

Transport fuels for the future – the long-term options and a possible development path

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Abstract

The aim of this paper is to review the prospect for large-scale automotive fuel and feedstock options and draw some conclusions regarding short and medium-term policy. We are looking at 10-50 year perspective and a robust/flexible strategy based on carbonaceous feedstock that could act as a bridge supporting the long-term development of zero emitting fuel cell or electric vehicles but would not be dependent solely on a specific technical breakthrough. Due to mainly the technology path dependence and the low cost, fossil based fuels will dominate both the medium-term supply and the long-term development of alternatives. This will favor alternative fuels compatible both with fossil and renewable feedstock. Methane is identified as a possible bridge between what is short-term available and long-term possible. Gasification is another future key technology in this transition path that enables a relatively flexible transition to hydrogen, DME, methanol or even F-T fuels in the future. The long-term air quality and CO₂ reduction targets together with the cost development of advanced technologies will eventually determine whether future transport fuels will be based on solar or carbonaceous feedstock.

1 Introduction

Concerns for energy security and environmental protection have been the main driving forces for research and development efforts into new vehicle technology and new fuels, but economic restrictions and market trends have so far, in most countries, hindered the introduction and diffusion of fundamentally new vehicle technologies and alternative fuels. The transport sector is far away from meeting any set reduction targets for greenhouse gases and a continuing growing demand for transport services, high costs for carbon dioxide neutral fuels, and a slow market development for energy efficient cars, makes the transition to a sustainable transport sector seem difficult today.

1.1 Transport energy use today and tomorrow

The global transport sector use approximately 70 to 90 EJ energy per year¹. In OECD countries, 97% of the transport sector uses petroleum-based fuels. Biomass based fuels (mostly ethanol) currently accounts for less than 1% of total transport energy use within the OECD.

¹ 70 to 90 EJ/year reflects the most estimates. Generally, the transport sector uses about 22 to 25% of the worlds total energy use of ~370-400 EJ/year (IPPC 1996, IEA 2003).

The energy use within the transport sector is expected to continue to grow the coming years. According to World Energy Outlook, global energy use within the transport sector will grow from current estimate of 80 EJ/year to 140 EJ/year in 2030 (IEA 2004a). These numbers are uncertain but give an approximate range of the current and future energy use.

The long-term CO₂-reduction targets for society vary but is usually set around -50% in 2050 and -90% to 2100 from current emission levels, see IPCC (1996). These cuts are necessary for stabilizing the atmospheric CO₂ levels at 550 ppm or below. The dramatic required cuts in CO₂ emission will lead to a high demand and strong competition for renewable energy sources. As the transport sector seems to have the most costly way of reducing CO₂-emission (Gustavsson et al 1995) it has been suggested that the reduction target for this sector should be less stringent than for other sector in society (Kågesson 2001) or that the transport sector should wait until high tech solutions such as PV-cells and fuel cell cars become available (Azar et al 2003). Another way of looking at it is that the high willingness to pay in the transport sector creates a political room of maneuver for promoting more expensive, carbon-neutral fuels.

1.2 Alternative fuels as a long-term solution to CO₂ mitigation

Hydrogen and electricity from solar, hydro, or nuclear power are inherently zero emitters of CO₂ as essentially no carbon enters the life cycle. The hydrogen/electricity options have also the major benefit of being zero emitters of all other air pollutants when used in an electric or fuel cell car. All biomass-based fuels have the potential to be zero, or close zero, net CO₂-emitters over a full life cycle. However, depending on how the biomass is produced, the conversion route taken, and the input fuel needed, the net CO₂-emissions can vary substantially; see IEA 1999 for an overview. Using a fossil feedstock with CO₂ sequestration, only hydrogen has the potential to become a zero CO₂-emitting fuel.

A strict long-term CO₂-reduction target together with strict air quality measures can force solar hydrogen and renewable electricity to the automotive market. Although zero emitting vehicles using solar energy might be necessary for the future, we think that a transition period must involve other low-carbon gaseous or liquid fuels that are not based on dwindling conventional oil-resources. This calls for a strategy that does not exclude this future shift but is neither dependent on e.g. the successful development of fuel cells, solar power or high energy density batteries for electric vehicles (EVs).

1.3 Aim

The aim of this paper is to review the prospect for the most promising large-scale automotive fuel and feedstock options and outline possible development paths based on what alternative fuel/feedstock combinations are available today. We are thus looking at 10-50 year perspective and a robust and flexible strategy based on carbonaceous feedstock that could act as a bridge supporting the long-term development of zero emitting vehicles. Robust in the sense that it has a strength in a broad resource base and flexible in the sense that it can adapt to new, different, or changing requirements

The analyzed carbonaceous feedstock includes wood, starch/sugar, and fossils. Biodiesel from vegetable oils is excluded, as this feedstock is too limited on a global scale. Small-scale biogas derived from waste streams have no major potential in itself but is compatible with natural gas (both ~95% methane) and is thus included indirectly here as part of a suggested transition strategy.

2 Transport energy supply – technical assessment

The basic factors determining the long-term success of alternative fuels is in this paper assumed to be the *potential availability* and the *potential cost*, which can be narrowed down to the technical and physical availability of feedstock, possible future fuel-vehicle combinations, available production facilities and the production cost.

Figure 1 below outlines the different conversion routes explored in this paper from carbonaceous feedstock to usable automotive fuels. The key conversion technologies that are expected to play a significant role during the coming 50 years are thus hydrolysis & fermentation, gasification, steam reforming and CO₂-sequestration.

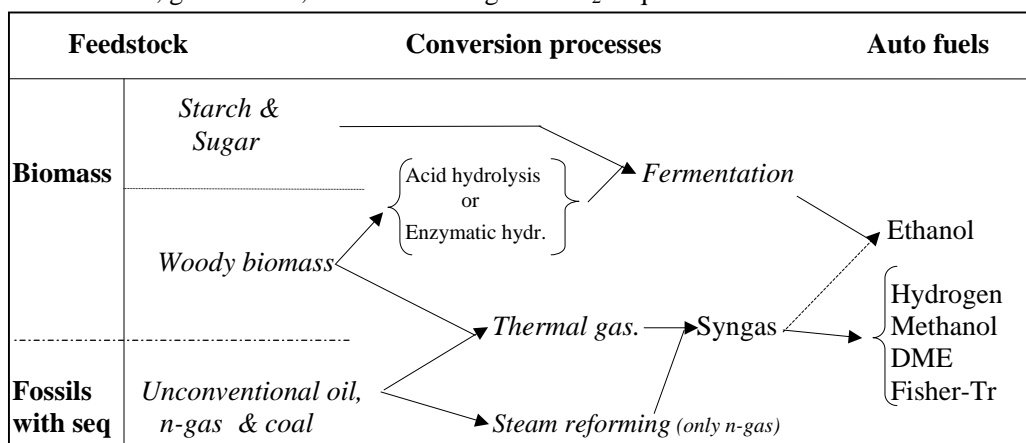


Figure 1. Conversion routes for automotive fuels from carbonaceous feedstock.

2.1 Feedstock resources

The availability of an alternative fuel is in this paper defined as enough potential feedstock resources for the fuel to become a contender on a global scale and a conversion technology that makes the fuel technical possible and affordable. In Table 1 follows an overview of feedstock availability assessments and a brief discussion on some major assumptions.

Table 1. Global carbonaceous feedstock resources.

	Biomass (EJ/Year)	Fossil energy (EJ)	Oil		Natural gas		Coal
			Conv.	Unconv.	Conv.	Unconv.	
Current use	33-55	Reserves	6004	5108	5454	9424	20666
Future estimated	270- 450	Resources	6071	15240	11113	23814	179 000
Energy use in transport sector	70 – 90 (2004) ^140 (2030)	Historical consumption (1860 to 1998)	4854	285	2346	33	5990

Sources: (Turkenburg 2000; Hoogwijk et al 2003; Rogner 2000).

Biomass

Theoretically 2900 EJ/year of biomatter could be harvested but typically 270 to 450 EJ/year is considered sustainable available, see Table 1. Current bioenergy use is estimated to 33 to 55 EJ/year. Hoogwijk et al. (2003) estimates that 38 EJ is traditional

use and only 7 EJ is use of modern biomass. With assumed conversion efficiencies of 50 to 70%, the potential biomass correspond to 130 to 310 EJ/year of transport fuel.

The major biomass feedstock in all future estimates is woody biomass from dedicated energy plantations but cellulose from waste streams and residues from forestry will also contribute. Starch and sugar-rich plants do not seem to have the large-scale global potential and is more seen as a regional resource that nevertheless could in specific cases contribute substantially.

The potential for future biomass availability rests on a number of assumptions including the development of dedicated energy plantations and that the inherent land use conflict between food production and biomass for energy purposes be resolved. In the estimates in Table 1, this is accounted for and partly responsible for the varying numbers. As an example, in (Hoogwijk et al 2003) the estimates of available biomass from surplus agricultural land varies between 0 to 988 EJ/year².

Fossils

The physical availability of fossils is finite but exactly how much of the resources hidden in the earths' crust that could be utilized have been debated. A *reserve* has typically been defined as "occurrences that are identified, measured and at the same time known to be technically and economically recoverable" (Rogner 2000). However, a *resource* is defined as "occurrences with less certain geological assurance and/or with doubtful economic feasibility" (ibid). Oil companies usually cite a reserves-to-production ratio of 20 to 40 years. This has over the years misled some to believe that we are running out of oil, but the definition of a reserve is dynamic and changes overtime as a result of technological advances and economic incentives. With better extraction technology more resources will become economically feasible and are thus transformed to reserves.

In Table 1, the estimates by Rogner (2004) on reserves and resources for conventional and unconventional fossils are given. There is no immediate or even long-term shortage of fossil material for energy use. However, most analysts are aware of that no more large resources of low cost crude oil will be found and that the *cost* of extracting fossil energy will rise in the future (not necessarily the price). Natural gas, coal, tar sands, oil shale, and other low grade resources are still relatively abundant and a huge amount of these resources can become available at costs not much higher than the average oil price the last 15 years, that is 22 to 30 dollars/barrel oil equivalent (ibid).

2.2 Conversion processes for carbonaceous feedstock

Ethanol by fermentation

Fermentation is used for producing ethanol and can use any biological feedstock that contains sugar (e.g. from sugar cane or sugar beets) or materials that can be converted into sugar such as starch or even cellulose. Ethanol production from the fermentation of sugar by yeast has been known for thousands of years. Starch from cereals like corn and wheat can relatively easily be converted into sugar and then fermented in a similar way as sugar. The organisms and enzymes necessary for conversion of starch and sugar are commercially available and used on large scale already. Cellulose is more difficult as raw material because it must be broken down into sugars through a process called saccharification. Chemical and biological saccharification processes are under

² In Hoogwijk et al (2003), the total biomass energy supply varies between 33 and 1135 EJ/year.

development. In the chemical route (acid hydrolysis) cellulose is treated by chemicals (e.g. sulphuric acid) in one or two steps for getting five- and six-carbon sugars that can finally be fermented. Another possibility is to use special enzymes, which can “chop” the cellulose molecules into sugar (enzymatic hydrolysis). Extensive research, especially on enzymatic hydrolysis, is ongoing in several countries.

Enzymatic hydrolysis is the most promising conversion route for the future in terms of potential cost and efficiency, but this technology is still under development and not ready for commercialization. Acid hydrolysis is relatively well known and could be available today but is not seen as a competitive route in the long-term.

Syngas from thermal gasification or steam reforming

Gasification is a process that converts carbonaceous material through a process involving partial oxidation with air or oxygen into a syngas consisting mainly of hydrogen and carbon monoxide. Contrary to combustion, the deficit of oxygen in the gasifier reactor does not lead to carbon dioxide and water, which are the usual end products from oil and coal combustion. The syngas can be used in two ways. By using a combination of gas turbine and steam turbine (so called combined cycle) it is possible to generate more electricity compared with only the steam turbine cycle. Another possibility is to use the syngas as chemical building blocks from which a number of chemicals can be produced via synthesis. The end products can be fertilizers or energy-rich products like hydrogen, methanol, methane, Fischer-Tropsch diesel (F-T diesel) or dimethylether (DME) which all can be used as motor fuels. Today only F-T diesel is used as fuel on small scale and limited production from coal gasification exists.

A vision put forward is the creation of a “biorefinery” which, like present oil refineries, could produce a wide range of products including motor fuels but also more advanced chemical products or other energy products. The basic rationale is that the original feedstock could be used much more efficiently and that the economics would, if all the outputs find a market, be advantageous. Polygeneration of heat, electricity and fuels in a “once-through process” has been suggested by Williams (2000). Here syngas is passed once through the reactor to produce a fuel and the unconverted syngas is burned to produce electricity in a combined cycle (trigeneration). Trigeneration offers a technical opportunity to produce fuel from syngas (methanol or hydrogen) and to use part of syngas to fuel a cogeneration plant (heat and electricity) would lower the cost substantially as the syngas does not need to be recycled (ibid).

The least costly way of producing syngas is by *steam reforming* of natural gas and in combination with CO₂ sequestration this is forwarded as an alternative for the future, see below. Producing advanced fuels from natural gas derived syngas without CO₂ sequestration has the drawback (apart from not being CO₂ neutral) that it may be less costly and more efficient to use the gas directly in compressed natural gas (CNG) vehicles.

Sequestration of CO₂ from fossil feedstock

Fossil feedstock can be used for producing CO₂-neutral transport fuels if the process is complemented with CO₂-sequestration, which includes separation, transport and final storage of the CO₂. Storage of CO₂ is already being done in depleted gas and oil fields but the assessed storage capacity in these abandoned fields varies greatly and is probably limited in the long-term. The large-scale and long-term CO₂-storage is to be found in saline aquifers and deep into the oceans, but this technology is still on a premature level

of development and many uncertainties remain as to whether the sequestered CO₂ will remain where it is put or the final cost (Williams 2000).

The scale of the “CO₂-source” is of significance. It is not economically or technical possible to sequester CO₂ from automobiles or from small facilities at e.g a pump station. The scale for making this alternative reasonable requires typically CO₂-rate of 10kg/second, which is comparable to the emissions from a coal power plant of 500 to 1000 MW (Azar et al 2003).

The most realistic and near term conversion route including CO₂-sequestration, both from an economic and technical view point, is hydrogen production from steam reforming of natural gas. Hydrogen production from gasification of coal or/and biomass is also possible but more complex and costly (Williams 1998). The cost of carbon management in these alternatives depends strongly on whether the CO₂ is sequestered in a depleted gas field or in dedicated CO₂-storages such as e.g saline aquifers. In the least costly alternative, hydrogen is produced at the gas field and the CO₂ is directly sequestered.

2.3 Compatibility with vehicles and fuel infrastructure

Compatibility with the existing or future vehicle fleet is necessary. It's no coincidence that ethanol is the currently favored alternative fuel due to the almost perfect match between current internal combustion vehicles (ICEVs) and ethanol as a fuel. The other fuels discussed all require changes to the vehicles, the supply infrastructure, or both.

The internal combustion engine can be adapted, with minor costs, to ethanol, methanol, methane³ (CNG or biogas), hydrogen and DME. F-T fuels needs no adaptation. Several of the mentioned fuels have already been available on the market such as ethanol, methanol (M85), CNG/biogas. Low blending (<10-15%) is also possible as a “soft” strategy for introducing ethanol and methanol. Vehicle development will to some extent influence the desired fuel. If fuel cell vehicle comes to market as a competitive solution, this will narrow down the fuel selection to hydrogen and/or methanol.

Distribution of the fuel to the engine is a more difficult problem. Here, the difference is to be seen between liquid and gaseous fuels. Liquid fuels (ethanol, methanol, F-T diesel) could use the same modular distribution structure as petrol and diesel (tankers, trucks, pump stations, and fuel tanks). For gaseous fuels, there is a need for a more centralized organization of pipelines supplying the gas. However, the existing natural gas infrastructure can be used as a transition strategy from natural gas based to renewable hydrogen, see Ogden (1999), easing the “chicken or egg” problem. There is also a need for compressing the gas in the vehicle at high pressure adding both cost and energy losses. DME needs to be pressurized to ~5 bars, methane to 200 bars whereas as hydrogen needs to be stored at 300 to 350 bars in order to give the vehicle an acceptable range. Storing hydrogen under low pressure in nanofibre structures is a possible future solution but so far development this technology has not been demonstrated and the feasibility remains highly uncertain.

The need for costly new infrastructure and new vehicles should not be overemphasized. Ethanol, methanol, and F-T diesel poses no *major* technical obstacles to future use in

³ Methane is used as a proxy for natural gas and biogas that contains mostly methane (>95%). The vehicles (CNG) are relatively flexible regarding exact the methane content.

vehicles whereas the gaseous fuels, methane, DME and hydrogen puts a demand on technical development, especially of high pressure vessels for onboard storage.

3 Costs

The interesting cost aspect here are the future costs that could be attained if development is successful. In Table 2 is an overview of cost estimates presented.

Table 2. Estimated production costs

Cost assessments		Current technology	Future estimates	Distribution costs
Petrol/Diesel		4 – 6 USD/GJ	8-11 USD/GJ	3,5 – 3,9 USD/GJ
Ethanol	starch/sugar	15-20 USD/GJ (Beet) 8-10 USD/GJ (Cane)	15-20 USD/GJ (Beet) 8-10 USD/GJ (Cane)	~4,2 USD/GJ
	cellulose	10-15 USD/GJ	6-9 USD/GJ	~4,2 USD/GJ
Methanol (cellulose)		11-13 USD/GJ	7-10 USD/GJ	~4,6 USD/GJ
DME (cellulose)		11-13USD/GJ	7-10 USD/GJ	6,2 - 8,1 USD/GJ
Fisher-Tropsch (cellulose)		~20 USD/GJ	~13 USD/GJ	3,5 – 3,9 USD/GJ
Hydrogen	cellulose	10-14 USD/GJ	5-8 USD/GJ	8 – 15 USD/GJ
	from n.gas & coal with seq.	n.a	9-11 USD/GJ (coal) 5- 6 USD/GJ (gas)	
	solar power	n.a	18 to 28 USD/GJ	

Sources: Primarily based on overview in Turkenburg (2000) complemented with numbers from Rogner (2000), Hamenlinck and Faaij (2001), Hamenlinck et al (2004), IEA (2004b), Williams (1998) Ogden (1999). Cost on distribution numbers from Ecotrafic (2002),IEA (1999) and Ogden (1999).

The Rotterdam price of petrol has varied around 7 USD/GJ in 2003 but in a longer perspective, the price has varied between 4 and 8 USD/GJ (BP 2004). The average cost of extracting the fossils from the earth will rise in the future, but not much higher than current selling prices (Rogner 2000). However, the price for petrol and diesel is expected to rise to 8 to 11 USD/GJ in the longer-term (Turkenburg 2000). Crude oil prices have long been hovering around 20 to 30 USD₂₀₀₄/barrel but have lately peaked up to 50 USD/barrel. A crude oil price of 50 USD/barrel translates to 8,8 USD/GJ (add to this the cost of refinement to get the petrol cost). In the oil crises of 1979, crude oil prices peaked at 80 USD₂₀₀₄/barrel (BP 2004).

The long-term cheapest alternative seems to be ethanol from cellulose, but these estimates all depend on the successful development of enzymatic hydrolysis. Methanol and DME have, approximately, the same future cost between 7 to 10 USD/GJ, where the lower values depicts large scale manufacturing in ~2000MW facilities. F–T fuels is inherently ~40% more expensive than methanol/DME according to Hamenlinck et al (2004).

Hydrogen costs range between 5 and 28 USD/GJ in the estimates, depending on from which feedstock it has been derived. Cellulose is the least costly with a future cost as low as 5 USD/GJ. This low cost is dependent on the same technical development as future methanol, DME and F-T fuels (gasification). Hydrogen from natural gas or coal with sequestration also offers an interesting alternative. The cost of natural gas derived hydrogen could also come as low as 5 USD/GJ largely depending on the low cost of

natural gas and a simple well-known production technique (steam reforming). Here, it is assumed that the hydrogen is produced at the gas field and that the CO₂ can be sequestered directly. The higher costs for coal stems from the need to transport and to sequester the CO₂ in aquifers (Williams 1998).

Given the major uncertainties in these cost estimates, it can be concluded that ethanol, methanol, DME, and hydrogen from cellulose and fossils with sequestration all *could* become competitive with future petrol and diesel. The only fuel that seems too expensive is ethanol from traditional sugar/starch (note that this is on a global scale), and solar powered hydrogen. F-T fuels seem also to have an inherent cost penalty and will unlikely be competitive in the long term.

One key assumption underlying the cost reductions above is that cellulose biomass will be produced competitively at a cost of 1,5 to 2 dollars/GJ as compared to approximately 3 dollars/GJ today. This requires using modern technologies and dedicated plantations as well as international biofuel markets for bringing costs down. In most studies cited above, cost reductions that stems from learning by doing have been assumed. This requires substantial “learning” investments often dwarfing previous R&D investments in a, at the time, non-competitive technology (Rogner 1998, Åhman 2003).

Table 1 also includes estimates on the cost of fuel distribution. These are the long-term cost for new fuel infrastructure thus including sunk cost in current fuel infrastructure. The cost for supplying the fuel usually represents around 30 to 45% of the total cost of delivered fuel. All fuels except F-T diesel carry a cost penalty for the distribution compared to conventional fuels. Ethanol can be supplied at almost the same cost as petrol and the cost of supplying methanol is 30% higher than for supplying petrol. A more pronounced cost penalty comes with gaseous fuels that need to be supplied under pressure. For hydrogen, the few assessments available on the cost of supplying hydrogen to a fuel cell differ between 8 to 15 USD/GJ. DME is also in gaseous form but needs a lower pressure than hydrogen and the cost is therefore also less; between 6 to 8 USD/GJ.

4 Development paths for bridging short-term opportunities and long-term visions

4.1 The long-term options

Electricity from solar or nuclear power

Assuming stringent long-term CO₂-emission and air quality targets, the fuel options will be hydrogen from renewable electricity used in zero emitting fuel cell vehicles or, if battery development surprises us all, electric vehicles fuelled with renewable electricity. Solar electricity has the technical potential to replace all future use of fossil energy. However, the success of solar power rests on the development of photovoltaics and especially major cuts in the production cost before becoming an alternative on the market. Nuclear power can also make a major contribution but faces a number of problems including, weapons proliferation, accident risks, and waste management. Cost is also an issue for nuclear facilities.

Using electricity or hydrogen derived from electricity requires the development of either fuel cell vehicles or high energy-density batteries. High hopes were placed in Lithium-polymer batteries in the mid 1990s, especially by the company 3M/Hydro-Quebec, but hopes vanished as development targets were not reached and the joint venture between

3M and Hydro-Quebec was dissolved. The French company SAFT and Japanese Panasonic continues battery development but aims at the hybrid vehicle market instead requiring high *power-density* batteries, not high *energy-density* batteries. The continued development of advanced high energy density batteries will have to rely on the home electronics market as a driver.

Fuel cells are a very promising technology but the barriers facing the technology in terms of development needs have often been underestimated by companies and governments. This is partly due to the rapid development of fuel cell technology that took place in the mid 1990s, driven by the Canadian company Ballard, when fuel cells were developed from an item at the research lab to functioning demonstration vehicles in 5 years. Since then, development has been ongoing in a more normal pace. The major issue that needs to be solved is the cost. The cost of a fuel cell system needs to come down to approximately 50 USD/kW from current levels of 1500 to 3000 USD/kW if to compete with the internal combustion engine (Åhman 2003).

Gasification of biomass

Biomass derived hydrogen can also become a future zero emitting fuel. Other biomass-derived fuels such as methanol, ethanol, DME and F-T fuels might also become long-term winners if emissions of ozone precursors (NO_x, HC) and PM could be kept within acceptable limits. The future available biomass has the potential to replace petrol/diesel in the transport sector if used only here. However, it is doubtful whether all the potentially available biomass will be used in the transport sector, as CO₂ mitigation with biomass usually is more cost efficient in other sectors such as heating.

A future biomass derived fuel must come from *woody biomass* if to contribute substantially. This narrows down the options to *syngas derived fuels* via gasification or the successful development of enzymatic hydrolysis for producing ethanol from cellulose. In the choice between a conversion routes from gasification compared to enzymatic hydrolysis followed by fermentation we think that gasification holds a number of advantages when it comes to flexibility and technology risk. Gasification not only applies to biomass-derived fuels but also open up for fossils like coal or natural gas combined with sequestration. Syngas can also be produced from steam reforming of natural gas. From syngas it is possible to manufacture several fuels such as methanol, methane, hydrogen, and F-T fuels.

Gasification of biomass has been tried in pilot scale (e.g. Värnamo in Sweden). At present no private actors are willing to finance the further development and demonstration efforts to bring biomass gasification to a commercially ready technology as the revenues from power generation or motor fuel cannot justify the capital investment.

Biorefineries or polygeneration has been suggested as a way to making large-scale gasification of biomass (and coal) economically and technically attractive. However, a polygeneration facility is a very complex and capital-intensive process. The balance between the different “outputs” cannot be chosen freely and, once built and running, this balance is only changed at high costs. This inflexibility poses a major risk for business requiring stable markets for all outputs. The coming years, polygeneration facilities will only be built in countries with a strong government role, such as China, and be based on the gasification on coal and not biomass. Recently some gasification plants of the trigeneration type have been built at oil refineries. Residual oil products like asphalt are gasified and converted into hydrogen, electricity and steam mainly for internal use.

These investments are in the order of 1 billion EUR, which necessitates a very high throughput (>2000 t/day) to be competitive.

Time scales for development

All the long-term options considered here depend on major development efforts and will not be commercial for a great number of years. The “hydrogen vision” is typically assumed to be possible first after 2050 in a major scale. Biomass-derived fuels through gasification is not a commercial route yet and will need considerable time to develop. The scale and financial risks with thermal gasification of biomass suggest that this technology will be developed only after syngas derived fuels have been proven feasible on the market. In the medium term (the next 50 years!) several fuels based on carbon should be tried and developed for supporting the development of key conversion and vehicle technologies necessary for the long-term alternatives.

As a starting point, the short-term options available today are basically ethanol from sugar/starch, RME from rapeseed oil and methane (natural gas or biogas). RME will remain a niche fuel as the overall potential is too low. For ethanol and methane, vehicles and some infrastructure exist today, and both have an interesting potential. However, the key technologies and the development path for large-scale ethanol is inflexible with regards to feedstock and fuel choice whereas methane offers a possible flexible, low risk path outlined below.

4.2 Methane as an intermediate fuel and feedstock?

Methane is the major component in natural gas and biogas and is currently used in CNG vehicles in large parts of the world. Argentina, Italy, New Zealand, United States, Brazil, India and Egypt all have major fleets of CNG vehicles due to an already existing natural gas infrastructure making it relatively easy and low cost to introduce CNG vehicles. In Europe as a whole, CNG vehicles are expected to increase substantially the coming years with the expansion of the natural gas grid (EU 2003).

Starting with expanding the use of natural gas and biogas the coming 5 to 10 years would build up consumer confidence in gaseous fuels, infrastructure and support the further development of high pressure vessel for gas storage in vehicle hopefully bringing costs down. This expansion can be done without excessive costs due to the relatively low cost of natural gas and biogas in countries where a natural gas infrastructure already exist. Note also that gas as an energy carrier is relatively common in developing countries where the major growth of vehicles is expected to occur and that retrofitting conventional vehicles to gas vehicles is relatively easy and low cost. Switching from petrol/diesel to methane in developing countries would mean a lot to air quality as gas is a cleaner fuel than petrol/diesel with no exhaust cleaning devices (such as a catalyst).

However, after an initial build up period of gas vehicles and the associated infrastructure there is a need to avoid a lock-in to “fossil gas”. The shift from natural gas to renewable sources will not be resource driven as the total feedstock of conventional natural gas is huge, see Table 1. The life-cycle emissions of CO₂ is lower than using diesel/petrol due to the low carbon to energy ratio in natural gas and even lower using renewable biogas (IEA 1999) but eventually stricter CO₂-emission targets will force the use of CO₂-sequestration techniques for fossil fuels. For natural gas, this necessitates the production of syngas for CO₂-sequestration (done by steam reforming). Another alternative is to mandate methane derived from biomass to be included in sold gas. Methane from biomass is either biogas from waste streams or methane from syngas. These both

conversion routes offer a CO₂-neutral contribution to the solid methane gas. As soon as syngas derived fuels starts entering the market, there will be opportunities for syngas based fuels derived from thermal gasification of biomass and coal although the original track from natural gas favors hydrogen. Which fuel to produce from this syngas is a matter of vehicle development and CO₂-reduction targets.

In conclusion, methane offers an intermediate solution that is both short term available and does not lock out any of the hoped for fuels in the future but instead could help to push development in some key technologies regarding gas storage and possibly gasification.

5 Conclusions

The long-term feedstock options that technically have the potential to supply a growing transport sector with renewable energy are solar-based systems (electricity or hydrogen) and fuels from woody biomass. The most likely long-term fuels are thus solar or biomass based hydrogen and electricity and biomass-based methanol and DME. The currently favored renewable fuel, ethanol from agricultural products, will be an important fuel for many decades (especially if enzymatic hydrolysis develops and enables ethanol from cellulose) but nevertheless a parenthesis in the global energy transport supply.

Due to mainly the technology path dependence and the low cost, fossil based fuels will dominate both the medium-term supply and thus the long-term development of alternatives. This will favor alternative fuels that are compatible both with fossil and renewable feedstock.

Methane from both fossil or biomass origin is identified as a possible bridge between what is short-term available and long-term possible. Syngas production by thermal gasification or steam reforming is another key technology in this transition path and opens up for a relatively flexible transition to hydrogen, DME, methanol or even F-T fuels .

The long-term ambition target for the transport sector and the cost development of some other key technologies, notably photovoltaic, fuel cells, and nuclear, will eventually determine whether future transport fuels will be based on solar or carbonaceous feedstock.

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