In all cities biogas originated from municipal sewage treatment plants.

Of these cities only Stockholm has preserved hardware and exhibits them at a municipal transport museum. Figure 18a shows a city bus trailer containing 150 bar CBG bottles. The use of upgraded biogas began in 1942 with 23 buses and 17 service vehicles[60]. The consumption of biogas in municipal transport in Stockholm in the 1940's is shown in Figure 17.

Figure 17. Consumption of biogas in municipal transport in Stockholm in the 1940's.[61]

In the 1940s biogas was used mostly in trailers towed by city buses (Fig. 18b), but also in various municipal vehicles with on-board storage cylinders (Fig. 18c).

Figure 18. Biogas vehicles of Stockholm municipal transport company in the 1940's: a) Biogas trailer at the Stockholm Spårvägsmuseet. b) City bus with a biogas trailer. c) Service vehicle with on-board biogas storage.[62]

This business ended in Stockholm in 1946, but began again in 1996 at Bromma sewage treatment plant and came back to the Henriksdal plant in 2004 (Fig. 19a). Biogas trailers are no longer used, but all vehicles have on-board storage. In October 2013 there were 20 public biogas filling stations in Stockholm (Fig. 19c). In addition, there were private filling stations for buses and waste trucks (Fig. 19b).

[59] Fuhrman (1940, 1088).
[60] ASS (1943).
[61] Data has been compiled from the annual reports of Stockholm's municipal public transport company Aktiebolaget Stockholms Spårvågar (ASS 1943, 1944, 1945, 1946 and 1947).
[62] Black and white photos are from the archives of the Stockholm Spårvägsmuseet.

Figure 19. Different types of CBG filling stations in Stockholm: a) Private station at Söderhallen bus depot near Henriksdal. b) Private waste truck station with LBG storage. c) Public station.

In Borås transport use of upgraded biogas originating from a sewage treatment plant started already in 1941[63] (Fig. 20).

Figure 20. CBG filling station in Borås in the 1940's.[64]

Borås abandoned traffic biogas use in the late 1940s, but began again in 2002. Now, in addition to sewage sludge, also municipal solid waste is utilized and biogas is sold to the public in three filling stations operated by municipal energy and waste company Borås Energi och Miljö (Fig. 21). The text "Biogas för en fossilbränslefri stad" in the station means "Biogas for a fossil fuel free city" showing municipal goals being implemented in practise by a municipal company. In addition to municipal vehicles, waste trucks and city buses run on biogas produced on municipal waste. The same practise has been adopted by many Swedish municipalities during the past two decades.

Figure 21. CBG filling station in Borås in 2011.

[63] Fransson (2009).
[64] Photos are from the archives of City of Borås (Fransson 2009).

In Helsinki CBG use began in 1941 with biogas from Kyläsaari sewage treatment plant and in 1943 another production site opened at Rajasaari sewage treatment plant. The first filling station was designed for 150 bar storage cylinders, whereas the second station (Fig. 22) could fill up to 200 bars.[65]

Figure 22. Ford truck filling biogas at a CBG filling station at Rajasaari Sewage treatment plant in Helsinki in 1943.[66]

Unlike Stockholm and Borås, Helsinki has not yet restarted CBG production, but in October 2013 there were four public (Fig. 23) and one private CBG filling stations in Helsinki (operated by state company Gasum) for selling biogas produced at sewage treatment plants of other cities: Kouvola (since 2011) and Espoo (since 2012).

Figure 23. CBG filling station in Helsinki in 2012.

[65] Lampinen (2012a).
[66] Photo: Foto Roos/Photo archive of Helsinki City museum.

Upgrading of raw biogas by removing most of inert gas carbon dioxide by water scrubbing was developed in Germany around 1930[67]. Figure 25 shows a water scrubber taken into use in Borås in 1941. In the beginning of the 1940s water scrubbers could increase the methane content from the typical 60 per cent in the raw gas to 95 per cent[68], which is near the performance of modern water scrubbers (Fig. 36b). Cryogenic upgrading, capable of removing also another inert gas nitrogen (it is found in large quantities in landfill gas and some raw natural gas wells), was already available in the 1920s, but it was used for SNG production only. Later it became important in natural gas upgrading and in the past few years it has been used for biogas upgrading, too (Fig. 24). Many other upgrading technologies have later been developed and are commercially available in the market.

Figure 24. a) Natural gas cryoupgrading plant (Statoil) with LNG powered LNG carrier in Hammerfest, Norway. b) Landfill gas and biogas cryoupgrading plant (GtS) in Haarlem, the Netherlands.

Since raw biogas typically contains about 40 per cent carbon dioxide, removing it increases the energy density of the methane fuel substantially (Table 1). However, carbon dioxide is not a pollutant harming engine or fuel systems, and the same applies to nitrogen. Therefore, vehicles can be adjusted to operate on purified biogas, where only sulphur compounds and water have been removed, but without upgrading. It still has clearly higher energy content than town gas (Table 1). For example in Essen, Stuttgart and Helsinki biogas was not upgraded in the 1940s, and in Stockholm purified biogas was used first and upgrading was later added. In addition to Stockholm, upgraded biogas was produced in the 1940s in Munich, Halle, Berlin, Borås (Fig. 25) and Johannesburg, in all these cities by water scrubbing.

Figure 25. Water scrubber in 1941 in Borås, Sweden.[69]

It has often been claimed by the natural gas industry that biogas requires upgrading to meet the quality of natural gas. This is misleading. Both biogas and natural gas require upgrading before feeding them into gas pipelines or vehicle filling stations. Natural gas upgrading plants are massive installations as seen in Figures 15 and 24a, whereas biogas upgrading plants are usually small scale installations as seen in Figures 24b and 36b. In principle, the same upgrading technologies can be applied to both raw gases.

Currently compressed biogas (CBG) is available at hundreds of filling stations in Europe either as 100 per cent biogas (CBG100, see Fig. 26a) or blended with natural gas (e.g. CBG10 and CBG50, see Fig. 45). Most of

[67] Deublein & Steinhauser (2008, 29). Currently many other upgrading technologies are also used (Petersson & Wellinger 2009).
[68] Walter (1940, 434).
[69] Photo is from the archives of City of Borås (Fransson 2009).

the filling stations are located in Germany and Sweden, but availability is spreading in many other countries, too, e.g. the Netherlands, France, Switzerland, Austria, Finland, Norway, Iceland and Great Britain. It is used mostly in road vehicles.

The first commercial liquefied biogas (LBG) filling station opened in 2005 in Los Angeles utilizing landfill gas from Puente Hills landfill, serving mostly waste trucks. In addition to the United States, LBG filling stations are in operation in a few European countries, e.g. Great Britain, Sweden (Fig. 26b) and the Netherlands, mostly for trucks but also for buses. There are also CBG stations, where the storage is in the form of LBG (Fig. 19b). In these so-called LCBG stations LBG is regasified and pressurised for transport use in CBG vehicles, like was done with coal-based SNG in Germany already in the 1920s.

Figure 26. Modern 100 % biogas filling stations in 2013: CBG100 filling station (Mabagas) in Fulda, Germany (a) and LBG100 filling station (Fordonsgas) in Gothenburg, Sweden (b). Biogas filling is similar and takes similar time as gasoline and diesel oil filling.

Although the use of traffic biogas is increasing rapidly in Europe, outside Europe its use is still rare. In Europe almost all biogas in transport use is waste based, resulting in very good environmental performance.

Besides biogas, other types of renewable methane (Fig. 1) are used for transport purposes. Biomethane can also be manufactured thermochemically: in this case we talk about synthetic biogas (SBG) to distinguish it from microbiologically produced biogas (BG). Other renewable energy sources besides bioenergy, including solar and wind energy, may also be utilized for methane production. The scientific basis for production of all these types of renewable methane has been known for over a century, but actual production for transport applications began just a few years ago.

2.3.5. Synthetic biogas (SBG)

Synthetic biogas (SBG) is a renewable methane fuel manufactured by thermochemical methods from wood and other biomass. The methods are the same as the ones used for manufacturing synthetic natural gas (SNG) from coal or other fossil fuels. SBG and SNG are chemically similar, but the former is a renewable fuel, whereas the latter is a fossil fuel (Fig. 1-2). Just like in the case of raw natural gas and raw biogas, upgrading is necessary to be able to use SBG and SNG in normal[70] methane vehicles.

[70] Here 'normal' means modern factory made vehicles or vehicles converted using standard conversion kits. However, with additional modifications, modern vehicles can be adjusted to a raw biogas use. It is a rare practice.

SBG has been applied to transport since 2009, when the first compressed SBG filling station in the world was opened in Güssing, Austria utilising wood. It was built by a consortium of private and municipal companies and research institutions, of which the Austrian company Repotec was in charge of delivering the plant technology. Figure 27a shows a thermal gasification plant (left), an SBG synthesis (methanation) plant in the middle (the white building in the background) and a high pressure SBG storage and filling station in the small white building on the right.

Figure 27. a) SBG production plant and filling station in Güssing, Austria. b) SBG production plant under construction in Gothenburg, Sweden, in June 2013.

The SBG synthesis plant in Güssing is a 1 MW demonstration plant. The first commercial 20 MW plant begins production in 2013 in Sweden (Fig. 27b). The plant is constructed by a municipal energy company Göteborg Energi applying the same core technology from Repotec as demonstrated in Güssing. Later it will be expanded to at least 100 MW capacity. All of the produced SBG is intended for transport. There are plans in Sweden to build another, a 200 MW plant in Malmö, also for transport use.

2.3.6. Wind methane, solar methane and other renewable methane types

Solar and wind methane (Fig. 1) are produced by Sabatier reaction from carbon dioxide and solar or wind hydrogen. This catalytic high temperature and moderate pressure reaction was discovered by Paul Sabatier in 1897[71]. Carbon dioxide may be separated from the atmosphere, exhaust gases of combustion plants or industrial processes (such as biogas and ethanol production). Hydrogen is produced by electrolysis (Fig. 28b) using solar or wind electricity[72]. Any other type of renewable electricity can be used as well. For solar methane there are also other possible production chains than the one described above.

Solar and wind methane production and use were first demonstrated by SolarFuel company in Stuttgart, Germany in 2009 in co-operation with Fraunhofer Institute and ZSW Stuttgart. This container based production unit is currently located at the research centre of Fraunhofer Institute in Bad Hersfeld. Figure 28a shows wind methane filling in operation there. The first commercial wind methane plant by Audi started production in June 2013 in Werlte, Germany in connection with a biogas plant owned by EWE (Fig. 29). This plant uses wind power from offshore wind turbines and carbon dioxide from raw biogas. Carbon dioxide from raw biogas can be utilized without separating it, because methane does not interfere with the

[71] Sabatier (1912). It was one contribution towards the Nobel Prize in chemistry he received in 1912.

[72] For this reason these are sometimes called power-to-gas technologies (it is not a methane specific term, but may refer to hydrogen as well, and in principle other gases, too). However, if hydrogen is produced by other methods than electrolysis, the term power-to-gas does not apply. Especially for solar methane there are possible production chains, where power-to-gas is not an applicable term. The term power-to-gas includes renewable, fossil and nuclear electricity based gases.

Sabatier reaction. Therefore, it is a wind methane and biomethane co-production facility. In this case the Sabatier reactor also replaces an upgrading plant.

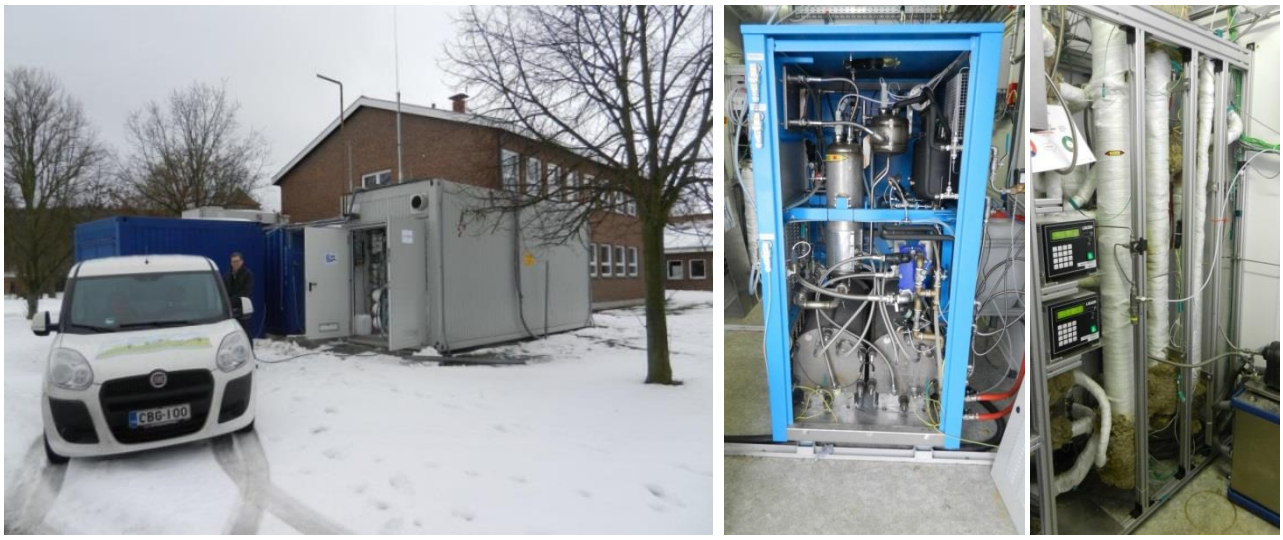

Figure 28. Wind methane demonstration plant and filling station (a) in Bad Hersfeld, Germany and its electrolyser (b) and Sabatier reactor (c).

Since the resource base of all renewable energy sources combined is order of 100,000 times larger than the resources base of bioenergy[73], Sabatier reactors (Fig. 28c) may potentially increase the production of renewable methane to cover not only all transport needs, but also other energy needs. The reason for utilizing Sabatier reactors is the ability of methane to act as a chemical storage for intermittent renewable energy sources. Therefore, the storage problem of solar and wind energy can be solved. For example, in Germany the gas network has a storage capacity of over 200 TWh, whereas the storage capacity of the German electricity network is only 0.04 TWh.

Figure 29. EWE biogas plant in Werlte, Germany, where the first commercial wind methane production plant opened for production in 2013.

2.4. Review of transport use of compressed gases in the 1940s in Europe

In 1937 there were 28,000 compressed gas vehicles in use in Europe, whereas the amount of producer gas vehicles was only 9,000[74]. By 1941 the amount of compressed gas vehicles had grown to over 107,000 (Table 4) and the amount of producer gas vehicles to over 443,000[75]. Manufactured gas bag vehicles were also used (Fig. 6b), but much less than during the First World War. The leading countries were Germany and Italy, with a fleet of almost 100,000 vehicles. Their combined production of compressed gases in 1941 was

[73] UN (2000, 166-168).
[74] Egloff (1938).
[75] Egloff & Arsdell (1942).

estimated to be between 2 and 2.3 million barrels of oil equivalent (12-14 PJ). There were more than 50 filling stations in operation in 1941 in Germany.[76] In Italy, the government prohibited the use of natural gas for any other purpose than transport[77].

Table 4. Number of compressed gas vehicles in Europe in 1941.[78]

Country	Number of vehicles	Types
Germany	75,000	Mostly CTG and CMG, also LPG
Italy	20,000	CNG (CBG?)
Great Britain	10,000	mostly CTG
Sweden	1,367	CBG
France	500	CTG
Denmark	358	CNG
Finland	53	CBG
Soviet Union	?	CNG
TOTAL	> 107,278	

The amount of CBG vehicles and their use of biogas in Europe in the 1940s are not known. Complete statistics have been compiled only for Finland (Fig. 35)[79]. In addition, in this paper statistics of traffic biogas consumption by the Stockholm municipal transport company is published (Fig. 17). In fact, there are no global, European or even European Union statistics of biogas use in transport for any other time period either, including the current situation[80]. Therefore, there is a need for future research to be able to compile global and continental statistics on the development of traffic biogas use[81].

Figure 30. Italian CMG tractor (a) and CMG locomotives (b-c) at Varese railway station in Northern Italy in 1940.[82]

[76] Egloff & Arsdell (1942).
[77] Stodolsky & Wilund (1997, 1444).
[78] Sources: Lampinen (2012a) for Finland, Egloff & Arsdell (1942) for other countries. "Types" have been assessed in this work. These compressed vehicle statistics include LPG vehicles, because in the 1940s they were also so called. This is no longer the case. They are one class of liquefied gas vehicles. Other classes include liquefied methane, liquefied hydrogen and liquefied dimethyl-ether vehicles. According to Egloff & Arsdell (1942, 654), in 1941 in Germany "Methane and city gas are more widely available than propane and butane". According to Krammer (1978, 414) in 1944 LPG was used almost 10 times more than methane, which was used 12,000-42,000 toe (0.5-1.8 PJ) in 1944. LPG was a side product of coal based synthetic liquid fuel production.
[79] Traffic biogas statistics of Finland in the 1940s is available in the article by Lampinen (2012a).
[80] For European Union, compilation work is going on. Currently traffic biogas statistics are included in the annual national biogas statistics only in Sweden (available at www site of Energigas Sverige) and in Finland (available at www site of Finnish Biogas Association). Statistics of actual consumption is only available in Sweden from 1995 and in Finland from 1941 until 2012 (Lampinen 2013b). Currently in most countries natural gas companies only publish combined sales of natural gas and biogas. Therefore, in most countries where natural gas companies are involved in traffic biogas business, biogas consumption is not currently available. Sweden and Finland are exceptions.
[81] For methane such statistics exist, but renewable and fossil methane are not separated. They can be found at www sites of NGV Global and NGVA Europe and the Gas Vehicle Report magazine.
[82] IWM (1940).

In the 1940s compressed gases (CTG and CMG) were stored in pressures ranging from 150 to 275 bars in road vehicles and mobile working engines (Fig. 30a), with 200 bars the most common choice. In locomotives the choice was 300 bars (Fig. 30b-c).

In filling stations 350 bars was the most common storage pressure (Fig. 31). Since the 1940s storage cylinder technology has greatly improved and much larger pressures could be used for increased range and decreased weight. This has not happened, because the 200 bar choice became standardised (however, weights of the 200 bar cylinders have decreased). Therefore, almost all CMG vehicles today use 200 bar storage, although modern compressed hydrogen vehicles have a 700 bar standardised storage system and even in the 1940s much higher pressures than 200 bars were used. In filling stations 300 bars or even lower pressures is the common practice today, although higher pressures were achieved already in the 1940s. Lack of progress since the 1940s can be attributed not only to the effect of standardisation but also to the minimization of compression and investment costs. Although these may help the dissemination of CMG vehicle technology, both of them also form a barrier in the development of CMG vehicles especially for road transport. For locomotives, ships, airplanes and spacecraft these restrictions do not apply, since they do not have standards covering this issue, they have independent refuelling systems, and LMG is usually chosen for these applications instead of CMG.

Figure 31. Italian Agip CMG filling station in 1940.[83]

2.5. Methane gas bag vehicles

The use of manufactured gas in gas bag vehicles ended in the 1940s. This technology has survived with methane, especially natural gas, but also biogas. It was introduced in Germany in the 1940s[84] (Fig. 32). In China the use of natural gas in gas bag vehicles has continued in present time.

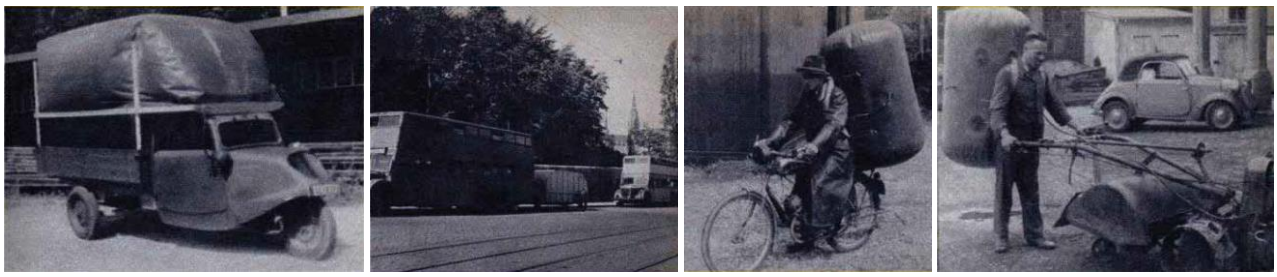

Figure 32. Biogas use in gas bag vehicles in the 1940's in Germany: a) Three-wheeled delivery truck with a gas bag on the roof. b) Munich city buses with gas bags in trailers. c) Moped with a gas bag in driver's back. d) Rotary tiller with a gas bag in operator's back.[85]

[83] IMW (1940).
[84] Imhoff (1946).

It is quite often claimed that gas bag vehicles were a step of development on the way to compressed methane vehicles. This is not the case. Methane was first used in CMG vehicles and this technology still dominates methane use today (although LMG vehicles already have an important role and AMG vehicles are coming to the market). Methane gas bag technology was adopted after CMG technology as a low-tech alternative, where compression was not necessary. Therefore, it did not contribute to the development of modern methane use in transport.

3. Governance of renewable methane technology systems for transport

Figure 33 gives an overview of timelines and governance of renewable methane systems for transport in Finland and globally. Three waves are identified in their use: the Second World War, the oil crises in the 1970s and the current era of sustainable development. Biogas has a dominating role in the history of renewable methane. Synthetic biogas, wind methane and solar methane emerged in the market only a few years ago, although knowledge of their manufacturing goes back over a century.

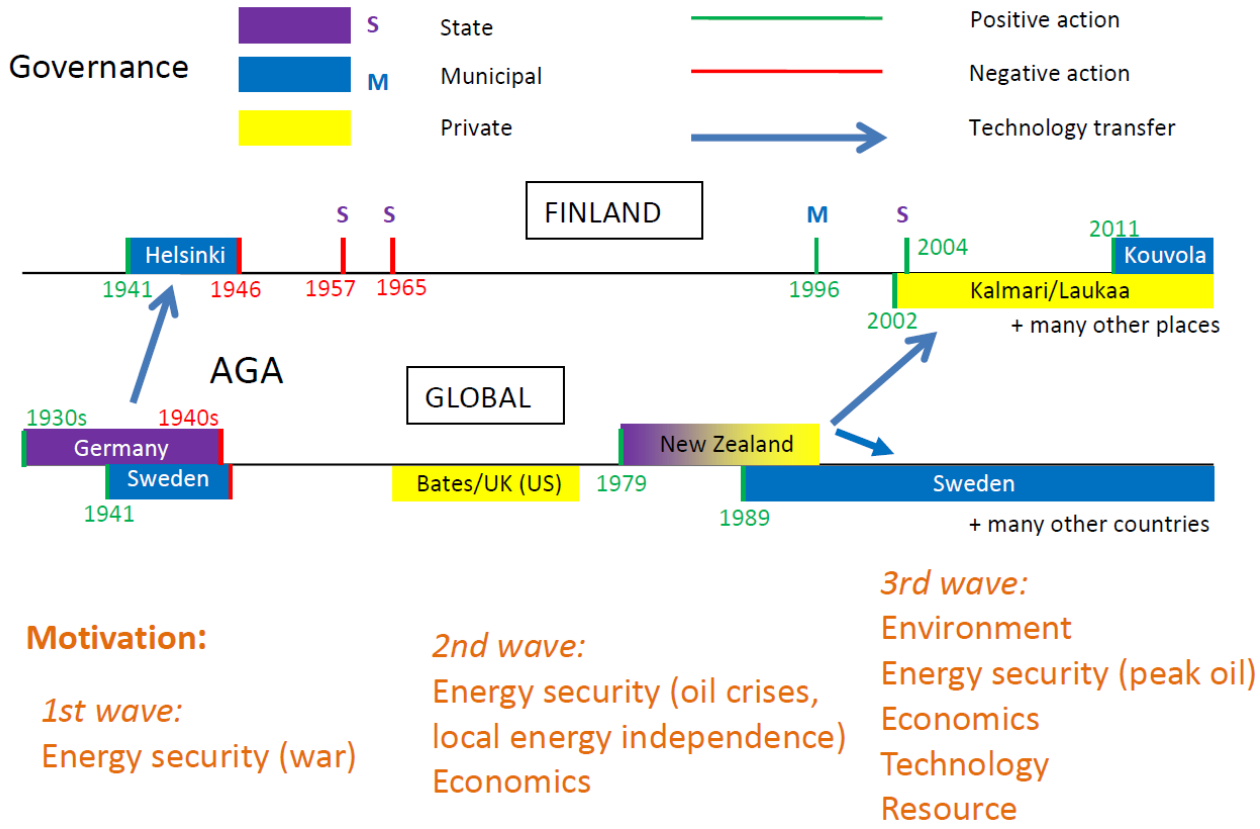

Figure 33. Timelines of renewable methane use in transport, with governance and motivation in Finland and globally.

3.1. First wave: the Second World War

Both compressed (CMG) and liquefied methane (LMG) were first demonstrated in transport use in Germany and CMG was taken into commercial use there in 1932. This all happened due to the efforts of

[85] The origin of these photos is unknown.

private companies and individuals as well as the municipality of Oberhausen. However, CMG became a significant fuel for transport in the late 1930s and early 1940s because of government policy. Germany did not have its own crude oil resources. Therefore, governance of alternative fuels for transport was essential in preparation for war since 1933 and in wartime since 1939.

In 1939 German government established the Central Bureau for Mineral Oil (Zentralbüro für Mineralöl GmbH) originally under the Economic Ministry, but it was later moved under the Ministry of Armaments and War Production, to control not only petroleum but also the alternative fuel technologies and businesses. Its tasks included controlling gaseous fuel production and setting up filling stations, controlling manufacturing of storage cylinders and other vehicle components, and controlling conversions of vehicles for gas use. The bureau set up 16 regional offices for supervising the work. Vehicles were ordered for conversion by public announcements starting from the vehicles with the highest consumption, as soon as production and filling stations were set up.[86]

Large amounts of many alternative fuels were used in Germany during the Second World War. Of these, synthetic liquid fuel use is much better known than gaseous fuel use, with the exception of producer gas vehicles. However, slightly more than 50 per cent of fuels used in civilian vehicles during the war in Germany were compressed and liquefied gases, including methane[87]. In addition, hydrogen was produced in large quantities for manufacturing of liquid synthetic fuels, especially synthetic gasoline, by Bergius synthesis.

Biogas was one of many alternative transport fuels taken into industrial production in Germany by state governance. In Sweden and Finland, production and use of traffic biogas in the 1940s was not governed by the state, but by municipalities. But the motivation was the same: wartime energy security.

3.1.1. Case Finland

The traffic biogas system in Helsinki in the 1940s is one of the clearest examples of municipally governed technology systems. It was created and completely controlled by the Helsinki City Board (Fig. 4). Restrictions caused by the war were certainly one powerful motivation for this action, but not the only one. There were five other municipalities that also had biogas production during the war in Finland, but they did not use it for transport. The success story in Helsinki was the result of a long-term capacity building of municipal civil servants and employees of municipal companies, and four decades of progress in the use of biogas technology in sewage treatment. In the 1930s biogas was already being used in power and heat production. Transport applications were a logical step forward. Almost 100 vehicles of various types were converted by the City Construction Office using kits bought from Germany. Except for one vehicle owned by AGA, biogas use was restricted to the captive fleets of the City of Helsinki, its offices and companies. The City Board gave permissions for each vehicle conversion on application. The two filling stations (Fig. 22 and 34) were operated by Finska Aktiebolaget Gasaccumulator Oy, which in 1944 was renamed AGA Oy Ab[88].

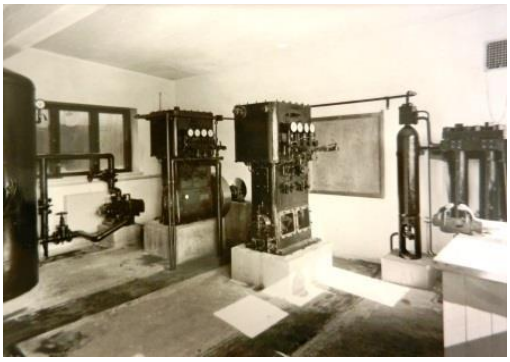

Figure 34. Compressors and high pressure storage at Rajasaari CBG filling station in Helsinki in 1943. [89]

[86] Simola (1940), Stokes (1985).
[87] Krammer (1978, 414).
[88] AGA currently operates filling stations in Sweden (Fig. 19b) and Norway, but not in Finland.

For the City of Helsinki the value of traffic biogas was over seven times higher than the value of biogas sold for power and heat production. This was one reason why the majority of biogas produced during the war was used in transport. After the war there was a debate whether to continue and expand the use of traffic biogas. The decision of the City Board was to shut down the traffic biogas system completely in 1946, when crude oil imports resumed. Graphs in Figure 35 show development of the amount of biogas vehicles and use of biogas in those vehicles in the 1940s in Helsinki.[90] Consumption of biogas was about the same as in Stockholm in 1942-1946 (see Fig. 17).

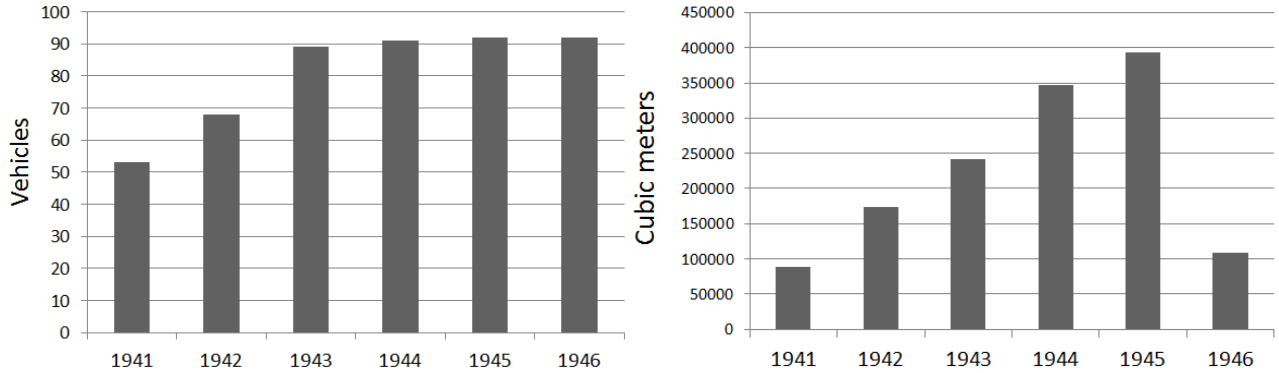

Figure 35. The number of CBG vehicles (a) and annual consumption of biogas (b) in transport in Finland in the 1940s.[91]

During the war many alternative fuels had been taken into use in many countries, but almost all, including biogas, were given up after the war in favour of crude oil based fuels. In Finland some alternative fuels were more persistent than others and they were removed from the market by state level actions, including a motive power tax of 1964 for promoting gasoline and diesel oil. This was done by setting an annual tax of about 10,000 euros for owners of vehicles, which were able to use renewable energy, such as biogas, renewable electricity, renewable hydrogen and lignocellulosic ethanol.[92]

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[89] Photo: Foto Roos/Photo archive of Helsinki City museum.

[90] The success story and downfall in Helsinki is described in detail by Lampinen (2012a).

[91] Data is from Lampinen (2012a).

[92] More information on these issues, i.e. subsidizing crude oil based fuels against renewable energy sources in Finland can be found in the article by Lampinen (2008). Also, wood waste based ethanol offers an interesting example of state policy. In the 1940s it originated from 14 factories established at sulphite pulp mills and still in 1957 it was distributed in 400 filling stations as E20-E30 (20-30 % vol. ethanol blended with gasoline). It was the high-octane premium fuel available at that time, suitable for all gasoline cars. However, in 1957 the first Finnish crude oil refinery in Naantali, owned by state company Neste, opened for business. By state level decision ethanol as an octane enhancer was given up and replaced by lead in 1957. Within a year all E20-E30 filling stations were shut down, the Finnish forest industry lost an important source of income and a fuel currently strongly promoted for environmental reasons, wood waste based lignocellulosic ethanol, was lost in the market. However, some alternative fuels still survived. To protect the imported crude oil business of a state company, which opened its second refinery in Porvoo in 1965, against domestic fuels originating from agriculture, forest industries and municipal wastes, a law on annual motive power tax was passed in 1964. This law, which came into effect in 1965, set a very large annual tax for owners of vehicles capable of using renewable energy sources, such as biogas, and alternative fossil fuels, such as natural gas. Annual tax rate in 2003 was about 10,000 euros for cars. This tax was removed in 2004 due to demands of majority of Finnish Parliament members and the EU Commission. The tax was in violation of the RES-T Directive (2003/30/EC) for promotion of renewable transport fuels. This tax was never applied to buses, meaning that bus use of biogas could have started at any time. It did not happen, but natural gas was taken into bus use in Helsinki in 1996 by municipal decisions. The decisions on taking CNG into bus use in Helsinki in 1996 was challenged in court by a diesel bus company, which lost the bid organised by the City of Helsinki despite being the lowest bid, due to higher emissions. The case went all the way to the EC court (C-513/1999), which ruled that the decision of the City of Helsinki were correct according to the

Removal of the motive power tax in 2004, 12 years after the Rio summit, enabled taking biogas again into transport use in Finland. The pioneer was the farmer Erkki Kalmari with Metener company, which he co-founded. He already started in 2002 with a demonstration project for which the tax was lifted (see lobbying work in Fig. 36a). Most of the technology of his farm scale traffic biogas production system is self-made.[93]

Figure 36. a) Erkki Kalmari showing the first biogas car in Finland since the war to Members of Parliament in front of the Parliament House in connection with a traffic biogas seminar in 2002[94]. b) Water scrubber at Kouvola sewage treatment plant in 2011.

In 2011 the first municipality, the City of Kouvola, joined using an upgrading plant bought from New Zealand (Fig. 36b). After that several other upgrading plants have been brought online. The largest of them is located at the City of Espoo sewage treatment plant. It is owned and operated by the state gas company Gasum. Gasum also operated, in October 2013, 17 public and 1 private (Helsinki bus depot) CBG filling stations. In addition, there were two public (Kalmari farm and Hamina municipal energy company) and two private (Haapajärvi agricultural school and Envor Biotech in Forssa) CBG filling stations operating in Finland in October 2013[95].

3.2. Second wave: Oil crises in the 1970s

Before the oil crises, biogas use in transport was almost, but not completely, forgotten. The British farmer and inventor Harold Bates began using biogas (as CBG) in his car in the 1960s and continued it in early 1970s (Fig. 37). His work was motivated by self-sufficiency based on local resources and a do-it-yourself

EU law, i.e. emissions can be taken into account in the bidding process. Later EU law has been improved in a way that taking emissions into account is no longer only allowed, but is mandatory (Directive 2009/33/EC).

[93] Lampinen (2004).

[94] Very much political lobbying work has been required in Finland to get biogas into transport use and maintain such use – the farmer Erkki Kalmari from Laukaa has not only pioneered traffic biogas use but has also done the hardest lobbying work to enable others to follow him. Unlike in most countries, in Finland the lobbying work for biogas and other renewable energy forms is not so much about increasing support for renewables as about decreasing support from fossil fuels. State level fossil fuel support in Finland includes, but is not limited to, tax and other financial benefits and state company ownership policy. A quantitative analysis of 38 financial support mechanisms for fossil fuels and a review of state energy companies are given by Lampinen (2013d). The main route for the 3rd wave, and sustainable development in general, to reach Finland has been the policy and legislation of the European Union.

[95] In addition, there were one public CNG filling station and two LNG ships in October 2013. The LNG ships are refilled from tank truck and tank boat. LBG production infrastructure existed, but only for export by tank trucks.

(DIY) mentality. He sold DIY conversion kits especially in Great Britain, but also in the United States, where a few of them were used as one technical option for reducing gasoline use during the first oil crisis.[96]

Figure 37. Harold Bates and his converted biogas powered model 1953 Hillman car in 1971.[97]

During the oil crises in the 1970s many alternative fuels entered the market, motivated mostly by energy security, like during the war. However, not much happened in the field of traffic biogas. New Zealand was a notable exception.

3.2.1. Case New Zealand

New Zealand created an excellent best practice case of state governed policy, for other countries to follow. During the first oil crisis the New Zealand Ministry of Agriculture set up a research group to investigate agriculture based energy sources, including biogas. During the second oil crisis the Ministry of Agriculture funded a biogas demonstration reactor, an upgrading unit and a filling station. The CBG filling station opened in 1979 and served a fleet of converted Ministry vehicles (Fig. 38a). The Ministry established a state company, Waste Solutions, for carrying out project development and commercialisation. After successful commercialisation the New Zealand Government sold Waste Solutions to a private company Suffill Watts.[98]

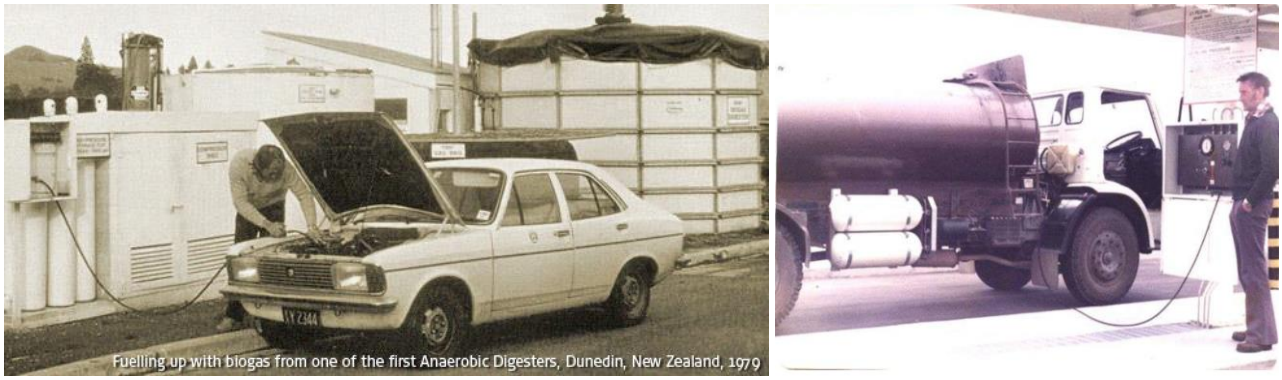

Figure 38. CBG filling stations in New Zealand: Dunedin agricultural reactor in 1979 (a) and Christchurch sewage treatment plant in 1983 (b).[99]

Simultaneously, natural gas was employed in transport using domestic resources. Fleet conversions began in the late 1970s. To promote adoption, the New Zealand government provided financial incentives in the form of cash grants and low-cost loans both to motorists and distributors. Within just six years, by December 1985, the number of CMG vehicles had grown to represent about 10 per cent of the total fleet and the annual CMG use increased from zero to 5.9 PJ.[100]

The City of Christchurch became the first municipality in the world to use biogas for transport since the 1940s. They opened an upgrading plant and a CBG filling station at a municipal sewage treatment plant in 1983[101] (Fig. 38b). It was designed to serve 70 municipal vehicles of different kinds, including sewage trucks.

[96] Grindrod (1971), MEN (1974).
[97] Grindrod (1971).
[98] Waste Solutions (2011).
[99] Photos are from: a) Waste Solutions (2011), b) Bourke (2010).
[100] Lonergan & Cocklin (1990), Yeh (2007).
[101] Bourke (2010).

Other projects followed. By the end of the 1980s New Zealand had become the leading country in the world in the number of methane filling stations: 450 (CNG and CBG). And it was second in the world after Italy by the number of MGVs: 110,000, all of which had been converted in New Zealand within a decade.[102]

Very innovative state level actions followed by municipal level actions created a private domestic industry covering all aspects of traffic biogas production and use. However, biogas use in New Zealand ended after the oil crises, as a result of state policy[103]. The pioneering production plant in Christchurch was shut down in 1994. By December 2010 the amount of MGVs had plummeted to 200 and only 14 filling stations remained for their service (traffic biogas use was restarted in 2010).

Despite the collapse of the domestic market the New Zealand companies benefited from their pioneering position and were instrumental in initiating traffic biogas production in many other countries, like Sweden and France in the 1990s. Some New Zealand companies have maintained a strong global market presence, for example the upgrading plant manufacturer Flotech Greenlane (Fig. 36b shows a Greenlane water scrubber in Kouvola) and filling station component manufacturer Compac (Fig. 19a shows a Compac filling station in Stockholm).

3.3. Third wave: Sustainable development since the Rio summit

Sustainable development rose into global, national and local political agendas by the early 1990s due to the efforts of the United Nations, especially the Bruntland report in 1987 and the Rio summit in 1992. Many environmental technologies benefited from this new policy direction, traffic biogas technology being one of them. Unlike in the cases of the war (1st wave) and the oil crises (2nd wave), when traffic biogas technology was temporarily employed for energy security reasons, now (3rd wave) traffic biogas became a permanent part of the portfolio of technologies for reducing environmental impacts.

Technical motivation, the superior technical characteristics of methane as a 130 octane engine fuel, has supported environmental and energy security motivations. As the price of crude oil has risen, the economic motivation has become continuously stronger. Currently the tax free price of biogas is lower than the tax free price of gasoline and diesel oil. It means that it is competitive even without tax benefits, which most countries grant. These four motivations have recently been joined by a resource motivation. It has been shown that the biogas and synthetic biogas resources in the European Union are larger than the EU transport energy consumption[104]. And the total renewable methane (Fig. 1) resource is much larger especially due to the solar and wind energy potential. On the other hand, methane may act as the storage of solar and wind energy, enabling a very high share for these intermittent energy sources in energy consumption, including also electricity and heat. For these and many other reasons a renewable methane economy could serve as the backbone in the sustainable societies of the future[105].

[102] Stephenson (1991).
[103] All incentives were withdrawn from methane use coincidentally with rapidly lowering price of crude oil. This was a part of a wider failure in New Zealand to reduce crude oil dependency by adapting a more "market oriented" approach, see Lonergan & Cocklin (1990).
[104] FTF (2011).
[105] In 2012, the Finnish Biogas Association published a roadmap of renewable methane in all transport modes until 2050, as part of a sustainable development roadmap. The original 133-page publication is in Finnish, but a 31-page extended summary is available in English (Lampinen 2012b).

3.3.1. Case Sweden

Swedish municipalities were the initiators and leaders in the third wave. It began in the City of Linköping, which started experimenting with raw purified biogas in 1989, upgraded biogas in 1992 and finally brought the technology into commercial use in 1996, first as a fuel for city buses. This development was run by the Linköping technical office, Tekniska Verken, which also began vehicle conversion work in 1992. The municipal company Linköping Biogas AB was established in 1995 for the production of biogas and upgraded biogas as well as for running public filling stations and a private filling station at the city bus depot (Fig. 39).

Figure 39. CBG filling stations in Linköping in January 2003 before founding of Svensk Biogas: a) public station, b) bus depot.

In 2003 the municipal company Svensk Biogas was established for expanding sales of traffic biogas both in Linköping and elsewhere in Sweden[106]. In 2006 biogas use expanded to regional rail transport, by introducing the first biogas powered train in the world (Fig. 40), and a private company Swedish Biogas International was founded to export the extensive process knowledge that has evolved in Linköping to a national and international market.[107]

Figure 40. The first biogas powered train in the world started operation in 2006 between Linköping and Västervik.

The extremely innovative municipal work in Linköping, where almost all the related business was vertically integrated and controlled by Tekniska Verken, soon gained followers. Demonstration use of traffic biogas began in Gothenburg in 1992 and commercial use in 1996 in Trollhättan, Uppsala and Stockholm. Currently dozens of municipalities have started the work and many private companies have joined the business, which has expanded to about 50 upgrading plants and 200 filling stations. In several municipalities public-

[106] Currently Svensk Biogas operates 12 filling stations, of which 5 in Linköping, and also transports CBG by trucks to other filling stations in several cities, for example Stockholm.
[107] The success story in Linköping is described by Linköpings kommun (2008).

private partnerships have been actively created and maintained, Stockholm being the prime example[108]. In addition to CBG filling stations, LBG filling stations have been operated since 2010.

Provincial work is also significant for traffic biogas in Sweden. Regional biogas centres (Biogas Öst, Biogas Syd, Biogas Väst, Biogas Sydost, Biogas Mitt and Biogas Norr) have been established by provinces, municipalities and private companies to coordinate work. Many provinces have set their own ambitious targets for traffic biogas production and use and implemented them, for example in regional public transport in the province of Skåne.

The original source of biogas for transport use was sewage treatment plants (like in the 1st wave) and they still form the main source of traffic biogas in Sweden today. However, the role of municipal and industrial solid waste and agricultural waste is increasing. In 2012 over half (51 %) of all biogas produced in Sweden was used in transport (98.3 % as CBG and 1.7 % as LBG)[109]. This is expected to grow to 86 per cent by 2020 according to the Swedish national renewable energy action plan.

The Swedish government has supported traffic biogas development by research and investment grants, and also helped initiating similar development in other countries. For example, in Delhi biogas was introduced in transport in 2013 as a result of Swedish official development assistance.

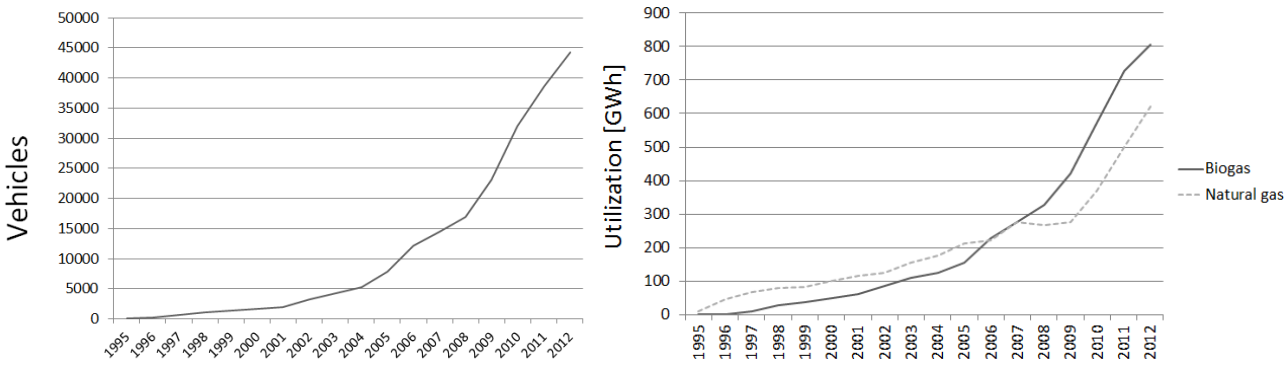

Figure 41. Development of MGV fleet (a) and utilization of biogas and natural gas in transport (b) in Sweden in 1995-2012.[110]

Public policy on municipal, provincial and national level has helped creating a large Swedish private industry for production and use of CBG and LBG resulting in strong growth as shown in Figure 41. Biogas surpassed natural gas in 2006 and the current share of biogas is about 60 per cent of traffic methane use in Sweden.

[108] The success story in Stockholm is described e.g. by Vernay et al. (2013).

[109] Statens energimyndighet (2013). In the end of 2012 there were 53 upgrading plants in Sweden. Of these 11 injected upgraded biogas into natural gas pipeline. The rest (42) were outside of the NG pipeline. Most of upgraded biogas was transported by local biogas pipelines and trucks. The rest (28 %) was transported by NG pipelines. There were 195 biogas filling stations, of which 138 were public. The rest (57) were private. Most of these (37) were located at bus depots. The rest were located at waste truck, municipal vehicle and private transport company depots. There were 44,000 MGVs of which 1800 were buses and 600 trucks. Of traffic methane use 59.5 % was biogas and the rest was natural gas.

[110] Data is from Energigas Sverige (Gasbilen.se).

3.3.2. Development in other countries

City of Lille in France was the first municipality outside Sweden to be start utilizing biogas in transport during the third wave. The first four biogas city buses started operation in 1994 after two years of experimentation (Fig. 42a).

Figure 42. a) Biogas bus in Lille, France. b) The first CBG filling station in Germany since the war opened in Jameln in 2006.

Many countries have followed Sweden and France. Germany, the original pioneer in the first wave, was very slow to join the third wave: the first upgrading plant and filling station was opened as late as 2006 in Jameln (Fig. 42b). Rapid development has followed, however: there are now over 100 upgrading plants and 300 CBG filling stations (and 600 CNG filling stations), of which over 100 are CBG100 stations.

Currently CBG filling stations are found in Germany, Sweden, Finland, Norway, Iceland, the Netherlands, France, Switzerland, Austria, Spain, Italy, the United Kingdom, New Zealand, India, China, South Korea, Japan, Canada and the United States. LBG filling stations are found in the United States, the United Kingdom, the Netherlands, Norway and Sweden. In Denmark upgraded biogas is injected in to NG pipeline and there are CNG filling stations, but biogas is not yet available in the stations. All of the CBG and LBG stations mentioned above sell biogas (including landfill gas). Other types of renewable methane are still rare. In October 2013 SBG was available only in Austria and wind methane only in Germany. By the end of 2013 SBG will be available in Sweden.

Table 5 shows a great diversity in the characteristics of a few countries participating in the third wave. The development in all countries has started either by municipal or by private efforts. In addition, provincial governance is important in Sweden and state governance in Finland (by state company Gasum). The original primary motivation is environmental or economic in most countries. However, in Finland it was the energy self-sufficiency of a farm. The original source of biogas is sewage sludge, municipal solid biowaste, manure or landfill gas. The traffic use of biogas usually starts with compressed biogas. However, in the United Kingdom it started with liquefied biogas. Iceland is the only country in the world where all methane fuel is renewable. In all the other countries natural gas is also used, and in the United States also shale gas.

Table 5. Characteristics of traffic biogas systems in the third wave in selected countries.[111]

Country, year and city	**Original source**	**Original form**	**Governance /original**	**Governance /other**	**Original primary motivation**
Sweden 1989 (Linköping)	Sewage	CBG	Municipal	Provincial, Private	Environment
France 1992 (Lille)	Solid waste	CBG	Municipal	Private	Environment
USA 1993 (Los Angeles)	Landfill gas	CBG	Private		Economics
Switzerland 1995 (Rümlang)	Solid waste	CBG	Private	Municipal	Economics
Italy 1996 (Rome)	Landfill gas	CBG	Municipal		Environment
Iceland 1999 (Reykjavik)	Landfill gas	CBG	Municipal		Environment
Finland 2002 (Laukaa)	Manure	CBG	Private	Municipal, State	Energy security
Germany 2006 (Jameln)	Manure	CBG	Private		Economics
United Kingdom 2008 (Albury)	Landfill gas	LBG	Private		Economics

There is also a great diversity in the characteristics of natural gas systems for transport in various countries, as seen in Table 6. Most noteworthy are Pakistan and Bangladesh, where the penetration of MGVs is already over half of the total national motorised road vehicle fleet (not including motor cycles and other light vehicles). The role of state governance is stronger than in the case of biogas systems, because natural gas pipelines are state controlled. Private and municipal governance are also important. Although provincial governance does not have a primary role in any country, it is significant in the United States. Already in 1969 the Governor of California Ronald Reagan announced that his states fleet of 28,500 vehicles would eventually be moved to natural gas use[112]. In 2012 Governors from 22 US states announced that a coalition of 22 states will buy 10,000 new CMG vehicles annually. This way demand was created for the domestic manufacture of CMG vehicles.

Table 6. Methane gas vehicle (MGV) statistics, vehicle market penetration, governance and motivation in the end of 2010 in selected countries.[113]

World position	Country	MGVs	MGV share of cars, vans, trucks and buses	Filling stations	Primary governance	Primary motivation
1.	Pakistan	2,850,000	82 %	3300	State	Energy security
2.	Iran	2,070,000	17 %	1600	State	Energy security
3.	Argentina	1,920,000	15 %	1900	Private	Economics
4.	Brazil	1,660,000	4.7 %	1800	Private	Economics
5.	India	1,100,000	7.5 %	600	Municipal	Environmental
6.	Italy	770,000	1.8 %	830	Private	Economics
11.	Bangladesh	200,000	61 %	500	State	Energy security
13.	Egypt	140,000	5.9 %	130	State	Energy security
16.	USA	110,000	0.04 %	1100	Private	Economics
17.	Armenia	100,000	30 %	300	State	Energy security

[111] These are author's assessments based on a large amount of magazines, conferences and private communications of the trade as well as many studies, including those found in the bibliography.
[112] Gross (1970).
[113] Sources for statistics: Boisen (2011) for market penetration, GVR (2011) for other. Numbers are rounded. Primary governance and motivation are author's assessments based on a large amount of magazines, conferences and private communications of the trade as well as many studies, incl. Yeh (2007), Collantes & Melaina (2011) and IGU (2012). Most or all of the traffic methane in these countries is natural gas. Biogas is used in Argentina, India, Italy and USA, and shale gas is used in USA.

Although methane use in transport started in Europe, and Europe was leading the global market until the late 1980s, since then the growth has been larger in other continents. In the 1980s the Oceanian market was strong due to the efforts in New Zealand. The South American market dominated development between 1995 and 2007 driven by Argentina and Brazil. After that the Asian market has been the largest, especially due to the very large growth in Pakistan, Iran, India and China. The global development in the number of MGVs since the 1980s is shown in Figure 43. The collapse of the market in New Zealand is visible as a decreasing trend until the early 1990's.

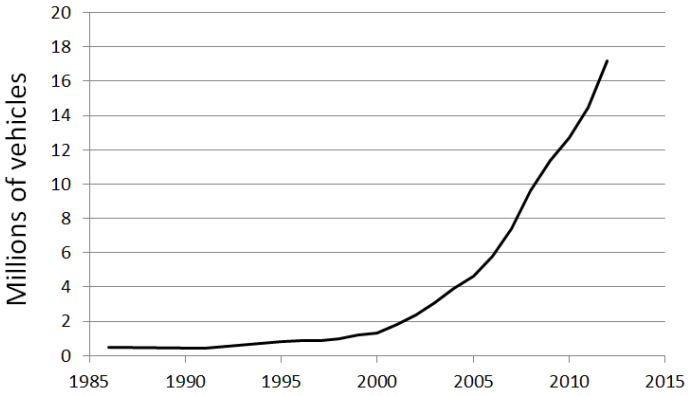

Figure 43. Development of global fleet of MGVs from 1986 to 2012.[114]

Germany was the top country from 1920s until 1940s, but has now fallen into 19th position with just under 100,000 MGVs (April 2013). After Germany, Italy kept the number one position until the early 1990s and is still number seven in the world with a fleet of 820,000 (July 2013). Italian conversion kits, for example by Tartarini company (Fig. 16a), have been instrumental in development of MGV fleets in most countries.

Argentina, currently in third position in the world with 2.3 million MGVs (June 2013), had the largest market from the early 1990s until 2007 and was the first country to pass the 1 million MGV mark in 2003. In 2003 the sales of methane for transport reached the sales of gasoline. This was a result of a state controlled development, which began after discovery of natural gas field in Patagonia in 1980. The main reason for the success has been fuel price regulation[115]. Argentinian filling station manufacturers are strong in the global market (Fig. 44). The most northern public CMG filling station in the world, in the city of Hammerfest, Norway, has an Argentinian Galileo filling station (only CNG is sold there).

Figure 44. An Argentinian Galileo filling station in Stavanger, Norway. In this station CBG100 and CBG33 are sold.

Pakistan passed Argentina in 2008 and was also the first country to reach 2 million MGVs that same year. In Pakistan the development began after the oil crises in the mid-1980s, when the Hydrocarbon Development Institute of Pakistan, a government agency, opened filling stations in two of the largest cities. Pakistan is currently number two in the world with a fleet of 2.8 million MGVs (March 2013).

[114] Sources of data: Harris (1988), NGV Global and NGVA Europe.
[115] The Argentinian success story is described by Collantes & Melaina (2011).

Iran became the number one country in 2011 and reached 3 million MGVs in 2012. In the latest statistics from April 2013 Iran was the world leader with 3.3 million MGVs. The development in Iran has almost completely taken place during the administration that was in power in 2005-2013. It is a result of a very strong emphasis on energy security. The growth rate has been phenomenal: in the end of 2004 there were only 1000 MGVs.

3.3.3. The consumer perspective

Consumer demand is, of course, important part of the third wave. There are increasing number of consumers who are responding to the global sustainable development challenges by changing their market behaviour. Consumers wishing to move their vehicles to 100 per cent renewable energy use face many obstacles still today. Brazil is the only country in the world, where 100 per cent biofuels (E100, i.e. 100 % ethanol) are commonly available. In Europe biodiesel and ethanol are the leading biofuels. However, ethanol is never available as a 100 per cent fuel, but always in blends (usually E5, E10 or E85) with crude oil based fuels. Biodiesel is available as 100 per cent fuel (B100), but it is very rare. Almost always it is used in blends (B7, B20 etc.) with crude oil based diesel oil. Pure plant oil is available in a few stations as a 100 % fuel (PPO100). Electricity is available in many countries for charging electric vehicles, but very rarely 100 % renewable electricity. Almost always consumers must use mixed electricity, which usually has large fossil energy content.

In many countries biogas (CBG100) is the only 100 per cent renewable fuel available to consumers in public filling stations. Currently it is, in principle, possible to drive, for example, from Helsinki to Monaco by CBG100. However, in practice, there are obstacles in all countries on the way. And they are different in each country:

1. In Finland only one public CBG100 station accepts credit cards and none accept cash. In all other stations specific customer cards are required.
2. In Sweden many CBG100 stations are available, but this information is never given at the station (although many CBG50 stations are clearly marked, see Fig. 45) and it is not given at national biogas station guide publications either. Therefore, customer needs to find the information from other sources (considerable amount of expertise and work is required). Skellefteå is one example (Fig. 46).

Figure 45. CBG50 pump in Stockholm.

3. In Denmark there are currently no CBG stations of any kind and only two public CNG stations. But it is possible to drive through Denmark without refilling.
4. In Germany about 150 CBG100 stations are available and they can be found using national methane station guides. However, at the filling stations this information is rarely given to the consumer.
5. In Switzerland CBG100 is available in many stations, but only using specific customer cards with special contracts. For customers using credit cards or cash, only CBG10 or other low blend mixture with natural gas is available. However, there are no stations selling 100 per cent natural gas, only blends with at least 10 per cent biogas, because this minimum is required by national legislature.
6. In France CBG100 is only available at three public stations. The rest are private.
7. In Italy CBG100 is only available at private stations.

Due to the network of over 3000 public methane stations in Europe (including CBG100 stations, CNG stations and stations, where CBG/CNG blends are for sale) there are only a few completely crude oil

dependent regions remaining in Europe. However, much needs to be done for making CBG100 widely available for consumers wishing to refill with it (Fig. 46).[116]

Figure 46. A Finnish consumer obviously wishing to refill with CBG100 doing so in Skellefteå, Sweden.

The private sector has partially solved this in some countries, but for international travellers practises in different countries will continue to differ, unless intervened by EU wide public sector policies. The first step is to require a Certificate of Origin of the type of sold gas the same way as is required from electricity today, for example in the European Union. This makes it possible for consumers to choose the type of gas they buy, not only for transport, but for power and heat production also. This also makes it easier to apply environmental policies both to promote sustainable renewable methane and to discourage the market introduction of unconventional fossil methane. To enable European wide availability of 100 per cent renewable methane, it is also necessary to remove the type of obstacles mentioned above. In all methane stations, where renewable methane is available, all customers should be able to purchase 100 per cent renewable methane.

4. Conclusions

Technology for utilizing biogas in transport applications evolved from transport use of manufactured gas and synthetic natural gas in the 1930s in Germany. By the 1940s technical maturity was reached, and only marginal development has been needed since then. The main reason for the early technological success was Nicolaus Otto's engine, which became the most widely used engine in transport applications. Otto's engine is a gas engine, making it easier to use gaseous fuels than liquid fuels. Technologies of compression and compressed gas storage reached maturity by the 1930s. Almost all modern compressed methane vehicles have 200 bar storage cylinders because that pressure was adopted in compressed town gas vehicles in the 1930s.

Three distinct waves of traffic biogas utilization have been identified in this paper. The first two waves, the Second World War in the 1940s and the oil crises in the 1970s, were both motivated by energy security and the second wave also by economics, the high price of crude oil. State governance was crucial to initiate traffic biogas system creation in both the first wave (Germany) and the second wave (New Zealand), but without municipal governance the diffusion of technology would have been slow. In the cases of Finland and Sweden traffic biogas systems would not have been created during the first wave without very strong municipal governance.

[116] The Finnish Biogas Association published a set of proposals in a form of a discussion paper to enable CBG100 network development in Europe (Lampinen 2013c).

A common feature of the first and the second wave is the abandonment of the technology after the crises, when crude oil deliveries resumed and the price came down. After the first wave not only was the use abandoned, but all the technology disappeared from the market, and had to be rediscovered later. The second wave was different in this respect: the technology developed in New Zealand survived, despite the home market being shut down by state policies, and had a crucial role to play in initiating the third wave. Energy security was not a strong enough motive either for state or municipalities for operating traffic biogas systems, when crude oil was available at a low price. In the absence of a severe crisis, practical policy making concerning energy security is in many countries very vulnerable to low prices of imported fossil fuels, regardless of what have been adopted in national strategies. This is sometimes called market oriented policy or neoliberal policy. The same approach is often applied at a municipal level to avoid efficient utilization of local resources, such as municipal solid and liquid wastes. However, in several countries, for example in Pakistan, natural gas use in transport has survived the crude oil price fluctuations. With over 80 per cent share for natural gas in the road transport energy consumption, Pakistan has showed that crude oil dependency can be broken. In this case energy security has had more political weight than in other countries without the presence of an acute crisis.

The third wave differs significantly from the first two. The primary motivation is sustainable development, with energy security, economics, technology and resources also as important motivations. Sweden was the initiator of this wave, with municipal governance varying diversely from vertically integrated control to management of public-private partnerships. Many countries have followed, with different types of governance, including private, municipal, provincial, state and their combinations. The diversity of motivation and governance has guaranteed that the use of biogas – and due to the emerging technological developments during the past few years also other types of renewable methane – is constantly increasing. It does not seem likely that the technology would be abandoned this time. On the contrary, renewable methane is one of the most sustainable transport power sources, together with renewable hydrogen and direct and indirect renewable electricity. These are expected to be used also in the long term, when non-renewable and unsustainable renewable energy forms have been phased out. However, despite the strong factual basis for rapid market diffusion of these technologies, the lock-in to crude oil based technology is very difficult to break. History offers both good and bad examples for others to follow. Large diversity is expected to continue on the ways multinational, national, provincial and municipal policies are able to deal with it.

The selection of sources of methane is crucially important for environmental reasons. Renewable methane (Fig. 1) offers large environmental benefits compared to natural gas, whereas SNG and unconventional fossil methane (Fig. 2) offer large environmental risks compared to natural gas. Coal based SNG, which was the first methane fuel taken into transport use, is no longer so utilized. However, the first unconventional fossil resource, shale gas, was adopted for transport use in the United States a few years ago. Unconventional fossil methane has a significantly larger resource base than natural gas, even much larger than all other fossil fuels combined, but utilization of these resources also carries risks for severely more serious and diverse negative environmental impacts than natural gas utilization has. Since sustainable renewable methane resources are also vast, it is up to the political decision makers at all levels to control which sources are accepted and disseminated in the market.

Glossary

AMG	Adsorbed/Absorbed Methane Gas; fossil or renewable energy.
BG	BioGas; bioenergy. Biogas is a methane fuel produced by microbial metabolism from biomass (in the context of transport use it usually means upgraded biogas). Note: raw biogas can not be used in normal MGVs (and neither can raw natural gas).
BG100	100 % biogas. Methane fuel consisting of biogas only.
Bifuel MGV	MGV able to use other fuel (usually gasoline) in addition to methane fuels.
Biomethane	Methane fuel originating from biomass, based on biogas and/or synthetic biogas. It usually means upgraded gas.
CBG	Compressed BioGas (mostly methane); bioenergy.
CBG100	100 % compressed biogas, i.e. not a blend with CNG or other type of CMG (the definition may be extended to include other renewable methane fuels such as CWM and CSM).
CBGxx	Blend of CBG and CNG, where "xx" gives the percentage of CBG in the mixture, e.g. CBG20 and CBG50.
CBM	Compressed BioMethane, i.e. consisting of BG and/or SBG based methane fuels.
CFM	Compressed Fossil Methane, i.e. consists of natural gas and/or SNG and/or unconventional fossil methane, such as shale gas.
CMG	Compressed Methane Gas; fossil or renewable energy. Compressed methane gas may originate from any source, including biogas and other renewable methane fuels as well as natural gas and other fossil methane fuels.
CNG	Compressed Natural Gas (mostly methane); fossil energy.
CRM	Compressed Renewable Methane, i.e. methane fuel originating from any renewable energy source, including but not limited to CBM, CSM and CWM.
CSBG	Compressed Synthetic BioGas.
CSM	Compressed Solar Methane, i.e. methane fuel manufactured by solar energy using various methods.
CTG	Compressed Town Gas (mostly hydrogen and carbon monoxide); fossil or bioenergy.
CWM	Compressed Wind Methane, i.e. methane fuel manufactured from carbon dioxide and wind hydrogen (wind hydrogen is manufactured by electrolysis from water using wind power).
DME	DiMethyl Ether (gaseous diesel engine fuel).
Dualfuel MGV	MGV with compression ignition engine, where ignition fuel is a diesel fuel.
Hybrid MGV	MGV with electric motors, either with electricity charging option (plug-in hybrid) or not (in this case it is a monofuel MGV).
Hythane	Blend of methane and hydrogen suitable for use in MGVs.
LBG	Liquefied BioGas (mostly methane); bioenergy.
LBG100	100 % liquefied biogas.
LMG	Liquefied Methane Gas; fossil or renewable energy.
LNG	Liquefied Natural Gas (mostly methane); fossil energy.
LPG	Liquefied Petroleum Gas (mostly propane and butane); fossil energy.
LSNG	Liquefied Synthetic Natural Gas (mostly methane); fossil energy.
Methane fuel	Mixture of gases, where all or most energy is in the form of methane (CH_4); usually it means upgraded gas, where the shares of inert components have been substantially reduced.
MG	Methane Gas, i.e. any type of methane fuel; renewable or fossil energy.

MGV	Methane Gas Vehicle, i.e. a vehicle able to use methane fuels (in addition it may be able to use other energy sources such as gasoline, ethanol, diesel oil or electricity). MGVs include but are not restricted to CMG and LMG vehicles.
Monofuel MGV	MGV using methane fuels only (and like all MGVs can utilize hydrogen, propane and butane in small percentage of the fuel).
Multifuel MGV	MGV able to use at least two other fuels (usually gasoline and ethanol) in addition to methane fuels.
Natural gas	Methane fuel produced and stored by nature; fossil energy.
NG	Natural Gas; fossil energy. Natural gas usually means upgraded natural gas. Note: raw natural gas can not be used in normal CMG vehicles, only upgraded natural gas can be used.
NGV	Natural Gas Vehicle. In most uses an obsolete term, because these vehicles can use CBG and any other methane fuel (see MGV). However, it is a relevant term, when meaning only NG and excluding other methane fuels.
Purification	Removal of pollutants such as sulfur compounds from raw gases, e.g. raw biogas and raw natural gas. Note: this is different from upgrading.
RE	Renewable Energy.
SBG	Synthetic BioGas (mostly methane); bioenergy. SBG is a methane fuel produced by thermochemical methods from biomass.
SNG	Synthetic Natural Gas (mostly methane); fossil energy. SNG is a methane fuel produced by thermochemical methods from coal or other fossil fuels.
Solar methane	Solar energy based methane fuel.
Synthetic gas	Man-made gas, produced using various thermal, biological and chemical conversion processes, e.g. manufactured gas, biogas, synthetic biogas, synthetic natural gas and hydrogen.
Traffic biogas	Biogas used in transport applications.
Traffic methane	Methane fuel used in transport applications.
Upgrading	Reduction (by various methods) of inert components, always CO_2 and sometimes also N_2 (which are not pollutants), from purified biogas, purified synthetic biogas, purified natural gas or purified synthetic natural gas to increase the energy density of the gas mixture. This is required for utilization of NG, SNG, BG, SBG and other methane fuels in modern factory made MGVs. Note: all natural gas and biogas transported in the European gas transmission pipelines and most gas transported in local distribution pipelines are upgraded.
Wind methane	Wind energy based methane fuel.

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