

# DEVELOPMENT OF BIOGAS TECHNOLOGY SYSTEMS FOR TRANSPORT

Ari Lampinen

Biogas was first adopted as fuel for transport use in Germany in the 1930s. These days it is widely used as a sustainable alternative to fossil fuels. This article examines the historic background and the motives for the use of traffic biogas. The emphasis is on sustainability issues, but other renewable methane fuels, such as synthetic biogas, wind methane, and fossil methane fuels such as natural gas and synthetic natural gas, are also included. The history of pressurised town gas, which played an important part in the adoption of methane for traffic use, is also examined. Three key 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. The article looks at the use of traffic biogas in a global perspective, although most of the examples are from Europe, as the majority of the technological and political advances have been European.

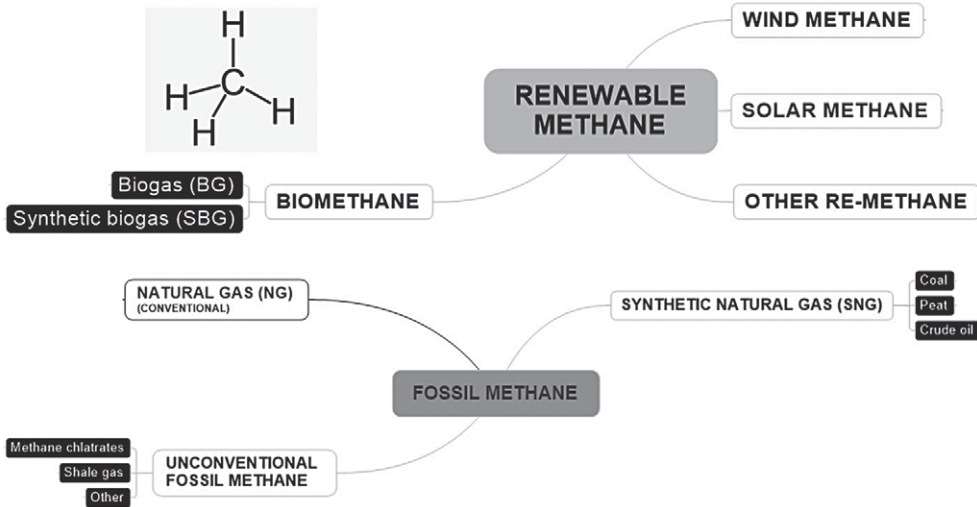
## 1. INTRODUCTION

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 5). Use of methane in transport is

Figure 1. Types of renewable and fossil methane.



a mature technology in all parts of the fuel chain and there are almost 20 million methane vehicles in use today globally.<sup>1</sup> Waste based biogas is already available in almost 1000 filling stations in Europe enabling European-wide transport by sustainable renewable energy (Fig. 9).

Methane ( $\text{CH}_4$ ) can be produced from all types of renewable energy sources as well as many fossil energy sources (Fig. 1). The available resources are much larger than the global total energy consumption and can easily fulfil all transport energy needs.<sup>2</sup> 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 (COM(2013)17), which requires a certain minimum filling station and charging network for these three, potentially the most sustainable technologies, to be established in all member countries.

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.<sup>3</sup> Sustainability issues also limit the use of energy crops for the production of bio-methane.<sup>4</sup> Until the 1990s, all biogas used for transport was produced from biowaste, mostly municipal sewage. Since then some energy crops have also been used, but almost all traffic biogas is still produced from waste materials globally. Biogas and other renewable forms of 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.<sup>5</sup>

This article gives a review of the historical development of methane based transport systems, the governance of such systems and the motives behind building such systems. The 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 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 battery-powered electric vehicles.<sup>6</sup>

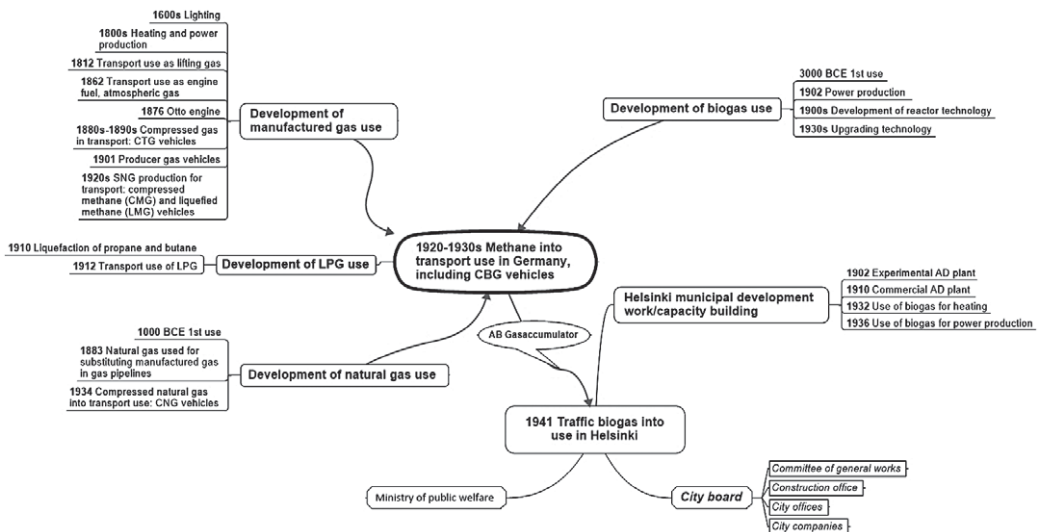
A review is also given of the use of manufactured gas in transport, because it paved the way for methane fuels. The transport use of manufactured gas has been almost forgotten, with the exception of producer gas vehicles. The use of manufactured gas in gas bag vehicles and in compressed town gas vehicles ended in the 1940s and those vehicles are very rare in museums 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 article contains a description of global technological development of gaseous fuels used in motorised transport since the first demonstration in 1808 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 an interesting time also because of the especially high diversity of gaseous fuel use. For these reasons more space in this article is devoted to the 1940s than to other time periods. Part 2 also presents a brief history of other, recently adopted, types of renewable methane fuels, and fossil methane fuels, which today are more common than renewable methane fuels.

Part 3 contains an analysis of the governance and motivations behind setting up

**Figure 2.** 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.



waste based biogas 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 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 for engines for mechanical transport. Hydrogen ( $H_2$ ) was used in the first ever demonstration of an internal combustion engine powered car in 1808 in Switzerland by François Isaac de Rivaz<sup>7</sup>. 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 2 depicts technological pathways leading to the use of methane in transport. Both biogas and natural gas have been used for millennia, but their transport applications only emerged a few decades ago.

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.

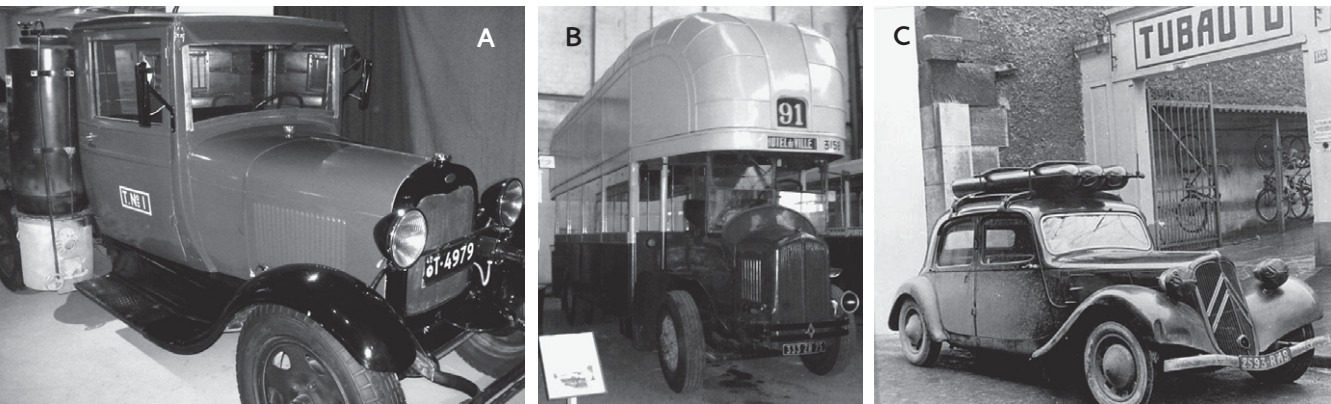
### 2.1. Manufactured gas

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.<sup>8</sup>

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 (discovered in natural gas in 1876) are lighter and thus have better lifting properties.

Energy gas	LHV [kcal/Nm <sup>3</sup> ]
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

**Table 1.** Lower heating values (LHV) of selected energy gases in the 1940s. Adapted from Talvitie (1944, 140 and 176).



**Figure 3.** 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 [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].

Transport fuel use began in the 1860s. Manufactured gas was demonstrated in the Hippomobile car of Jean Joseph Étienne Lenoir of Luxembourg in 1862<sup>9</sup>. Manufactured gas was also the original fuel of Nicolaus Otto's engine in 1876 in Germany. 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: 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).

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. 3). 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.

#### 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.

The first use of producer gas in transport was by the English inventor J.W. Parker, fuelling 2.5 and 25 horsepower cars

in 1901–1903.<sup>10</sup> 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.<sup>11</sup> 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 (more often called defence policies), because of the excellent availability of local fuel for them even in crisis situations, when trade is interrupted.

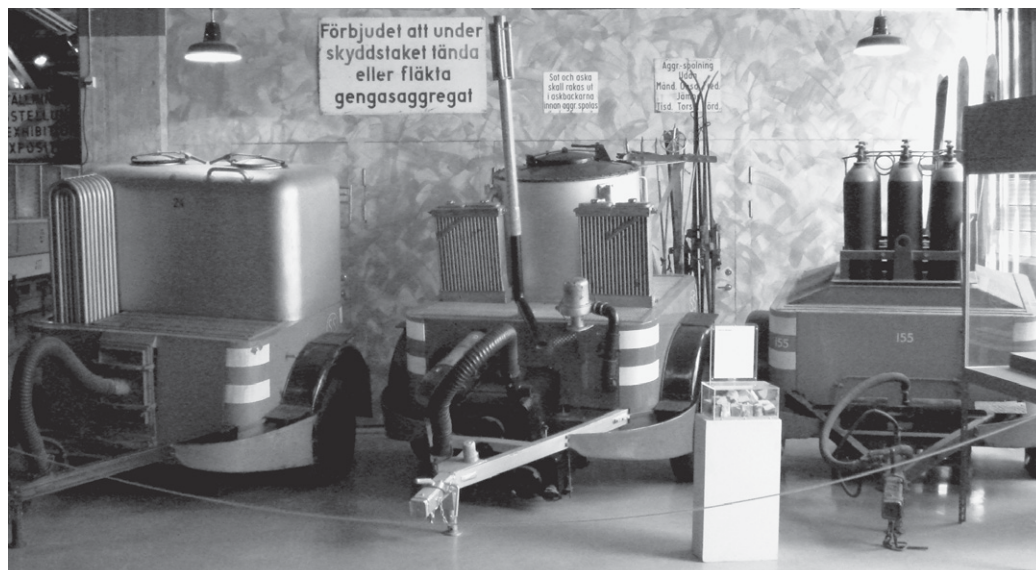
Figure 3a is from the Finnish railway museum in Hyvinkää showing a Finnish railway company owned Ford AA truck model 1929 fitted with a producer gas system for charcoal use. This truck was used

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 4 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 Spårvägmuseet. They were interchangeable between buses and could also be exchanged for biogas trailers, which contained compressed biogas. The biogas originated from a municipal sewage treatment plant.

### 2.1.2. Gas bag vehicles

Atmospheric gas storage with centralised production and refuelling was the original way of using manufactured gas. It was most frequently used during the First World War, but also during the Second World War in Europe. Gas was stored in flexible bags

**Figure 4.** 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. Photo: Ari Lampinen.



either on the roof of the vehicle or on a trailer<sup>12</sup>. 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 3b. 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.<sup>13</sup> But there were still 80 filling stations in London in 1940.<sup>14</sup> The gas bag technology had improved to use up to 10 bar low pressure gas.<sup>15</sup> 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 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 used. A CTG vehicle example is shown in Figure 3c. 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.<sup>16</sup> 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.<sup>17</sup> In Australia, one gas tram was operated in Melbourne in 1886–1888.<sup>18</sup>

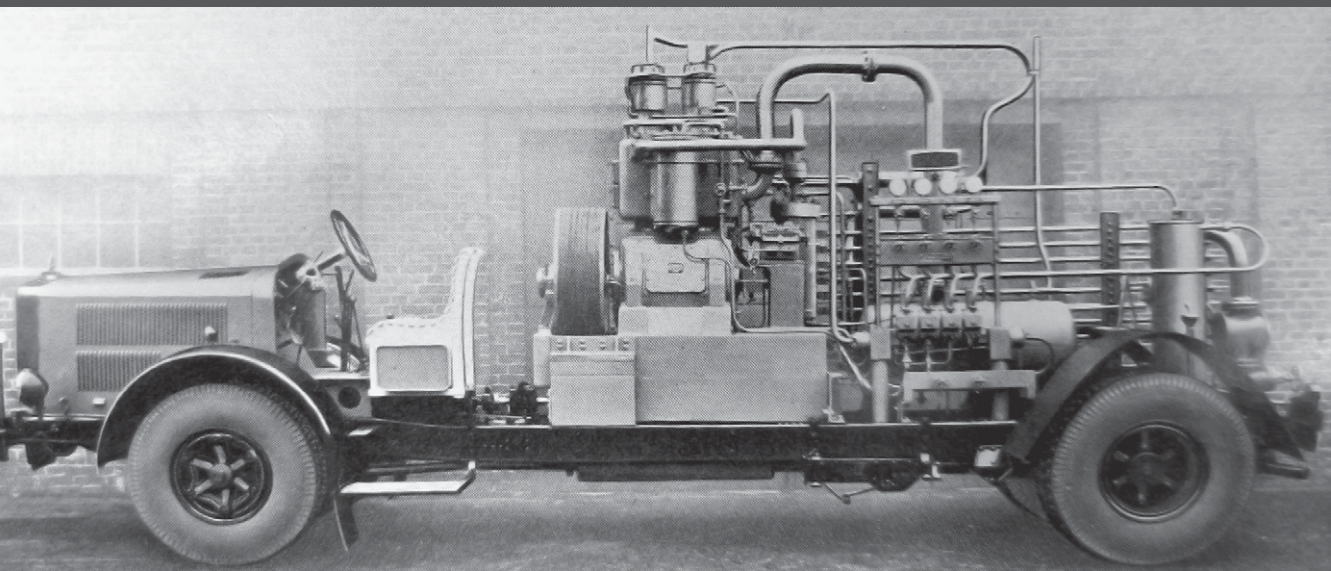
In Europe compressed manufactured gas was used in trams from 1893 until 1920.

CTG trams were introduced in 1893 with technology provided by the German company Lührig using 8–10 bar storage pressure and Otto engine.<sup>19</sup> CTG trams were used in Germany, Great Britain and Switzerland. 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 in 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.<sup>20</sup> 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.<sup>21</sup> Vehicle use of manufactured gas was a major driver for the storage cylinder development.

Figure 5 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 vehicles the 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.<sup>22</sup> The filling time for CTG vehicles in such stations was 3 minutes, which corresponds to the filling time of methane (CMG) vehicles today.<sup>23</sup> In Germany there were 41 CTG filling stations and 1000 vehicles using them in 1937.<sup>24</sup> France also introduced CTG road vehicles early, in the 1920s (Fig. 3c).<sup>25</sup>

CTG vehicles were not factory made, but converted from gasoline vehicles (Fig. 6). Because gasoline vehicles have Otto engines, which are gas engines, additional technology is needed for using them with liquid fuels. Therefore, modifying from



**Figure 5.** 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. 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.

**Figure 6.** Advertisement of CTG components for vehicle conversion on page 9 of *Technica* journal, published in Lyon, November 1943 issue.

**GAZ DE VILLE**  
COMPRIMÉ

Le Carburant de remplacement idéal



**PROPRETÉ**

**ÉCONOMIE**

**M.A.**  
13 bis, Rue de Bézang  
Tél. P. 71-68 - P. 71-82

ATELIERS DE MONTAGE



**S.E.**

Longue Expérience  
Nombreuses Références

••

**DÉTENDEURS**  
à double détente :  
**TRACTOGAZ**



**CARBURATEURS : SOLEX**

Le Gaz de Ville se monte sur  
Véhicules de toute cylindrée  
et de toute marque

liquid to gas use is actually a reverse-conversion. The changes needed were adding gas storage cylinders with the necessary piping, reducing the valve and air-gas mixer, and adjustment of ignition timing – increase of compression ratio by replacing cylinder heads was an optional change.<sup>26</sup>

Both monofuel and bifuel CTG vehicles were in use. In monofuel vehicles only CTG could be used, 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.<sup>27</sup>

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 dual fuel Diesel engines with a compression ratio of 16:1, giving slightly higher power compared with diesel oil used in monofuel Diesel engines.<sup>28</sup>

## 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.<sup>29</sup> 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.<sup>30</sup>

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 transport fuel: it is used in over 17 million vehicles globally. The vast majority of these are cars. In

Figure 9a 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 a 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.<sup>31</sup> Therefore, whenever methane is mentioned in this article, 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 use 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.

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

**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

storage in centralised 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) and it is the only fuel that can be used in all transport engine types, i.e. Otto, Diesel, 2-stroke, Wankel, steam, 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.

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.<sup>32</sup> The shares of renewable versus fossil methane sources will depend mostly on environmental policies. The resource base for both is significant.

### 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 ( $\text{CO} + \text{H}_2$ ) and methane is synthesised by catalytic reaction of  $\text{CO}$  and  $\text{H}_2$  in high temperature and pressure. This method, also called methanation, was first proven in 1902.<sup>33</sup> The 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 adopted for transport use in Germany in the early 1920s. Methane was separated from coal gas by a cryogenic process called Bronn-Concordia-Linde process.<sup>34</sup> The temperature of coal gas was lowered down to  $-190\text{ }^\circ\text{C}$  to liquefy the methane and leave the 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 other thermochemical methods including coke hydrogenation, which was available in the 1930s.<sup>35</sup> 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.<sup>36</sup> 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<sup>37</sup>. LMG was also used together with liquid oxygen by Johannes Winkler in 1931 in the first gaseous fuel rocket launch in the world. Later liquefied gas fuelled (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.

### 2.3.2. *Natural gas (NG)*

Natural gas is a heterogeneous mixture of fossil gases, of which methane usually has the 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. 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, 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, up-

**Figure 7.** Kårstø natural gas processing plant north of Stavanger, Norway. Photo: Ari Lampinen.



grading, 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. 7).

Compressed natural gas (CNG) was first used in vehicles in 1934 in Italy 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.<sup>38</sup> Most of 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.

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 almost 500 ships, of which most are LNG carriers. Many other types of ships have recently been launched as a result of United Nations (IMO) 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.

### 2.3.3. Unconventional fossil methane

Shale gas was the first unconventional fossil methane type (Fig. 1b) adopted for transport use in the United States a few years ago. Unconventional fossil methane resources are substantially larger than the resources of natural gas, but they also pose far greater environmental risks.<sup>39</sup> 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 use of these resources may impede implementation of renewable energy policies, as has been warned for example by the OECD International Energy Agency.<sup>40</sup>

### 2.3.4. Biogas (BG)

Biogas is a renewable methane fuel produced microbiologically from biomass, usually biowaste, using microbial metabolism.<sup>41</sup> Traditions of biogas utilisation go back thousands of years. The earliest references are from Sumeria 3000 BCE.<sup>42</sup> China is currently the leading country with over 40 million biogas reactors. There the earliest references are from 1500 BCE.<sup>43</sup> Biogas was first used for city lighting in Exeter, England in 1895 and for electricity production in Matunga, India in 1902.<sup>44</sup>

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.<sup>45</sup> In 1945 the situation was, according to Karl Imhoff, that: “*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.*”<sup>46</sup>

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*



**Figure 8.** Ford truck filling biogas at a CBG filling station at Rajasaari Sewage treatment plant in Helsinki in 1943. Photo: Foto Roos/Photo archive of Helsinki City museum.

*sewage. In Sweden, as well as in other countries, there has been development in this line.”<sup>47</sup>*

The author has found data on 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. Outside Europe, biogas was used in transport in Johannesburg (from 1940) in South Africa.<sup>48</sup> All of these cities used biogas in compressed form (CBG) based on compression and vehicle technologies developed originally for manufactured gas and SNG. In all these cities biogas originated from municipal sewage treatment plants.

Of these cities only Stockholm has preserved hardware used at the time and exhibits them at a municipal transport museum. Figure 4 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.<sup>49</sup> This business ended in Stockholm in late 1940s, but began again in 1996 at Bromma sewage treatment plant and came back to the Henriksdal plant in 2004. In the 1940s biogas was used mostly in trailers towed by city buses, but also in various municipal vehicles with on-board

storage cylinders. Currently trailers are no longer used.

In Borås transport use of upgraded biogas originating from a sewage treatment plant started already in 1941.<sup>50</sup> Borås abandoned traffic biogas use in the late 1940s, but started again in 2002. Now, in addition to sewage sludge municipal solid waste is also used and biogas is sold to the public in three filling stations operated by municipal energy and waste company Borås Energi och Miljö.

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. 8) could fill up to 200 bars.<sup>51</sup> Unlike Stockholm and Borås, Helsinki has not yet restarted CBG production, but in August 2013 there are three CBG filling stations in Helsinki (operated by state company Gasum) for selling biogas produced at sewage treatment plants of Kouvolaa (since 2011) and Espoo (since 2012).

Upgrading of raw biogas by removing most of the inert gas, carbon dioxide, by



**Figure 9.** Modern 100 per cent 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. Photos: Ari Lampinen.

water scrubbing was developed in Germany around 1930.<sup>52</sup> 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<sup>53</sup>, which is near the performance of modern water scrubbers (Fig. 14b). Cryogenic upgrading, capable of also removing nitrogen (it is found in large quantities in landfill gas and some raw natural gas), 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. Since raw biogas typically contains about 40 per cent carbon dioxide, removing it increases the energy content of the methane fuel substantially (Table 1). However, carbon dioxide is not a pollutant that harms 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, 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 and Johannesburg, in all these cities by water scrubbing.

It has often been claimed 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 Figure 7, whereas biogas upgrading plants are usually small-scale installations as seen in Figure 14b. 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. 9a) or blended with natural gas (e.g. CBG10 and CBG50). Most of the filling stations are located in Germany and Sweden, but availability is spreading in many other countries, too. It is used mostly in road vehicles.

The first commercial liquefied biogas (LBG) filling station opened in 2005 in Los Angeles using landfill gas from Puente Hills landfill, serving mostly waste trucks. In addition to the United States, LBG filling stations (Fig. 9b) are in operation in a few European countries, mostly for trucks but also for buses.

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. 1a) 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). All renewable energy sources besides bioenergy, including solar and wind energy, may also be used for methane production. The scientific basis for the production of all these types of renewable methane has been known for over a century, but actual production for transport applications only started recently.

### 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). 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 methane vehicles.<sup>54</sup>

SBG was applied to transport use in 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

**Figure 10.** SBG production plant and filling station in Güssing, Austria. Photo: Ari Lampinen.



**Figure 11.** Wind methane demonstration plant and filling station in Bad Hersfeld, Germany. Photo: Ari Lampinen.



in charge of delivering the plant technology. Figure 10 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.

The SBG synthesis plant in Güssing is a 1 MW demonstration plant. The first commercial 20 MW plant begins production in 2013 in Sweden. 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 a 100 MW capacity. All of the produced SBG is intended for transport use. 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. 1a) 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.<sup>55</sup> 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 using solar or wind electricity (for this reason these are sometimes called power-to-gas technologies). Any other type of renewable electricity can be used as well.

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 11 shows wind methane filling in operation there. The first commercial wind methane plant by Audi starts production in 2013 in Werlte, Germany in connection with a biogas plant owned by EWE. This plant uses wind power from offshore wind turbines and carbon dioxide



from raw biogas. Carbon dioxide from raw biogas can be used without separating it, because methane does not interfere with the Sabatier reaction. Therefore, it is a wind methane and biomethane co-production facility. In this case the Sabatier reactor also replaces the upgrading plant.

Since the resource base of all renewable energy sources combined is far larger than the resource base for biomethane, Sabatier reactors may potentially increase the production of renewable methane to cover not only all transport needs, but also other energy needs. The reason for using 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.

#### 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.<sup>56</sup> By 1941 the amount of compressed gas vehicles had grown to over 107,000 (Table 3) and the amount of producer gas vehicles to over 443,000.<sup>57</sup> Manufactured gas bag vehicles were also used (Fig. 3b), 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 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.<sup>58</sup> In Italy, the government prohibited the use of natural gas for any other purpose than transport.

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. 13).<sup>59</sup> 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.<sup>60</sup> Therefore, there is a need for future research to be able to compile global and continental statistics on the development of traffic biogas use.<sup>61</sup>

Country	Number of vehicles	Types
Germany	75,000	Mostly CTG and CMG, also LPG
Italy	20,000	CNG
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	

**Table 3.** Number of compressed gas vehicles in Europe in 1941.

Sources: Lampinen (2012a) for Finland, Egloff & Arsdell (1942) for other countries. "Types" have been added in this article. 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.

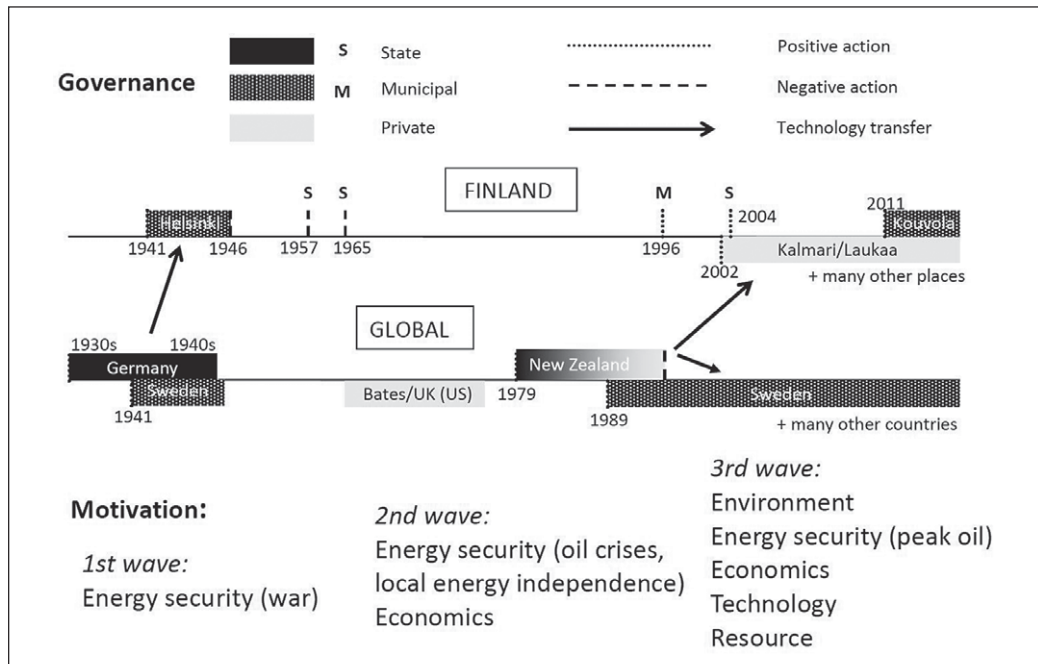
In the 1940s compressed gases (CTG and CMG) were stored in pressures ranging from 150 to 275 bars in road vehicles and mobile working engines, with 200 bars the most common choice. In locomotives the choice was 300 bars. In filling stations 350 bars was the most common storage pressure. Since the 1940s 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 common practice today, although higher

pressures were achieved in the 1940s. Lack of progress since the 1940s can be attributed not only to the effect of standardisation but also to the minimisation 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.

### 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.<sup>62</sup> In China the use

Figure 12. Timelines of traffic biogas use with governance and motivation in Finland and globally.



of natural gas in gas bag vehicles has continued until the present time.

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 entering 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 TRAFFIC BIOGAS TECHNOLOGY SYSTEMS

Figure 12 gives an overview of the timelines and governance of biogas systems for transport in Finland and globally. Three waves are identified in the use of traffic biogas: the Second World War, and the oil crises in the 1970s and the current one, which is one result of the global sustainable development policy process.

#### 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 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 war-time since 1939.

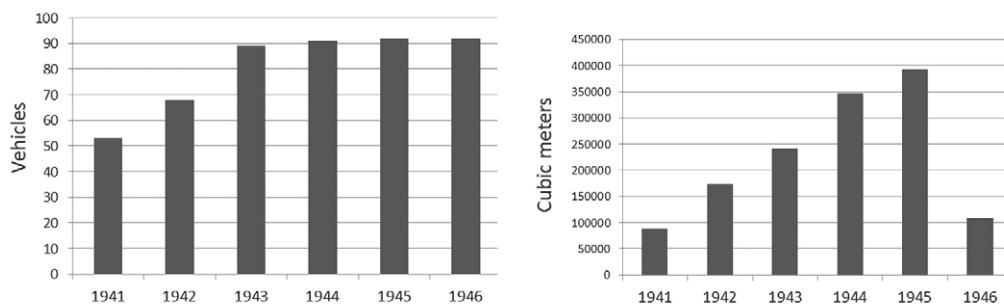
In 1939 the German government established the Central Bureau for Mineral Oil (Zentralbüro für Mineralöl GmbH). Originally under the Economic Ministry, it was later moved under the Ministry of Armaments and War Production, to control not only petroleum but also the alternative fuel technologies and businesses. 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 announcement, starting from the vehicles with the highest consumption, as soon as production and filling stations were set up.<sup>63</sup>

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.<sup>64</sup> 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. The motivation was the same: war time energy security.

##### 3.1.1. Case Finland

The 1940s biogas transport system in Helsinki is one of the clearest examples of municipally governed technology systems. It was created and completely controlled



**Figure 13.** The number of CBG vehicles and annual consumption of biogas in transport in Finland in the 1940s. Data is from Lampinen (2012a). Corresponding statistics have not been compiled for any other country.

by the Helsinki City Board (Fig. 2). 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. 8) were operated by Finska Aktiebolaget Gasaccumulator Oy, which in 1944 was renamed AGA Oy Ab. 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 13 show development of biogas vehicles and use of biogas in those vehicles in the 1940s in Helsinki.<sup>65</sup>

During the war various alternative fuels had been used 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.<sup>66</sup>

Removal of the motive power tax in 2004 enabled the transport use of biogas in Finland. The pioneer was the farmer Erkki Kalmari with Metener Company, which he co-founded. He started in 2002 with a demonstration project for which the tax was lifted (Fig. 14a). Most of the technology of

his farm scale traffic biogas production system is self-made.<sup>67</sup>

In 2011 the first municipality, the City of Kouvola, joined using an upgrading plant bought from New Zealand (Fig. 14b). 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 August 2013, 16 public and one private (Helsinki bus depot) CBG filling stations. In addition, there were two public (Kalmari farm and Hamina municipal energy company) and one private (Haapajärvi agricultural school) CBG filling stations and one public CNG filling station operating in Finland in August 2013.

### 3.2. Second wave: the 1970s oil crises

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. His work was motivated by self-sufficiency based on local resources and a do-

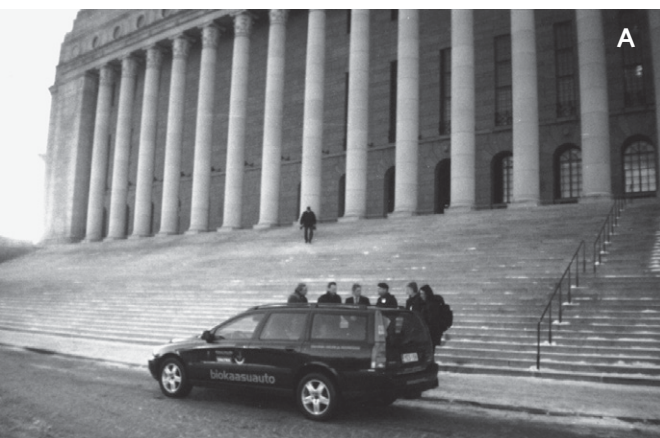
it-yourself (DIY) mentality. He sold DIY conversion kits especially in Great Britain, but also in the United States, where a few of them were used as one technical option for reducing gasoline use during the first oil crisis.<sup>68</sup>

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. However, 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. The Ministry

**Figure 14.** a) Erkki Kalmari showing the first biogas car in Finland since the war to Members of Parliament in front of the Parliament House in 2002. b) Water scrubber at Kouvola Sewage treatment plant in 2011. Photos: Ari Lampinen.



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.<sup>69</sup>

Simultaneously, natural gas was employed in transport using domestic natural gas resource. 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 to both motorists and distributors. Within six years, by December 1985, the number of CMG vehicles had grown to represent about 11 per cent of the total fleet and the annual CMG use increased from zero to 5.9 PJ.<sup>70</sup>

The City of Christchurch became the first municipality in the world to use biogas for transport purposes since the 1940s. They opened an upgrading plant and a CBG filling station at a municipal sewage treatment plant in 1983.<sup>71</sup> It was designed to serve 70 municipal vehicles of different kinds, including sewage trucks. 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). It was the second in the world after Italy in the number of MGVs: 110,000, all of which had been converted in New Zealand within a decade.<sup>72</sup>

Very innovative state level action followed by municipal level action 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.<sup>73</sup> 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 very strong global market presence, for example the upgrading plant manufacturer Flotech Greenlane (Fig. 13b shows a Greenlane water scrubber in Kouvola) and the filling station component manufacturer Compac.

### 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 Brundtland 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 (first wave) and the oil crises (second wave), when traffic biogas technology was temporarily employed for energy security reasons, now (third 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, i.e. 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.<sup>74</sup> The to-



**Figure 15.** CBG filling stations in Linköping in January 2003 before founding of Svensk Biogas: a) public station, b) bus depot. Photos: Ari Lampinen.

tal renewable methane resource (Fig. 1a) 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.<sup>75</sup>

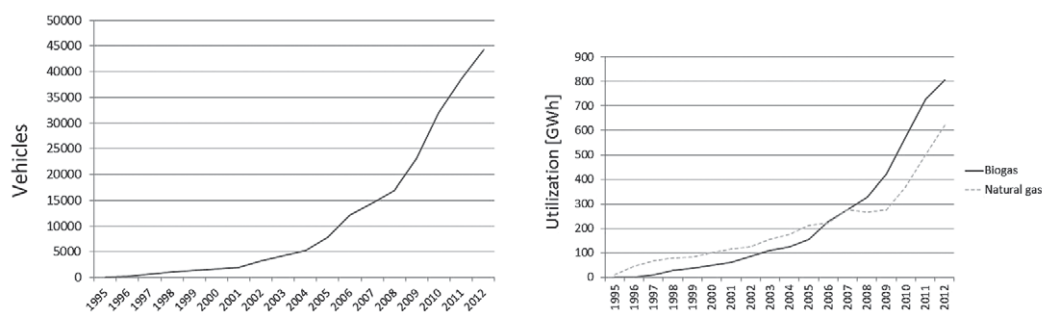
### 3.3.1. Case Sweden

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. 15). In 2003 the municipal company Svensk Biogas was established for expanding sales of traffic biogas both in Linköping and elsewhere in Sweden.<sup>76</sup> In 2006 biogas use expanded to regional rail transport 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.<sup>77</sup>

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 50 upgrading plants and 200 filling stations. In several municipalities public-private partnerships have been actively created and maintained, Stockholm being the prime example.<sup>78</sup> In addition to CBG filling stations, LBG filling stations have been operated since 2010.

Provincial work is also significant for



**Figure 16.** Development of MGV fleet (a) and use of biogas and natural gas in transport (b) in Sweden in 1995–2012. Data is from Energigas Sverige.

traffic biogas in Sweden. Regional biogas centers (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 first 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 2011 50 per cent of all biogas produced in Sweden was used in transport. 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 initiate similar development in other countries. For example, in Delhi biogas for transport use was introduced in 2013 as a result of Swedish official development assistance.

Public policy on municipal, provincial and national level has helped create a large Swedish private industry for production and use of CBG and LBG resulting in

**Table 4.** Characteristics of traffic biogas systems in the third wave in selected countries. These are the author's assessments based on a large number of magazines, conferences and private communications of the trade as well as many studies, including those found in the bibliography.

Country 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 (Jamein)	Manure	CBG	Private		Economics
United Kingdom 2008 (Albury)	Landfill gas	LBG	Private		Economics



**Table 5.** Methane gas vehicle (MGV) statistics, vehicle market penetration, governance and motivation in the end of 2010 in selected countries.

Sources for statistics: Boisen (2011) for market penetration, GVR (2011) for other. Numbers are rounded. Primary governance and motivation are the author's assessments based on a large number of magazines, conferences and private communications of the trade as well as many studies, including Yeh (2007), Colantanes & 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 the United States, and shale gas is used in the United States.

World position	Country	MGVs	MGV share of motorized road vehicles	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

strong growth as shown in Figure 16. Biogas surpassed natural gas in 2006 and the current share of biogas is about 60 per cent of traffic methane used in Sweden.

### 3.3.2. *Development in other countries*

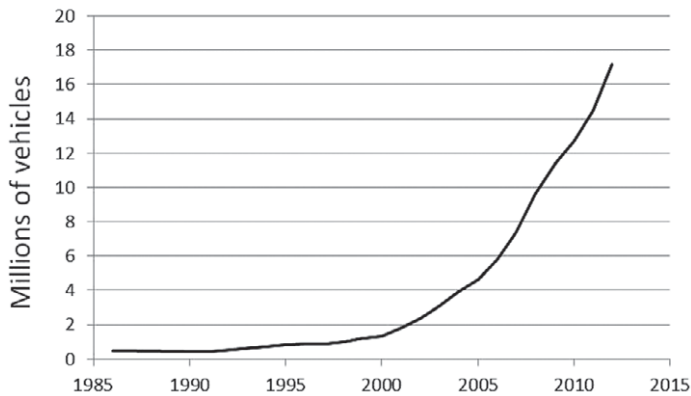
The City of Lille in France was the first municipality outside Sweden to start using biogas in transport during the third wave. The first four biogas city buses started operation in 1994 after two years of experimentation.

After Sweden and France, many countries have started using biogas in transport. Germany, the original pioneer in the first wave, was very slow to join the third wave: the first upgrading plant was opened as late as 2006 in Jameln. Rapid development has followed, however: there are now over 100 upgrading plants and 300 CBG filling stations (and 600 CNG filling stations).

Table 4 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 almost always 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.

There is also great diversity in the characteristics of natural gas systems for transport in various countries, as seen in Table 5. Most noteworthy are Pakistan and Bangladesh, where the penetration of MGVs is already over half of the total national motorised road vehicle fleet. The role of state governance is stronger than in the case of biogas systems, because natural



**Figure 17.** Development of global fleet of MGVs from 1986 to 2012.

Sources of data: Harris (1988), NGV Global and NGVA Europe.

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 state's fleet of 28,500 vehicles would eventually be moved to natural gas use.<sup>79</sup> In 2012 Governors from 22 US states announced that a coalition of 22 states would buy 10,000 new CMG vehicles annually. This way demand was created for the domestic manufacture of CMG vehicles.

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 17. Germany was the top country from 1920s until 1940s, but has now fallen into 19th position with just under 100,000

MGVs. After Germany, Italy kept the number one position until the early 1990s and is still number seven in the world with a fleet of 750,000.

Argentina, currently in third position in the world with 2.2 million MGVs, 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.<sup>80</sup>

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.

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: at the end of 2004 there were only 1000 MGVs in Iran.

#### 4. CONCLUSIONS

Technology for using 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 use have been identified in this article. 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, i.e. 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.

A common feature of the first and second waves 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 the national strategies are. This is sometimes called market oriented policy or neoliberal policy. The same approach is often applied at a municipal level to avoid the efficient use 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 an 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 continue in long-term use, 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. 1a) offers large environmental benefits compared to natural gas, whereas SNG and unconventional fossil methane (Fig. 1b) offer large environmental risks compared to natural gas. Coal based SNG, the first methane fuel used for transport, is no longer used in this way. 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 the use of these resources also carries risks for significantly more serious and diverse negative environmental impacts than natural gas use 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.

Ari Lampinen is a researcher working on renewable energy use in transport applications, including the history of such technologies. He is also the chairman of the Finnish Biogas Association.

This article has been peer-reviewed. Tekniikan Waiheita would like to thank the reviewers for their valuable comments.

<sup>1</sup> Methane vehicle statistics are published monthly in the magazine Gas Vehicle Report. In the August 2013 issue the total number of vehicles was 17.2 million. This is not the situation in August 2013, but a sum of national situations reported between March 2006 and April 2013 from 85 countries in all continents. Also, these statistics do not include all types of methane vehicles, for example most methane powered ships. Therefore, the total fleet in August 2013 was much more than 17.2 million. It is about 100 times more than the global fleets of electric and hydrogen vehicles combined.

<sup>2</sup> 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 using algae for fuel production). Seaweed and other marine bioresources are also not included. The total renewable methane potential is defar larger, because all renewable energy resources can be used and bioenergy constitutes only a marginal share of the total. The global potential of all renewable energy forms is found in the United Nations publication (UN 2000). On the other hand, fossil methane resources are much larger than the resources of all other fossil energy sources combined (IPCC 2001, 315).

<sup>3</sup> 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.

<sup>4</sup> 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 produced in this way. 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.

<sup>5</sup> Biowaste based biogas is the only fuel that may offer over 100 per cent 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 for example the study published by the European Commission Joint Research Centre together with vehicle and fuel industry (JEC 2011) and the study on Swedish traffic biofuels (Börjesson et al. 2010).

<sup>6</sup> For example the biogas van in Fig. 11 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 vehicles (MGVs) and almost 2000 models are available in the global market. 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 article, 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 per cent) are MGVs. Historical development of the global MGV fleet since 1986 is shown in Fig. 17.

<sup>7</sup> Echerman's (2001, 18-19) book includes a drawing of the four-wheeled de Rivaz car taken from his patent in 1807.

<sup>8</sup> Large amount of literature exist of the basics of manufactured gas, see e.g. Higman & van der Burgt (2003).

<sup>9</sup> 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).

<sup>10</sup> Cash & Cash (1942).

<sup>11</sup> 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 the

selected 27, meaning that their total number exceeded a million.

<sup>12</sup> See for example De Decker's (2011) article: it includes many historical photos of such vehicles.

<sup>13</sup> Simola (1940).

<sup>14</sup> Egloff & Arsdell (1942).

<sup>15</sup> Walter (1940, 421).

<sup>16</sup> Bourcier (1941, 165).

<sup>17</sup> Argus (1886, 5).

<sup>18</sup> Isaacs (2011).

<sup>19</sup> Klapper (1961), Hermann (2013).

<sup>20</sup> This applied specifically to cars and vans used by medical doctors, as explained by Buist (1917).

<sup>21</sup> Marsh (1932), Bourcier (1941, 173). If 400 bars had been used in the cylinders of the car in Fig. 3c 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).

<sup>22</sup> Engineer (1933).

<sup>23</sup> Engineering (1934).

<sup>24</sup> Simola (1940).

<sup>25</sup> Engineering (1932b), Bourcier (1941, 165).

<sup>26</sup> Engineering (1932b).

<sup>27</sup> 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.

<sup>28</sup> Walter (1940, 424).

<sup>29</sup> Leffingwell (1995).

<sup>30</sup> Simola (1940).

<sup>31</sup> It is enough to have 84 per cent methane (although it also depends on what the other gases in the mixture are). Usually in CBG methane content is 95-99 per cent. Situation is different for hydrogen, since fuel cells require 99.9 – 99.9999 per cent purity.

<sup>32</sup> IEA (2011, 119).

<sup>33</sup> Sabatier & Senderens (1902). This was one contribution towards the Nobel Prize in chemistry for Sabatier in 1912.

<sup>34</sup> Engineering (1932a).

<sup>35</sup> 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 ntpcr cent (weight) of methane is produced in coal hydrogenation as a side product (Bergius 1932, 274).

<sup>36</sup> Roth (1932).

<sup>37</sup> This is based on information given by Professor Fritz Frank (Walter 1940, 443-444).

<sup>38</sup> Buses: Sansone (1936) and Bourcier (1941, 201), locomotives: Egloff & Arsdell (1942).

<sup>39</sup> IPCC (2001, 315).

<sup>40</sup> IEA (2011, 9).

<sup>41</sup> 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 cannot 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.

<sup>42</sup> Deublein & Steinhauser (2008, 27).

<sup>43</sup> He (2010).

<sup>44</sup> Fuhrman (1940, 1096).

<sup>45</sup> Deublein & Steinhauser (2008, 29) give 1930 as the approximate year of first demonstration of biogas use in automobiles. It means that biogas was used in transport before natural gas. According to Simola (1940, 73), sewage treatment based biogas was used in internal combustion engines 180,000 m<sup>3</sup> in 1935 and 1.25 million m<sup>3</sup> in 1937 in Germany. However, it is not mentioned whether all or part of this was in transport.

<sup>46</sup> Imhoff (1946, 17).

<sup>47</sup> Egloff and Arsdell (1942, 654).

<sup>48</sup> Fuhrman (1940, 1088).

<sup>49</sup> ASS (1943).

<sup>50</sup> Fransson (2009).

<sup>51</sup> Lampinen (2012a).

<sup>52</sup> Deublein & Steinhauser (2008, 29). Currently many other upgrading technologies are also used.

<sup>53</sup> Walter (1940, 434).

<sup>54</sup> 'Normal' here means modern factory made vehicles or vehicles converted using standard conversion kits. However, with additional modifications, modern vehicles can be adjusted to raw biogas use. It is a rare practice.

<sup>55</sup> Sabatier (1912). It was one contribution towards the Nobel Prize in chemistry he received in 1912.

<sup>56</sup> Egloff (1938).

<sup>57</sup> Egloff & Arsdell (1942).

<sup>58</sup> Egloff & Arsdell (1942).

<sup>59</sup> Complete traffic biogas statistics in Finland in the 1940s is available in the article of Lampinen (2012a).

<sup>60</sup> 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](http://www.site of Energigas Sverige))

and in Finland (available at [www site of Finnish Biogas Association](http://www site of Finnish Biogas Association)).

<sup>61</sup> 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](http://www sites of NGV Global and NGVA Europe and the Gas Vehicle Report magazine).

<sup>62</sup> Imhoff (1946).

<sup>63</sup> Simola (1940), Stokes (1985).

<sup>64</sup> Krammer (1978, 414).

<sup>65</sup> The success story and downfall in Helsinki is described in detail by Lampinen (2012a).

<sup>66</sup> More information on these issues, i.e. subsidising 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 (25-30 per cent 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 the 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, forestry industries and municipal waste, 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 used in buses in Helsinki from 1996 by municipal decision. The decision to use CNG 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 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).

<sup>67</sup> Lampinen (2004).

<sup>68</sup> Grindrod (1971), MEN (1974).

<sup>69</sup> Waste Solutions (2011).

<sup>70</sup> Lonergan & Cocklin (1990), Yeh (2007).

<sup>71</sup> Bourke (2010).

<sup>72</sup> Stephenson (1991).

<sup>73</sup> 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).

<sup>74</sup> FTF (2011).

<sup>75</sup> 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).

<sup>76</sup> Currently Svensk Biogas operates 12 filling stations, of which 5 in Linköping, and also transports CBG by truck to other filling stations in several cities, for example Stockholm.

<sup>77</sup> The success story in Linköping is described by Linköpings kommun (2008).

<sup>78</sup> The success story in Stockholm is described e.g. by Vernay et al. (2013).

<sup>79</sup> Gross (1970).

<sup>80</sup> The Argentinian success story is described by Collantes & Melaina (2011).

## GLOSSARY

AMG: Adsorbed Methane Gas; fossil or renewable energy

BG: BioGas; bioenergy

Biomethane Bioenergy based methane fuel

CBG: Compressed BioGas (mostly methane); bioenergy

CMG: Compressed Methane Gas; fossil or renewable energy

CNG : Compressed Natural Gas (mostly methane); fossil energy

CTG: Compressed Town Gas (mostly hydrogen and carbon monoxide); fossil or bioenergy

LBG: Liquefied BioGas (mostly methane); bioenergy

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: Fuel, where most of the energy content is in the form of methane (CH<sub>4</sub>), e.g. BG and NG; methane fuels also contains other energy gases and non-energy gases

MG: Methane Gas, i.e. any type of methane fuel; renewable or fossil energy

MGV: Methane Gas Vehicle of any type, including but not restricted to CMG and LMG vehicles

Natural gas: Methane fuel produced and stored by nature; fossil energy

NG: Natural Gas; fossil energy

NGV: Natural Gas Vehicle: obsolete (but frequently used) term, since such vehicle can utilize any type of methane (see MGV)

SBG: Synthetic BioGas (mostly methane); bioenergy

SNG: Synthetic natural gas (mostly methane); fossil energy

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

Upgrading: Removing by various methods most of inert gases (always CO<sub>2</sub> and sometimes also N<sub>2</sub>) in methane fuels for increasing its energy density; this is required for utilization of natural gas, biogas, synthetic biogas and other methane fuels in modern factory made methane vehicles

Wind methane: Wind energy based methane fuel

## BIBLIOGRAPHY

ARGUS: The Argus newspaper (Melbourne, Australia), December 29, 1886.

ASS: Styrelse och revisionsberättelser för år 1942 samt årsredogörelse mod statistiska uppgifter. Aktiebolaget Stockholms Spårvagnar, 1943.

BERGIUS, Friedrich: Chemical reactions under high pressure. Nobel Lecture, May 21, 1932. Nobel lectures in chemistry 1922–1941, Elsevier Publishing Company, Amsterdam, 1966, 244–276.

BOISEN, Peter: The worldwide market shows a strong and steady growth. Gas Vehicle Report, March 2011, 22–23.

BOURCIER, Lucien: *Automobiles à gazogène et automobiles à gaz d'éclairage*. Garnier Frères, Paris, 1941.

- BOURKE, Mike: Christchurch City Council Biogas Vehicle Fuel Experience. Presentation at Biogas Vehicle Fuel Conference in Auckland, New Zealand, 18.11.2010.
- BUIST, H. Massac: Motor notes for medical men – The development of coal gas as a motor fuel. *The British Medical Journal*, October 20, 1917, 521.
- BÖRJESSON, Pål, TUFVESSON, Linda & LANTZ, Mikael: *Life Cycle Assessment of Biofuels in Sweden*. Report No. 70, Department of Technology and Society, Environmental and Energy System Studies, Lund University, 2010.
- CASH, John D. & CASH, Martin G.: *Producer gas for motor vehicles*. Second, revised edition, Angus and Robertson Ltd., Sydney and London, 1942.
- COLLANTES, Gustavo & MELAINA, Marc W.: The co-evolution of alternative fuel infrastructure and vehicles: A study of the experience of Argentina with compressed natural gas vehicles. *Energy Policy*, Vol. 39, 2011, 664–675.
- DE DECKER, Kris: Gas Bag Vehicles. *Low-tech Magazine*, November 13, 2011. <http://www.lowtech-magazine.com/2011/11/gas-bag-vehicles.html>
- DEUBLEIN, Dieter & STEINHAUSER, Angelika: *Biogas from Waste and Renewable Resources*. Wiley-VCH, Weinheim 2008.
- EC: GHG emissions from shale greater than conventional gas, coal or oil. *Science for Environmental Policy*, DG Environment News Alert Service, European Commission, 1 September 2011.
- ECKERMANN, Erik: *World History of the Automobile*. Society of Automotive Engineers, Warrendale, USA, 2001.
- EGLOFF, Gustaf: Motor fuel economy of Europe. *Ind. Eng. Chem.* Vol. 30(10), 1938, 1091–1104.
- EGLOFF, Gustaf & Van ARSDELL, Prudence: Substitute Fuels as a War Economy. *Chem. Eng. News*, Vol. 20(10), 1942, 649–658.
- EGLOFF, Gustaf & Van ARSDELL, Prudence: Motor Vehicles Propelled by Producer Gas. *Petroleum Eng.*, Vol. 15(3), 1943, 65–73.
- ENGINEER: Methane gas for heavy motor vehicles. *The Engineer* Vol. 64, 1932, 15.
- ENGINEER: A compressed gas filling station. *The Engineer* Vol. 66, 1933, 509.
- ENGINEERING: Compressed gas for motor vehicles. *Engineering* Vol. 61, 1932a, 753–754.
- ENGINEERING: Town's gas operated motor vehicle. *Engineering* Vol. 84, 1932b, 605–606.
- ENGINEERING: The use of coal derivatives for motor vehicles. *Engineering* Vol. 87, 1934, 685.
- ENGINEERING: Gaseous hydrocarbons at high pressure. *Engineering*, Vol 146, 1938, 602–674.
- FRANSSON, Anders: Uppgradering av biogas i Borås. Presentation at seminar organized by Swedish Water & Wastewater Association in Jönköping, Sweden, 16.4.2009.
- FTF: *Future Transport Fuels*. Report of the European Expert Group on Future Transport Fuels, January 2011.
- FUHRMAN, Ralph E.: Sludge Gas Utilization. *Sewage Works Journal*, Vol. 12, No. 6, 1940, 1087–1097.
- GRINDROD, Barry: Chicken manure fuel can power your car. *Mother Earth News*, July/August 1971.
- GROSS, Edward: Driving with methane. *Science News*, Vol. 97(3), Jan. 1970, 73–74.
- GVR: Worldwide NGV statistics. *Gas Vehicle Report*, March 2011, 29.
- HARRIS, F.S.: NGV around the world. Proceedings of NGV-88: "NGV – the new direction in transportation", First International Conference and Exhibition, 27–30 October 1988, Sydney, Australia. Cited by Stephenson (1991).
- HE, Pin Jing: Anaerobic digestion: An intriguing long history in China. *Waste management*, Vol. 30(4), 2010, 549–550.
- HERMANN, Lars: Gasstraßenbahn. *Dresdner Stadtteile*, [http://www.dresdner-stadtteile.de/Neustadt/Leipziger\\_Vorstadt/Grossenhainer\\_Strasse/Gasstrassenbahn/gasstrassenbahn.html](http://www.dresdner-stadtteile.de/Neustadt/Leipziger_Vorstadt/Grossenhainer_Strasse/Gasstrassenbahn/gasstrassenbahn.html), accessed 4 May 2013.
- HIGMAN, Christopher & van der BURGT, Maarten: *Gasification*. Gulf Professional Publishing, Burlington, USA, 2003.
- IEA: *Are we entering a golden age of gas?* Special report, International Energy Agency, Paris 2011.
- IGU: *Natural Gas for Vehicles*. Joint report of International Gas Union and United Nations Economic Commission for Europe, June 2012.
- IMHOFF, Karl: Digester gas for automobiles. *Sewage Works Journal*, Vol. 18(1), 1946, 17–25.
- IPCC: *Climate Change 2001 – Synthesis report*. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T. and the Core Writing Team (eds.)]. Cambridge University Press, 2001.
- ISAACS, Albert: The Alphington Gas Tram. *The Times* (An Australian journal of transport timetable history and analysis), Vol. 28(10), 2011, 14–15.
- JEC: Well-to-Wheel analysis of future automotive fuels and powertrains in the European context. Version 3c, October 2011. European Commission Joint Research Centre (JRC), The oil companies' European association for environment, health and safety in refining and distribution (CONCAWE) & European Council for Automotive R & D (EUCAR). Report EUR 24952 EN – 2011, European Commission, Joint Research Centre, Institute for Energy and Transport.
- KLAPPER, Charles F.: *The Golden Age of Tramways*. Routledge & Kegan Paul, London, 1961.



- KRAMMER, Arnold: Fueling the Third Reich. *Technology and Culture*, Vol. 19(3), 1978, 394–422.
- LAMPINEN, Ari: Biogas Farming – An Energy Self-Sufficient Farm in Finland. *Refocus*, Vol. 5(5), 2004, 30–32.
- LAMPINEN, Ari: Development of tax subsidy mechanisms for fossil traffic fuels in Finland (in Finnish with English abstract). *Oikeus* (Finnish Law Journal) Vol. 37(4), 2008, 453–473.
- LAMPINEN, Ari: Introduction of Traffic Biogas Technology in Finland (in Finnish with English abstract). *Tekniikan Waiheita* (Finnish Quarterly for the History of Technology), Vol. 30(1), 2012, 5–20. (2012a)
- LAMPINEN, Ari: *Roadmap to renewable methane economy – extended summary*. Finnish Biogas Association & North Karelian Traffic Biogas Network Development Programme. Publications of North Karelian Traffic Biogas Network Development Programme 2/2012, (2012b), available: [http://www.biokaasuyhdistys.net/media/Roadmap\\_renewable\\_methane\\_economy.pdf](http://www.biokaasuyhdistys.net/media/Roadmap_renewable_methane_economy.pdf).
- LONERGAN, Stephen C. & COCKLIN, Chris: In the aftermath of the energy crisis – New Zealand’s energy policy in the 1970s and 1980s. *Energy Policy*, Vol. 18, 1990, 100–116.
- LEFFINGWELL, Randy: *Farm Tractors – A Living History*. Motorbooks International, Osceola, USA, 1995.
- LINKÖPINGS KOMMUN: *Biogas i Linköping – Från idé till verklighet*. City of Linköping, 2008.
- MARSH, Frank S.: Light-weight high-pressure gas cylinders. *Engineering* Vol 85, 1932, 489–490.
- MEN: Mother’s biogas automobile. *Mother Earth News*, January/February 1974.
- ROTH, Walter: Methane used as motor fuel. *Chem. Eng. News* Vol. 10(13), 1932, 169.
- SABATIER, Paul & SENDERENS, Jean-Baptiste: Nouvelles Synthèses du méthane. *Compt. Rend.* Vol. 134, 1902, 514–516.
- SABATIER, Paul: The Method of Direct Hydrogenation by Catalysis. Nobel lecture, December 11, 1912. Nobel lectures in chemistry 1901–1921, Elsevier Publishing Company, Amsterdam, 1966.
- SANSONE, Raffaele: World-Wide Chemistry: Italy. *Chem. Eng. News* Vol. 14(6), 1936, 108–110.
- SIMOLA, Olli: Compressed gas motor cars (in Finnish with English abstract). *Teknillinen Aikakauslehti* Vol. 30, 1940, 72–75.
- STEPHENSON, John: *Learning from experiences with compressed natural gas as a vehicle fuel*. CADDET Analysis Series No. 5, CADDET/IEA/OECD, Sittard, The Netherlands, 1991.
- STOKES, Raymond G.: The Oil Industry in Nazi Germany 1936–1945. *The Business History Review*, Vol. 59(2), 1985, 254–277.
- TALVITIE, Arvi: *Kemiallinen teknologia (Chemical technology)*. Ensimmäinen osa. WSOY, Porvoo, 1944.
- UN: *World Energy Assessment – Energy and the Challenge of Sustainability*. Goldemberg J (ed.), United Nations Development Programme (UNDP), United Nations Department of Economic and Social Affairs (UNDESA) and World Energy Council (WEC), UN, New York, 2000.
- VERNAY, Anne-Lorène, MULDER, Karel Frits, KAMP, Linda Manon & de BRUIJN, Hans: Exploring the socio-technical dynamics of systems integration – the case of sewage gas for transport in Stockholm, Sweden. *Journal of Cleaner Production*, Vol. 44, 2013, 190–199.
- VERNE, Jules: *Paris au XX<sup>e</sup> siècle*. Written in 1863, but first published in 1994 by Hachett in Paris.
- WALTER, C.M.: Alternative motor fuels. *Journal of the Royal Society of Arts*. Vol. 88, 1940, 418–445.
- WASTE SOLUTIONS: Our History. WWW pages of former company Waste Solutions, accessed 28 February 2011 (no longer available in www).
- YEH, Sonia : An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles. *Energy Policy*, Vol. 35, 2007, 5865–5875.