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**Quality of Renewable Energy
Utilization in Transport in Sweden**

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Abstract

Renewable energy utilization in transportation (RES-T) is a long way behind its utilization in power (RES-E) and heat (RES-H) sectors. International and national environmental policies have recently given a lot of emphasis on this problem. For that reason information is sought on how to implement solutions both politically and technologically. As Sweden is a global leader in this area, it can provide valuable examples. In 2012 Sweden became the first country to reach the binding requirement of the European Union for at least 10 % share for renewable energy in transport energy consumption. But qualitative development has been even stronger than quantitative. Among the success stories behind qualitative progress, most noteworthy are those created by innovative municipal policies. By 2030 Sweden aims to achieve fossil fuel independent road transport system and by 2050 completely carbon neutral transport system in all modes of transport.

Keywords: *renewable energy in transportation, sustainable transport, sustainable biofuels, crude oil independence, environmental quality, municipal policy*



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1. Introduction to RES-T in Sweden

The Renewable Energy Directive (2009/28/EC) of the European Union, the RES Directive, includes a binding mandate for all Member States to provide a minimum of 10 % of their transport energy consumption by renewable energy sources (RES-T) by 2020 (see Annex 2 for an introduction to EU level RES-T policy and legislation). In 2012 Sweden became the first country to achieve the required level, by a share of 12.6 %, more than double the share in the EU as a whole. In 2013 the share was 16.7 %. Qualitatively Sweden is even stronger in comparison, since most EU Member States have fulfilled their mandate by low-level blending of food energy crop based biofuels with gasoline and diesel oil. It is easy to implement, but has the lowest environmental quality. Sweden is on track to reach 10 % share by 2020 without taking low-blend biofuels into account.

In 2013 consumption of biofuels in the EU transport sector dropped by 6.8 % compared to 2012, according to the Biofuels Barometer 2014.¹ It was the first time biofuel consumption has decreased in the EU. Although the use of all liquid biofuels fell, use of biogas increased by 7.4 %. As almost all liquid biofuels are produced from food energy crops and almost all biogas is produced from biowastes, this development is qualitatively in line with the purpose of the RES Directive.

In Sweden consumption of biofuels grew by 30 % in 2013. Use of synthetic biodiesel (SB), biodiesel (B) and biogas (BG) increased, but bioethanol (E), liquid bio-ether (ETBE) and gaseous bio-ether (DME) were consumed less than in 2012. Imported synthetic biodiesel produced by hydrotreating vegetable oils and fats was responsible for most of the growth. Imports dominated liquid biofuel market (B over 80 %, SB over 70 %, E almost 70 %), but almost all gaseous renewable fuels were domestically produced (CBG over 90 %, LBG 100 %, bio-DME 100 %, wind-hydrogen 100 %). Liquid biofuels were mostly produced from food energy crops (66 %) and gaseous biofuels from wastes (99 %).

The share of renewable energy in transport energy consumption in Sweden is the second highest in the world after Brazil, where almost all is food energy crop based ethanol and biodiesel.² Although quantitative merits in Sweden are high in comparison to other countries, the current share is still very low in absolute terms. By 2030 Sweden aims to achieve fossil fuel independent³ road transport system and by 2050 completely carbon neutral transport system in all modes of transport.

Qualitative merits are even stronger than quantitative merits so far in Sweden, although Iceland is qualitatively superior.⁴ Municipal policies are the core reason behind the high environmental quality.

¹ Biofuels Barometer is published by EurObserv'ER annually for the European Commission. It includes biofuel use in transport only (RES-T biofuels), not for electricity (RES-E) and heat (RES-H) production. It does not include other renewable fuels than biofuels, such as solar hydrogen and wind methane. Their use is currently marginal, but they represent very large potential of sustainable RES-T technologies for the future.

² In 2013 renewable energy sources covered 16.9 % of all transport energy and 18 % of road transport energy consumption in Brazil (Brazilian Energy Balance 2014 – year 2013). Ethanol was the most important source, but also biodiesel, biogas, some other biofuels and renewable electricity were used.

³ Secondary fossil fuel dependency will be tolerated until 2030, but it also should be phased out after that. This means that many vehicles that are able to use 100 % RES-T require crude oil for reasons of convenience for the vehicle or fuel manufacturers (creating inconvenience for consumers). Example 1: All electric cars (BEVs) need chemical fuels for heating, since electric engines do not supply enough of waste heat like internal combustion engines do, and separate electric space heating is not practical due to dramatic drop in driving range. This is almost always done with fossil fuels, although it could be done with biofuels. Example 2: All factory manufactured PHEV cars are designed for gasoline or diesel oil, although they could as easily be designed for renewable fuels. Example 3: Almost all bifuel CBG cars require gasoline for startup although it is not necessary (as numerous monofuel CBG cars, vans, truck and buses show). Example 4: Part of CBG/LBG dualfuel vehicles require fossil diesel for ignition, although it could be done with renewable diesel fuels. Example 5: Part of B100 vehicles require fossil fuels for preheating in cold conditions, although it could be done on renewables. Example 6: Fossil components are mixed with B100 and SB100 in cold conditions, although renewable components could be used.

⁴ In Iceland only renewable power, mostly geothermal and hydroelectric, are utilized for electric transport. Landfill gas is the only biofuel utilized in transport. Iceland is the only country in the world, where all traffic methane is renewable,

Purchasing policy and ownership policy of municipal companies are the main tools behind market creation of many sustainable RES-T technologies and their pure use. Enabling environment for it has been nationally maintained by not imposing mandatory blending. For the same reason development of RES-T technologies has been possible. This has resulted in European and global pioneering of many RES-T technologies.

2. Quality of RES-T

In this study quality means environmental quality in the whole lifecycle perspective. Lifecycle greenhouse gas (GHG) emissions (see Annex 1) are the most important due to the especially high risks related to anthropogenic climate change and because efforts required for lowering GHG emissions decrease many other types of environmental burdens simultaneously.⁵

Unlike emissions and land use, energy consumption is not primary, but secondary environmental indicator. In the case of traffic fuels it is usually a poor measure of environmental performance. Main reason is the inherently low energy requirements of conventional fossil fuel production. For that reason lifecycle energy consumption of renewable fuels is higher, as shown in Figure A1 of Annex 1. There are also many examples within biofuel production chains, where GHG emissions are substantially lower despite substantially higher energy consumption. And electric vehicles may have very high emissions despite low energy consumption, as shown in table A1. Therefore, lifecycle energy consumption is useful only as an auxiliary environmental indicator in certain cases, such as comparing different production paths leading to same fuel or different ways of producing fuels from the same resource. In other cases, it carries an inherent risk of misrepresenting environmental merits.

High environmental quality is often interlinked with high technical quality and high level of technical development. But there are many opposite examples. Low technical quality may lead to high environmental quality. Walking, bicycling, rowing and other human muscle powered transport technologies offer high lifecycle environmental quality, if quality of primary energy production is high, i.e. energy originates from plant food, which is produced by renewable energy utilizing recycled fertilizers and transported by renewable energy. But walking may also have larger GHG emissions than driving fossil fueled cars, if production chain of food is GHG intensive. Examples are shown in Fig. A1 and Table A1 in Annex 1. On the other hand, high technical quality may lead to low environmental quality. One example is hydrogen produced by electrolysis utilizing peat electricity. It has five times higher GHG intensity than gasoline as shown in Table A1.⁶

Instead of looking at emissions directly, a review is given on prerequisites for low emission RES-T system. Reduction of transport needs by modal shifts and by other means can also significantly decrease emissions in transport system. But reduction of energy consumption may increase emissions, as discussed above. The following prerequisites for low emission transport system are the most essential:

and all is biowaste based, i.e. natural gas and other fossil methane sources are not used. However, quantitatively Iceland is performing poorly. National plan to fix this by renewable hydrogen started well, e.g. in 2003 globally first large public filling station within a conventional fuel service station was opened. But this development has now stalled, at least temporary: hydrogen is no longer utilized in transport there.

⁵ See Börjesson et al. (2010) for a lifecycle study of Swedish traffic biofuels containing emissions of gases and particles with impacts on climate, eutrophication, acidification and photochemical ozone formation; and also direct and indirect land use and energy use.

⁶ In Sweden hydrogen used in transport is produced mostly by wind electricity and in Finland mostly by peat electricity. In Finland fossil hydrogen was introduced in transport in 2013 after almost 90 year history of 100 % renewable hydrogen utilization.

- 1) Use of emission-free primary energy sources, such as solar and wind energy. In the long term they need to fulfill most of transport energy needs, but currently their role is very low in all countries, including Sweden. They can be used as direct electricity, indirect electricity (e.g. compressed air and magnetic vehicles) or renewable fuels (e.g. hydrogen and methane). Some forms of renewable energy can also be utilized directly, without conversions. In Sweden solar and wind energy have been taken into transport use as direct electricity and renewable fuels (hydrogen and hythane). Wind energy is also used directly in water and air transport.
- 2) Use of wastes, such as sewage, solid municipal biowaste and wood waste for biofuel production. Lifecycle emissions and other environmental burdens of these fuels are very low compared to energy crop based fuels. Sweden is very advanced in this field. These fuels have significant role in the Swedish RES-T consumption and technological diversity is high. Biowastes are utilized as biogas (CBG and LBG) and synthetic biodiesel. Wood wastes are utilized as synthetic biogas, bio-dimethyl ether, synthetic biodiesel and ethanol.
- 3) Nutrient recycling. Nutrient recycling is a critical prerequisite for a sustainable bioeconomy. In addition to resource efficiency, it contributes to lowering emissions in food and fuel production. Therefore, it is necessary to recycle nutrients (especially phosphorus due to resource scarcity and nitrogen due to large emissions) while producing fuels from biowastes. This is normal practice in Sweden by utilization of biogas technology.
- 4) Use of gaseous renewable fuels, including biofuels and other renewable fuels. They enable lower emissions during use and in the whole lifecycle than liquid fuels. Sweden is very advanced in this field: these fuels have large share of the Swedish RES-T sector and diversity is high. Both gaseous biofuels (biogas, synthetic biogas, bio-dimethyl ether, wood gas) and other renewable gaseous fuels (wind-hydrogen and wind-methane) are utilized.
- 5) Pure use of RES-T. It is necessary to be able to utilize 100 % renewable energy instead of blends with fossil energy. Otherwise independency from crude oil is not possible. Share of RES-T utilized in pure form (RES-E, wind-GH2, CBG100, LBG100, bio-DME100, WG100, B100 and SB100) is exceptionally high in Sweden.
- 6) Technical diversity. Transition to renewable energy in transport requires that there are a lot of technical options for all types of transport needs. In Sweden energy and vehicle diversity of RES-T technologies is high in road transport but low in rail transport. It is low also in mobile working engines and other off-road applications. In water and air transport renewable energy use is marginal.
- 7) Public transport. In passenger transport modal shifts reduce share of private transport, but increase the role of public transport. Therefore, RES-T technologies have more lasting impacts in this application. Added benefits results from replacing diesel vehicles, which are the most polluting vehicles. In Sweden RES-T is dominant in rail transport and very significant in buses. It is also significant in taxis, but completely lacking in water and air transport.
- 8) Cargo transport. Volumes in cargo transport grow faster than volumes in passenger transport. Reducing cargo transport is not in sight. It means that the share of cargo transport will grow and RES-T use in that sector becomes more important. In Sweden RES-T use is dominant in rail transport and significant in trucks and vans. But it is lacking in water and air transport.
- 9) Local energy. Distributed energy production and its local consumption increases resource efficiency, enables large role for renewables with distributed resources and reduces emissions and energy consumption related to transport and conversion of energy. In Sweden significant amount of RES-T is consumed locally, especially biogas but also wind electricity, solar electricity and wind hydrogen.

3. Qualitative development

3.1. Share of pure RES-T

More than a third (36 %) of renewable energy use in the Swedish transport sector is in the form of pure (100 %) or high blends (> 50 energy-%). This is exceptional, since almost all other countries focus on low blends of biocomponents in gasoline and diesel oil.

For the fossil free road transport system in 2030 it is not required that fossil fuels disappear from the market, but it is required that they do not need to be used. It means that pure (100 %) renewable energy is made available widely. And it means that fuel flexibility of the road vehicle fleet is developed into level where vehicles do not demand fossil fuels. They must be able to operate on 100 % renewable energy, whether they can also operate on fossil fuels or not. This is a truly excellent goal, which does not require any new technological development due to successful pioneering efforts in Sweden in the past (Chapter 4). But the market demand incentive created by this target will certainly lead to further technical innovation and commercialization.

However, market development is now the main challenge. Currently the following seven pure renewable energy sources are commercially available in the Swedish market: RES-E100, CBG100, LBG100, B100, SB100, Bio-DME100 and RES-GH2.

1. **RES-E100, 100 % renewable electricity** (Fig. 1). RES-E100 use in rail transport began in the 1890's with hydropower, and rail transport is still dominating consumer. RES-E100 is domestically generated by hydropower, wind power, solar power, wave power and biopower. For road transportation there are a lot of public charging stations, where only RES-E100 is available (mixed electricity with fossil and nuclear sources cannot be chosen in those stations). Some of those stations include on-site solar power production and there is one with on-site wind power production. RES-E100 has been available in public charging stations and for all consumers for their private charging stations since the 1996.



Figure 1. a) RES-E100 train with “Bra Miljöval” label. It means that only sustainable RES-E100 certified by the Swedish Society for Nature Conservation is used. b) Solar electric charging station, with solar panels also acting as sun and rain shelter, in Helsingborg. c-d) Bra miljöväl certified public RES-E100 charging station in Stockholm.

2. **CBG100: 100 % compressed biogas** (Fig. 2). CBG was first used in the 1940's and again since 1989. Until 1996 only private filling stations were in use, but since then a constantly growing public filling station network has been in service to the general public. In December 2014 there were 218 CBG filling stations, of which 155 were public. City buses are main users, utilizing private filling stations at bus depots. Until 2014 all CBG was biogas (**BG**) based and almost all produced from biowastes, toilet waste as the main

resource. Starting from December 2014 also synthetic biogas (**SBG**) was available. Main resource for SBG production is wood waste.



Figure 2. Public CBG100 filling station in Grästorp (a-b). Private CBG100 slow filling station at a bus depot in Norrköping.

3. **LBG100: 100 % liquefied biogas** (Fig. 3). First private LBG100 station was opened in 2010 and first public station in 2012. In December 2014 there were six public LBG stations and several LCBG stations (CBG stations, where biogas is stored in liquefied form). LBG is produced from biowastes and used in heavy vehicles, mostly in trucks.



Figure 3. Public LBG100 filling station in Gothenburg (a) and LBG100 powered tanker truck, which delivers LBG100 to stations (b).

4. **B100: 100 % biodiesel** (Fig. 4). Most of biodiesel consumption is in small blends (such as B2 and B5) with fossil diesel oil, but there is also pure use. Biodiesel is produced by a chemical reaction, transesterification, which produces fatty acid alkyl esters (FAEE). Of these, fatty acid methyl esters (FAME) are the most common. RME (rape methyl ester), made from rape seed oil, is one type of FAME biodiesels. It is currently the only type of biodiesel in commercial use in Sweden. For private use, other types of biodiesels are also produced.



Figure 4. RME biodiesel in Sweden: a) B2 (left) and B100 (right) pumps at a public multifuel filling station, where also E85 and CBG100 are sold, in Norrköping. b) B100 bus in Malmö. c) Rape cultivation for RME production in Mjölby.

- SB100: 100 % synthetic biodiesel.** SB was introduced in the Swedish market in 2011: a HVO fuel with a brand name “Evolution diesel” is domestically produced from tall oil, a wood waste. SB is currently the most popular traffic biofuel in Sweden, and most of it is imported. All synthetic biodiesel currently consumed in Sweden is produced by hydrotreating vegetable oils and fats resulting in a SB variant called HVO (hydrotreated vegetable oil). HVO is the cheapest SB fuel to produce, but has the smallest resource base. Almost all consumption is in low blends (such as SB15 and SB35) with fossil diesel oil (Fig. 5), but some in pure form. Synthetic fossil diesel produced by another method, FT synthesis, is used in Sweden, but not with renewable feedstocks.



Figure 5. Evolution diesel filling stations (SB15) for cars and trucks and a tanker truck in Södertälje.

- Bio-DME100: 100 % bio-dimethyl-ether** (Fig. 6). DME is a gaseous diesel engine fuel. Bio-DME has since 2011 been domestically produced from black liquor, which is wood waste. It is available in four filling stations for trucks.



Figure 6. Bio-DME100 filling station in Stockholm (a) and DME truck in Gothenburg (b).

7. **RES-GH2: 100 % renewable gaseous hydrogen** (Fig. 7). Hydrogen has been used since 2003. It is produced by electrolysis mostly by wind power. It is available in two public filling stations. Currently it is used in cars, but earlier also in city buses.



Figure 7. a) Public wind-GH2 station in Malmö. b) Private RES-GH2 station at a bus depot in Stockholm (no longer in use). c) Fuel cell car in Stockholm in 2004.

Small amounts of some other pure renewables are also used:

- Wood gas (WG100) in producer gas vehicles.
- Wood in steam vehicles.
- Direct wind in sailing boats, ships and sailplanes (without engines).

In addition to pure renewable fuels, high blends are utilized. In these fuels at least 50 % of energy content is renewable. There are four such fuels in the Swedish market. Although still partly fossil, they promote the fossil fuel independency target in various ways. E85 requires improving fuel flexibility of gasoline vehicles. ED95 requires development of new vehicle technology. CBG50 and LBG50 are used, because demand of these biofuels is larger than supply. It would be detrimental to the market of these biofuels if consumers failed to get fuel at the stations. Therefore, natural gas is used as backup until renewable methane supply will meet demand.

1. Bio-E85: 85 vol-% anhydrous bioethanol in a gasoline engine fuel (Fig. 8a): at most 85 vol-% is ethanol and at least 15 vol-% is gasoline. Maximal ethanol share is possible in summer conditions, but in winter the share is much lower. Since volumetric energy content of ethanol is about 30 % lower than gasoline has, the share of ethanol in this fuel is 50-70 energy-%. E85 has been used since 1994. Note: E100 is not used in Sweden or anywhere else in Europe.
2. Bio-ED95: 95 vol-% hydrous bioethanol in a diesel engine fuel (Fig. 8b). In this blend 90 energy-% is ethanol and the rest is a mixture of fossil⁷ components for various purposes, of which ignition improving is the most important. Since the cetane number of ethanol is low, very high cetane number component is needed to enable utilization of this fuel in diesel engines. ED95 has been used in buses since 1986 and since 2008 also in trucks. Almost all ED95 stations are private, but there is one public station, first in the world, which opened in 2010.
3. CBG50: at least 50 % biogas with fossil methane (Fig. 8c). In this case difference of vol-% and energy-% is marginal. Blends of CBG and CNG were taken into use in 2001. Before that only CBG100 was available. Fossil methane is currently natural gas, but there are plans to begin importing unconventional fossil methane.
4. LBG50: at least 50 % biogas with fossil methane (currently natural gas). In this case difference of vol-% and energy-% is marginal.

⁷ Bio-ED95 could quite easily become a RES-T100 fuel by utilizing renewable components instead of fossil. They could be synthesized at biorefineries, but it has not yet been done.



Figure 8. Public high-blend biofuel stations: a) E85 in Kiruna. b) ED95 in Stockholm. c) CBG50 in Stockholm.

Low blends (such as E5, ETBE5, B5 and SB15) are also used, but they do not require improvement of fuel flexibility of vehicles and development of filling station networks. Therefore, they do not contribute to the target of fossil independent transportation system. They are not biofuels, but fossil fuels fulfilling the fossil gasoline and diesel oil quality standards.

Figure 9 shows shares of pure and high-blend renewable energy sources in 2013.⁸ Biogas means renewable part of CBG100, LBG100, CBG50 and LBG50. Electricity is almost completely RES-E100 in rail transport, since the consumption of battery electric vehicles is marginal. Bioethanol means renewable part of E85 and ED95. Biodiesel means B100 and SB100. Consumption of RES-GH2, WG100, direct wood and direct wind are very small and not shown in the diagram. The share of renewable fuels other than biofuels is currently marginal: this group is represented only by wind hydrogen.

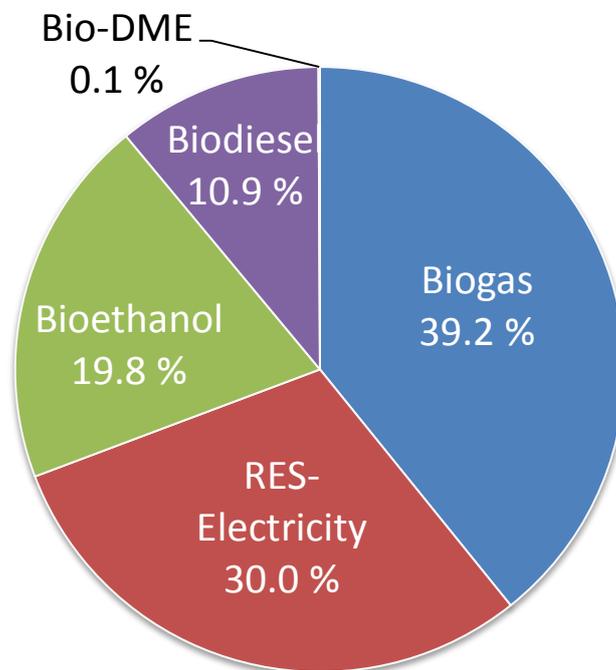


Figure 9. Shares of pure and high-blend renewable energy sources in transport in Sweden in 2013.

⁸ Most of the data is from *Hållbara biodrivmedel och flytande biobränslen under 2013* by the Swedish Energy Agency. But it does not include imported biogas, although it includes imported liquid fuels. Therefore, biogas data is from the *EU Biofuels Barometer 2014*. RES-E is from the Eurostat Shares database. Calculation is according to the RES Directive.

3.2. Sustainability

Average sustainability of biofuels is high in Sweden compared to most other countries, since 41 % of them are waste based (in 2013). The rest are energy crop based, but most of them fulfill the sustainability criteria of the RES Directive. Waste based biofuels have superior environmental merits compared to energy crop based biofuels (Annex 1). Bio-DME is 100 % waste based, since it is produced from black liquor. Biogas is 99 % biowaste based, with toilet waste the largest source. Synthetic biodiesel is 80 % waste based, with slaughterhouse waste the main resource. But less than 1 % of ethanol and 0 % of biodiesel consumed in 2013 was waste based. Significant share of electricity used in rail transport is generated by wind power. It has higher environmental quality than hydropower, which is the most common source of RES-E rail transport globally.

There is a clear emphasis for using RES-T in public and cargo transport. This is an environmental priority, since these transport modes will always be needed and reduction of volumes are not in sight. In sustainability strategies private transport is the main target for volume decrease.

Since 1994 the Swedish Society for Nature Conservation has granted sustainability certificates (Bra miljöval = good environmental choice) for public transport operators and since 1997 for cargo transport operators based on their energy use (Fig. 10a-b). Most RES-E100 in transport use is Bra miljöval certified meaning that the least sustainable forms of renewable electricity (part of hydropower and biopower) are not accepted. Tendency is to increasingly favour emission free renewables – like wind, solar and wave power – which also have low overall environmental risks, instead of biopower and hydropower that generate also other environmental problems besides emissions.



Figure 10. Environmental certification: Bra miljöval certified RES-E100 train (a) and CBG100 bus in Stockholm (b). Nordic environmental label (Swan label) at a CBG100 filling station in Lidköping (c). This station is located at a biogas plant with LBG100 and CBG100 production (Fig. 27b).

Nordic Swan label is also found in the Swedish traffic fuel market. It has been available since 2008, but only one company, FordonsGas, has been granted it, for CBG100, LBG100, CBG50 and LBG50 (Fig. 10c).

Both “Bra miljöval” and “Swan” certification have the fundamental weakness, that 100 % renewable energy is not required. Actually, it is possible to get Bra miljöval certification with 100 % fossil and Swan certification with 66 % fossil energy. It means that environmentally irresponsible use of these labels is possible. Even more worrying is that consumer trust on these labels could be lost not only in this case but all of their applications.

3.2.1. The 2050 target

The environmental quality of the Swedish transport system will improve further in the future. It means that the share of renewable energy increases and within it the most sustainable renewables grow at the expense of the less sustainable ones. By 2050 Sweden aims to achieve a completely renewable transport energy system. It is obvious that within it the most sustainable renewable will dominate. Although already now quite many sustainable options are available, more will enter the market in the future.

The only required additional components are wind and solar methane, which already are commercially produced in Germany. This technology is needed for large scale storage of intermittent renewables, especially wind and solar energy, to enable large share for them in transport and total energy consumption. Methane offers the largest storage capacity and the longest storage duration of all technologies available for storing electricity. Already now, methane storage capacity is over 200 TWh in Germany and over 2000 TWh in UNECE countries. Also, solar and wind methane have orders of magnitude larger resource base than biomethane (Fig. 11).

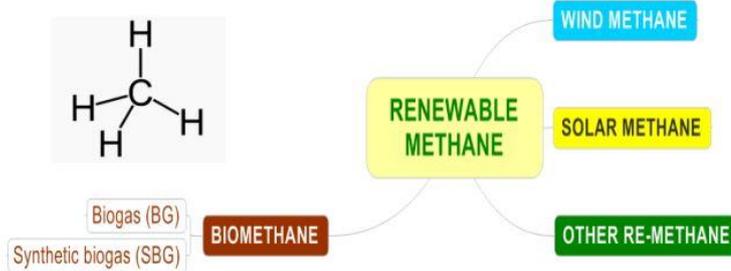


Figure 11. Types of renewable methane.⁹

Solar hydrogen will certainly be taken into use as well many other alternatives for the most sustainable transport. These include other emission-free electricity and hydrogen, indirect electricity (such as magnetic engines and compressed air) and direct wave power in water transport. Renewable hythane, a mixture of wind hydrogen and biogas, is an excellent fuel from environmental point of view.

It is clear that in a truly sustainable transport system of the future overwhelming part of primary energy must come from emission-free renewable energy sources, such as solar and wind energy.¹⁰ These are already used in Sweden as wind electricity in rail vehicles, solar and wind electricity in road vehicles and wind hydrogen in road vehicles. Earlier wind power was also used as part of hythane.

Wastes will be produced anyway. They need to be utilized as resource efficiently as possible. Material use takes precedence over energy use. For most biowaste, fertilizers are the only material use. Both fertilizer and energy value of these resources can be utilized by biogas technology, as has been done in Sweden. Conventional biogas technology is able to utilize all biowastes, while biodiesel, HVO and ethanol technologies are specialized for certain compounds, which form only small shares of total biowaste resource base.

For other types of waste, especially wood based, which has the largest resource, there are many alternative uses. However, a significant part is and will be available for energy production. Synthetic biogas and bio-DME are the two fuels that can be produced at the highest material and energy efficiency from wood waste, as has been done in Sweden.

Chemical fuels will be used in the sustainable energy system of the future, but only the best ones. Gaseous fuels, such as hydrogen, methane and DME, have inherently highest conversion efficiency potential in heat engines. And both hydrogen and methane are already now used also in fuel cells.¹¹ Hydrogen is the cleanest fuel in heat engines, but also other gaseous fuels have much lower emissions than liquid fuels have. From lifecycle energy consumption and greenhouse gas emission perspective biogas, synthetic biogas and bio-DME are the best biofuels.¹²

The most sustainable technologies, which would have dominating role in 2050 and beyond, are hereby called the 2050 technologies. Figure 12 shows which of them are already now in use in Sweden.

Figure 12. Shares of 2050 technologies in 2013 in Sweden. Fuels are used in road transport only. "Other" means wind hydrogen, waste wood, waste wood gas and direct wind.

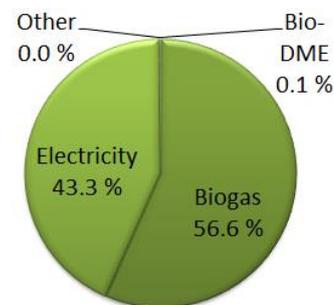


Table 1 shows secondary energy sources (fuels and electricity) already

⁹ Lampinen (2012).

¹⁰ Lampinen (2012) gives an example of a sustainable development path for transport to 2050.

¹¹ In Sweden only hydrogen fuel cells are currently used in transport, but e.g. in Norway also methane fuel cells.

¹² JEC (2011).

available for fulfilling sustainable energy needs of all transport modes. Most of them have not yet been implemented in the market.

Table 1. Sustainable transport opportunities based on secondary energy sources in Figure 12. Only one addition has been made: liquefied hydrogen is not yet in the Swedish market, but it is included in the table. CBG100 and LBG100 mean both BG (biogas) and SBG (synthetic biogas) based fuels.

Transport mode	Submode	Main	Supportive	Supplementary
Road	Light	RES-E100	CBG100	Wind-GH2
	Cars	CBG100, RES-E100, Wind-GH2		Bio-DME100, Wind-LH2, LBG100, WG100
	Vans	CBG100, Bio-DME100	RES-E100, Wind-GH2, LBG100	Wind-LH2, WG100
	Buses	CBG100, Bio-DME100, Wind-GH2, LBG100	RES-E100, Wind-LH2	
	Trucks	Bio-DME100, LBG100, CBG100	Wind-LH2	Wind-GH2, WG100
Off-road		Bio-DME100, CBG100, RES-E100	LBG100	Wind-LH2, Wind-GH2
Rail		RES-E100	Bio-DME100, LBG100, CBG100, Wind-LH2,	Wind-GH2, Waste wood
Water		Bio-DME100, LBG100	Direct wind, CBG100, Wind-LH2, Wind-GH2	RES-E100, Waste wood
Air		LBG100, Wind-LH2, Bio-DME100		Direct wind, RES-E100, CBG100
Space		Wind-LH2, LBG100		

Within transport modes, the share of public and cargo transport will increase, because reductions of traffic volumes emphasize private transport. Already now most of RES-T use, and especially pure RES-T use, is in the public and cargo transport modes.

As a conclusion, the choices already made in Sweden have included many technologies that are the most sustainable, not only for 2050 but beyond. But also some less sustainable technologies to be phased out in medium term are part of the current diverse portfolio.

3.3. Diversity

Technical diversity of the Swedish RES-T system is high. In short term it is necessary to exploit all possibilities for phasing out fossil fuels. Large diversity means that there are a lot of options to choose at filling stations in addition to the conventional gasoline and diesel oil, and vehicles are flexible¹³ to use many energy sources.

Figure 13 shows examples of diversification of supply at filling stations in Stockholm (a-b), Malmö (c) and Gothenburg (d). There are over 2000 stations offering pure or high-blend RES-T in Sweden.

¹³ Opposition to energy flexibility of vehicles exists. The argument is that vehicles should not be developed even though it is easy, but renewable fuels should be developed to meet specifications of fossil fuels (so called drop-in fuels). It is logical argument only from the perspective of supporting continuous crude oil dependency. Gasoline and diesel oil are very low quality fuels not only environmentally but also from engine technological point of view (efficiency) compared to renewable fuels. It is illogical to require lowering technical quality of renewable fuels and resist development of vehicles for higher efficiency and lower emissions.



Figure 13. Examples of multifuel stations: B100, CBG100 and E85 (a), CBG100, E85 and RES-E100 (b), CBG50, Wind-GH2 and RES-E100 (c), LBG100, CBG100, B100, E85 and SB35 (d).

Table 2 shows types of RES-T used commercially in Sweden in 2013. In addition, wood gas, direct wood and direct wind were used privately. There are plans for begin large scale production of biomethanol. Fossil methanol was utilized in the past and biomethanol is currently used for production of bio-DME and biodiesel.

Table 2. Types of RES-T used commercially in Sweden in 2013.

Secondary energy	Types	Products	Primary energy	Notes
Synthetic biodiesel (SB)	HVO (hydrotreated vegetable oil)	SB15, SB30 and others	Wood waste, biowaste and energy crops	FT fuels are also used, but only with fossil feedstocks
Biodiesel (B)	RME (rape methyl ester)	B2, B5, B6, B100	Energy crops	Other types in private use, including waste based
Bioethanol (E)	hydrous, anhydrous	E5, E85, ED95	Energy crops (> 99 %), wood waste	Biowaste based from 2015
Liquid bioethers	Bio-ETBE	ETBE5	Energy crops	
Biomethane (BM)	BG (biogas)	CBG50, CBG100, LBG50, LBG100	Biowastes (99 %), energy crops	Wood waste based synthetic biogas (SBG) from 2014
Bio-DME		Bio-DME100	Wood waste	
RES-hydrogen (RES-H2)	GH2	RES-GH2 (200, 350 and 700 bars)	Wind power	Until 2006 also wind-HCNG (8-20 % wind-hydrogen with CNG) was used
RES-electricity (RES-E)		RES-E100, mixed electricity	Hydropower, biopower, wind power, solar power, wave power	Direct use by wires, indirect use by battery and capacitor storage with conductive and inductive charging

There is also a high diversity of alternative fossil fuels in road transport (meaning other than gasoline and diesel oil): CNG (since 1987), LNG (since 2010), LPG (since 1970s) and synthetic GTL diesel (FT-diesel from natural gas, since 1999). Fossil methanol (M15 and M100) was used in 1980-1986 and fossil DME in 1995-2012.

Table 3. shows types of vehicles able to use 100 % renewable energy in Sweden. In addition, the Swedish industry manufactures E100 buses and cars for export; E100 is not available in Sweden (or anywhere else in Europe).

Table 3. Types of RES-T100 vehicles in the Swedish market.

Secondary energy	Vehicle class	Engine	Type	Other RES-T
RES-E100	Light, car, van, bus, truck, boat	Electric	BEV	
	Car	Otto-electric, Electric	PHEV	CBG100
	Car	Diesel-electric, Diesel, Electric	PHEV	
	Bus	Electric, diesel-electric	PHEV	
	Train, metro, tram, bus	Electric	EV	
CBG100	Car, van	Otto	Bifuel	
	Car	Otto	Multifuel	E85
	Car	Otto-electric	PHEV	RES-E100
	Bus, truck, train, van, car	Otto	Monofuel	
	Bus	Otto-electric	Monofuel-HEV	
	Truck, bus	Diesel	Dualfuel	SB100
	Tractor	Diesel	Dualfuel	B100, SB100
LBG100	Truck	Diesel	Dualfuel	SB100
	Truck	Otto	Monofuel	
	Truck	Otto	Bifuel	CBG100
Bio-DME100	Truck	Diesel	Monofuel	
WG100	Car, van, truck, tractor	Otto	Bifuel	
	Tractor	Diesel	Dualfuel	
RES-GH2	Car	FC-electric	Monofuel-FCEV	
	Car	Otto-electric, Otto	Monofuel-HEV	
B100	Bus, truck, car	Diesel	FFV	SB100
	Bus	Diesel-electric	FFV-HEV	SB100
	Tractor	Diesel	Dualfuel	CBG100, SB100
Wood	Train, ship, mobile working engine	Steam	Multifuel	Other solid biomass
Wind	Boat, ship, aeroplane	none	Direct	

Vehicle fleet is developing more energy flexible. Figure 14 shows two excellent examples from Sweden. Saab Trifuel (Fig. 14a) is a multifuel car able to use CBG100 and E85 (and CNG and gasoline). It is able to exploit the high octane numbers of E85 (108) and CBG100 (140) compared to gasoline (95-99) by lower energy consumption and higher power. By pressing a button driver can switch from gasoline to E85 or CBG100 and experience a 30 horsepower increase in power. Sweden is the first country in the world to produce such technology.

Biogas version of Opel Ampera in Figure 14b is a plug-in-hybrid¹⁴ owned by city of Malmö. It uses locally produced wind electricity in city driving, locally produced biogas for regional driving and utilizes the large biogas filling station network in Sweden and Europe for long-distance driving. It is a conversion from a

¹⁴ Note: conventional hybrid vehicles (HEVs) are not alternative fueled vehicles, since they can use only gasoline or diesel oil. But if they use alternative fuels, they are alternative fuel vehicles. For example, ethanol-HEV vehicles have been used in Sweden since 1997, biogas-HEVs since 1998 and biodiesel-HEVs since 2012. Plug-in-hybrid vehicles (PHEVs) are alternative fueled vehicles, since they can charge electricity from the grid in addition to using chemical fuel. Unfortunately, currently the chemical fuel of choice by automakers for PHEVs is either gasoline or diesel oil. Therefore, conversions are needed.

gasoline-PHEV made by replacing gasoline system by biogas system (it cannot be driven by gasoline). This technology is not yet factory manufactured.



Figure 14. Multifuel (a) and biogas-PHEV (b) cars are examples of advanced energy flexible vehicles in Sweden.

Development of the RES-T road vehicle fleets has progressed best for buses. Between the years 2000-2013, the RES-T bus fleet grew from 400 to 4700 units. In 2013 RES-T buses represented 27 % of the whole registered bus fleet and 30 % of buses in commercial traffic. This success story is due to municipal policies, since municipalities have procured 4300 RES-T buses for public transport, representing 45 % of all buses in procured public transport.¹⁵ This has helped private sector to acquire another 400 RES-T buses for other services. Four RES-T bus types are in use: their shares are found in figure 15. Only ED95 buses are dedicated for a single fuel. CBG100 buses may use any type of methane fuels: in addition to biogas, also natural gas was used in 2013 and from 2014 also synthetic biogas. B100 buses may also use SB100 and fossil diesel oil. BEV buses may use any type of electricity, including fossil and nuclear. These buses covered 30 % of bus use nationally. It is more than their share of the national fleet, since the average use (in kilometers) of ED95 and CBG100 buses were substantially more than the average use of all other types of buses, including fossil diesel buses. On the other hand, the average use of electric buses (all BEV) was about half as much. Electric buses are used only in specially designed routes in city traffic. Other types of RES-T buses are utilized in all types of routes in city traffic as well as in intercity services.

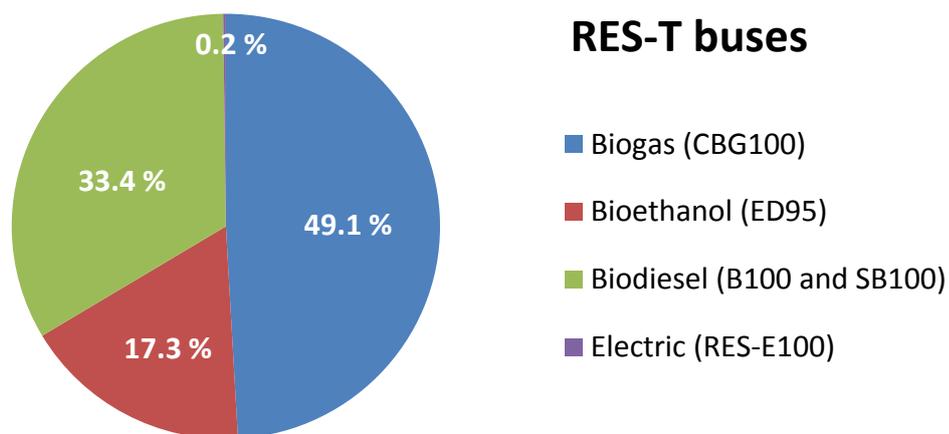


Figure 15. Shares of energy sources utilized by the RES-T bus fleet (4700 buses) in 2013.¹⁶

¹⁵ More on the role of municipal policies in this major success story can be found at Lampinen (2014).

¹⁶ Data is from *Statistik om bussbranschen* (2014). Earlier some other types have been used, e.g. hythane buses in 2003-2006 and hydrogen buses in 2004-2006.

RES-T vehicles for road cargo transport are shown in Figure 16. The RES-T fleet consisted of 830 trucks and 9000 vans in 2013. RES-T technologies are especially important in cargo transport, since it increases emissions more than any other sector. Biogas trucks usually can use only CBG100 or LBG100, but some have both options. These vehicles can operate also on fossil fuels or non-renewable electricity, but for ED95 and DME trucks fossil options were not available.

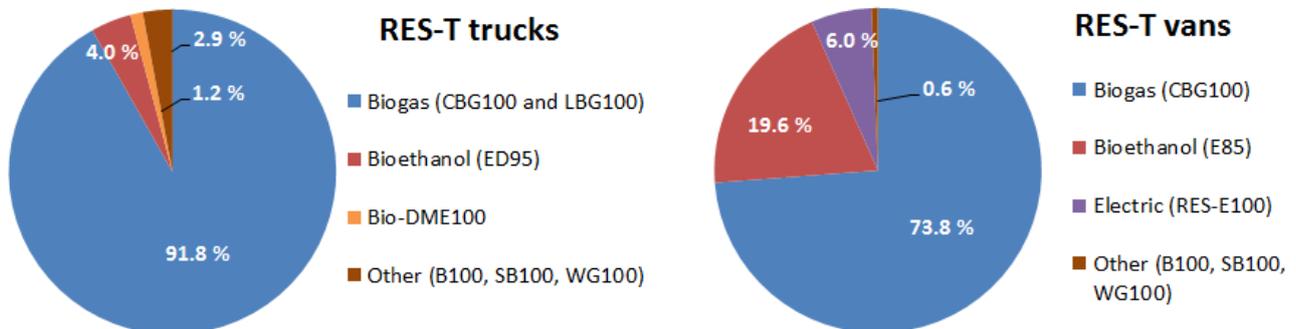


Figure 16. RES-T truck (a) and van (b) fleets (10,000 vehicles) in 2013.¹⁷

Figure 17 shows shares of technologies in the RES-T car fleet and utilization of these technologies in 2013. There are two reasons for differences between these two charts. First, biogas cars were used in average significantly more (in kilometers) than any other car types (including diesel oil and gasoline cars), and about 50 % more than E85 cars. It means they were used a lot in long distances and commercial traffic. Electric cars were used less than any other car type, and 60 % less than E85 cars. Their use concentrated in local city traffic. Majority of electric car use is in commercial traffic. These charts do not include other types of RES-T cars, because their share is only 0.01 %: B100 (Fig. 45), WG100 and wind-GH2.

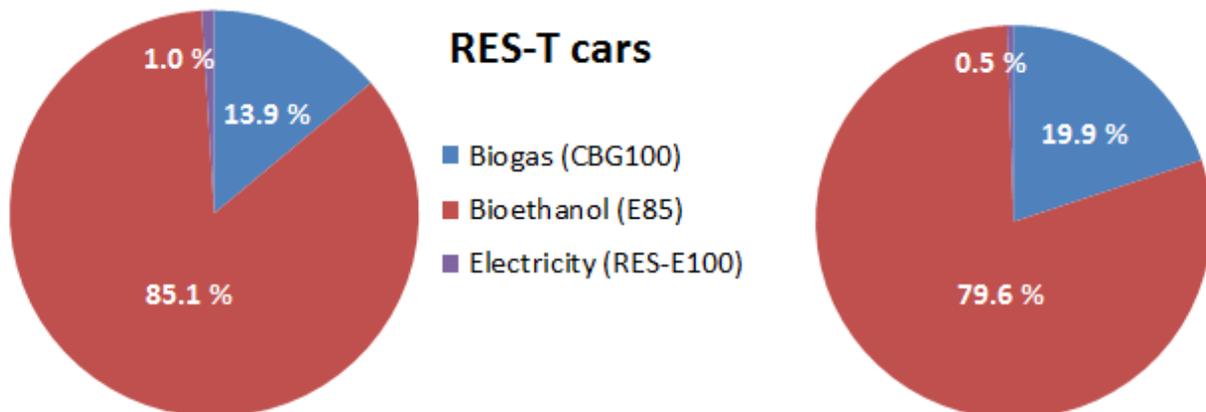


Figure 17. RES-T car fleet (a) of 270,000 cars and their utilization (b) in 2013.¹⁸

There is a significant difference in the current RES-T car fleet and new registrations in 2013 (Fig. 18). This development is mostly positive but partly negative from environmental point of view. Increase of BEVs is positive, since they can be operated by especially sustainable energy sources, solar and wind power. The same applies to wind-GH2 cars, which are included in the "Other" group. Increase of CBG100 cars is positive, since 99 % of biogas is produced from biowastes. Decrease of E85 car share is positive since over 99 % of ethanol is food energy crop based and they depend on gasoline for 30-50 % of their energy consumption (they can not be operated on E100 so they retain fossil fuel dependence).

¹⁷ Data is mostly from SCB/Fordon 2013, but since Bio-DME trucks are not separately classified by SCB, their number is from the BioDME project.

¹⁸ Data is from SCB/Fordon 2013.

Increase of PHEVs is negative, because they are mostly used by gasoline or diesel oil. Although they are fossil fuel independent in theory, only 0-50 km range (some of them have zero electric range) on electricity means that chemical fuel is the main fuel for most of them. The chemical fuel of choice by the auto industry is, unfortunately, either gasoline or diesel oil. If that was not the case PHEV cars could be exceptionally sustainable. This is demonstrated by the only RES-PHEV car registered in 2013 (Fig. 14b). It is powered by wind electricity in city traffic and biogas in road traffic, which is the ideal solution from environmental point of view. It is a conversion, where gasoline use was removed and biogas use added.

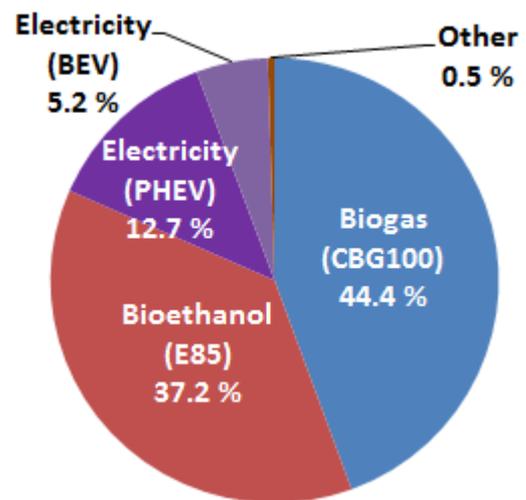


Figure 18. New registrations of RES-T cars in 2013.¹⁹

As seen above, for road transport large diversity of excellent choices are already available. But for other types of transport Sweden is still in early stage of development, except for RES-E100 rail transport with very long history (Fig. 19a). One biogas train was introduced in 2005, but was taken out of service in 2010 (Fig. 19b). A few RES-T tractors are in use. An example is a dualfuel tractor powered by biogas and biodiesel (Fig. 19c).



Figure 19. a) Electric train (EV) in Stockholm uses RES-E100 certified by the Swedish Society for Nature Conservation. b) CBG100 monofuel train in Linköping. c) Valtra CBG100/B100 dualfuel tractor. These Finnish tractors were introduced in Skåne in 2011.

¹⁹ Data is from SCB/Fordon 2013.

4. Pioneering

An essential reason for the Swedish qualitative RES-T success is pioneering. Large technical diversity is a result of continuous introductions of new technologies and creating markets for them. Often it has involved new Swedish technological innovations, but it has not been a prerequisite. Since the 1980's the following seven are the most noteworthy pioneering RES-T achievements:

1. First country in the world to take bio-DME into use (2011).
2. First country in the world to take tall oil based synthetic biodiesel (SB, HVO) into use (2011).
3. First country in the world to take ethanol (ED95) into use in diesel engines (1986).
4. First country in Europe to take high-blend ethanol (E85) into gasoline engine use (1994).
5. Restarted biogas (BG) use (as CBG) globally and permanently (1989).
6. Fourth country in the world to take liquefied biogas (LBG) into commercial use (2012).
7. First country in the world to take synthetic biogas (SBG) into commercial use (2014).

In all these cases primary energy resource was domestic and produced fuels were especially sustainable:

- Biowaste for CBG and LBG
- Wood waste for ED95, E85, bio-DME, SB and SBG

This is still the case for all of them except for ED95 and E85 that now are almost completely (> 99 %) produced from food energy crops.

Except for bio-DME, which is currently in demonstration phase, commercial markets have been created. Very noteworthy and unique feature of the Swedish success story is that municipalities played a key role in market creation for all these fuels except for SB.

Technology for both production and utilization were domestically developed for bio-DME, ED95 and CBG. Technology for production was domestically developed for SB. Technology for utilization was domestically developed for LBG. Creation of domestic markets has led to commercial manufacturing of production, distribution, fueling and utilization technologies in addition to the fuels. And it has led to market creation in many other countries. The Swedish industry supplies foreign markets by production technology (CBG), distribution technology (CBG), fueling technology (ED95, CBG), utilization technology (DME, ED95, E85, CBG, LBG) and fuels (ED95, E85). Only the least sustainable fuels are exported.

Regarding utilization technologies (vehicles) there are many pioneering achievements due to the large and innovative Swedish vehicle industry and interest in testing new technologies developed abroad. These are examples since the 1980's:

- Battery electric (BEV) buses since early 1980's (Volvo)
- Flywheel buses were demonstrated in the 1980's (Volvo)
- Hydraulic transmission buses were demonstrated in the 1980's (Volvo)
- Methanol (M100) vehicles were demonstrated in the 1980's (not manufactured in Sweden)
- Ethanol diesel (ED95) buses since 1986 (Scania)
- Hybrid (HEV) buses since 1986 (Scania)
- Methane (CMG) buses since 1987 (not manufactured in Sweden until 1992)
- Biogas (CBG100) monofuel buses since 1992 (Scania and Volvo)
- Ethanol otto (E100) monofuel buses since 1992 (for export only) (Volvo)
- Stirling engines in commercial submarines since 1992 (Kockums)
- Ethanol otto (E85) FFV cars since 1994 (originally from abroad, domestic manufacturing since 2004: Saab, later Volvo and Koenigsegg)
- Dimethyl ether (DME) monofuel trucks since 1995 (Volvo)
- Biogas (CBG100) bifuel cars since 1995 (Volvo)
- Gas turbine hybrid multifuel buses and trucks were demonstrated in 1995-1999 (Volvo)
- Biogas (CBG100) monofuel trucks since 1996 (Volvo, later Scania)
- Ethanol-HEV buses (E85, ED95) since 1997 (first foreign buses with Saab engines, later Scania)
- Biogas-HEV (CBG100) buses since 1998 (not manufactured in Sweden)

- Hythane (wind-HCNG) buses were demonstrated in 2003-2006 (Volvo)
- Hydrogen (FCEV) buses were demonstrated in 2004-2006 (not manufactured in Sweden)
- Biogas (CBG100) monofuel train was commercially used in 2005-2010 (Volvo)
- E100 concept cars in 2006-2007 (Saab)
- Wind hydrogen (otto-electric HEV) cars since 2008 (not manufactured in Sweden)
- Ethanol diesel (ED95) trucks since 2008 (Scania)
- Prototype Solar electric car (car which generates propulsion energy in integrated solar panels) 2009 (Koenigsegg)
- Ethanol otto (E100) monofuel cars since 2010 (for export only) (Koenigsegg)
- Liquefied biogas (LBG100) monofuel and dualfuel buses since 2010 (not manufactured in Sweden)
- Biogas/ethanol/gasoline (CBG100/E85) trifuel cars in 2011 (Saab)
- Biogas/biodiesel (CBG100/B100) dualfuel buses since 2011 (Volvo)
- Liquefied biogas/biodiesel (LBG100/B100) dualfuel trucks since 2011 (Volvo)
- Biogas/biodiesel (CBG100/B100) dualfuel tractors since 2011 (not manufactured in Sweden)
- Electric (BEV) cars with inductive charging since 2012 (Volvo)
- Biodiesel-HEV (B100) buses since 2012 (Volvo)
- Plug-in-hybrid (PHEV) buses since 2013 (Volvo)
- Biogas plug-in-hybrid (biogas-PHEV) cars since 2013 (converted)

Scania is one example of exceptional innovation, including the first hybrid buses in the world, first ethanol diesel buses in the world and biogas otto buses with the highest efficiency in the world (Fig. 20). Scania holds the world record in thermal efficiency of commercial automotive otto engines.²⁰



Figure 20. Scania's innovative heavy vehicles: a) Hybrid bus (HEV) from 1993 at Stockholm municipal transport museum. b) Ethanol diesel (ED95 monofuel) bus in Stockholm. c) Biogas otto (CBG100 monofuel) truck in Katrineholm.

4.1. Technology implementation

Taking a completely new renewable fuel bio-DME into use in 2011 was a major achievement, especially because bio-DME is manufactured from black liquor, a wood waste. Dimethyl ether (DME) is gaseous fuel stored in liquefied form in vehicles. Fossil DME has been used in transport since early 1990s, first in Denmark, where its excellent properties as diesel engine fuel were first discovered, and since 1995 also in Sweden. Much of the research work was conducted at gasification demonstration plant in Varnamö since

²⁰ New Scania Euro 6 biogas (CBG and LBG) engine has 40 % thermal efficiency, a world record for commercial automotive otto engines. Corresponding Scania Euro 6 diesel engine has 42 % thermal efficiency. Thermal efficiency of Euro 6 ethanol diesel engine is between these. To comply with the new EU Euro 6 emission regulation, thermal efficiencies of fossil diesel, biodiesel and synthetic biodiesel engines are lower (about 2 percentage points) than for Euro 5 engines. This is due to the inherently high emissions of diesel cycle engines and these high molecular weight fuels. But low molecular weight gaseous fuel DME enables Euro 6 compliance with higher diesel engine efficiency. For gaseous fuel otto engines the Euro 6 limits are easy to achieve. Stirling engines would enable higher thermal efficiency than diesel and otto engines in truck/bus use, but they are not found in the market for this application. In submarines they are commercially applied by the Swedish industry, but with fossil diesel only. Thermal efficiency of these engines, which are the same size as truck and bus engines, is 48 %.

2003.²¹ Production began in 2011 in Piteå at Chemrec plant, which is connected to a Kappa pulp plant for pipe transport of black liquor (Fig. 21a). Bio-DME100 has been used for long-distance, regional and local cargo transport by dedicated trucks utilizing filling stations in four cities (Fig. 6a). Although bio-DME use is still in a demonstration phase, it has resulted in factory manufacturing of DME trucks (Fig. 6b), including for export to countries using fossil DME.



Figure 21. Two wood waste based biofuel production plants in Piteå: a) Chemrec Bio-DME production plant (left), gasifier (middle) and Kappa pulp factory, where black liquor originates (right). b) SunPine plant for tall oil biodiesel production.

The same year also tall oil based biodiesel production began in Piteå (Fig. 21b). Tall oil is a waste product originating from pulp mills. It is transesterified in Piteå for production of raw biodiesel. Instead of cleaning it for using as a FAME biodiesel, all is shipped to Gothenburg, where it is hydrotreated at Preem's refinery resulting in synthetic biodiesel called hydrotreated vegetable oil (HVO). Sweden was the first country where tall oil based HVO was commercially produced and introduced into the market (Fig. 5). And it was the first HVO type fuel and the first synthetic biodiesel in the Swedish market. Since 2012 more HVO has been imported than is domestically produced. In 2013 HVO use tripled from 2012 level and it became the RES-T market leader in Sweden (in 2012 it was fourth). Imported HVO is not produced from tall oil: it is partly waste based (animal fats) and partly food crop based (palm oil). Except for experimental use as SB100, HVO is consumed in low blends with fossil diesel oil. Technology for SB100 use is in place, since all B100 buses can utilize also SB100. Regular diesel vehicles can not utilize SB100, B100 and PPO100, since these fuels do not fulfil the international fossil diesel specifications. But it is easy to manufacture vehicles, which are able to use SB100, B100 and fossil diesel. With some more effort, also PPO100²² could be used in the same vehicle.

Production and consumption of ED95 (1985) and E85 (1994) also started with waste wood, but currently energy crop based ethanol has over 99 % share (imported, produced from imported feedstocks and since 2001 produced from domestic feedstocks). Ethanol originated from brown liquor of a sulphite pulp mill and since 2004 also from a small demonstration plant utilizing wood chips in Örnsköldvik. Use of ED95 first began in Örnsköldvik in 1985 (Fig. 22) and E85 use began in 1994 (Fig. 23a). Sweden was the first country to utilize ethanol in diesel vehicles. In addition to ED95, other blends like ED10 and ED15 have been used. Scania was the first bus company to start commercial production of ED95 buses and since 2008 also ED95 trucks. ED95 technology has later diffused to other countries.

²¹ City of Växjö was one of the driving forces behind this work since 2003. The idea was to take DME into city bus use, but plans for commercial production did not materialize there (they materialized in Piteå, which is located 1300 km North of Växjö). Although DME demonstration buses have been built, DME is only utilized in trucks in Sweden.

²² PPO100 (pure plant oil) has not belonged to the RES-T portfolio in Sweden since the 1940s. But it is in use in many European countries, e.g. Germany, Austria, Hungary and Denmark. There are currently no factory manufactured PPO100 vehicles in the market (although they were produced earlier, e.g. in Sweden), so all are converted from fossil diesel vehicles. After conversion they become multifuel vehicles, since in addition to PPO100 and fossil diesel they can also be operated on B100 and SB100. PPO can also be used as blends. Almost all PPO has until now produced from food crops, i.e. it does not belong to the most sustainable alternatives. However, it is also produced from plants with inedible oils and waste oils. Main benefits of PPO compared to B and SB are low energy consumption, avoidance of chemical use during production and applicability to very small scale production. PPO was the original diesel engine fuel in 1895.



Figure 22. SEKAB wood waste based ethanol production plant (a) and a Scania city bus powered by wood waste based ED95 (b) in Örnsköldsvik.

The case of E85 was different. It was widely used in the USA and technology was commercial there, but in the 1990s it was not used in Europe. Sweden was the first country to introduce it in Europe with vehicles imported from USA (Fig. A3.2). This led to commercial production in Europe first by Ford (1999) and later by Swedish car companies Saab (2004), Volvo (2005) and Koenigsegg (2007). Saab was the first company to make use of the high octane number (108) of E85: Saab Biopower introduced in 2004 delivers 30 horsepower more power when the tank has been filled with E85 than when it is filled by gasoline (Fig. 23b-c). Koenigsegg CCXR introduced in 2007 delivers 200 horsepower more on E85 than on gasoline (Fig. 24b). These were the first cars demonstrating in practice for consumers the superior engine technological quality of biofuels compared to conventional fossil fuels. In addition to ethanol this applies to many other biofuels in both otto and diesel engines. For biogas this was first implemented in Saab Trifuel in 2011 (Fig. 14a).



Figure 23. a) Pump for wood waste based E85, E10 and E5 in Örnsköldsvik. b) E85 car Saab Biopower. c) Saab poster at Stockholm railway station in 2004 tells that a forest based biofuel delivers 30 horsepower more power and 40 Nm more torque than gasoline in the new Saab Biopower.

E100²³ is not available anywhere in Europe. But the Swedish automotive industry has supplied E100 vehicles for the Brazilian market: buses since 1992 (Fig. 24a) and cars since 2010 (Fig. 24b). Saab produced concept E100 cars in 2006-2007, but all production models have had E85 system (Fig. 23b). In the process leading to crude oil independence the E100 technology might be introduced in the Swedish market.²⁴

²³ E100 usually means 100 % hydrous ethanol, i.e. mixture of about 95 % ethanol and 5 % water. All energy content is in ethanol, therefore abbreviation E100 is used. Sometimes E100 means anhydrous ethanol, i.e. about 99.5 % ethanol with 0.5 % water. Rarely other mixtures of ethanol and water are also used. A century ago the Swedish industry was able to manufacture vehicle engines running on a mixture of 15 % ethanol with 85 % water, i.e. wines. These especially fuel flexible engines, hot bulb engines, are no longer found in the vehicle market.

²⁴ Just like in the case of ED95 for diesel engines, there is a need for adding some chemicals for engine technological reasons. In the case of otto engines the reason is low evaporation of ethanol in cold conditions (in principle ethanol is better fuel than gasoline in cold conditions due to much lower freezing temperature, but when using otto engines



Figure 24. Swedish hydrous²⁵ E100 monofuel vehicles for the Brazilian market: a) Volvo E100 BRT²⁶ buses in Curitiba in 2000. b) Koenigsegg CCXR E100 car²⁷.

Although biogas as CBG had been utilized in transport in some countries before (including Sweden in the 1940s) it disappeared in the 1980s. Sweden restarted it in 1989 and began the 3rd wave of traffic biogas.²⁸ From Sweden the wave has spread to all continents. In Europe it is the most important traffic biofuel after biodiesel, ethanol and synthetic biodiesel. This development was initiated by City of Linköping: originally biogas was produced at a municipal sewage treatment plant and since 1996 also at a municipal biogas plant digesting solid biowaste (Fig. 25).



Figure 25. Municipal biogas reactors at sewage treatment plant (a) and solid biowaste treatment plant (b) are the sources of traffic biogas in Linköping.

In most countries national gas grid is the most common way for long distance transport of biogas to filling stations. However, in Sweden the grid covers only very small part of the country and 20 % of biogas transport. Truck transport by CBG containers had the main role in creating a filling station network (Fig.

their ignition requirements gives advantage to gasoline). In the Brazilian climate this is not obligatory: in exceptionally cold circumstances electronic preheating is applied there. But for the Swedish winter conditions it is likely that components with high vapor pressure would be added. They can be renewable and even made from ethanol (like diethyl ether, which was used for this purpose already more than a century ago in Sweden).

²⁵ Hydrous ethanol is much cheaper to produce than anhydrous, but cannot be blended with gasoline.

²⁶ BRT (bus rapid transfer) means a public transport system, where buses have dedicated lanes, where no other vehicles have access to. Therefore congestion does not affect them and similar service level to those of metros can be achieved. Buses used for the purpose are usually extra-long like those shown in the photo. City of Curitiba in Brazil was the first in the world to implement such system – and they used E100 buses for it. The first Swedish BRT system was taken into use in Malmö in 2014. There buses are CBG100 hybrids (see chapter 3.2.4).

²⁷ Photo courtesy of Koenigsegg Automotive AB, Ängelholm, Sweden. Koenigsegg models CCXR and Agura R are FFV cars able to use anhydrous E100, E85 and gasoline. With gasoline, power drops by 200 hp due to its low octane number. Third model, Koenigsegg One:1 can use E85 and gasoline. Only for CCXR a monofuel a E100 version for hydrous ethanol is available for the Brazilian market.

²⁸ Third wave is related to the global sustainable development policy. First wave was during the Second World War and second wave after the 1970's oil crises. New Zealand was global leader in the late 1970s and early 1980s (headquarters of global MGV trade association is still there), but the CBG infrastructure was shut down in favour of imported crude oil based fuels. However, strong global business (upgrading plants and filling stations) had been created there helping the Swedish restart with existing commercial technology. Finally in 2010 also New Zealand restarted; based on the Swedish example. CBG was used in the UK in the 1960s and 1970s in a single farm. In Czechoslovakia two upgrading plants were built in the 1980s for vehicle use, but technology did not diffuse elsewhere. In the 1980s biogas upgrading began in the Netherlands, but not its vehicle use. (Lampinen 2013b)

26a). It is used up to distances of 500 km. Local and regional biogas pipelines have increasing importance in distances up to tens of kilometres (Fig. 26c). According to the Swedish strategy for crude oil independency, the national natural gas grid will not be extended, but local and regional biogas grids will be created instead.²⁹ Fourth method is LBG truck transport (Fig. 3b). This opened the possibility to international biogas trade, which began in 2011, first in the world, by importing landfill gas based LBG100 from the United Kingdom (Fig. 26b). LBG tanker ships enable transport distances of thousands of kilometres.



Figure 26. Biogas transport: a) CBG container transported by truck from Linköping being unloaded at a filling station in Stockholm. b) Private LCBG station for waste trucks in Stockholm using landfill gas based LBG100 imported from United Kingdom. c) Local biogas pipeline in construction in Örebro.

Swedish automotive industry has contributed to the success. Volvo began manufacturing of CBG monofuel buses in 1992 (and trucks in 1996), CBG bifuel cars in 1995 and LBG dualfuel trucks in 2011. Although otto engines used in the monofuel buses and trucks have lower efficiency than diesel engines, the Swedish automotive industry, especially Scania, has reduced the difference to minimal level by exploiting the high octane number of biogas (Fig. 20c). Saab multifuel car is the best car in the world for demonstrating the high engine technological quality of biogas (Fig. 14a).

Liquefied biogas (LBG) production began in Sundsvall, where experimental cryougrading plant was opened in 2010 at a municipal biogas plant (Fig. 27a). It only produced small amounts of LBG for the first LCBG filling station in Sweden, opened in Sundsvall in 2009, and for one LBG demonstration bus. Larger scale LBG use started in 2011 by imported landfill gas³⁰ based LBG from the United Kingdom to Stockholm. Commercial domestic production began in Lidköping in 2012 at a municipal biogas plant (for digesting solid municipal biowaste, Fig. 27b). LBG is transported by Fordonsgas company to LBG and LCBG filling stations (Fig. 3a). There were 6 LBG filling stations in operation in December 2014 and also several LCBG filling stations, where biogas is stored in liquid form and vaporized for CBG filling units.



Figure 27. LBG production began in Sweden with a demonstration plant in Sundsvall in 2010 (a) and a commercial plant in Lidköping in 2012 (b).

²⁹ The Swedish strategy for crude oil independency was published by the Swedish government in 2006 (Sveriges Regeringskansliet 2006).

³⁰ In Sweden landfill gas has not yet been used for vehicle fuel production, like in many other countries (in Iceland all traffic methane is landfill gas based). It is planned in Helsingborg, where it would be produced in a form of LBG100 for truck and ship use. In the United Kingdom commercial landfill gas based LBG production began in 2008, 1st in Europe and 2nd in the world.

The first commercial³¹ synthetic biogas (SBG) production plant in the world, by municipal energy company Gothenburg Energy, was taken into use in Gothenburg in December 2014 (Fig. 28a). SBG is produced from waste wood, upgraded and transported to CBG filling stations by gas grid. There is an option for liquefaction of SBG in case LBG demand grows above current production capacity.



Figure 28. SBG plant (GoBiGas1) of Gothenburg Energy (a) and one of Fordonsgas CBG filling stations selling SBG in Gothenburg (b).

SBG is one of many synthetic fuels, which can be produced from waste wood by gasification combined with thermochemical synthesis. Other main options are DME, methanol, FT-diesel and FT-gasoline. Of these SBG synthesis offers the highest efficiency³², lowest investment cost, lowest production cost, lowest lifecycle greenhouse gas emissions and lowest exhaust pipe emissions. There are plans for another, larger plant in Gothenburg and even larger plant in Malmö or Landskrona³³. SBG and BG complement each other. SBG technology is suitable for large scale centralized production using wood waste, whereas BG technology is more suitable for decentralized production using biowastes. The SBG plants are urgently needed, since for many years growth of BG production has been inadequate for satisfying growth in BG demand. Although part of the gap has been covered by imports, natural gas has supplied most of it.³⁴

4.2. Market creation by municipalities

Of the seven pioneering RES-T solutions, bio-DME is in a demonstration phase³⁵ and for the rest commercial market has been successfully created. Except for synthetic biodiesel, municipal policies played key roles for all the rest.

This is unique. Many people believe that in the transportation sector very little can be done even nationally to solve the crude oil dependency problem: UN level treaties and EU level legislation is expected to solve it in the long term. But in Sweden tens of municipalities have shown that major advances can be done by local by policies. Transition to RES-T can be implemented at municipal level, even utilizing solutions that are not applied anywhere else. In the cases of CBG, ED95 and E85 municipal market creation has led to national

³¹ First SBG demonstration plant and the first SBG100 filling station in the world were taken into use in 2009 in Austria.

³² Thermal efficiency of SBG production from wood is about 80 %. For DME and methanol it is about 65 %. For synthetic biogasoline and biodiesel it is only about 40 %. This means that from a unit of wood SBG synthesis produces twice the amount of transport fuel than FT synthesis, on energy basis.

³³ The new Gothenburg plant has a production capacity of 0.2 TWh/a. The planned second Gothenburg plant is 5 times larger and the planned Malmö/Landskrona plant is 8 times larger.

³⁴ This has decreased the share of biogas in traffic methane consumption to less than 60 %, when water transportation is taken into account. First LMG ship began operating in 2013, but only on LNG despite excellent availability of LBG.

³⁵ There was a plan to start commercial production in Örnsköldsvik, but it failed.

and international market creation. Some Swedish municipal policies have been models for EU level policies. Instead of waiting for the EU to act, municipalities can show the path for the EU to follow.

These municipal policies have also enabled companies and private citizens to make RES-T transition for their part and move to 100 % renewable energy in their transport energy consumptions immediately, without need to wait until 2050, which is the national target year.

Successful market creation has been implemented politically and technologically diverse ways. Main instruments have been ownership policy of municipal companies and purchasing policies. Municipal waste and energy companies have created supply and all municipal companies have created demand for local RES-T. Municipalities have not only utilized their existing companies, but also established new companies for this sector, for example distribution companies Svensk Biogas and Fordonsgas. Public purchasing policy legislature has been effectively implemented for vehicle and their energy purchases as well as for transportation service procurements (e.g. city buses and waste trucks) for all municipal organizations.

Biogas is the most obvious example of municipal opportunities, since municipalities control both the source of biogas, biowastes, and large amount of transport. Therefore, they can create both supply and demand locally. Municipalities are responsible for biowaste management and they can decide it to be used for traffic fuel production. They can also decide that their own vehicles, municipal buses and waste trucks will use the local fuel. It means that municipalities can create local isolated markets independently, even without involvement of private companies and even if those fuels are not used elsewhere. At first it was necessary that municipalities with their companies controlled the business, and in some municipalities it is still the case. But after markets had been created by several municipalities, private companies got involved and they control the business in some municipalities. And there are municipalities, where the business is controlled by public-private partnerships.

Swedish municipalities have acted as market creators by a large diversity of policies. Cases of some of them are presented below.³⁶

4.2.1. City of Linköping

City of Linköping was the first to implement municipal transport by biogas produced from municipal biowastes, and was followed by tens of other municipalities.³⁷ Linköping has shown extreme innovation and independence.

Biogas use started with purified, but not upgraded, CBG in 1989 by a converted Saab car. Upgraded biogas use began in 1992 with Scania LPG buses converted for CBG. Biogas was originally produced from sewage (Fig. 25a) and since 1996 also from solid biowastes (Fig. 25b). City buses were the original main consumers in 1992 (Fig. 29a) and they remain the main focus today.³⁸ Use in waste trucks began in 2000 (Fig. 29b). Until 2001, when the first public station was opened³⁹, only large private depot refilling stations were used by buses, waste trucks and municipal vehicles. Linköping became the first city in the world where all city buses are powered by biogas produced locally from municipal biowastes.

³⁶ Study on the municipal role on the RES-T development on Sweden was published by Lampinen (2014). Here an extended version is presented.

³⁷ Other municipalities starting it in the 1990s were Gothenburg, Trollhättan, Stockholm, Uppsala, Helsingborg, Eslöv, Kalmar and Kristianstad. Since 2000 tens of other municipalities have followed. Borås and Stockholm had started it already in the 1940's, but also ended it in the 1940s (Borås restarted in 2003 and Stockholm in 1996). Consumption of biogas in Stockholm city buses in the 1940s was published by Lampinen (2013b). For 40 years there was no traffic biogas use in Sweden, until Linköping restarted it.

³⁸ This is the case with most other cities as well, because large fuel consumption of buses makes it easy to invest in CBG production. However, there are exceptions such as Stockholm, which started with municipal and private CBG cars and moved to buses and waste trucks later.

³⁹ The first Swedish public CBG100 stations were opened in Stockholm in 1996.



Figure 29. City buses and waste trucks are the primary consumers of biogas in Linköping: a) Slow filling station at a city bus depot. b) Waste truck at a Svensk Biogas fast filling station.

All related technologies and businesses are controlled by the city technical office, Tekniska Verken, which created production and distribution technology and even vehicles, by converting them. Three municipal companies were established for taking care of the business: Linköping Biogas for local business (1996), Svensk Biogas for regional and national business (2003) and Swedish Biogas International for national and international business (2006). Svensk Biogas helped to create markets in other cities by establishing filling stations, production plants and transporting biogas by CBG containers. Tekniska Verken is in charge of research in co-operation with University of Linköping. Major innovations have been:

- Conversion of vehicles for CBG. It started with cars in 1989 (Fig. 30a) and buses in 1992.
- Possibly⁴⁰ the first biogas train in the world in 2005 (Fig. 19b).
- Slow filling stations for bus depots (Fig. 29a). They became the most used filling stations (by volume) in Sweden and in use not only in bus depots, but also in waste truck depots, municipal vehicle depots and depots of transport companies. They are cheap to construct and maintain, because high pressure storage is not needed (like in all public CBG stations). Filling takes overnight, while buses are parked.
- Network of public fast CBG stations first for Linköping and later for neighbouring cities. Currently Svensk Biogas has the 3rd largest filling station network in Sweden (Fig. 29b).
- Export of CBG to other cities by CBG containers (Fig. 26a).
- CBG requirement for city buses and waste trucks. This policy was followed by other municipalities with the result that in 2013 there were over 2000 city buses and 700 waste trucks powered by biogas in Sweden.
- CBG requirement for municipal vehicles.
- Free parking for CBG vehicles.
- Best taxi stands reserved for CBG and other RES-T taxis (Fig. 30b).



Figure 30. Car innovations: a) Citroën C5 CBG is a conversion model by Tekniska Verken. b) Only RES-T taxis ("miljötaxi", i.e. ecotaxi) are allowed to wait customers in the best taxi spots in Linköping, such as the central railway station here.

⁴⁰ There were CMG trains in the 1930s and 1940s in Italy, but it is not known if they used CBG or only CNG (Lampinen 2013b). Both CNG and LNG trains have since then been used in several countries, but not CBG or LBG.

Linköping was followed many other municipalities creating a network of production plants and filling stations. Private companies joined in later, but they now have a large share of the business. Swedish industry has benefited by manufacturing products first for domestic market and then by exporting them to other countries: biogas plants, upgrading plants, distribution systems (CBG container systems), filling stations and vehicles (cars, buses and trucks).

4.2.2. City of Stockholm

City of Stockholm created market for ED95, a whole new fuel, which had never been used anywhere in the world, and new vehicle technology for it. It was first demonstrated in Örnköldsvik by Sekab and Scania (Fig. 22), but commercial use required a large fleet. City of Stockholm made it possible by ordering enough of Scania ED95 city buses for commercial manufacturing to begin (Figs. 20b and 31a). In 2008 also ED95 trucks entered serial manufacturing. ED95 refilling is almost always done in private filling stations. The first public filling station in the world opened in 2010 (Fig. 8b). Use of ED95 later diffused to other countries. Swedish industry has benefited by manufacturing fuel, distribution technology and vehicles first for domestic market and later for export.



Figure 31. Public transport in Stockholm is RES-T powered and run by the municipal transport company SL: a) ED95, CBG100 and B100 buses. b) RES-E100 metro. c) RES-E100 tram.

City of Stockholm also created market for E85. It had been used in North and South America in large scale, but nowhere in Europe. It was first demonstrated in Örnköldsvik, but commercial use required large fleets. Since there was no E85 car manufacturing anywhere in Europe, city of Stockholm initiated and carried out a technology procurement of 3000 E85 cars from Ford. This enabled Ford to begin manufacturing Ford Focus E85 cars in Europe (Fig. 32a). Later Swedish and other European car manufacturers followed. Such a large order was possible by collecting together a group of fleet buyers from several municipalities, state organizations and private organizations. Sekab manufactured E85 in Örnköldsvik and distribution company OK created commercial filling station network for it in locations, where technology procurement partners needed them. From Sweden E85 has diffused to other European countries.⁴¹



Figure 32. A few firsts in Stockholm: a) First European E85 car: Ford Focus FFV. b) First RES-T ambulance (CBG100) in the world taken into use in 2009: MB Sprinter NGT. c) Camera of the first congestion charge system in the world, where RES-T vehicles are exempt.

⁴¹ Review of the highly innovative municipal policy of City of Stockholm is described in Stockholm (2010). This review begins from 1994, so earlier work, e.g. CBG100 city buses in the 1940s are not included, see Lampinen (2013b) for a review of these earlier municipal achievements of Stockholm.



Figure 33. First Swedish multifuel station opened in 1996 with CBG100 and E85. Fast charging of environmentally certified RES-E100 was added there in 2000. Pylon of this station is shown in Fig. 13b.

City of Stockholm has many other pioneering RES-T merits as well, including⁴²:

- Technology procurements, with other fleet owners in Sweden and abroad, of electric mopeds, cars and vans, biogas cars, vans and trucks and E85 cars. These created or extended markets for these vehicles.
- CBG production and use since 1996, including the first public multifuel filling station in the world with CBG. This station also had E85 in 1996 and since 2000 also fast RE-E100 charging (Fig. 33).
- Use of RES-T in public transport (Fig. 31). All metros, trams and local trains use RES-E100, all buses in central Stockholm use ED95 or CBG100. Most buses in greater Stockholm region use ED95, CBG100 or B100.
- Almost all taxis use RES-T as a result of innovative municipal policies, including the right of RES-T taxis to pass fossil diesel monofuel taxis in taxi lanes.
- Ending use of fossil-hybrid buses and converting them to ethanol-hybrid buses in 1997 (Fig. A3.1a).
- RES-hydrogen was used in fuel cell city buses in 2004-2006 with hydrogen produced at a bus depot (Figs. 7b and A3.1c).
- Bio-DME has been used in trucks since 2011 (Fig. 6a).
- Creation of international biogas trade by starting import of LBG100 from United Kingdom in 2011, to be used in waste trucks (Fig. 26b). LCBG station had been opened in 2010 (2nd in Sweden). The first LBG station opened in 2013 (2nd in Sweden).
- Large amount of innovative policies and PR work for increasing RES-T use in companies and households, e.g. in 2006 the first congestion charge system in the world, where RES-T vehicles are exempt (Fig. 32c).
- Influencing national policies, EU policies and municipal policies in Sweden and abroad.

4.2.3. City of Gothenburg

City of Gothenburg is a pioneer in many types of biogas technology. Municipal waste water company began CBG100 production and opened the first private CBG100 filling station in 1992 at municipal sewage treatment plant (Fig. 34a). Since then Gothenburg has been one the largest CBG100 producers in Sweden, mostly based on municipal sewage.⁴³ Municipal company FordonsGas (means vehicle gas) was established

⁴² Part of these are found in Stockholm (2010), but a few have been added. This list only contains actions since the 1990s. In the 1980s ED95 was not the only new technology for buses, but also battery electric (BEV), hybrid (HEV) hydraulic and flywheel buses were first demonstrated then.

⁴³ Also in whole Sweden municipal sewage is the most important source of biogas. Sweden is the only country in the world where more than half of biogas is consumed in transport. Over 1 TWh of biogas was consumed in transport in

in 1998⁴⁴ for distributing and selling CBG100. It is the largest Swedish biogas filling station operator with over 50 CBG and LBG stations in service (Figs. 3 and 28b). Municipal energy company Gothenburg Energy is co-owner (with municipality of Lidköping) of the Lidköping LBG plant, the first commercial LBG production plant in Sweden (Fig. 27b) and the owner of the Gothenburg SBG plant, the first commercial SBG plant in the world (Fig. 28a). Biogas is consumed in municipal vehicles, city buses and waste trucks. Waste trucks in Gothenburg were the first application for Volvo CBG trucks in 1996 (Fig. 34b). Volvo 850 Bi-fuel cars (Fig. 34b) were first demonstrated in Gothenburg 1995. It entered commercial production in 1996 and became, after BMW 316g (Fig. 33), the second factory manufactured methane car in the world. Until then all CMG cars had been converted from gasoline cars. Since then 50 other car manufacturers have followed resulting in a large global manufacturing business with output of over a million CMG cars annually.



Figure 34. a) Municipal sewage treatment plant has been the source of CBG in Gothenburg since 1992. b) Municipal Volvo CBG monofuel waste truck and Volvo 850 Bi-fuel car in 2003.

City of Gothenburg has pioneering merits also in other RES-T fields. Gothenburg demonstrated gas turbine HEV city buses powered by renewable energy in 1998-1999. These were based on the Volvo ECB concept bus of 1995, which was demonstrated on E100 in Curitiba, Brazil (Fig. 35a). The fuel of choice in Gothenburg demonstration was E85, but any gaseous RES-fuels (like CBG100) and liquid RES-fuels (like B100) are possible due to the inherently high fuel flexibility of the gas turbine.⁴⁵ These buses did not enter commercial production and use, but later diesel B100-HEV city buses did so. They were first demonstrated in Gothenburg in 2012 (Fig. A3.1d).



Figure 35. a) Gas turbine HEV concept bus Volvo ECB. b) Volvo C30 Electric (BEV) with inductive charging capability.

Gothenburg has demonstrated wind-PHEV city buses with conductive charging via overhang cables at the ends of an 8.3 km route since 2011.⁴⁶ Wind power covers 70 % of energy requirement, but the rest is fossil diesel. Since 2012 inductive (wireless) wind electric charging demonstration has taken place with 20 BEV

2014, more than in any other country in the world. However, Germany is the world leader in production of upgraded biogas, more than 8 TWh/a. In Sweden almost 100 % of upgraded biogas is consumed in transport, but only 5 % in Germany.

⁴⁴ In 2014 Fordonsgas was sold to a private French company Air Liquide.

⁴⁵ Commercially manufactured CMG gas turbine buses are in use in several cities in North America, but they use CNG instead of CBG. LMG gas turbines are used commercially in locomotives and ships, but on LNG instead of LBG.

⁴⁶ Inductive charging of city buses is being tested and demonstration is planned to commence in 2015.

cars in the use of employees of cities of Gothenburg and Stockholm (Fig. 35b). Gothenburg is also one of four cities, where bio-DME100 has been demonstrated in trucks since 2011 (Fig. 6b).

City of Gothenburg was the first city to restrict best taxi stands for RES-T taxis⁴⁷ (Fig. 36a-b). Private RES-T car and van use has been promoted many ways, including free parking and access to bus lanes. Gothenburg was the first city to implement environmental zones for heavy vehicles in 1996 (Fig. 36c). This promotes heavy RES-T vehicles.



Figure 36. a-b) Diesel taxis are forbidden access to the best taxi stands in Gothenburg. c) Environmental zones for heavy vehicles restrict access to RES-T vehicles or very low emission diesel vehicles.

4.2.4. Province of Skåne⁴⁸

Advanced provincial level RES-T policy is globally even rarer than municipal. Province of Skåne is a prime example both in Sweden and globally. Skåne aims at 100 % renewable public land transport system by 2015 in the whole province based on locally produced wind power and biowastes. Train transport has been RES-E100 based for years. By 2015 all city buses and regional buses (Fig. 37) should be biogas powered.

By 2020 the RES-T requirement is extended to all transport, which is directly controlled by provincial and municipal governments: own /leased vehicles, waste trucks, ferries and water buses. RES-E100 is the main technology for rail transport, CBG100 for road transport and LBG100 for water transport. Main source of RES-E100 is wind power, which originates from offshore wind farms, onshore wind farms, individual onshore turbines and building integrated wind turbines. Great effort is made to utilize agricultural lands for wind power production (Fig. 38a). Even when maximal amount of turbines are erected, wind farm reduces net land area for cultivation by less than 1 %.

Currently locally produced biogas (Fig. 38b) is used as CBG in road transport and agricultural tractors (Fig. 19c). In addition, LBG produced elsewhere in Sweden is available for trucks. Local LBG production is planned and it will be used in water transport also. There are now 7 upgrading plants, over 40 CBG filling stations and 2 LBG stations in Skåne.

Provincial target for biogas production in 2020 is 3 TWh, of which 95 % originates from waste feedstocks. At least 85 % goes to vehicle use. Half of the production would come from biogas (BG) plants and half from one centralized synthetic biogas (SBG) plant. The SBG plant project is run by E.ON. The plant to be located either in Malmö or Landskrona is 9 times larger than the new plant in Gothenburg (Fig. 28a).

⁴⁷ So called environmental or ecotaxis (miljötaxi) defined as electric, methane, biodiesel and ethanol.

⁴⁸ Official English name for the province is Scania. As it is also a name of a Swedish automotive manufacturer and brand name of buses and trucks, the Swedish name of the province (Skåne) is used here to make the distinction clear.

Public-private partnerships are essential means for reaching the goals. E.ON is the most important private partner. In addition to the SBG plant project, E.ON operates upgrading plants and CBG (Fig. 13c), GH2 (Fig. 7a) and fast RES-E100 (Fig. 41b) filling stations.



Figure 37. Skåne regional biogas bus. These buses run on provincial intercity routes. Text on the roof means: Biogas bus for climate smart Skåne.

The advanced policy of Skåne originates from pioneering municipalities Helsingborg, Eslöv and Kristianstad, which began the work in the 1990s. All of these municipalities have pioneered in some areas of technology and policy.

City of Helsingborg was the first in Skåne (and 6th in Sweden) to begin production and use of CBG in 1997 (Figs. 38b and 39b). Biogas originates from municipal sewage, municipal solid biowaste and agricultural biowaste. Landfill gas is planned to be taken into traffic use as well, first in Sweden, as LBG. LBG is planned to be used in ships and trucks. Also wind (Fig. 38a) and solar electric vehicles are used. The first Swedish public BEV charging station with onsite solar power was taken into use in Helsingborg in 2012 (Fig. 1b).



Figure 38. The main RES-T production technologies in Helsingborg: a) Wind farm on agricultural field. b) Municipal biogas plant for municipal and agricultural biowastes.

Eslöv was in 1997 the first municipality in Sweden to begin CBG production from industrial biowaste (potato chip factory) instead of municipal waste, but municipal waste was added to increase production.

Municipal upgrading plant in Kristianstad in 1999 created a new business area for a local company Malmberg, which has become one of the leading upgrading plant producers globally (Fig. 39). In 1999 the Kristianstad city council declared unanimously its will to become fossil fuel free municipality, the first municipality to so declare. In transport sector biogas is the main option.



Figure 39. Global market creation for local upgrading plant producer Malmberg: a) Municipal CBG car of City of Kristianstad in front of a municipal upgrading plant. b) Municipal upgrading plant in Helsingborg.

City of Malmö was slow to start with biogas, but it became the first Swedish municipality to operate fossil methane (CNG) city buses in 1987; and by 2000 all city buses were running on CNG. Other types of vehicles started using CNG in 1996, when the first public filling station opened. Biogas (CBG) use started in 2008, when upgrading plant opened at a municipal sewage treatment plant. Since then the share of biogas in methane use has been increasing and it is the goal of municipal government to end using natural gas in city buses and municipal vehicles (Fig. 40a) in 2015. After that only renewable methane is used. By 2015 at least 75 % of municipal vehicles should be biogas powered, and the rest by other RES-T.

By 2020 Malmö aims at 100 % sustainable locally produced renewable energy use in all city organization and by 2030 for the whole city for all energy use.⁴⁹ To these ends Malmö has also co-funded private efforts. An excellent example is biogas powered milk transport: milk trucks and the first slow filling station at a dairy depot in 2009 (Fig. 40b). It was a new application for slow filling stations. Before that such stations were found only in bus, waste truck and municipal vehicle depots. This technology decreases investment costs of large private filling stations significantly. Malmö had CNG-HEV city buses already in 1998 and in 2014 they were the first city in Sweden to introduce a BRT system (Fig. 24a) and use CBG-HEV buses for it.



Figure 40. a) Municipal CBG van and pickup truck. b) CBG milk trucks at slow filling station of Skånemejerier dairy depot.

City of Malmö is a pioneer in the use of wind energy in transport with diverse portfolio of technologies. International ecological housing exhibition in 2001 included a wind turbine and wind power charging of BEV car pool for residents. Integrated onsite solar and wind power production and charging system was implemented there in 2013. Most local wind power originates from a 110 MW Lillgrund offshore wind farm, but there are also on-shore and building-integrated wind turbines of various sizes. In addition, a lot of building-integrated solar power exists and it is also used for charging BEVs. City of Malmö uses wind-E100 both in their BEV (Fig. 41a) and PHEV vehicles, including the first biogas-PHEV car in the world taken into use in 2013 (Fig. 14b).

⁴⁹ RES-E: 99.8 % wind power, 0.2 % solar power. RES-H: 85 % solar heat pumps, 12 % solar collectors, 3 % waste. RES-T: Most from renewable methane, supplemented by wind and solar energy in BEVs, PHEVs and FCEVs, and liquid biofuels.

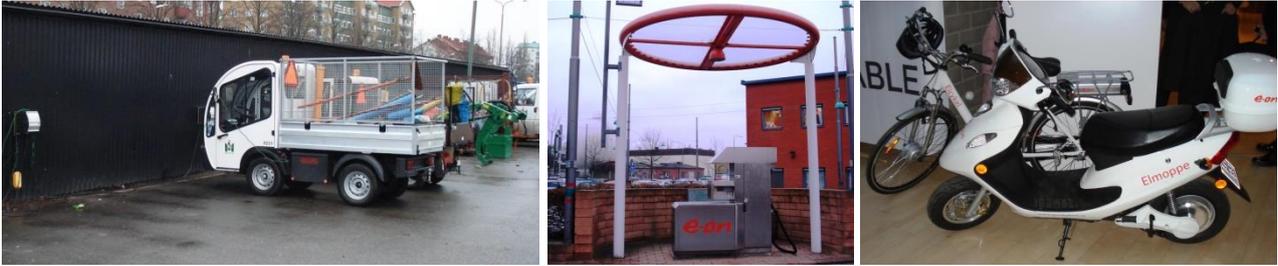


Figure 41. Wind-E100 in Malmö: a) Slow charging of a municipal light utility vehicle at a municipal depot. b) Public fast charging station. c) Light BEVs.

Wind-hythane was demonstrated in Malmö city buses in 2003-2006, first in Europe. Hythane is a mixture of hydrogen and methane. It had been demonstrated in city buses in Canada in 1995-1996 (fossil hydrogen with natural gas) and in California in 2001-2004 (wind hydrogen with natural gas). In Malmö locally produced wind hydrogen was mixed with natural gas resulting in a fuel called wind-HCNG⁵⁰, which was stored in compressed form (200 bars). HCNG with 8 vol-% hydrogen was demonstrated in regular CNG buses and regular CNG cars. For 20 vol-% hydrogen, converted buses were utilized: conversion is easy and takes only 4 hours to do. Demonstration project ended in 2006.

Locally produced wind-hydrogen (Fig. 7a) is used in municipal vehicles: one otto-HEV car since 2008⁵¹ and one FCEV car since 2014⁵², when the 2nd GH2 filling station was opened in Malmö⁵³. The main component still missing from the wind RES-T technology portfolio of Malmö is wind methane.

4.2.5. City of Trollhättan

City of Trollhättan entered fully commercial CBG production and city bus utilization in 1996. It was the first to take *Bra miljöval* certification (Fig. 10) for transport operations (CBG100 city buses), first to subsidize CBG100 car and fuel purchases of municipal citizens and first to offer free parking for RES-T vehicles. It is also the first to use Swedish made E85 cars (Fig. 23b) and CBG100/E85 multifuel cars (Fig. 14a), both manufactured by Saab locally. Trollhättan has actively engaged farmers in traffic biogas business.⁵⁴

As usual in Sweden, CBG in Trollhättan originates from municipal sewage treatment plant and city buses are the main consumers. For almost all people the idea of making car and bus fuel of toilet waste is irresistible, if only they reach understanding of the concept. However, it is so unimaginable that information tends to be passively blocked.

Landmark advertising is found at public toilets in Trollhättan by municipal bus company Västtrafik (Fig. 42). Translations of the texts are:

⁵⁰ If biogas had been used, the fuel would have been wind-HCBG, and it would have been the first RES-hythane demonstration in the world. In 2003 there was no CBG production in Malmö, but CBG would have been available via gas grid from Laholm and from several places by CBG container trucks.

⁵¹ Fossil HEV cars had been used in Sweden since 2002. City of Malmö was the first to use a RES-HEV car, a Toyota Prius converted from gasoline to hydrogen.

⁵² FCEV cars had been demonstrated in Stockholm already in 2004 (Fig. 7c), but city of Malmö (2014) and province of Skåne (2013) were the first to take them into regular use. As they cost about 6 times more than corresponding biogas cars and 2-3 times more than corresponding electric cars it is obvious that their share of RES-T consumption is small. On the other hand, the cost of biogas cars are between the cost of gasoline and diesel cars, so their diffusion is easy to understand even without environmental motives.

⁵³ The first station supplied compressed hydrogen (GH2) in 200 bars and 350 bars, the second station in 700 bars.

⁵⁴ Biogas Brålanda is an excellent example: a system where biogas plants in several farms are connected by biogas pipelines to centralized upgrading plant.

- Here you fill in our buses. Lifecycle of environmentally friendly fuel for our buses starts here. Please leave your contribution.
- Poop for the environment! Welcome in and help us with environmentally friendly fuel for our buses.
- Biogas is clean poop. Leave here your contribution and help us with an environmental fuel for our buses.
- Thank you for contribution. Buses in Trollhättan run on biogas.



Figure 42. Practical learning experience provided by Västtrafik bus company in public toilets in Trollhättan.

4.2.6. Other municipalities

In addition to the municipalities described above, several other municipalities have been instrumental in RES-T market creation (Table 4 gives a list of top pioneers). Tens of municipalities have followed their examples. Municipalities promote pure and high-blend RES-T in many ways, including:

- RES-T requirement in municipal purchasing rules for vehicles and fuels
- RES-T requirement for public transport
- RES-T requirement for waste trucks
- free parking
- access to bus and taxi lanes
- congestion charge exemption
- access to environmental zones
- sole access or speeded access for best taxi spots for RES-T taxis
- investment support
- tax support
- information campaigns

Municipal policies have enabled their citizens and companies to make transition to renewable transport energy use well before 2050, when it is the goal for the whole nation to achieve it. Green electricity market since mid-1990's has been a model. Large amount of households and organizations have moved to green electricity, which always means 100 % renewable electricity. Green electricity consumers never buy blends of renewables with fossil or nuclear. It is logical that green transport energy consumers behave the same way: they want to consume 100 % renewable energy, not blends with fossil fuels. In this respect the biogas market is still not mature. About half of public CBG stations do not allow people to buy CBG100, although it is easy to implement and very common in other countries. Most CBG stations do not give information on the share of biogas, although this information is given in all liquid biofuel stations. Most of this elementary problem could be solved by municipal decisions. It is surprising that the problem still exists.

Table 4. Some of the most notable RES-T pioneering municipalities.

Municipality	RES-T	Notes
Linköping	CBG100	See 4.2.1
Stockholm	ED95, E85, RES-GH2, RES-E100, CBG100, LBG100, Bio-DME100, B100	See 4.2.2.
Gothenburg	SBG, LBG100, CBG100, Bio-DME100, B100, E85, inductive RES-E100	See 4.2.3
Malmö	Wind-HCNG, Wind-GH2, Wind-E100, CBG100, LBG, SBG	See 4.2.4
Helsingborg	Solar-E100, Wind-E100, CBG100	See 4.2.4
Kristianstad	CBG100	See 4.2.4
Eslöv	CBG100	See 4.2.4
Trollhättan	CBG100, E85	See 4.2.5
Borås	BG, CBG100	First in Sweden in 1941, restart 2003
Sundsvall	LBG100	First demonstration plant in 2010
Lidköping	LBG100	First commercial plant in 2012
Uppsala	CBG100	First to use biogas-HEV city buses (1998), podcar light rail demonstration track (2007)
Örnsköldsvik	ED95, E85	First to use wood waste based ED95 in city buses
Jönköping	CBG100, Bio-DME100, LBG	
Eskilstuna	CBG100	
Lilla Edet	CBG100	Smallest municipality (pop. 12,000) to implement production and use
Norrköping	CBG100, E85, B100	First RES-T-bioethanol/biogas integrated production
Västerås	CBG100	Partnerships with farmers
Boden	CBG100	Most northern in the world and most isolated in Sweden
Skellefteå	CBG100	
Östersund	CBG100, RES-E100	Green highway to Sundsvall and Trondheim
Växjö	CBG100, RES-E100, Bio-DME100	Target: fossil free by 2030

Annex 3 contains information of environmental vehicles eligible for municipal support.

5. National policy support for RES-T quality

The main tool for RES-T promotion in almost all countries is an obligation to blend biocomponents into fossil gasoline and diesel oil. This can fulfil very low quantitative objectives, such as the EU 10 % requirement for 2020.⁵⁵ But it cannot fulfil large quantitative objectives. And most importantly, as markets have proven, it leads to lowest possible quality of RES-T dominated by energy crop based ethanol and biodiesel, and gives no incentive for vehicle development. This instrument is in use in 22 EU countries and is being implemented in 2 more EU countries. In Sweden, Latvia, Lithuania and Cyprus this instrument is not used. Otherwise, performance of these countries varies widely. While Sweden is a European and global RES-T leader, Latvia and Lithuania are in average level within EU and in Cyprus RES-T is absent.

Not having implemented the blending mandate is the single most important national action for promoting high environmental quality in the RES-T sector in Sweden. But it is only one of many actions.

⁵⁵ Although the EU 10 % requirement for 2020 is quantitatively low, it is very important, because otherwise it is likely that most countries would not have any promotion policies for RES-T. EU Commission originally proposed a 20 % requirement for 2020, but it was not accepted by the EU Council.

Sweden supports RES-T with a diverse portfolio of instruments including tax exemptions and reductions for fuels and alternative fuel vehicles, investment subsidies, research support and RES-T supply obligation. Environmental quality is promoted by all of them with minimum requirements and differentiation.

Promotion of pure and high-blend RES-T is crucial for fossil-free transport system. Both supply and utilization are supported for it in Sweden. Landmark law on RES-T supply mandate (SFS 2005:1248⁵⁶) came into force in 2006. It requires that all large fuel stations offer at least one pure or high blend RES-T alternative starting from the largest stations and gradually extending to smaller ones. In the beginning all stations chose E85, which is the cheapest to invest in, but the least sustainable. Therefore, investment subsidy was added for promoting the most sustainable alternatives, such as CBG100, LBG100, RES-E100 and RES-GH2. Several pure and high-blend RES-T options were available in many fuel stations already before the supply obligation law came into force. CBG100, B100, RES-E100 and E85 in Figure 13a-b are examples. However, this law is the primary reason for current wide availability, in over 2000 stations.⁵⁷ Although most of them offer only one pure or high-blend RES-T alternative, there have been multifuel stations offering many of them since 1996 (Fig. 33). Despite the significance of the supply mandate, dedicated stations have always been and still are more important for the most sustainable RES-T alternatives. Majority of CBG (Fig. 29), LBG and RES-E (Fig. 1b-d), and all DME (Fig. 6a), ED95 (Fig. 8b) and RES-GH2 are sold at dedicated stations, where no other fuels are available. Creation of these dedicated filling station networks is mostly a result of municipal, not national policies.

State investment programs LIP (Local Investment Program, 1998-2002) and KLIMP (Climate Investment Programme, 2003-2008) have supported municipal RES-T actions. Before them research and development funding by Communication Research Agency (KFB, 1993-1997) was important to overcome initial barriers of technology producers (Table 5).

Table 5. The funding of RD&D of the use of alternative fuels and vehicles in 1993-1997 administered by KFB (MSEK).⁵⁸

	KFB	Stakeholder	Total
Biogas	30	120	150
Ethanol	47	73	120
DME	4	9	12
Methanol	0.5		0.5
Not fuel specific	28	4	32
TOTAL	110	206	315

Development of vehicle fleet to fossil fuel independence is promoted by various ways. Such vehicles benefit from tax exemptions, reduced taxes and investment refunds. However, there are major problems in definitions on which technologies are accepted within the support program (Annex 3).

EU level legislation on RES-T quality was introduced in 2009 and is constantly evolving. But it is not yet in a satisfactory level to guarantee good environmental quality. It has caused some negative effects in Sweden as discussed in Annex 2.

⁵⁶ Official name of this law is "Lag om skyldighet att tillhandahålla förnybara drivmedel", i.e. law on renewable transportation fuel supply mandate. It is also called by nick name "pumplagen". Sweden was the first country in the world to enact such law for the whole transportation fuel market. In Brazil similar action was made by state ownership policy requiring

⁵⁷ Negative feature is the dominance (over 95 % share) of food energy crop based high-blend (i.e. non-pure) fuels (mostly E85) in these stations. Much more work is needed for tuning the supply mandate law to serve the target of fossil fuel independence.

⁵⁸ Sandén & Jonasson (2005, 30).

6. Discussion

Technological creativity and successful market creation has led Sweden to a leading position in Europe and globally in the use of renewable energy in transportation, both quantitatively and especially qualitatively. Very special feature is the pivotal role of municipalities and provinces for creating markets for new RES-T technologies. By setting up ambitious targets and following them they have become models to follow nationally and internationally. Municipal policies have earlier enabled electricity and heating for their citizens and since 1990's they have showed that also transport energy can be provided – based on locally produced renewable energy sources.

High level of environmental quality is a result of emphasizing waste based biofuels instead of energy crop based biofuels, gaseous fuels instead of liquid fuels, pure use of renewables instead of blending them with fossil fuels, and electricity production with low environmental risks. Emphasis on public and cargo transport instead of personal transport gives another positive contribution. This differs fundamentally from the EU wide situation. Low-blend food energy crop based liquid fuels in personal transportation dominate renewable energy consumption in the transport sector in the EU.

Sweden is one of only four Member States, which have not imposed mandatory blending of biocomponents to gasoline and diesel oil. This opens the market for pure and high-blend fuels, gaseous fuels and electricity. It is enhanced by the unique RES-T Supply Act, which came into force in 2006. It requires that all large fuel stations supply at least one pure or high-blend RES-T alternative. There are also tax support mechanisms for RES-T vehicles and fuels.

Although environmental differentiation in fuel and vehicle taxes and the innovative RES-T supply mandate have been essential, the most important Swedish national level contribution to good environmental quality has been not to introduce blending mandates of biocomponents to gasoline and diesel oil.

Several Swedish municipalities serve as best practise examples, since they have a long history of emphasising the most sustainable options, i.e. waste based gaseous fuels and wind/solar electricity and hydrogen used in pure form. And many municipalities have ambitious goals of becoming fossil free in all energy consumption, including transportation applications.

The national goal of fossil fuel independent road transport by 2030, and to achieve it by disseminating the most sustainable RES-T technologies is excellent and there is high political will to reach the goal. But there are also shadows. It would be very important not only for Sweden, but – due the Swedish leadership – for other countries as well, that policy makers would act to remove barriers on the way to the goal.

Despite a lot of progress, fossil fuels still dominate transportation energy consumption in Sweden and fossil backups are used for some renewable fuels. But unlike in most countries fossil fuels are not seen as a never-ending bridge to renewables. Instead, there is a clear and practical political will to end the bridge. It is the core of the lesson to be learned from the Swedish evolution.

Annexes

Annex 1: Lifecycle environmental impacts of energy use in transportation.

Lifecycle analysis of environmental impacts

Environmental impacts during whole lifecycle of transportation energy, from production to use and disposal, are assessed by lifecycle analysis (LCA). Energy consumption in transportation creates multitude of environmental problems. Below only impacts related to anthropogenic climate change are discussed, but many other environmental issues, such as acidification, eutrophication, air quality and resource depletion are covered in LCA studies.⁵⁹ In Sweden societal cost evaluations of transportation options include LCA based environmental and health costs.⁶⁰

As lifecycle analysis can be performed in various ways, results of different LCA studies are not directly comparable. The International Standardization Organization (ISO) has developed standards⁶¹ for quality control of LCA studies. Although not even LCA studies meeting the quality requirements are not directly comparable, they give useful information on the subject of the analysis. Below only results from LCA studies meeting the requirements of the standards are shown.

However, it is necessary to point out that the methodology applied within the RES Directive (2009/28/EC) is in violation of the standards.⁶² It is a model designed for a different purpose, to verify fulfillment of the minimum sustainability criteria of the RES Directive. It means that the model is meant only to yield a yes/no answer. Other information obtained by it is of academic interest only. Therefore, the model should not be applied to other purposes than the one it was meant for. However, it is often misused. Compared to LCA studies meeting quality requirements, this method brings fossil fuels closer to renewable fuels, less sustainable renewable fuels closer to more sustainable ones and changes the order of environmental merit of technologies. As a consequence, policy makers and consumers may be misled.

Climate impact

Climate impact is measured by combining emissions of greenhouse gases, other gases, aerosols and particles with direct and indirect warming and cooling impacts. Various metrics are applied. For policy purposes the most relevant is the Global Warming Potential (GWP) in time horizon of 100 years, because it is applied in emission inventories and emission limitation objectives of the United Nation Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol.

⁵⁹ University of Lund has carried out comprehensive LCA studies on Swedish traffic biofuels, including climate, acidification, eutrophication and air quality; see e.g. Börjesson et al. (2010).

⁶⁰ Official Swedish assessment of external cost of traffic, maintained by the Swedish transport administration (Trafikverket) is used as one component in total economic evaluations of transport alternatives by municipalities and other organizations.

⁶¹ ISO 14040 and ISO 14044.

⁶² This method is described by the Joint Research Center of the European Commission the following way: "Although such allocation methods have the attraction of being simpler to implement they have no logical or physical basis" (JEC 2011, WTW Report Version 3c, page 17). Allocation methods essentially mean what issues are taken into account and how. ISO standards and all best practice lifecycle analysis guidelines require all essential issues to be taken into account. For example, avoided methane emissions are very essential to the lifecycle greenhouse gas emissions because methane is much stronger greenhouse gas than carbon dioxide. But the simplistic method does not allow for taking this into account. With biogas technology very large methane emissions can be avoided, but it is forbidden in this model to show them. It means that reasons behind the negative WTW values shown in Figure A1 and Table A1 can not be taken into account.

In the examples below it has been applied to the three most important greenhouse gases emitted during the lifecycles of transport energy products. The combined greenhouse gas (GHG) emissions mean carbon dioxide equivalent (CO₂eq) emissions, where methane (CH₄) and nitrous oxide (N₂O) emissions have been added to carbon dioxide (CO₂) emissions weighted by their relative greenhouse warming strength (Global Warming Potential). Values for 100 year time horizon from the IPCC 4th Assessment Report in 2007 are used: CH₄ is weighted by 25 and N₂O by 298.⁶³

Three types of data are shown here:

1. Well-to-wheel GHG and energy
2. GHG intensity
3. Mitigation cost

Well-to-Wheel (WTW) analysis

Well-to-Wheel (WTW) analysis takes into account lifecycle impacts of energy sources from production of primary energy until movement of vehicles, but excluding lifecycle impacts of production and maintenance of vehicles and machinery utilized for energy production, supply and other purposes. Many types of impacts can be analyzed, including GHG and other emissions, and energy use. Unit for emissions is grams (or other mass unit) per kilometer (or other distance unit). Figure A1 shows ranges for WTW GHG emissions and energy use for selected energy sources. Main conclusions are:

- Conventional liquid fossil fuels gasoline and diesel oil as well as gaseous fossil fuels natural gas (CNG) and liquid petroleum gas (LPG) have very small differences in both their GHG emissions and energy use. Therefore, shifting between these fuels does not change GHG emissions much.
- Solid fossil fuels, such as coal and peat, increase GHG emissions by about 100 % compared to conventional crude oil and natural gas based fuels. Their energy consumption is higher due to the energy losses in converting solid fuels to liquid (such as CTL) or gaseous fuels.
- Unconventional fossil fuels (not shown in figure) have extreme differences in their GHG emissions. Due to potentially large leakages, unconventional fossil methane resources (such as methane clathrates and shale gas) may have orders of magnitude larger GHG emissions than coal based fuels.
- Biofuels differ greatly in both GHG emissions and energy use. Their energy use is higher than conventional fossil fuels have, in some cases (ethanol from wood) several times higher. Energy crop based biofuels may have small GHG reductions and for some production chains they even have higher emissions than conventional fossil fuels. But waste and residue based biofuels offer large reductions.
- For some waste based biogas production chains WTW GHG emissions are negative. This is mostly due to avoided methane emissions.
- Food production chains differ in their GHG emission characteristics much more than biofuel production chains for internal combustion engine use. It means that also WTW emissions for walking on different diets have large differences. Two examples (beef and ecological plant diets) are shown. Walking on beef energy represents the largest WTW energy use of any transport energy option and WTW GHG emissions are in the same range with cars using coal based fuels. On the other hand, plant diets may have very low energy use and emissions if ecological considerations in

⁶³ These choices are due to sources used here. More rigorous analysis would take into account all greenhouse gases and other emissions impacting climate; see the IPCC 5th assessment report (IPCC 2013, 2014), which also includes updated values for global warming potentials (IPCC 2013). GWP of methane had earlier been underestimated and was increased from 25 to 34. It means that the negative values for biogas in Figure A1 would be even more negative had the new GWP value been applied.

productions are well implemented. However, usually plant diets result in large WTW GHG emissions, comparable to gasoline cars, due to unsustainable production practices.

- Hydrogen, electricity and indirect electricity (not shown in figure) have very large differences in their GHG emissions. Several examples are provided in Table A1.

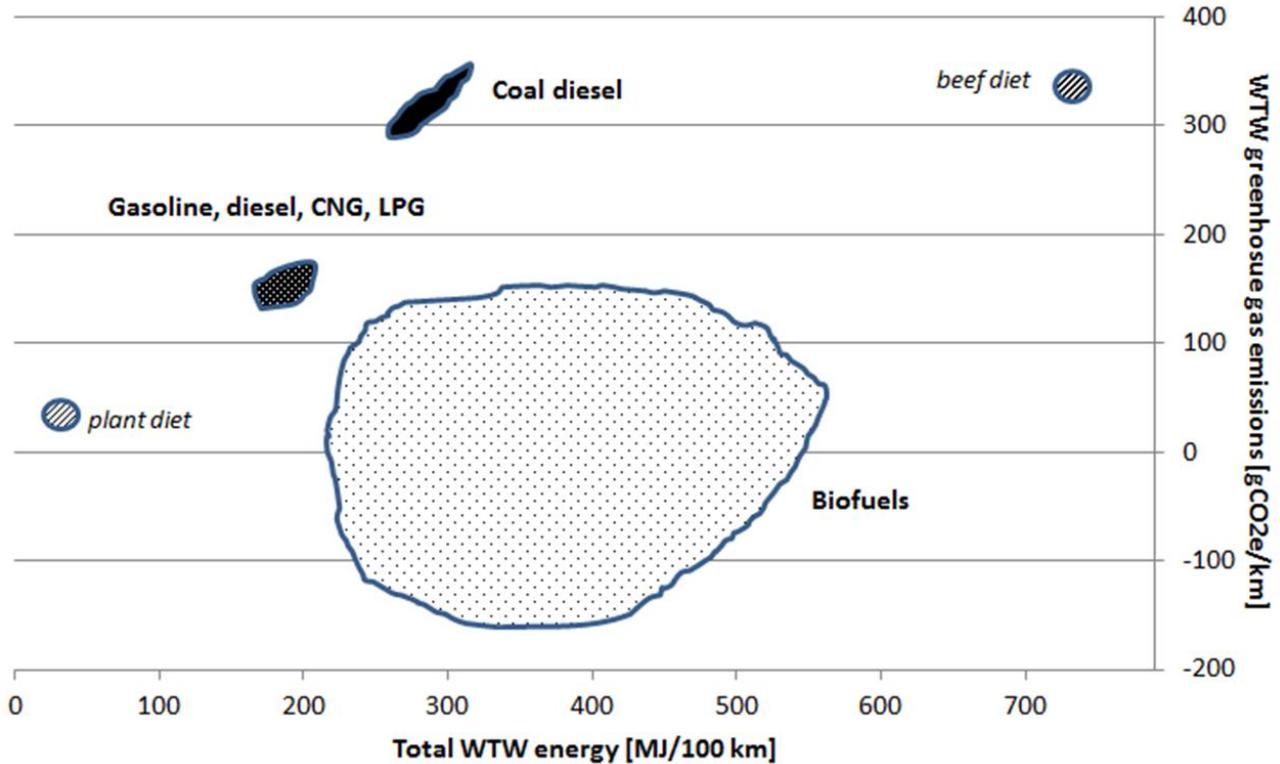


Figure A1.1. Lifecycle greenhouse gas emissions and energy consumption of selected fossil fuels and biofuels in transport. Plant and beef diet mean walking; the rest represent ranges for an average car powered by an internal combustion engine (otto or diesel).⁶⁴

Greenhouse gas intensity (GHG intensity)

Greenhouse gas intensity means WTW GHG emissions, where impacts of vehicle technology have been removed. Many examples are presented in Table A1. Most of the values in the table are directly from or calculated based on data published by the Joint Research Center of the European Commission. WTW emissions for vehicles can be calculated from these values by multiplying with energy consumption and adding tailpipe emissions of GHGs other than CO₂ (because CO₂ for the whole lifecycle is included in the GHG intensity value).

⁶⁴ This illustration is mostly based on data produced and published by the Joint Research Center of the European Commission (JEC 2014) for an average car. Plant and meat beef diet values represent walking in extreme cases. They have been calculated from carbon footprint data of supermarket chain Tesco (Tesco 2012). These values are higher for most other supermarket chains, since Tesco utilizes landfill gas based LBG for goods transport.

Table A1. Greenhouse gas intensities of various energy sources in transport.⁶⁵

Energy product	Description	Type	Resource	GHG intensity [gCO ₂ eq/MJ]
Food	Corned beef hash (without cooking)	Solid	Energy crop	1136
GH2	Compressed peat hydrogen	Gas	Fossil	475
E	Coal electricity	Electricity	Fossil	346
Food	Hamburger/ecologically produced	Solid	Energy crop	260
LH2	Liquefied hydrogen/EU average electricity	Gas	Fossil	254
CTL	Synthetic diesel from coal	Liquid	Fossil	200
E	EU average electricity	Electricity	Fossil	150
M100	Synthetic methanol from natural gas	Liquid	Fossil	101
DME	DME from natural gas	Gas	Fossil	98
Diesel oil	EU average	Liquid	Fossil	95
GTL	Synthetic diesel from natural gas	Liquid	Fossil	94
Gasoline	EU average	Liquid	Fossil	93
ETBE15	Ethanol from wheat	Liquid	Fossil	87
LNG	Liquefied natural gas	Gas	Fossil	75
LPG	Liquefied petroleum gas	Gas	Fossil	74
CNG	Compressed natural gas	Gas	Fossil	69
HCNG	Compressed wind/natural gas hythane	Gas	Fossil	66
E85	Ethanol from wheat	Liquid	Energy crop	59
B100	Biodiesel from rape seeds (RME)	Liquid	Energy crop	52
Food	Packed fresh carrots	Solid	Energy crop	50
ED95	Ethanol from wheat	Liquid	Energy crop	49
SB100	Synthetic biodiesel from palm oil (HVO)	Liquid	Energy crop	44
E85	Ethanol from waste wood	Liquid	Waste	43
CBG100	Compressed biogas from maize	Gas	Energy crop	41
E85	Ethanol from biowaste	Liquid	Waste	38
ED95	Ethanol from waste wood	Liquid	Waste	29
SB100	Synthetic biodiesel from waste oil (HVO)	Liquid	Waste	21
LBG100	Liquefied biogas from municipal solid biowaste	Gas	Waste	20
CBG100	Compressed biogas from municipal solid biowaste	Gas	Waste	15
RES-E	EU average renewable electricity	Electricity	Renewables	12
CBG100	Compressed biogas from municipal sewage	Gas	Waste	11
HCBG	Compressed wind/biogas hythane	Gas	Renewables	10
RES-GH2	Compressed wind hydrogen	Gas	Wind	9
Bio-DME	Bio-DME from waste wood	Gas	Waste	5
CBG100	Compressed wind methane	Gas	Wind	3
CBG100	Compressed synthetic biogas from waste wood	Gas	Waste	3
WG100	Waste wood gas in producer gas vehicles	Gas	Waste	2
Wood	Waste wood directly in steam vehicles	Solid	Waste	1
RES-GH2	Compressed solar hydrogen/local production	Gas	Solar	0
RES-E	Solar electricity/local production	Electricity	Solar	0
CBG100	Compressed biogas from manure	Gas	Waste	-70

⁶⁵ Values other than for food are directly or calculated from data published by the Joint Research Center of the European Commission (JEC 2014, JRC 2014). Food values have been calculated from carbon footprint data of supermarket chain Tesco (Tesco 2012), except the case of ecologically produced hamburger, which is from footprint data of a Swedish hamburger restaurant chain Max, as published in their www pages (www.max.se).

Mitigation cost

Mitigation cost is a measure combining GHG emissions and technology costs. Figure A2 shows an example, where cost of reducing one ton of GHG emissions per year from average gasoline light duty vehicle is depicted. Negative values represent economic benefits instead of costs. Hybrid technology (HEV) and diesel technology enable emission reductions at rather low cost or even slightly negative cost. Natural gas (CNG) offers significant negative cost and biogas (CBG) very large negative cost. All these vehicles have approximately same purchase price. As electric vehicles (BEV) cost about twice as much, it is hard to reach low mitigation costs with that technology, especially when the share of fossil electricity generation is high (600 g CO₂eq/kWhe). Low share of fossil electricity (200 g CO₂eq/kWhe) alleviates the problem.

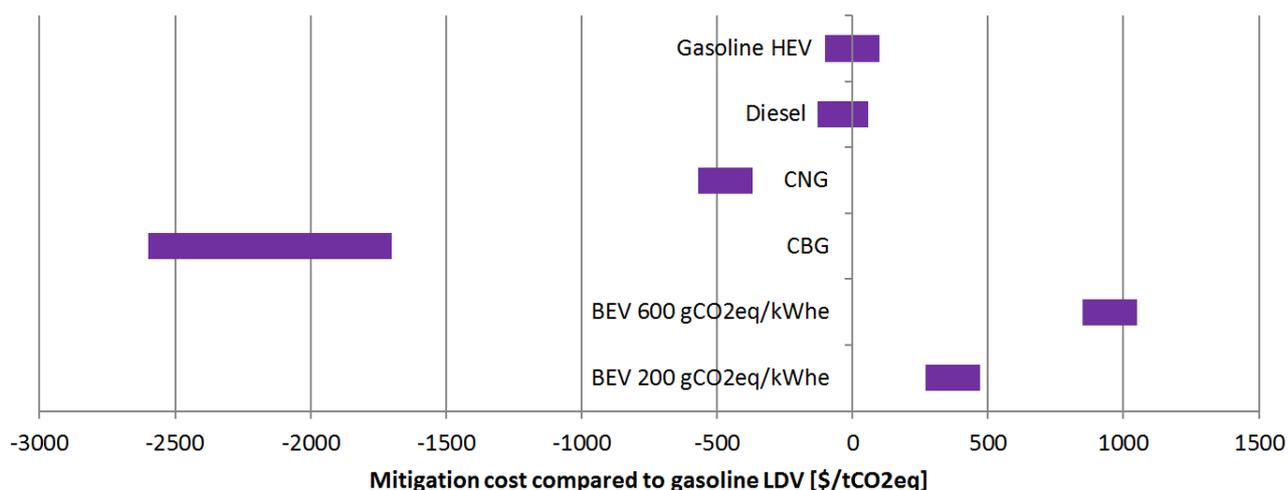


Figure A1.2. Mitigation cost of reducing one ton of carbon dioxide equivalent emissions from average conventional gasoline light duty vehicles by a selection of technologies: hybrid (HEV), diesel, natural gas (CNG), biogas (CBG) and electricity (BEV). For electric vehicles two results are shown based on different average GHG emissions from power generation.⁶⁶

Annex 2: Introduction to EU level RES-T policy and legislation

This is a modified version of text earlier published in an article by Lampinen (2014). It is included here by permission from Lexxion, publisher of Renewable Energy Law and Policy Review journal.

This annex is provided for background information, because the RES-T sector development in Sweden is interlinked both quantitatively and qualitatively with the RES-T sector development in the European Union. Therefore, the Swedish situation cannot fully be understood without the EU context.

The EU level quantitative requirements introduced in 2003 by the RES-T Directive (2003/30/EC) have been crucial for the RES-T sector development in all Member States, including Sweden. Although Sweden was the leading EU country in RES-T technology adoption already before 2003, significant share was not achieved due to dominance of crude oil in transportation fuel market. Without binding EU level mandates, RES-T would be insignificant in all EU countries and would even be absent in some of them.

⁶⁶ Adapted from data presented by IPCC (2014).

The EU level qualitative requirements introduced in 2009 are also necessary for most Member States, but Sweden is an exemption. High environmental quality in Sweden has been negatively affected by the EU level legislation.

Development of the EU RES-T policy

The European Union promotes utilization of renewable energy sources (RES) in all energy end-uses: transport (RES-T), electricity (RES-E) and heat (RES-H). This policy is based on the renewable energy strategy published in 1997⁶⁷ and several later strategies and action programmes. Only transport sector still increases greenhouse gas (GHG) emissions in the EU⁶⁸ and it is responsible for most of the air quality problems, too. It also poses energy security concerns due to almost complete reliance on crude oil and natural gas. Therefore, additional legislation is necessary to address the transport sector specifically.

RES-T specific legislation has proven extremely successful in changing market trends and enabling renewables to have significant and growing presence in the transportation energy market. This is one of the best examples, where only EU level legislation could provide the necessary impact.

The EU renewable energy strategy of 1997 sets targets and proposes actions for all renewable energy sectors. The target for RES-T was 20 % share of transportation sector energy consumption in 2020. The purpose was that it would be achieved according to the subsidiarity principle, by policies and legislation enacted by Member States to best serve their national conditions. Progress proved to be very slow and some Member States ignored this common policy and targets completely.⁶⁹ Therefore, EU wide binding regulations were required.

Quantitative requirements

Quantitative requirements were introduced in 2003 by the RES-T Directive (2003/30/EC). Its scope included biofuels and other renewable fuels⁷⁰, but not electricity. Gradually increasing minimum quota obligation was set until 2010, when 5.75 % was to be reached. Although the EU finished below target at 4.5 % (4.7 % with electricity) the Directive had a large impact by changing the trend. Before it renewables were insignificant in the transport sector, with only 0.6 % share in 2003 (biofuels 0.5 %⁷¹), and crude oil had 98 % share. Five Member States, including Sweden, met the 5.75 % target.⁷²

The RES-T Directive was repealed by the RES Directive (2009/28/EC), which sets 10 % quota obligation for 2020 taking into account both fuels and electricity⁷³. It includes sustainability criteria and environmentally

⁶⁷ The European Union Renewable Energy Strategy, published in 1997, includes a 20 % target for RES share in transport in 2020: Communication from the Commission - Energy for the future: renewable sources of energy - White Paper for a Community strategy and action plan, COM(97)599.

⁶⁸ From 1990 to 2013 in EU, all sectors reduced GHG emissions, except the transport sector, where GHG emissions increased by 14 %, see EEA (2014, 44).

⁶⁹ E.g. Finland applied annual motive power tax of about 10.000 euros for cars able to use renewable energy (Lampinen 2013a). It was the main reason why renewable energy was not utilized in the transportation sector and why development of the RES-T sector was impossible. This tax had been in force since 1965, and the EU renewable energy strategy of 1997 with its RES-T targets had no impact. The tax was finally repealed in 2003 as a result of the RES-T Directive. Only binding EU level mandate could deliver this.

⁷⁰ Fuels from non-biological renewable origin, e.g. solar hydrogen and wind methane.

⁷¹ Sweden was the leading Member State already in 2003, but the share was only 1.32 %.

⁷² Renewable energy progress report of the European Commission, SWD(2013)102.

⁷³ Renewable fuels mean biofuels and fuels of non-biological renewable origin (e.g. solar methane and wind hydrogen). Renewable electricity include direct and indirect (e.g. compressed air and magnetic engines) electricity.

weighted calculation method for supporting the most sustainable options.⁷⁴ Sweden was the first country to achieve the target in 2012 with a share of 12.6 %. In the whole EU, 5.1 % was achieved in 2012.⁷⁵

The RES Directive is complemented by several other directives. The Low Carbon Fuel Standard Directive (2009/30/EC) is an amendment to the Fuel Quality Directive (98/70/EC) requiring 6-10 % decrease of greenhouse gas intensity of road and inland waterway vessel fuels by 2020 compared to the situation in 2010. This can be achieved by increasing market share of renewable fuels or low carbon fossil fuels.

The Clean Vehicle Procurement Directive (2009/33/EC) addresses public sector procurement of vehicles and transport services with a purpose to expand RES-T vehicle fleets.

The Alternative Fuel Infrastructure Directive (2014/94/EU) requires building up filling station networks for methane, hydrogen and electricity, which offer the most sustainable mobility.

Qualitative requirements

As some renewable energy forms have large negative environmental impacts, it is necessary to guide markets towards the most sustainable ones. Policies and targets of most Member States have emphasized low-level blending of food energy crop based biofuels in gasoline and diesel oil. This is the option with lowest environmental qualities. Among many of their negative environmental issues is the climate impact: as shown in Figure A1 these fuels may even increase greenhouse gas emissions compared to the fossil fuels they replace. Therefore, legislative EU level intervention has been required.

Qualitative requirements were first introduced in 2009 by the RES Directive (2009/28/EC) and the Low Carbon Fuel Standard Directive (2009/30/EC) as minimum sustainability requirements. Additional benefits for most sustainable biofuels (2-counting) and battery electric vehicles (2.5-counting) were incorporated into the RES Directive.

The Alternative Fuel Infrastructure Directive (2014/94/EU) is the latest addition. As the most sustainable RES-T technologies (renewable methane, hydrogen and electricity) cannot be served by liquid fuel filling stations, and in many Member States development of their dedicated station network is slow or absent, EU level action was needed. This Directive guarantees that methane will be available all over EU for road and marine transport, electricity will be available in all cities and hydrogen will be available in certain priority areas.

Several other legislative proposals have been published by the European Commission and more are being planned.

Proposal for the so called iLUC directive⁷⁶ intends to limit the consumption of the least sustainable biofuels, which are liquid biofuels produced from food crops: a cap of 5 % is suggested, which means that at most half of the RES-T obligation for 2020 can be covered by such fuels. It also introduces a new weighting class 4

⁷⁴ Specific rules for counting RES-T are defined in the RES Directive. All technologies are included: biofuels and other renewable fuels as well as renewable electricity. All modes of transport are included. RES-T use is not counted by direct energy consumption, but environmental weights are employed with a purpose to direct production and consumption to the most sustainable alternatives in a whole lifecycle perspective. For this purpose sustainability criteria have been defined. Biofuels not meeting minimum requirements are not counted as renewable energy (weight 0). Consumption of best biofuels (mostly waste based) are double-counted (weight 2) compared to other biofuels meeting the sustainability criteria (weight 1). To promote electric car use, consumption of renewable electricity in battery electric vehicles (BEV) has a weight 2.5 compared to renewable electricity use in conventional electric vehicles (EV), which are rail vehicles and trolley buses, where electricity is fed in by conducting wires.

⁷⁵ Eurostat SHARES database on renewable energy use. Eurostat is using the environmentally weighted calculation method as required by the RES Directive.

⁷⁶ Proposal for amending Directives 98/70/EC and 2009/28/EC, COM(2012)595. The nick name iLUC (indirect land-use change) implies that the indirect environmental impacts of conversion of fields from food to fuel production are the main motive behind this act.

(in addition to the existing 0, 1 and 2) in the RES Directive for the most sustainable biofuels and other renewable fuels, such as solar hydrogen and wind methane. These two legislative measures are necessary, because most Member States have fulfilled their quota obligations by low level blending of food energy crop based biofuels with gasoline and diesel oil.

Nutrient recycling is a critical issue for bioeconomy due to resource efficiency and environmental impacts of food, fuel and other production. Wasting all or most nutrients is usual practise in production of biofuels from biowastes. Although in waste hierarchy, the foundation of the EU waste legislation, recycling has priority over energy utilization, current legislation allows for overlooking it. In current situation Member States may regard production of traffic biofuels from biowastes as recycling even when nutrients are wasted. Proposal for a Directive amending six waste sector directives⁷⁷ aims to fix these errors, especially in the Waste Directive (2008/98/EC). After this correction traffic biofuel production from biowaste is regarded recycling only if nutrient content of the biowaste is recycled.

In effect, the existing and proposed legislation results in five main categories for traffic biofuels based on their environmental quality (although there are exemptions):

1. Biowaste based fuels, when nutrients are recycled
2. Other waste based biofuels
3. Energy crop based fuels from lignocellulosic resources
4. Other energy crop based fuels, which fulfil sustainability criteria
5. Biofuels, which do not fulfil sustainability criteria of the RES Directive

Legislative challenges in environmental quality development

Qualitative RES-T requirements emerged in the EU legislation in 2009 due to emphasis on the lowest environmental quality in most Member States. They are still an evolving legislative field unable yet to guarantee good environmental quality. Actually, the reverse is true in several cases, where the EU level environmental legislature not only makes improvement of quality more difficult, but also gives pressure to decrease existing quality in countries where high quality has been reached.

First example is the requirement for “cost-effective implementation” in the RES Directive, restricted to transport sector only, i.e. it is not applied to electricity and heat sectors. According to normal interpretation, it means that renewable energy is consumed as low-blend biocomponents within existing gasoline and diesel oil standards. Clearly this is not cost-effective for greenhouse gas mitigation as seen in Figure A1.2, but implementation costs are lowest.⁷⁸ Therefore, new vehicles and new filling station pumps are not needed. This favours lowest environmental quality and does not give incentives for development of RES-T vehicles and their filling station infrastructure. Consequently, crude oil dependency remains unaffected. Member States implement this in practise by mandatory blending. It dominates the RES-T policy leaving little room for instruments targeting high environmental quality.

Sweden is one of only four Member States, which have not imposed mandatory blending. This opens the market for pure and high-blend fuels, gaseous fuels and electricity. It is enhanced by the unique RES-T Supply Act, which came into force in 2006. It requires that all large fuel stations supply at least one pure or high-blend RES-T alternative starting from the largest stations and gradually extending to smaller ones. There are also tax support mechanisms for RES-T vehicles and fuels. Several Swedish municipalities serve as best practise examples, since they have a long history of emphasising the most sustainable options, i.e. waste based gaseous fuels and wind/solar electricity and hydrogen used in pure form. However, there is political pressure for adopting blending mandate.

⁷⁷ Proposal for amending six waste sector directives, COM(2014)397.

⁷⁸ It is cost-effective to implement in the same sense as using streets as landfills instead of creating another waste management system. Investment costs are minimized and needs for technology development and infrastructure built-up are avoided.

Second example is related to first and fifth examples. The Clean Vehicle Procurement Directive requires calculation of operational lifetime costs of road transport vehicles, e.g. buses. It includes a model, which emphasizes energy efficiency instead of emissions. Gaseous fuels are negatively affected, since they are usually used in otto engines, which have lower efficiency than diesel engines. Renewable gaseous fuels offer large emission and cost reductions compared to fossil diesel oil, but lifetime energy consumption is higher. The model is weighted in a way that gas buses cannot compete with fossil diesel buses. Utilization of this calculation model is voluntary, but since it is there, it is applied. As a result, many municipalities have rejected gas buses.

In Sweden total economic evaluation, where societal costs of emissions are included, has traditionally been used instead. For example, in Stockholm biogas buses provide about 1 € of societal benefits for every litre of diesel they replace. This is based on official Swedish assessment of external cost of traffic, maintained by the Swedish transport administration (Trafikverket). It is used as one component in total economic evaluations of transport alternatives by municipalities and other organizations. This policy is under threat by the Clean Vehicle Procurement Directive.

Third example is the method used to determine compliance to the sustainability criteria in the RES Directive and in the Fuel Quality Directive. Whole lifecycle of biofuels is considered, when compliance to GHG emission standards is determined. It is correct. However, it is done in a simplified manner, which is in violation of international lifecycle analysis (LCA) standards (see Annex 1). Taking into account all factors relevant to the purpose of the analysis is the core of a reliable LCA, but it is not allowed in the method created specifically for the directives. This method is simple, but lacks logical and physical basis, as characterized by the Joint Research Centre of the European Commission (Annex 1). It impacts waste based biofuels by not crediting many GHG emission reductions in their production chains. This favours energy crop based biofuels against waste based biofuels. The simplistic method was adapted because it only needs to give yes/no answer on the question of GHG emission standard compliance. It should not be used for other purposes, but most national and municipal administrations and market actors have replaced scientifically reliable LCA by it.

Sweden has a long history of excellent research of lifecycle environmental impacts of transport⁷⁹. Scientifically sound LCA approach has been utilized for a long time without difficulties by municipalities, companies and non-governmental organizations. But this has recently changed as it is easier to utilize the simplistic method.

Fourth example is the proposed amendment to the Energy Taxation Directive (2003/96/EC), which sets minimum levels for fuel taxes. Formal intent of the proposal⁸⁰ is to improve environmental quality of transport fuels by splitting tax into energy content and CO₂ emission based components. As the CO₂ component has only about 10 % weight, all fuels would have almost equal tax regardless of their climate impact. Compared to the directive in force environmental impact is negative. Tax level of gasoline, fuel with the highest CO₂ emissions, will not change (11.2 €/GJ), but tax level of natural gas, fossil fuel with the lowest CO₂ emissions, would increase 312 % from 2.6 to 10.7 €/GJ. Tax level of waste based biogas, which offers the lowest lifecycle emissions, would increase from 0 to 10 €/GJ.⁸¹

In Sweden fuel tax with energy and CO₂ components has been in force since 1995.⁸² Unlike in the EU proposal, it has effective environmental differentiation. But the EU level legislation may end effective environmental differentiation not only in fuel taxation, but also in vehicle taxation, as discussed below in connection with energy efficiency legislation.

Fifth and the most serious example is the conflict with energy efficiency legislation. Energy efficiency of cars and vans is promoted based on an inherently invalid indicator. Showing the indicator in vehicle advertising, attaching it in new vehicles at points of sale and distributing it in vehicle comparison catalogues is required (Directive 1999/94/EC). The same indicator is used in energy efficiency standards, where manufactures of

⁷⁹ E.g. Börjesson et al (2010).

⁸⁰ Proposal for amending Directive 2003/96/EC, COM(2011)169.

⁸¹ In Sweden and some other countries renewable gases do not have fuel taxes.

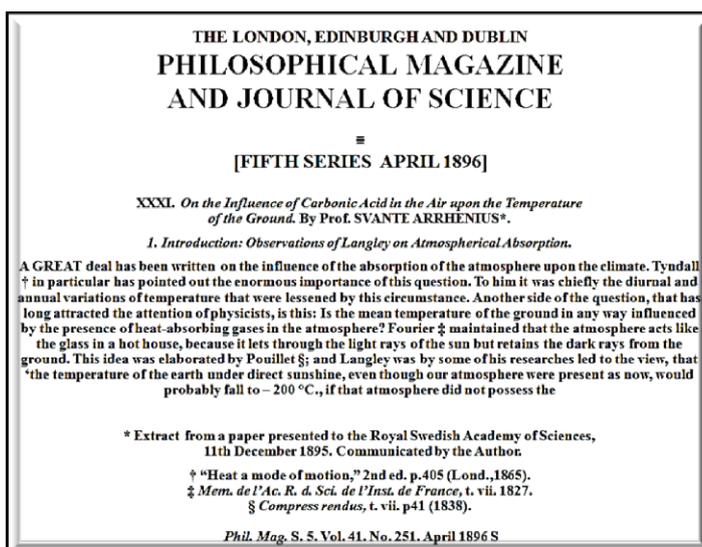
⁸² Lag (1994:1776) om skatt på energi.

cars (Regulation (EC) 443/2009) and vans (Regulation (EU) 510/2011) are obliged to improve average energy efficiency of new vehicles. The chosen indicator is tailpipe CO₂ emission, where distinction between fossil and biogenic carbon is not made.⁸³ It is a valid indicator for vehicles using same organic fuel, but not if fuel is different. It cannot be applied at all to inorganic fuels and electricity. It is inherently invalid indicator for comparing greenhouse gas emissions. However, its use for GHG emission comparisons has become widespread. It means that many vehicles, which are unable to utilize renewable energy, pass RES-T vehicles in environmental merit tables.

Environmental vehicle promotion has been negatively affected by this (see Annex 3). Swedish municipalities originally promoted only or mostly RES-T vehicles. But this is not the case with the new Swedish national environmental vehicle definition. Environmental quality of fuel is not taken into account, distinction between fossil and biogenic carbon dioxide emissions are not made and renewability of primary energy is irrelevant. Acceptance is based on energy efficiency, which is not a primary indicator of environmental quality (see Chapter 2 and Annex 1). Unlike in municipalities, nationally monofuel gasoline and diesel oil vehicles are in the focus of environmental car promotion. Most of related government funding is delivered to vehicles, which are to be phased out by 2030. In 2013 only 6.7 % of supported vehicles were fossil fuel independent and 55 % were completely gasoline or diesel oil dependent.⁸⁴ For the same reason emission based vehicle taxation is negatively affected.⁸⁵

This is reflected in the market. It is common for car manufacturers to offer some energy efficiency technologies (e.g. hybrid systems) only for fossil monofuel cars, not for RES-T cars. This is due to political demand. Of course, all technologies available on energy efficiency improvements can be applied on RES-T cars. But this is not done, if environmentally based demand is incorrectly defined. As explained in Chapter 2 and Annex 1 energy efficiency is not a primary environmental indicator. Its use may have adverse effect on sustainability of transportation.

The difference between fossil and biogenic carbon dioxide emissions is one of the most fundamental issues in climate science and policy. It has formed the core of understanding anthropogenic climate change since the first scientific article on the topic was published by Swedish physicist and Nobel laureate Svante Arrhenius in 1896.



⁸³ According to the United Nations level rules, as decided within the universally ratified Framework Convention on Climate Change, it is mandatory to make distinction between fossil and biogenic CO₂ emissions, i.e. tailpipe CO₂ emissions of biofuels are zero.

⁸⁴ Swedish official transport statistics: "Fordon 2013" by SCB.

⁸⁵ In several countries vehicle sales tax and annual vehicle tax have CO₂ based components, which do not make distinction between fossil and biogenic carbon.

Annex 3: Alternative fueled and environmental vehicles

This annex is provided for basic information on alternative fueled vehicles (AFVs) and environmental vehicles.

Alternative fueled vehicles (AFVs)

Alternative fueled road vehicles are vehicles manufactured or converted for other energy sources than gasoline or diesel oil.⁸⁶ They may or may not be able to use also gasoline or diesel oil, but there must be type approval, conversion approval or other type of official document⁸⁷ for at least one other energy source.⁸⁸ Vehicles may be dedicated to one energy source or be flexible for many energy sources. There are many technologies in the market for all types of vehicles and transport modes. Below is a list of alternative road vehicle types that are now found in Sweden or have been there recently (after 2000) (*manufactured by Swedish auto industry):

- Electric vehicles
 - o Dedicated: battery electric vehicles (BEV), which can use only electricity*
 - o Dedicated: cable electric vehicles (EV), which can use only electricity
 - o Flexible: plug-in hybrid vehicles (PHEV), which can also use chemical fuels*
- Hydrogen vehicles
 - o Dedicated: fuel cell electric vehicles (FCEV), which can use only hydrogen (monofuel)
 - o Dedicated: otto-electric vehicles (HEV), which can use only hydrogen (monofuel)
- Methane vehicles = MGVs (methane gas vehicles)
 - o Dedicated: monofuel vehicles, which can only use methane either in compressed (CMG) or liquefied (LMG) form*
 - o Flexible: vehicles, which may use both CMG and LMG (bifuel)
 - o Flexible: vehicles, which may use also one liquid fuel separately (bifuel)*
 - o Flexible: vehicles, which may use also liquid fuel simultaneously with methane (dualfuel)*
 - o Flexible: vehicles, which may also use two liquid fuels (trifuel)*
 - o Flexible: plug-in hybrid vehicles (PHEV), which can also use electricity
- Hythane vehicles
 - o Flexible: in addition to hythane (HCMG) they can use methane (CMG)
- DME vehicles
 - o Dedicated: vehicles, which can use only DME*
- LPG vehicles
 - o Flexible: vehicles, which may use also gasoline (bifuel)*
- Wood gas vehicles
 - o Flexible: vehicles capable of using wood and other solid biomass with onboard gasifier, and either gasoline or diesel oil
- Ethanol vehicles
 - o Dedicated: diesel vehicles, which can use only ED95*
 - o Flexible: E85 vehicles, which may use also gasoline*
 - o Flexible: vehicles, which may use E85, gasoline and methane (triifuel)*

⁸⁶ Specifically, the vehicle must have acceptance for other energy sources than specified by EN 228 (gasoline) and EN 590 (diesel oil) standards. For new vehicles this means that alternative fuel is permitted and does not affect warranties. For converted vehicles situation is the same except that for fuel system warranty of vehicle manufacturer is replaced by warranty of conversion system manufacturer.

⁸⁷ Other type of document is needed especially for renewable fuels without international standards and type approval procedures. National standards can be applied in those cases.

⁸⁸ If warranties or other type of legal protection is not needed, vehicles can be converted for a large amount of energy sources. They can be driven in open traffic, if permitted by national legislation. In special applications (off-road, race, demonstration etc.) there is even more freedom, but some rules exist in all cases.

- Methanol vehicles
 - o Flexible: M85 vehicles, which may also use E85 and gasoline
- Biodiesel and synthetic biodiesel vehicles
 - o Flexible: vehicles, which can use B100, SB100 and diesel oil*
 - o Flexible: vehicles, which can use B100, SB100 and methane (dualfuel)
- Kerosene vehicles
 - o Flexible: can use also gasoline
- Steam vehicles
 - o Flexible: vehicles are capable of using wood and other solid biomass

There are also many other types of AFVs elsewhere in Europe. Examples are PPO vehicles and compressed air cars. In Sweden only compressed hydrogen (GH2) is used, but in other European countries also liquefied hydrogen (LH2). In addition to otto, diesel, steam and electric engines, also 2-stroke and wankel engines are used in Europe. Some other engine types (hot bulb, stirling⁸⁹ and gas turbine) and fuels (for example M100) have been used in Sweden earlier.

In 2013 there were about 300,000 alternative fuel road vehicles in Sweden (Table A3.1). AFV vehicle registration is not fully developed: many of them are still classified as gasoline or diesel monofuel vehicles. But there is a clear improvement since the 1990's due to municipal policy⁹⁰.

Table A3.1. AFV road vehicles in Sweden in 2013.⁹¹

Energy source	Buses	Heavy trucks	Vans	Cars	Tractors	Other
Biogas (CBG and LBG)	2 315	755	6 470	37 325	?	?
Ethanol (ED95 and E85)	815	33	1 788	228 726		
Electric (BEV and EV)	10	0	548	1 010		?
Plug-in-hybrid (PHEV)	2			1 637		
Propane and butane (LPG)				180		?
Wood gas (WG)		?	?	16	?	
Biodiesel (B100) and synthetic biodiesel (SB100)	1576	?		3 ¹	?	
Bio-DME		10 ²				
Hydrogen (GH2)				3		
Methanol (M100 and M85)				0 ³		
Other and unknown ⁴	64	34	57	7	198	?

? These types of vehicles are in use, but not separated in vehicle statistics.
¹There are more, but most of them are classified as fossil diesel cars.
²Bio-DME trucks are classified within "other". Here their number was taken from the Biodme project.
³Methanol cars were last time in registry in 2009.
⁴No information is given on what these are.

Conventional hybrid vehicles (HEVs) have caused a lot of confusion. It is obvious that they are not alternative fueled vehicles, since they are fueled by gasoline or diesel oil only. They are monofuel vehicles. All diesel locomotives have for decades applied the same principle (of using electric motors for turning wheels) but they are not called hybrids or electric vehicles. They are fueled by diesel oil and therefore they are diesel monofuel vehicles and have always been so called. Although this technology had been used also with cars since the early 20th century, automotive industry did not begin calling them hybrids and HEVs until late 1990s. This marketing language has caused a lot of misunderstandings. However, most important is that this technology can, is and should be applied with alternative fuels. For example, in Sweden ethanol-

⁸⁹ Stirling engines are commercially manufactured for submarines and used in military submarines in Sweden, but with fossil fuels only. It is very fuel flexible engine type, so it would be easy to use any renewable fuels. Stirling engines were demonstrated in experimental trucks and cars in Malmö in the 1970s.

⁹⁰ This has been one of the activities of City of Stockholm (Stockholm 2010).

⁹¹ Sources: Fordon 2013 (SCB) and Statistik om bussbranschen (Sveriges Bussföretag) with exceptions as noted in the table.

HEV vehicles have been used since 1997, biogas-HEV vehicles since 1999, hydrogen-HEV vehicles since 2004⁹² and biodiesel-HEV vehicles since 2012 (Fig. A3.1). All these technologies are manufactured commercially. In addition, fossil HEV vehicles have been converted for RES-T⁹³.



Figure A3.1. RES-HEV vehicles in Sweden: a) Ethanol-HEV technology was first taken into use in Stockholm city buses in 1997. b) Biogas-HEV technology was first taken into use in Uppsala city buses in 1998. c) RES-hydrogen-HEV technology was first taken into use in Stockholm city buses in 2004. d) Biodiesel-HEV technology was first taken into use in Gothenburg city buses in 2012.

Differences in HEVs compared to ordinary vehicles are that they have secondary energy storage for propulsion (in addition to chemical fuel storage) as a battery and instead of (or in addition to) mechanical power transmission they have electronic power transition for electric motors. But there are also other vehicles with unconventional energy storage and power transmission. Flywheel energy storage was used in Sweden in the 1980s and is used elsewhere today. Magnetic and hydraulic power transmissions have been used, including hydraulic buses in Sweden in the 1980s. None of these technologies make vehicle an alternative fueled vehicle, but all of them can be utilized in alternative fueled vehicles as easily as in gasoline and diesel oil vehicles. The same applies to all other technologies used for improving energy efficiency.

Environmental vehicles (ecovehicles)

Numerous Swedish municipalities have since the 1990s supported so called environmental vehicles (miljöbil, i.e. ecocar), with some differences in definitions. They include RES-T vehicles: AFVs for which renewable energy is available. As local availability of RES-T has varied, there have been differences between municipalities on supported vehicle types. Usually fossil monofuel vehicles, whether conventional or AFVs, have not been accepted.

LPG cars have always been excluded, because renewable LPG (bio-propane and bio-butane) has never been found in the Swedish market. For the same reason methanol monofuel (M100) cars would have been excluded, but they have not been available for decades. M85 cars imported from the USA are found in Sweden, but they are acceptable, since they are also able to use E85. Figure A3.2 shows Ford Taurus FFV, which was the first E85 car in Sweden and whole Europe in 1994; and instrumental in the introduction of E85 fuel in the Swedish market and later elsewhere in Europe.

Figure A3.2. First E85 car in Europe: Ford Taurus FFV is able to use E85, M85, gasoline and any mixture of them.



On the other hand, some RES-T vehicles have been excluded (wood gas and steam) and some municipalities have included selected fossil monofuel vehicles.

Despite some compromises municipal policy regarding environmental vehicles has been high quality and based on sound science.

This is not the case with the new Swedish national environmental vehicle definition (see Annex 2).

⁹² First FCEV, since 2008 also otto-HEV.

⁹³ E.g. Toyota Prius HEV cars have been converted for methane and hydrogen in Sweden and elsewhere.

Glossary and nomenclature

_50, 100 etc.	Number attached to fuel name means volume percent of RES-fuel mixed with fossil fuel, e.g. CBG100 = 100 % biogas in compressed form, CBG20 = 20 % biogas mixed with natural gas in compressed form
AFV	Alternative Fuel Vehicle: Vehicle manufactured for other fuels instead of or in addition to conventional fuels gasoline or diesel oil (in road transport; in other types of transport conventional fuels are different)
B	Biodiesel: Mixture of fatty acid alkyl esters made chemically from plant oils and fats
BEV	Battery Electric Vehicle: EV where electricity is stored onboard electrochemically
BG	BioGas: Methane fuel made microbiologically from biomass
Bifuel	Vehicle with 2 fuel systems, fuels are used alternatively one at a time
Biofuel	Gaseous, liquid or solid chemical fuel made from biomass
BM	BioMethane: Methane fuel made from biomass by any method, incl. BG and SBG
BRT	Bus Rapid Transit: System, where buses run on dedicated lanes not accessible to other vehicles
CBG	Compressed BioGas: Upgraded biogas stored in compressed form (at least 200 bars)
CMG	Compressed Methane Gas: Methane fuel from any source
CNG	Compressed Natural Gas: Upgraded natural gas stored in compressed form (at least 200 bars)
DME	Dimethyl ether: Gaseous ether suitable for diesel engine fuel
Dualfuel	Vehicle with 2 fuel systems, fuels are used simultaneously (one for ignition, one for energy)
E	Bioethanol: Ethanol made by any method from biomass
ED	Bioethanol mixed with components enabling its use in diesel engines
ETBE	Ethyl tert-butyl ether: One type of liquid ether
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle: Monofuel fuel cell vehicle
FFV	Fuel Flexible Vehicle: Vehicle with 1 fuel system, but ability to use 2 fuels and their mixtures
Fuel flexibility	Ability to use many fuels
FT-diesel	Fischer-Tropsch diesel: One type of synthetic diesel (synthetic biodiesel if made from biomass)
GH2	Gaseous hydrogen stored in compressed form (usually 350 or 700 bars)
GHG	Greenhouse Gas
GWP	Greenhouse Warming Potential: Relative strength of a GHG compared to carbon dioxide per unit mass
HCMG	Compressed hythane (usually 200 or 250 bars)
HEV	Hybrid Electric Vehicle: Monofuel combustion engine (usually otto or diesel) vehicle with electric transmission
HVO	Hydrotreated Vegetable Oil: One type of synthetic biodiesel
Hythane	Mixture of methane and hydrogen
LBG	Liquefied BioGas: Upgraded biogas stored in liquefied form
LCBG	CBG station where storage is in LBG
LH2	Liquefied hydrogen
LMG	Liquefied Methane Gas: Methane from any source
LNG	Liquefied Natural Gas: Upgraded natural gas stored in liquefied form
LPG	Liquefied Petroleum Gas: mixture of propane, butane and other C3-C4 hydrocarbons
Methane fuel	Mixture of gases, where all or most of energy is in the form of methane
MGV	Methane Gas Vehicle: vehicle able to use methane and hythane
Monofuel	Vehicle which can utilize one fuel
Multifuel	Vehicle able to use at least 3 fuels
NG	Natural Gas: Fossil methane fuel originating from natural gas wells
PHEV	Plug-in Hybrid Electric Vehicle: Vehicle able to use both chemical fuels and electricity
RES	Renewable energy source
RES-E	Renewable electric energy
RES-H	Renewable heating energy
RES-T	Renewable transport energy
RES Directive	Directive 2009/28/EC for promoting RES in all energy use
RME	Rape Methyl Ester: One type of biodiesel, made from rape seed oil
SB	Synthetic Biodiesel: Diesel engine fuel made thermochemically from biomass, consists of a mixture of hydrocarbons and/or other liquid organic compounds
SBG	Synthetic BioGas: Methane fuel made thermochemically from biomass

SNG	Synthetic Natural Gas: Fossil methane fuel made thermochemically from coal or other fossil fuels
Solar fuels	Chemical fuels produced by solar energy, e.g. solar hydrogen and solar methane
Upgrading	Removing inert components from methane fuels for increased energy density, all biogas and natural gas sold for transport use in Sweden is upgraded
WG	Wood gas: mixture of carbon monoxide, hydrogen, methane and other gases made by thermochemical gas generator from wood
Wind fuels	Chemical fuels produced by wind energy, e.g. wind hydrogen and wind methane
WTW	Well-to-Wheel: Lifecycle of energy source in transport from source of primary energy until moving of vehicle, not accounting for production of vehicles and other machinery.

Acknowledgement

Most of Annex 2 and some text in other parts of this publication have earlier been published in an article by Lampinen (2014) and are included here by permission from Lexion, publisher of Renewable Energy Law and Policy Review journal.

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c) Photos: Ari Lampinen, except 24b, which is courtesy of Koenigsegg Automotive AB.