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Methanol: a future transport fuel based on hydrogen and carbon dioxide?

STUDY

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Methanol: a future transport fuel based on hydrogen and carbon dioxide?

Economic viability and policy options

Study

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Abstract

This study discusses the technological, environmental and economic barriers for producing methanol from carbon dioxide, as well as the possible uses of methanol in car transport in Europe. Costs and benefits are evaluated from a life-cycle perspective in order to compare different feedstocks for methanol production and to account for the potential benefits of CO_2-derived methanol in the transition to a more diversified fuel mix in the transport sector. Benefits in terms of reduced dependence on conventional fossil fuels and lower risks to security of supply can be envisioned in the medium and long term. It is nonetheless evident that considerable and sustained research efforts are necessary to turn CO_2 into an efficient and competitive prime materials, which would be attractive not only for the transport sector, but also other industries. Europe's increasingly limited and expensive access to fossil fuels makes it obligatory to consider policy options and smart strategies, combining market, regulatory and planning instruments, to bring down the direct and indirect costs of alternative fuels, so that transport services remain affordable for citizens and companies during the transition to a less petroleum-dependent economy.

CONTENTS

LIST OF ABBREVIATIONS

BEVs	Battery Electric Vehicles CCU Carbon capture and use
CCUS	Carbon capture, use and storage
CFF	Clean Fuel Fleet
CNG	Compressed natural gas
DME	Dimethil Ether
DMFV	Direct Methanol Fuel Cell
EPA	Environmental Protection Agency
FCV	Fuel Cell Vehicle
FFV	Flexible fuel vehicles
ICE	Internal Combustion Vehicles
LPG	Liquefied petrol gas
NEDC	New European Driving Cycle
PEMFC	Proton Exchange Membrane Fuel Cell
PHEVs	Plug In Hybrid Electric Vehicles
FFVs	Flexible vehicles
FCEVs	Fuel Cells Vehicles
RFG	Reformulated Gasoline
TBA	Tertiary Butyl Alcohol
TCO	Total Cost of Ownership
MTBE	Methyl Tertiary Butyl Ether

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SUMMARY

This final report on "Methanol: a future transport fuel based on hydrogen and carbon dioxide?" proposes a series of policy options to promote the use of CO_2 captured from flue gases for the production of methanol and use in transport, discussing

1. The level of priority awarded in transport policy to environmental considerations – first of all CO_2 abatement - and to security of supply concerns.
2. The uncertainty of future technology development in the transport sector and the need to avoid stranded investments in the medium and long-term.
3. The need for bringing down the costs of captured CO_2 and stimulating its potential uses, among them methanol production.
4. Improving the competitiveness of methanol fuel cells while respecting the free market rules.
5. Considering the need for diverse solutions for different types of transport fleets and the high likelihood of competition for fuels between all transport sectors.

The conclusions in the form of policy options suggest possible answers on how to overcome the technological and economic difficulties presently associated to CO_2 capture and conversion processes, as well as the opportunities which may arise from greater fuel variety in transport, among them methanol, and from putting recycled CO_2 to use by turning it into a potentially valuable prime material.

The report also adds relevant context variables, such as the Chinese and US CO_2 capture and fuel policies, as well as long-term outlooks from two scenario exercises on private road transport in Europe. While policy signals in China and the US with regard to methanol use are ambiguous, the idea of creating a new and powerful industry based on carbon capture, use and storage has found its way into Chinese policy documents. The revised, but not yet approved, flexible fuel standard in the US holds promise for the diversification of the transport fuel mix and new powertrain technologies, which, applied to Europe, could theoretically raise methanol use in private gasoline cars to 41.8 - 71.1 million tons of methanol and lead to the recycling of 68.7 to 104.3 million tons of CO_2, considering the restraints laid out in the reference scenario from DG Move and a more ambitious scenario study from McKinsey.

However, long-term trends in energy consumption for transport in Europe show that the potential for CO_2 abatement and the need for greater fuel flexibility are also extremely relevant for diesel road transport and aviation, and, in terms of enhanced security of supply, for the European economy and society at large. Methanol blends, hydrogen, biofuels, electric and hybrid cars, along with different powertrain technologies could find their place into the most suitable markets as the total cost of ownerships tends to converge over time, but both policy-makers and consumers should be able to make their choices based on exhaustive and comparative well-to-wheel analysis of different fuels and technologies, which are hard to conduct with the data presently available.

Finally, R&D efforts could be combined with smart production concepts, increased user awareness and market stimulation measures to limit the cost of transitioning to a more flexible and less petroleum-dependent transport sector, and to avoid the negative impacts of increasing fuel prices on competitiveness and cohesion in Europe.

1 OBJECTIVE OF THE STUDY

This study discusses the possibilities of closing the carbon cycle by producing methanol from carbon dioxide for use as substitute fuel in the European transport sector. As shown in Figure 1.1 (Olag et al 2009), there are several critical factors associated to the production of methanol from CO_2, which need clarification. These questions refer to:

- The long-term availability of CO_2 as a prime material for producing large quantities of transport fuel
- The efficiency and environmental implications of the different technologies available for carbon capture from power plants and industrial flue gases
- The energy balance of the conversion processes needed for turning CO_2 into fuel, since, presently, electricity has to be added, ideally from CO_2-free sources, in order to produce the hydrogen necessary for methanol production.
- The costs (including the adaptation of engines and infrastructure) and emissions related to fuelling different types of powertrains (ICE, hybrid or fuel cells) with methanol

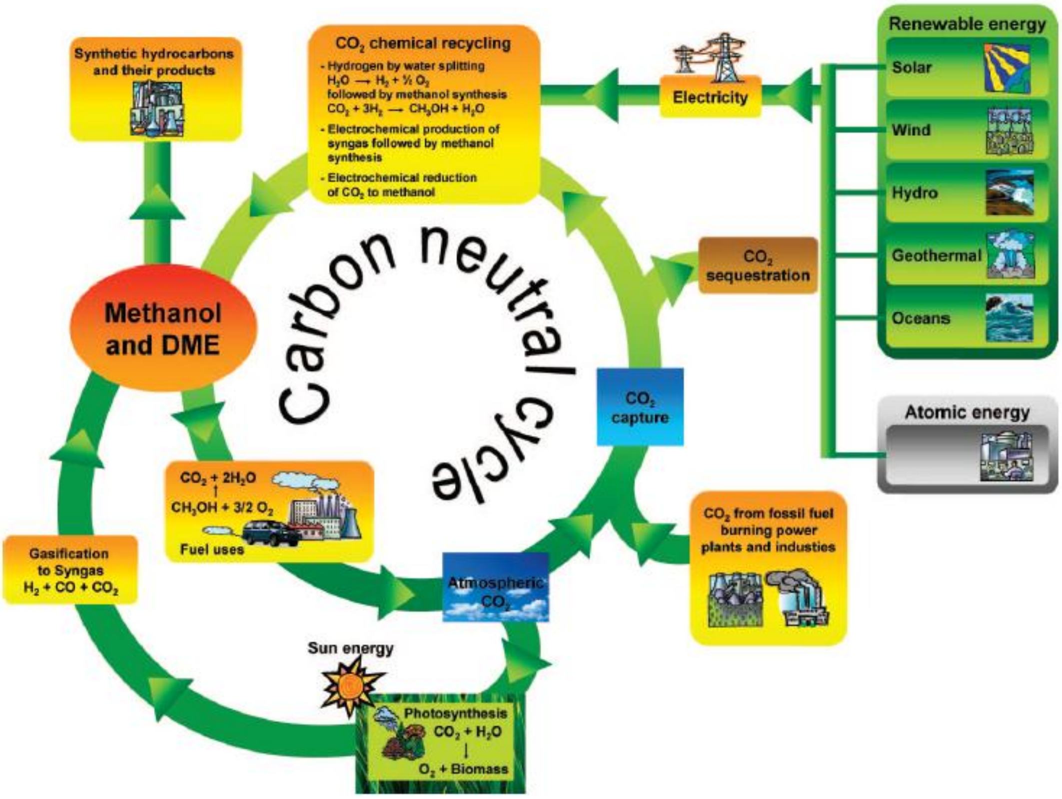

Figure 1.1 - Carbon dioxide recycling in the methanol economy

Source: Olah et *al* 2009

These basic questions were mainly addressed in the first report[1], while the second interim report[2]presented expert comments and recommendations, as well as a more detailed analysis of the costs, direct and indirect environmental impacts and the energy requirements of the different processes for carbon capture, methanol production and its use in road transport.

This final report looks into longer-term strategies and policy options promoting – or not – an increased production of methanol from CO_2 and its future use in transport. It first discusses the policy context and developments in two of the major world markets – the US and China and then draws on input from long-term scenarios for transport technologies in Europe. Conclusions in the form of policy options are presented in chapter 4.

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[1] State of the art of methanol production, distribution and use (May 2013).

[2] Economic and environmental sustainability of the different routes for methanol production and use (December 2013)

2 POLICY CONTEXT AND OBJECTIVES (EU AND REFERENCE COUNTRIES: US AND CHINA)

Since climate change concerns are shared worldwide and the automotive industry is operating on a global level, European policies should be aware of the strategic objectives pursued by the main players in the other regions of the world, with regard to both CO_2 capture and methanol use in transport. China and the US have been selected for this context analysis, since China is by now the largest producer of methanol, while the strongest defenders of the "methanol economy" are based in the US. However, as pointed out in the first report and confirmed by the policy analysis below, neither country has defined objectives for methanol production from CO_2, nor seems to be interested in supporting - at short or medium term - a viable policy for promoting non fossil fuels (i.e. biofuels and methanol) in the transport sector. China has called off central state support for methanol production from coal due to its growing concern on the environmental impact of this industry, while, in the US, researchers - and not car manufacturers - suggest using cheap supplies of shale gas for liquid fuel production.

2.1 *Carbon capture policy in China*

CCUS (carbon capture, utilization and storage) is part of the Chinese 12th Five-Year Work Plan on Controlling GHG Emissions, which promotes pilot projects in the entire country with the objective of building a "large–scale CCUS industry", although the Chinese government recognizes that "the cost and energy penalty [of CCUS] remain high" and that "the long-term safety and reliability need to be proved"[3]. Gu (2013) confirms that China has not yet developed a regulatory framework for CCUS, while devoting efforts to research, both on pre- and on post-combustion, as well as demonstration projects. The author reports 11 large-scale demonstration projects, half of which use Chinese technology. The research policy is guided by a CCUS roadmap elaborated in 2011 and incentives for CCUS, which are mentioned in the governmental *Notice of National Development and Reform Commission (NDRC) on Promoting Carbon Capture, Utilisation and Storage Pilot and Demonstration,* could eventually be funded by China's emerging carbon emission trading scheme, which is, however, still in the pilot stage.

The use of captured CO_2 for methanol production is not specifically mentioned in the official government notice published in 2013. However, it should be noted that China is the country holding the highest number of patents for CO_2 conversion to methanol issued between 2008 and 2013, as documented in the initial report. China is also exploring other ways of obtaining value from CO_2. For example, a detailed feasibility analysis has been carried out for CO_2 capture by algae at a planned waste incineration power plant on the Zhoushan islands, pointing to the strong future market potential of this technology (Sen 2012).

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[3] An English translation of the NOTICE OF NATIONAL DEVELOPMENT AND REFORM COMMISSION (NDRC) ON PROMOTING CARBON CAPTURE, UTILISATION AND STORAGE PILOT AND DEMONSTRATION, provided by the Global CC Institute has been used http://cdn.globalccsinstitute.com/sites/default/files/publications/102106/notice-national-development-reform-commission-ndrc.pdf

2.2 *Fuel policy in China*[4]

As outlined in the beginning of this chapter, China is by now the world largest producer of methanol. In this country methanol has actually received strong national support from the 1980s until 2008. The central government supported the early research and development of methanol fuel and automobiles and set up pilot projects to test their use. National ministries and universities cooperated with foreign partners, facilitating technology transfer and domestic production. Also, the government, with the help of the oil majors, contrary to the European and US policies, created standards for, and allowed, the sale of high level blend M85 and M100 methanol fuels. However, since 2008, this support has ceased. Subsidies to R&D pilot projects for vehicle conversion and incentives such as road toll exemptions were discontinued or passed on to provincial governments. The China Petrochemical Corporation, Sinopec, which regularly sold M15 blends during the 80ies and 90ies, up to the beginning of the years 2000, withdrew from the market in 2010 and, in the same year, methanol was excluded from the development plans of the Ministry of Industry (Kostka et al., 2011). According to the study carried out by Kostka, given the relative level of maturity reached by the methanol industry in China, these actions cannot be interpreted as a natural pulling out of the state from the support regime,. The withdrawal has been rapid and unexpected, thus revealing a sudden shift in policy focus.

The study actually argues that the national government's benefits in promoting methanol fuel, namely energy security and the possibility to reduce local emissions, were no longer balanced by other strategic considerations like the national preferences for long-term low carbon energy development plans and carbon emission reductions. Actually, the central government's withdrawal from the methanol fuel market coincided with the increased promotion of electric cars and other long-term, non-fossil fuel options, in line with the central government's commitment to ambitious carbon abatement policy 2020, which aims to reduce carbon intensity by 40-45 percent based on 2005 levels. It might also have played a role in the abandonment of policy support from central government that "the expansion of coal-based methanol could exacerbate water shortage in coal-rich but arid regions, increase greenhouse gas emissions, jeopardize consumer safety, and add possible volatility to coal prices in China and worldwide" (Yang et al 2011). It is a fact that unpublicized and illegal blending of gasoline with methanol is common in China, but the lower mileage of these blends and the lack of labelling amounts to actually cheating customers (Wang 2010).

In addition to the reference to this environmental strategy, the study also adds that the withdrawal is also the result of mismanagement and emerging policy gap during bureaucratic restructuring[5], and the opposition of state oil majors, due to low-level blend methanol's potential to lower gasoline profitability and market share.

It is nonetheless important to note that, despite the central government withdrawal, several provincial governments, as for example the Shanxi and Guizhou Provinces, have continued to support methanol fuel. In contrast with the national policy, provincial authorities took aggressive steps to promote methanol, recurring to unorthodox bureaucratic methods.. The provincial governments created and supported methanol promotion offices, developed their own provincial standards, planned the

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[4] The data and information provided in this paragraph are based on the study of the Frankfurt School. See Kostka et al 2011 in the references.

[5] According to the cited authors: "…Throughout the 2000s, frequent reforms of China's energy bureaucracy resulted in bureaucratic turmoil and conflict of competencies at the national level. Agencies in charge of methanol were not clearly appointed or lacked the authority, autonomy, and tools to govern the energy and fuel markets. As a result of the ongoing bureaucratic restructuring, a significant methanol policy gap emerged that deprived the methanol fuel market of central government management and coordination."

methanol engine conversion pilots, and formed closed alliances with local companies, negotiating pilot expansions and distribution.

The factors that led the provincial governments to this divergent policy with respect the central government are mainly two: a short-term and localized view of energy development, prioritizing economic benefits for local coal and fertilizer enterprises, as well as local, visible pollution reduction benefits from the use of methanol (i.e. reduction of smog), which was especially important to these provinces, in which the level of air pollution, especially at urban level, is very high.

It is not clear how long this divergent view on the energy and environmental policies might last (and it is beyond the remit of this study to analyse this complex situation in depth), but the lesson learned from the Chinese case is that despite the considerable resources invested to develop a methanol economy (certified by the strong resistance of some provinces to abandon it), China does no longer lay a bet on this fuel. Apparently the environmental issues linked to the greenhouse gases emissions prevail over energy security reasons and the development of local economies. In this framework, it may also be argued that, when (and if) CO_2 becomes a competitive feedstock for methanol production, the Chinese central state might reconsider its current position.

2.3 *Carbon capture policy in the United States*

The US has set clear and quantified research objectives for carbon capture at new power plants in its Clean Coal Research Program. The cost penalty for electricity production in plants equipped with capture technologies is to be brought down from roughly 70% nowadays to 35% (equivalent to about $40 or €30 per tonne of CO_2 captured). Research currently investigates possible improvements to post-combustion, pre-combustion and oxyfuel technologies (Smith 2013). Yet, when it comes to obtaining added value from the captured CO_2, the US government puts special emphasis on injection for enhanced oil recovery, as market prospects for other uses are considered to be limited. This policy focus on sequestration has been criticized recently by Nobel laureate Olah for wasting a prime material that could easily become a competitor for other alternative fuels, if "anticompetitive laws" favouring ethanol were phased out. Olah argues that recent technology advances, for example a CO_2 absorbing polymer material developed by his research team[6], now allow for producing methanol at a lower price than gasoline[7].

2.4 *Fuel policy in the United States*[8]

As described in the first report of this study, during the 80ies and 90ies of the past century, the car manufacturers and some chemical companies in the US showed strong interest for the development of a methanol economy. This notwithstanding, the Congress never fully supported the development of methanol and, at the end of the past century, car manufacturers also changed their minds and abandoned the pilot projects carried out until the 90ies. The present Congress fuel policy is well reflected in the Environmental Protection Agency (EPA), provisions, as briefly described in the following box 1.

As described in the box, the numerous iterations of the EPA provisions over time reflect an objective uncertainty concerning the optimal/maximum permissible level of oxygenation. In addition to this

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[6] http://inhabitat.com/nobel-laureate-develops-worlds-cheapest-and-most-effective-co2-sponge/

[7] http://online.wsj.com/news/articles/SB10001424127887324577304579057623877297840

[8] Paragraph based on the Methanol Institute paper: Use of Methanol as a Transportation Fuel, see references: Bechtold 2007

automakers and oil companies manifested a continuous opposition to the increase of oxygenates percentages in gasoline blends and this commercial policy became apparent when the Clean Air Act Amendments of 1990 (see box 1) envisaged that there would be a move towards vehicles designed to run on methanol, either neat or as M85, to meet various special programs for Flexible Fuel Vehicles (FFVs), including the Clean Fuel Fleet (CFF) Program and the California Pilot Test Program. Actually these stakeholders showed that they could meet the emission standards with the Reformulated Gasoline Program and argued that the FFV programs were not a cost-effective way to reduce pollutants, thus leading EPA into cancelling the FFVs option from the Clean Fuel Fleet program. Frustrated with the lack of progress in use of FFVs, Congress enacted limited fleet FFV acquisition requirements in the Energy Policy Act of 1992 (EPAct 92), which also contemplated methanol vehicle use.

At the beginning of the first decade of 2000, traces of MTBE were detected in groundwater in various locations of US. This fact raised concerns that led a number of states to ban the production of MTBE, and its use fell off sharply, being substituted by ethanol blends. The result is that, from 2006, MTBE has virtually disappeared from U.S. gasoline supply.

With the elimination of MTBE, the only significant use of methanol in U.S. fuel supply is in the production of methyl ester biodiesel, which however only represents a niche market that does not compensate for the loss of MTBE as a source of methanol demand.

Box 1: The regulatory framework in the US: a history of intense lobbying and many iterations

In the US, the Clean Air Act amendments of 1977 included the creation of section 211(f), which prohibits the commercial introduction of "*any fuel or fuel additive that is not substantially similar to fuels used in vehicle certification*". EPA is authorized to issue a waiver of prohibition (permit) if a party demonstrates that the fuel/additive will not cause or contribute to the failure of any emissions control device or system.

Accordingly, in 1979, EPA issued waivers allowing the blends in gasoline of methanol, ethanol and alcohol solvents (tertiary butyl alcohol, TBA, and methyl tertiary butyl ether, MTBE[1]) up to approximately 2% oxygen by weight in the fuel blends. It is worth noting that MTBE is a compound produced through a chemical process based on methanol so its blend in gasoline increased the production and sales of this alcohol in USA.

Subsequently, in July 1981, EPA issued a revised *Interpretive Rule* further defining what should be understood by "similar to fuels used in vehicle certification". This rule fixed a maximum of about 2% oxygen by weight in the fuel blend, corresponding to a maximum of 2.75% of methanol with an equal volume of TBA or MTBE, as previously prescribed.

While elaborating the rule, EPA was asked to increase the oxygen limit to 3.7%, equivalent to that already granted to some companies[1], but EPA declined to do so based on observed NO_x increases, keeping the oxygen limit for the oxygenated fuels at 2%. Notwithstanding this limit, EPA granted again some waivers to petitioners allowing up to 4.75% methanol and co-solvent combinations, which contain approximately 3.5 - 3.7% of oxygen. This oxygen level became the *de facto* limit thereafter.

In 1990 the Clean Air Act Amendments implemented a federal Reformulated Gasoline (RFG) program that envisaged the introduction of ethanol blends up to 10% (as in the EU Directive 2009/30). This would provide approximately 4% of oxygen by weight, slightly higher than the EPA threshold of 3.7%. EPA then confirmed that the use of 10% ethanol would be allowed in RFGs, even if the oxygen content was slightly above 3.7%.

It is interesting to note that, three years before the issuing of the Clean Air Act Amendments, EPA was asked by AM Laboratories, Inc. to grant a waiver for use of up to 5% methanol with 5% ethanol, for an oxygen contribution of 4.4%. The application attached a report of a major Canadian test program that included such 5%/5% blends and in which the driveability demerits were argued not to be excessive. The automakers fiercely opposed the application, arguing that other existing data clearly showed that an oxygen level above 3.7% would degrade the driveability to unacceptable levels. For the first time, opposition was not limited to U.S. automakers but included opposing submissions from Japanese companies such as Toyota. The waiver was then eventually denied by EPA.

Despite the rather fierce opposition of the car manufacturers and the oil companies to a change of the current status quo, there is still a large part of the public opinion, supported by congressmen and environmentalist associations, that advocates the development of a more sustainable and environmental friendly legislation. In this framework, a bill was introduced in the U.S. Congress in 2009 aiming to overcome the impasse of the current limit for oxygenates by introducing in the U.S. market flexible vehicles able to be fed by gasoline, methanol and ethanol. This bill, named the Open

Fuel Standard Act, has recently been updated (H.R. 2493 of June 2013) and would[9] make it mandatory that the fleet offered by each car manufacturer is comprised of

''(1) not less than 30 percent qualified vehicles beginning in model year 2016; and

(2) not less than 50 percent qualified vehicles beginning in model year 2017 and each subsequent year.

Qualified vehicles include the full array of existing technologies – including in particular ethanol, methanol and biodiesel -, and also plug-in electric and FCV vehicles. According to the promoters, "this requirement would provide certainty to investors encouraging the production of alternative fuels and fuelling stations supplying those alternative fuels[10]".

2.5 Fuel Policy in the EU

Contrarily to what happened in USA and in China, there has not been any real interest for developing a methanol economy In Europe, due to its scarce fossil energy resources and its stringent environmental policies. And, although there is a strong commitment towards the development of biofuels, at least for what concerns the ethanol and bio-methanol blends with gasoline, the current standards on fuel quality still hinder a major penetration of these fuels in the market.

As described in the second interim report, low-percentage methanol-gasoline blends can be effectively used in conventional spark-ignition engines with minor technical changes, while the use of alcohol fuels in heavy duty applications is being researched by motor manufacturers. Actually the current standard EN 228 on transportation fuel quality states that the oxygen content limit of the fuels blends with oxygenates is 2.7%[11]. This corresponds to a theoretical ethanol limit of 7.8%[4], - although the actual the limit was set at 5% - and to a methanol limit of 3%, with an additional requirement for "stabilizing agents" (co-solvents).

At EU level, this limit was initially fixed in 1998 (Directive 98/70/EC) that authorized alcohol blending in gasoline. On April 2009 the EC issued the Fuel Quality Directive (Directive 2009/30/EC) that amended the old 98 Directive and allowed to increase the biofuel content of the transportation fuels in order to reduce the greenhouse gas emissions from road transport. To this end, the Directive enabled a more widespread use of ethanol in petrol, with a gradual increase up to a blend of 10% of Ethanol (E10). To avoid potential damage to old cars, the Directive allowed a continued marketing of petrol containing a maximum of 5% of ethanol until 2013, with the possibility of an extension after this date, if needed. Although the directive recognized the potential of bio-methanol as a renewable energy source, the maximum allowed limit for this alcohol still remained at 3%. In order to increase this limit (as well as that of ethanol), and similarly to what is advocated in the USA, there seems to be a need to oblige the automotive industry to increase the production of Flexible Fuel Vehicles that can run indifferently on gasoline, ethanol or methanol fuels.

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[9] The bill is still being discussed in the Energy Committee

[10] Congressman Eliot Engel and congresswoman Ileana Ros-Lehtinen introducing the act to the Congress http://www.openfuelstandard.org/2013/06/the-open-fuel-standard-has-been.html, Accessed 07/2/2014

[11] The oxygen percentage is expressed in weight while the fuel blends are expressed in volume

3 LONG TERM PROSPECTS FOR AUTOMOTIVE FUELS AND TECHNOLOGIES

In the second interim report it was stated that transition strategies for the transport sector can be envisioned, in which methanol, in combination with fuel cell technologies, can make a major contribution. Fuel cell electric vehicles (FCVs) represent a strong potential for a decisive reduction of the greenhouse gas emissions from road transport but that these technologies are still far from being technologically reliable and economically competitive. Methanol-based FCEVs are less technologically mature than those fuelled by hydrogen, and they are notably more pollutant and more expensive . They can however represent a good compromise between security of supply and environmental concerns, bypassing, at the same time, the economic barriers and the safety concerns related to hydrogen distribution and dispensing.

In this framework, the use of blends of bio-methanol (and, in the future, of methanol produced by CO_2) with gasoline, along with the development of Flexible Fuel Vehicles, could represent an immediate and viable option that can also favour the transition towards methanol based FCVs.

Before analysing possible future developments, it is important to lay out a coherent overview of the advantages and the disadvantages of the different technology options presently available for road transport. These are summarized and qualitatively assessed in table 3.1. overleaf, using a set of criteria that are relevant for political decision-making.

Table 3.1 – Qualitative evaluation of fuels and powertrain technologies

Fuel and powertrain technology	Long-term security of supply	Production and powertrain costs	Cost of handling, storage and transport	Infrastructure investment	Energy (conversion) efficiency well-to-wheel	General safety issues (toxicity, inflammability,…)	Environmental impacts and CO$_2$ abatement	Vehicles performances (acceleration, mileage…)
Gasoline with ICE	🔴	🟢	🟢	🟢	🟡	🔴	🔴	🟢
Conventional diesel ICE	🔴	🟢	🟢	🟢	🟡	🟡	🔴	🟢
Biodiesel (from biomass) ICE	🟡	🟡	🟢	🟢	🟡	🟡	🟡	🟢
DME ICE[ii]	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟢
Direct hydrogen FCVs[ii]	🟡	🟡	🔴	🔴	🟢	🔴	🟢	🟡
CO2 capture and on board methanol reformer- FCVs	🟢	🔴	🟢	🟡	🟡	🟢	🟡	🟡
Hybrid vehicles	🟡	🟡	🟢	🟢	🟡	🟡	🟡	🟢
Electric vehicles	🟢	🔴	🔴	🟡	🟢	🟢	🟢	🔴

🟢 Clearly positive impact 🟡 Impact unclear or ambiguous 🔴 Clearly negative

The evaluation is based on the following assumption

i. It is assumed that electricity is obtained from CO$_2$-free and renewable sources

ii. In the medium-long term hydrogen is produced by a mix of natural gas, coal (with CO$_2$ sequestration) and electricity from renewables.

iii. DME is produced by black liquor (a cellulosic feedstock) and its well-to-wheel CO$_2$ emissions are comparable with biodiesel produced by biomass.

The conclusions of the second interim report stressed that "Europe is committed to bringing down CO_2 emissions from transport and is facing serious challenges to security of supply due to its dependence on fossil fuels. All this obliges to prepare for a transition process, in which methanol, first from renewable sources and, later on, from carbon dioxide capture, could play a relevant role, in combination with other alternative fuels". In the first interim report we also argued that, taking into account both the security of supply and the environmental challenges, "…methanol could become the reference fuel for the fuel cell electric vehicles (FCEV) if the hydrogen supply system (including the safety issues) turns out to be less competitive than methanol production and use."

In the following paragraphs, these considerations are contrasted with two reference scenarios, which analyse expected trends of road transport in 2050. It appears that the methanol option is hardly taken into account in the currently available (and most authoritative) papers dealing with future transport scenarios for Europe. For this reason, the project team has added own assumptions on the possible market penetration of this fuel, using the two alternative scenarios as reference, in order to highlight what may happen in terms of emissions, costs and required feedstock in case of a switch to a major use of methanol in transport. (see paragraph 3.3).

3.1 *Comparison and discussion on long-term scenarios for transport technologies*

3.1.1 The Reference Scenario

The final report of the TranScenario project (TETRAPLAN 2013), carried out for DG MOVE, provides a long-term quantitative outlook of the EU transport system on the basis of current trends and policies.

This reference outlook is built on a series of assumptions concerning

- The main macroeconomic and demographic drivers (annual average GDP growth and annual average population growth in EU Member States) as well the international fuel price trends:

Table 3.2 – Projections on international fuel prices

	2000	2010	2011	2020	2030	2040	2050
	($2010/boe)						
Oil	36.2	79.5	109.5	114.9	120.8	133.1	142.9
Gas	25.3	50.2	67.2	79.8	83.7	84.0	81.7
Coal	10.0	21.2	28.0	29.3	31.1	35.0	40.4

Source: TETRAPLAN 2013

- Policy and technology assumptions: these include national and EU policies and measures adopted up to spring 2012, the main eco-design regulations, the impact of the Energy Efficiency Directive and the effects of the legally binding targets from the Renewables Directive and the Effort Sharing Decision of 2009.

According to this scenario (EC 2013), the total passenger transport (public and private) in the EU is expected to increase by 41% by 2050 compared to 2010 levels, equivalent to an average growth of 0.9%

per year. Private road transport is expected to maintain its dominant role in passenger transport by 2050, but growing at lower pace than other transport modes (0.6% per year).

The starting point of the study is that **passenger cars** are still the main emitters of CO_2 emissions in EU transportation, being responsible for almost **45% of total emissions in the transport sector in 2010**.

Figure 3.1shows the effects of the different CO_2 mitigation measures (mainly the improvements in energy intensity gains and the decoupling of transport activity from GDP growth) on the total foreseen trend of CO_2 emissions. Significant reductions in CO_2 emissions from passenger cars are expected to take place between 2010 and 2020, while, after 2020, CO_2 emissions decrease at significantly lower rates.

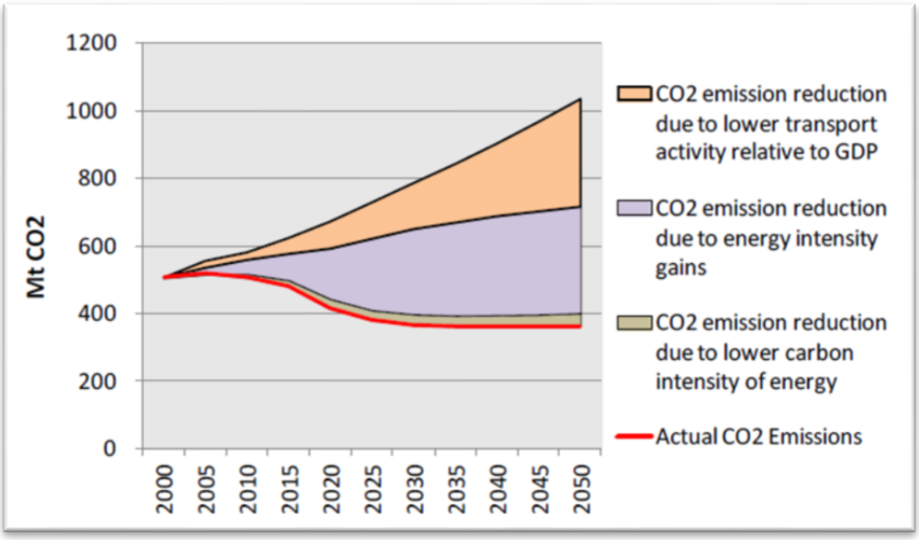


Figure 3.1 - CO_2 emissions from passenger cars

Source: TETRAPLAN 2013

Figure 3.2 shows the trend up to 2050 of a portfolio of powertrain technologies through which it will be possible to achieve the targets for CO_2 reduction highlighted in Figure 3.2.

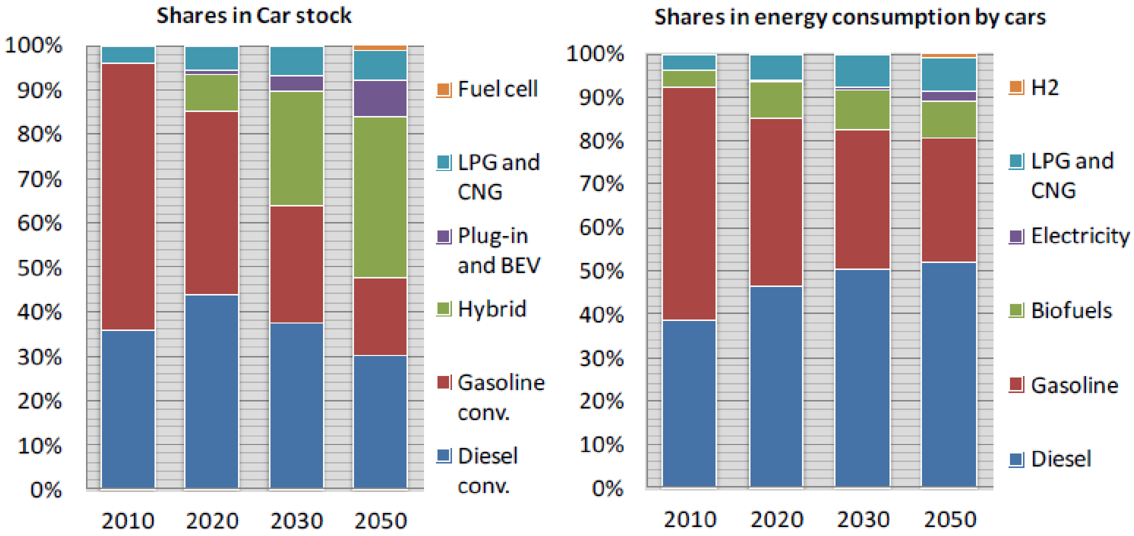


Figure 3.2 - Structure of car stock and associated energy consumption 2010 – 2050

Source: TETRAPLAN 2013

The reference scenario foresees that the powertrain portfolio is mainly composed by small diesel cars and more efficient gasoline cars featuring technological innovations such as full hybridization systems and other auxiliary units aiming to reduce specific fuel consumption and emissions.

Gasoline and diesel hybrid cars gain a notable share (about 8% of total passenger car stock in 2020) given their competitive performance in terms of specific consumption and emissions on the NEDC (New European Driving Cycle) and the assumed reduction in additional capital costs.

The electric vehicles stock share starts to be meaningful after 2030 as a result of national policies and incentive schemes aiming to boost their penetration in the market.

Plug-in hybrids (PHEVs) hold the largest share given their ability to run alternatively on both engine types (internal combustion engine or electric motor). High capital costs as well as limited recharging infrastructure development and low autonomy are among the main reasons for low consumers' acceptance.

Passenger cars running on LPG (liquified petroleum gases) and CNG (compressed natural gas) see a moderate increase, especially stemming from countries where refuelling infrastructure is already in place. In Member States, in which such infrastructure does not exist currently, the uptake of CNG and LPG vehicles on a commercial basis is limited.

The reference scenario is therefore quite conservative, entrusting the CO_2 reduction mainly to improvement of the environmental performance of ICE engines and to the introduction in the market of hybrid vehicles. Electric vehicles play a marginal role and the impact of fuel cells is absolutely negligible.

3.1.2 A more ambitious scenario

According to the study conducted by McKinsey in 2010, with the participation of the main car manufacturers, oil and gas companies and utilities, conventional vehicles alone may not achieve EU CO_2 reduction goal for 2050.

The fuel efficiency of traditional combustion engines is expected to improve by 30%, but quite obviously full decarbonisation is not possible through efficiency alone.

There is also uncertainty as to whether large amounts of (sustainably produced) biofuels will be available for passenger cars, given the potential demand for biofuels from other sectors, such as goods transport, aviation, marine, electricity producers and heavy industry.

The study makes the following assumptions:

- by 2020 biofuels are blended, delivering a 6% well-to-wheel reduction in CO_2 emissions for gasoline and diesel vehicles, in line with the EU Fuel Quality Directive;
- by 2050, biofuel blending increases but is limited to 24%, reflecting supply constraints.

Decarbonisation must therefore be entrusted to electric vehicles, which not only have zero tail-pipe emissions (significantly improving local air quality), but may eventually become part of an almost CO_2-free cycle over time and on a well-to-wheel basis, depending on the primary energy source used.

In addition, taking into account the recent technological breakthroughs in fuel cell and electric systems (which have now increased their efficiency and cost-competitiveness), the authors of the scenario considered it important to re-assess the role of FCEVs and they therefore developed a *balanced scenario* for the electrification of passenger cars in EU by 2050.

A combined forecasting and back-casting approach was then used to calculate the results:

- from 2010 to 2020, global cost and performance data were forecasted, based on proprietary industry data;
- after 2020, on projected learning rates.

In order to test the sensitivity of these data to a broad range of market outcomes, three European "worlds" for 2050 were defined, assuming various levels of penetrations of powertrain technologies in 2050:

a) A world skewed towards **ICE** (*5% FCEVs*, 10% BEVs, 25% PHEVs, 60% ICEs)

b) A world skewed towards **electric power-trains** (*25% FCEVs*, 35% BEVs, 35% PHEVs, 5% ICEs)

c) A world skewed towards **FCEVs** (*50% FCEVs*, 25% BEVs, 20% PHEVs, 5% ICEs).

These three "worlds" were then back-casted to 2010, resulting in a development pathway for each power-train technology. In this report, the second "world" has been taken as a reference, since it is more ambitious of the first one and more realistic than the third "world".

It is worth highlighting here that there are the three key crucial statements that make the accomplishment of the scenario described in "world 2" realistic and, with strong policy action, also the third and more ambitious scenario.

1. After 2025, the total cost of ownership (TCO) of all the power-trains converges
2. A diversified portfolio of power-trains allows to meet the needs of consumers and along with environmental sustainability requirements
3. Investment costs of a hydrogen infrastructure are approximately 5% of the overall cost of FCEVs (€1,000-2,000 per car)

These three conditions play a major role in the present study. In fact, the possibility that methanol might become a reference fuel for the future road transport technology depends on the actual materialization of these hypotheses (especially the first and the third one). Indeed, the fact that the FCEVs' TCO is expected to converge with that of the ICEs increases the chances that methanol-based FCEVs might have some chance of success (although, in this case, additional R&D efforts are required). On the contrary the fact that the costs for building a hydrogen infrastructure are expected to be as low as 5% of the overall cost of FCEVs, might hinder or at least greatly reduce the chances of development of a methanol economy. it must be added that cost is not the only variable to be considered when discussing the development of a hydrogen infrastructure, as safety issues and consumers' acceptance also play a major role.

The consequences of the three assumptions are further discussed in the following subchapter and comments are provided in the next paragraph on how the TCOs of the powertrains considered in the McKinsey report have been evaluated.

3.1.2.1 After 2025, the total cost of ownership (TCO) of all the power-trains converges

The McKinsey report compares the different powertrain technologies by calculating the total cost of ownership (TCO) for each of these technologies. In addition to the TCO, which captures all costs along the entire lifetime, individual customer criteria are then applied. Consumers buy cars for a wide variety of reasons, including purchase price, new vs. second-hand, depreciation rate, styling, performance and handling, brand preference and social image. The cost of driving the same vehicle when new is also greater than that for the next owner. All these aspects are included in the analysis carried in the McKinsey study.

Specifically, TCO includes:

- Purchase price: the sum of all costs to deliver the assembled vehicle to the customer for a specific power-train and segment
- Running costs:
    - Maintenance costs in parts and servicing specific to each vehicle type and power-train combination
    - Fuel costs based on the vehicle fuel economy and mileage, including all costs to deliver the fuel at the pump/charge point and capital repayment charges on investments made for fuel production, distribution and retail; or for BEVs/PHEVs, for charging infrastructure

Depreciation of money has not been taken into account. All taxes on vehicles and fuel (including VAT) are set to zero to ensure that comparisons reflect the true costs of driving and are revenue-neutral to governments.

TCO equation

TCO = Purchase price + Running cost

Purchase price = Parts cost + Assembly cost + SG&A + Margin

Running cost = Maintenance cost + Fuel cost (incl. infrastructure & fuel costs)

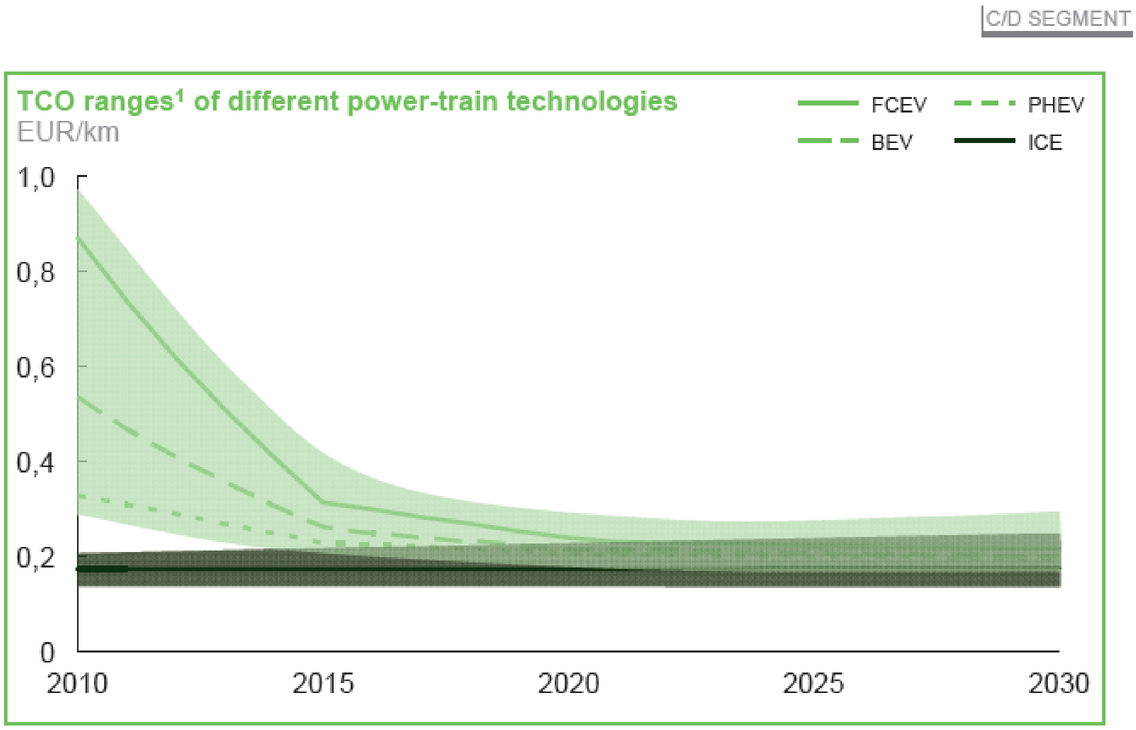
Legend: "SG&A"= Selling, General and Administrative Expenses;
TCO based on 15 years lifetime and 12,000 km annual driving distance

Figure 3.3 -Scheme of the variables used in the TCO calculation

Source: Mc Kinsey et al 2010

The TCO analysis is based on the following hypothesis, which were derived from foresight exercises of the car manufacturers:

- The cost of fuel cell systems is expected to decrease by 90% and component costs for BEVs by 80% **by 2020**, due to economies of scale and incremental improvements in technology.
- Around 30% of technology improvements in BEVs and PHEVs also apply to FCEVs and vice versa. This assumes that FCEVs and BEVs will be mass-produced, with infrastructure as a key prerequisite to be in place.
- The cost of hydrogen also falls by 70% by 2025 due to higher utilisation of the refuelling infrastructure and economies of scale. PHEVs are more economically convenient than BEVs and FCEVs in the short term. The gap gradually closes and by 2030 the TCO of the different powertrains tends to converge (Figure 3.4)



1 Ranges based on data variance and sensitivities (fossil fuel prices varied by +/- 50%; learning rates varied by +/- 50%)

SOURCE: Study analysis

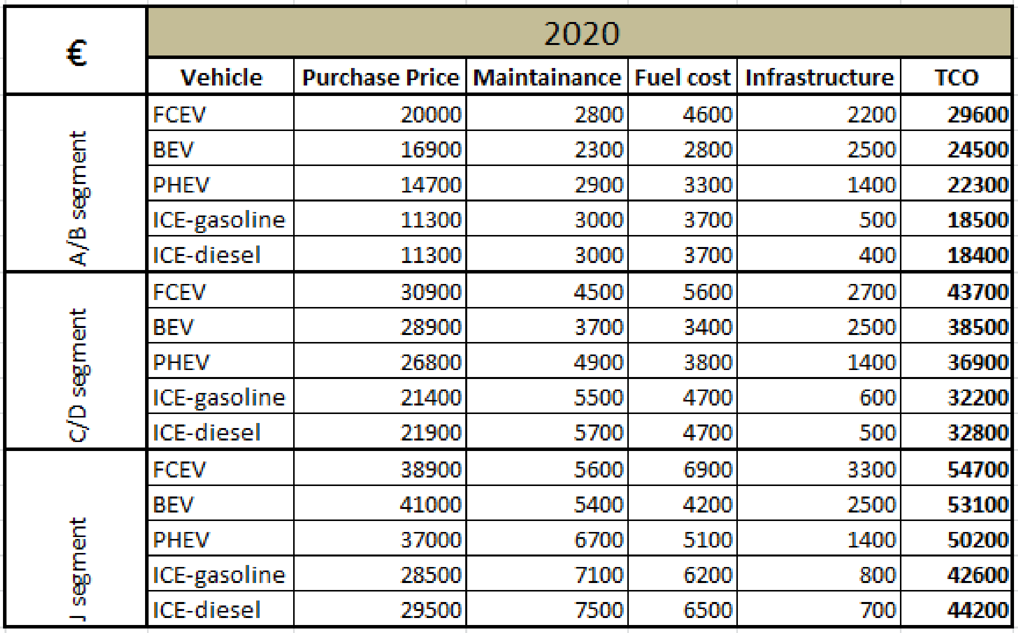
CD Segment = Medium and Large cars

Figure 3.4 - By 2030, BEVs, FCEVs, PHEVs are all cost-competitive with ICEs in relevant market segments

Source: McKinsey et al 2010

The three tables below provide the data used to plot the graph in Figure 3.4 for the years 2020, 2030 and 2050. As can been seen, the TCOs of all four power-train technologies is expected to converge after 2025 , or earlier, with tax exemptions and/or incentives during the ramp-up phase.

Table 3.3 – Total Cost of Ownership 2020



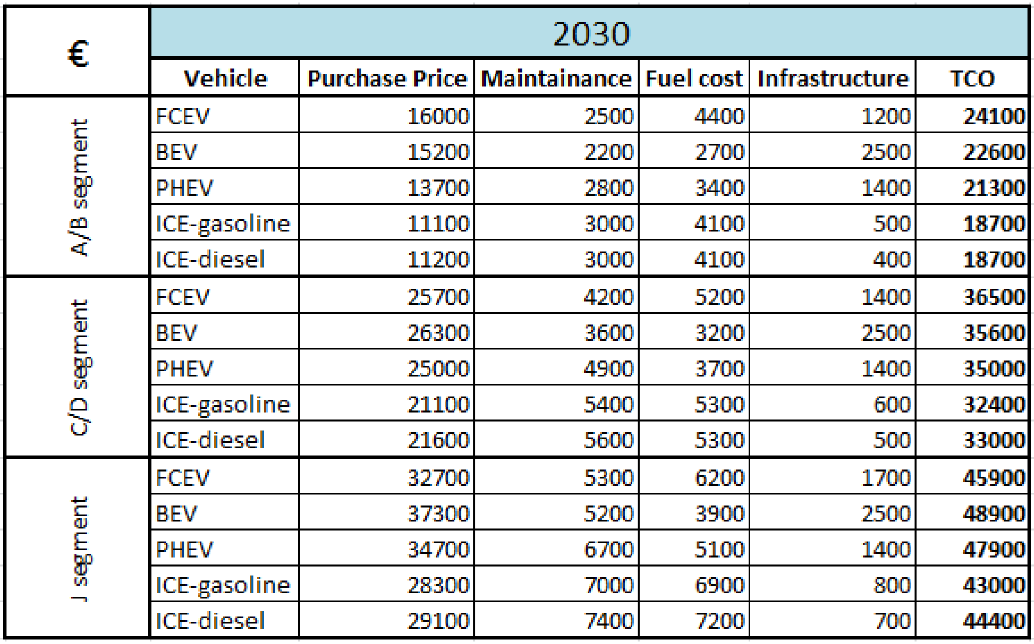
€	2020					
	Vehicle	**Purchase Price**	**Maintainance**	**Fuel cost**	**Infrastructure**	**TCO**
A/B segment	FCEV	20000	2800	4600	2200	**29600**
	BEV	16900	2300	2800	2500	**24500**
	PHEV	14700	2900	3300	1400	**22300**
	ICE-gasoline	11300	3000	3700	500	**18500**
	ICE-diesel	11300	3000	3700	400	**18400**
C/D segment	FCEV	30900	4500	5600	2700	**43700**
	BEV	28900	3700	3400	2500	**38500**
	PHEV	26800	4900	3800	1400	**36900**
	ICE-gasoline	21400	5500	4700	600	**32200**
	ICE-diesel	21900	5700	4700	500	**32800**
J segment	FCEV	38900	5600	6900	3300	**54700**
	BEV	41000	5400	4200	2500	**53100**
	PHEV	37000	6700	5100	1400	**50200**
	ICE-gasoline	28500	7100	6200	800	**42600**
	ICE-diesel	29500	7500	6500	700	**44200**

Legend: "A/B segment"= Mini and Small cars, "C/D segment"= Medium and Large cars, "J segment"= Larger car

Source: McKinsey et al 2010

By 2020 (Table 3.3) the purchase price of electric vehicles is still several thousand euros more than that of ICEs, but reasonable public incentives on vehicle, fuel and an attractive customer value proposition could be sufficient to bridge this cost gap. The purchase price of BEVs is lower than FCEVs.

Table 3.4 - Total Cost of Ownership 2030

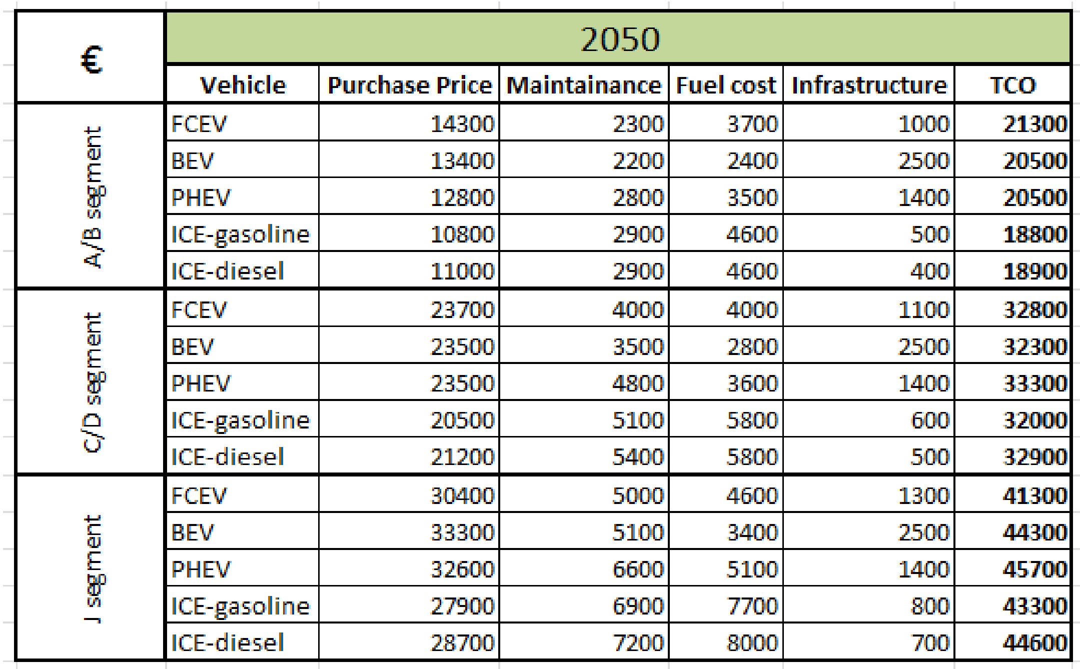


€	2030					
	Vehicle	**Purchase Price**	**Maintainance**	**Fuel cost**	**Infrastructure**	**TCO**
A/B segment	FCEV	16000	2500	4400	1200	**24100**
	BEV	15200	2200	2700	2500	**22600**
	PHEV	13700	2800	3400	1400	**21300**
	ICE-gasoline	11100	3000	4100	500	**18700**
	ICE-diesel	11200	3000	4100	400	**18700**
C/D segment	FCEV	25700	4200	5200	1400	**36500**
	BEV	26300	3600	3200	2500	**35600**
	PHEV	25000	4900	3700	1400	**35000**
	ICE-gasoline	21100	5400	5300	600	**32400**
	ICE-diesel	21600	5600	5300	500	**33000**
J segment	FCEV	32700	5300	6200	1700	**45900**
	BEV	37300	5200	3900	2500	**48900**
	PHEV	34700	6700	5100	1400	**47900**
	ICE-gasoline	28300	7000	6900	800	**43000**
	ICE-diesel	29100	7400	7200	700	**44400**

Source: McKinsey et al 2010

By 2030 (Table 3.4), the advantages of lower running costs almost outweigh the higher purchase price of electric vehicles, which start to close the gap with ICEs on both purchase price and TCO. Typically, electric vehicles (BEVs, FCEVs, PHEVs) cost 2-6 cents more per kilometre than ICEs.

Table 3.5 - Total Cost of Ownership 2050



€	2050					
	Vehicle	**Purchase Price**	**Maintainance**	**Fuel cost**	**Infrastructure**	**TCO**
A/B segment	FCEV	14300	2300	3700	1000	**21300**
	BEV	13400	2200	2400	2500	**20500**
	PHEV	12800	2800	3500	1400	**20500**
	ICE-gasoline	10800	2900	4600	500	**18800**
	ICE-diesel	11000	2900	4600	400	**18900**
C/D segment	FCEV	23700	4000	4000	1100	**32800**
	BEV	23500	3500	2800	2500	**32300**
	PHEV	23500	4800	3600	1400	**33300**
	ICE-gasoline	20500	5100	5800	600	**32000**
	ICE-diesel	21200	5400	5800	500	**32900**
J segment	FCEV	30400	5000	4600	1300	**41300**
	BEV	33300	5100	3400	2500	**44300**
	PHEV	32600	6600	5100	1400	**45700**
	ICE-gasoline	27900	6900	7700	800	**43300**
	ICE-diesel	28700	7200	8000	700	**44600**

Source: McKinsey et al 2010

By 2050 (Table 3.5), all electric vehicles are cost-competitive with ICEs, FCEVs are the lowest-cost solution for larger cars (J segment[12]).

Summarizing in brief:

- PHEVs are more economic than BEVs and FCEVs in the short term.
- All electric vehicles are viable alternatives to ICEs by 2025, with BEVs being more suited for smaller cars and shorter trips, FCEVs for medium/larger cars and longer trips.

Finally, it should be stressed that, with tax incentives, BEVs and FCEVs could be cost-competitive with ICEs as early as 2020.

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[12] J-segment is defined by European Commission as the segment of the sport utility cars (including off-road vehicles). It approximately corresponds to SUV (Sport Utility Vehicles), CUV (Crossover Utility Vehicles) and pickups segments in North America.

3.1.2.2 A varied portfolio of power-trains can meet the needs of consumers and the environment

This dimension has been discussed at length in the first interim report but, for the sake of completeness, it is worth summarising here the most relevant conclusions.

From the environmental point of view, ICE vehicles have the potential to reduce their CO_2 footprint significantly through improved energy efficiency and biofuels but after 2020, however, further engine efficiency improvements are limited and relatively costly, while the availability of biofuels may also be limited.

The main benefits of electric vehicles Vs ICE vehicles, are:

1. Electric vehicles have zero emissions while driving and they can be made close to CO_2-free, depending on the primary energy source used.
2. Electric vehicles can be fuelled by a wide variety of primary energy sources and, as the well-to-wheel efficiency analysis also shows, they are more energy-efficient than ICEs over a broader range of primary energy sources.

Within the electric technology the following pros and cons have been identified:

- BEVs: given their limited energy storage capacity and driving range (150-250 km) and a current recharging time of several hours, they are ideally suited to <u>smaller cars</u> and shorter trips.
- PHEVs: with a smaller battery capacity than BEVs, electric driving for PHEVs is restricted to short trips (40-60 km). Combined with the additional blending of biofuels, they also show emission reductions for longer trips, but uncertainty remains as to the amount of sustainably produced biofuels that will be available for this market. Nevertheless, they are an attractive solution, reducing emissions considerably compared to ICEs.
- FCEVs: Medium/larger cars with above-average driving distance account for 50% of all cars, and 75% of CO2 emissions. With a driving range and performance comparable to ICEs, FCEVs are the lowest-carbon solution for <u>medium/larger</u> cars and longer trips.

What is obvious is that no single powertrain can fully meet all the key criteria through which it can be classified on the base of consumer expectations and the environmental requirements (cost, performance and environmental characteristics). What can be expected and confirmed by all road transport scenarios analysed, is that this sector moves from the use of a single technology to a portfolio of powertrains in which BEVs and FCEVs play a complementary role.

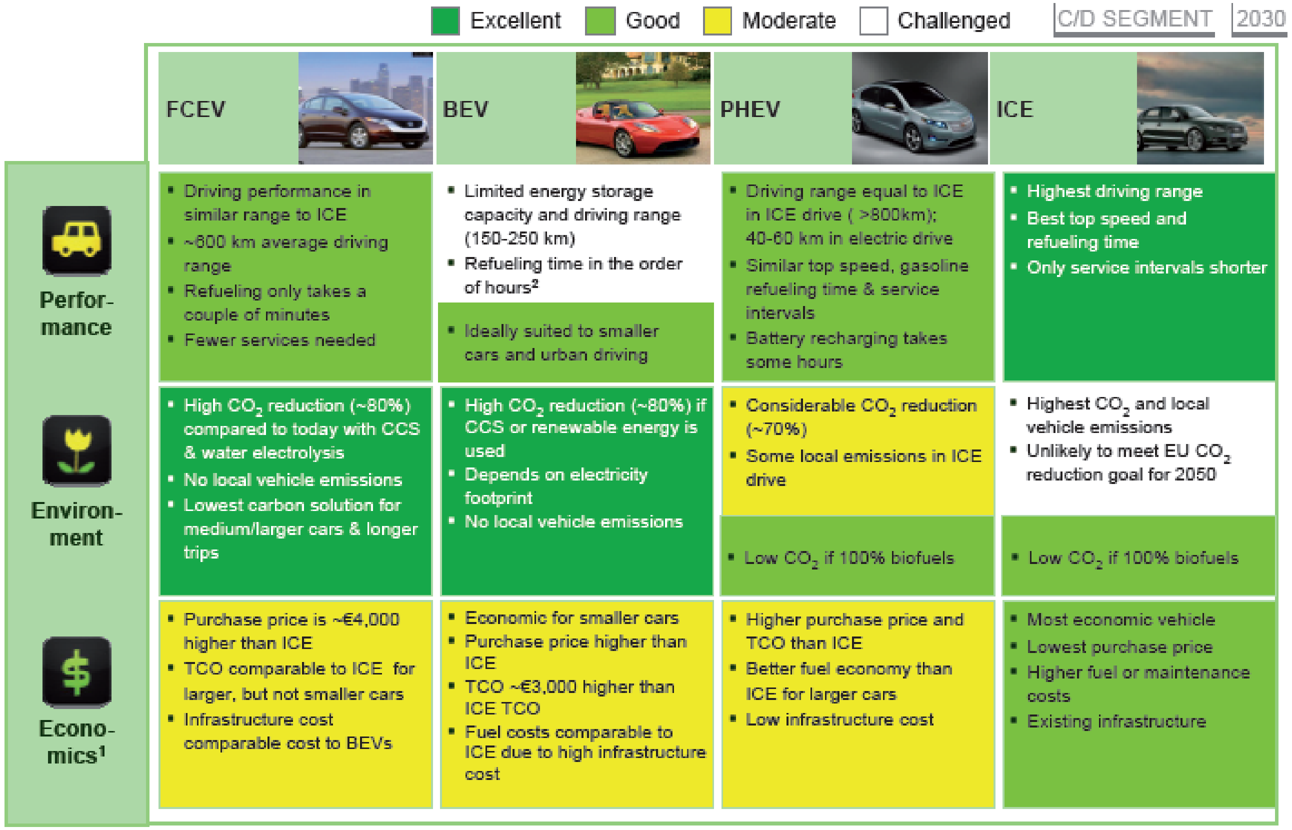
Figure 3.5 and Figure 3.6 below well summarize the main features of the different vehicles, highlighting the limitations of BEVs and enhancing the positive characteristics of FCEVs. Moreover, it is evident that PHEVs provide an intermediate solution for the transition to a zero-emission world. It must further be added that, in this framework, flexible vehicles have the same characteristics as traditional ICE vehicles, while the methanol based FCVs might have a longer refuelling time with respect the hydrogen ones but, at least for the moment, higher costs (see also the following paragraph).

1 Bars represent range of performance across reference segments
2 Fast charging; implies higher infrastructure costs, reduced battery lifetime and lower battery load
3 The gas tank of a PHEV has the same refueling time as a conventional vehicle

SOURCE: Study analysis

Figure 3.5 - FCEVs and PHEVs are comparable to ICEs on driving performance and range

Source: McKinsey et al 2010



🟩 Excellent 🟩 Good 🟨 Moderate ☐ Challenged

C/D SEGMENT 2030

	FCEV	BEV	PHEV	ICE
Perfor-mance	- Driving performance in similar range to ICE - ~600 km average driving range - Refueling only takes a couple of minutes - Fewer services needed	- Limited energy storage capacity and driving range (150-250 km) - Refueling time in the order of hours[2] - Ideally suited to smaller cars and urban driving	- Driving range equal to ICE in ICE drive (>800km); 40-60 km in electric drive - Similar top speed, gasoline refueling time & service intervals - Battery recharging takes some hours	- Highest driving range - Best top speed and refueling time - Only service intervals shorter
Environ-ment	- High CO_2 reduction (~80%) compared to today with CCS & water electrolysis - No local vehicle emissions - Lowest carbon solution for medium/larger cars & longer trips	- High CO_2 reduction (~80%) if CCS or renewable energy is used - Depends on electricity footprint - No local vehicle emissions	- Considerable CO_2 reduction (~70%) - Some local emissions in ICE drive - Low CO_2 if 100% biofuels	- Highest CO_2 and local vehicle emissions - Unlikely to meet EU CO_2 reduction goal for 2050 - Low CO_2 if 100% biofuels
Econo-mics[1]	- Purchase price is ~€4,000 higher than ICE - TCO comparable to ICE for larger, but not smaller cars - Infrastructure cost comparable cost to BEVs	- Economic for smaller cars - Purchase price higher than ICE - TCO ~€3,000 higher than ICE TCO - Fuel costs comparable to ICE due to high infrastructure cost	- Higher purchase price and TCO than ICE - Better fuel economy than ICE for larger cars - Low infrastructure cost	- Most economic vehicle - Lowest purchase price - Higher fuel or maintenance costs - Existing infrastructure

1 Consumer economics can be different, dependent on tax region

2 Fast charging for BEVs implies reduced battery lifetime, lower battery load and higher infrastructure costs than included in this study

SOURCE: Study analysis

Figure 3.6 - Snapshot of 2030: different power-trains meet different needs

Source: McKinsey et al 2010

3.2 *Sustainability issues: feedstock requirements and production costs in accordance with the scenarios conclusions*

3.2.1 Feedstock (CO_2) requirements

The purpose of this section is to calculate the amount of CO_2 needed to produce the methanol required to power all methanol vehicles in accordance with the assumptions made for the two scenarios described in the previous paragraph.

To this end, specific assumptions on the penetration rates of flexible engines must be made.

As seen in paragraph 3.1, private road transport growth up to 2050 is expected to be around 0.6% per year. Accordingly, the number of private cars in 2050 will be about 293 million (231 million [13]of EU private cars in 2010). Furthermore, the split between the different types of powertrains is expected to be rather different depending on the considered scenario as depicted in Table 3.6.

Table 3.6 - Stock penetration rate of powertrains in 2050 per scenario

Stock %	*Reference Scenario*	*Ambitious Scenario*
ICE- Diesel	33%	3,1%
ICE- Gasoline	18,0%	1,9%
HEV	35,0%	35,0%
FC	0,0%	25,0%
BEV	8,0%	35,0%
LPG and CNG	6,0%	0,0%

Source: Own calculations from EU 2013 and McKinsey et al 2010

To estimate the possible share of M85-flexible vehicles in 2050 with respect the total private road vehicles, we have set and applied the following two criteria, taking into account this share only concerns the ICE and HEV gasoline cars (see the highlighted boxes of Table 3.6):

a) By 2050, 50% of the stock of gasoline and hybrid passenger cars is composed of Flexible vehicles able to use ethanol and methanol (M85) blends. To this end, we assume that the EU will issue a policy measure similar to that currently proposed to the US Congress, which envisages: "30 percent of new automobiles manufactured or sold in 2016, 50 percent in 2017, and 50 percent in each subsequent year, to operate on non petroleum fuels, in addition to, or instead of, petroleum based fuels". Should such a measure be enacted, 50% of the stock of passenger cars would be composed by flexible ones already by 2035-2040.

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[13] ODYSSEE-Database ENERDATA, 2012

b) By 2050, 80% of the stock of flexible vehicles is composed of M85 vehicles. Ethanol has clear production limitations owing to the competition with the livestock feed and the human food while methanol production, if provided by CO2 from flue gases, has much higher production limits.

The final assumption regards the FCVs and hypothesizes that all these vehicles are fed by methanol. Table 3.7 shows the outcome of these hypotheses in terms of M85 flexible vehicles stock.

Table 3.7 - Stock of M85 vehicles in 2050 per scenario

Stock [Million]	Reference Scenario	Ambitious Scenario
ICE-gasoline	21	2
PHEV	41	41
FCV	0	73

Source: Own calculation

In order to calculate the amount of CO_2 needed to produce methanol for each scenario, we started from the data provided in the interim report on the unitary fuel consumption applying a (conservative) energy efficiency improvement of 20%, based on the general consensus among experts that ICE vehicles efficiency will improve by about 20-30% in the next 15 years. Table 3.8 shows then the future, expected, yearly unitary consumption of fuel (and CO_2 emissions) per type of powertrain.

Table 3.8 - Unitary data with efficiency improvement

ICE	Annual Consumption	kg fuel/year	913.6
	Annual CO_2 emissions	kg CO_2/year	1928.2
PHEV	Annual Consumption	kg fuel/year	548.2
	Annual CO_2 emissions	kg CO_2/year	1156.9
FC	Annual Consumption	kg fuel/year	634.0
	Annual CO_2 emissions	kg CO_2/year	869.8

Source: Own calculation

Combining the data of Table 3.7 and Table 3.8 we have calculated the total quantity of methanol required for each scenario, corresponding to respectively 41.8 million tons for the Reference Scenario and 64.8 million tons for the Ambitious Scenario. Starting from these figures, we have also calculated the quantity of CO_2 required to produce this fuel, in the hypothesis that the CO2 is sequestrated from power plants (sequestration efficiency of 88%, see the first interim report). Table 3.9 shows these results.

Table 3.9 - Total tons of Methanol and CO_2 needed in 2050 per scenario

Methanol and CO2 requirement (in million tons)	Reference Scenario	Ambitious Scenario
MeOH	41.8	71.1
CO_2	**68.7**	**104.3**

Source: Own calculation

It should however be considered that in the tank-to-wheel perspective, the same amount of CO_2 will be released once again in the atmosphere (actually slightly less for the ICE vehicles as carbon is partly combined to form CO).

In case the CO_2 is sequestrated from flue gases of power stations fed by fossil fuels (coal, natural gas and crude oil), the total required electricity production is **107** and **162** TWh for respectively the reference and the ambitious scenario[14], i.e. a very low share of the current EU electricity production from fossil fuels (4,841 TWh, Eurostat 2010)

3.2.2 Note on the vehicle costs

As for costs, the following observations can be made:

- it is conceivable that flexible vehicles, become competitive with ICE gasoline cars in the short term in terms of total cost of ownership (TCO).
- Yet, the cost of methanol FC vehicles is still between 50% and 150% higher than that of hydrogen FC (see Figure 3.7). This means that, in order to achieve a TCO comparable to that of H_2-FCEV, a considerable R&I effort is required.

At the present stage, CO_2 emissions from FCVs with on-board reformer are quite high (around 100 gCO_2/km). Direct methanol FCVs technology is still in its infancy and uncertainty about future improvements is high, calling for additional research efforts on both types of powertrains.

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[14] Based on the unitary coefficient emission of 642 g/kWh corresponding to the average EU energy production mix (2010)

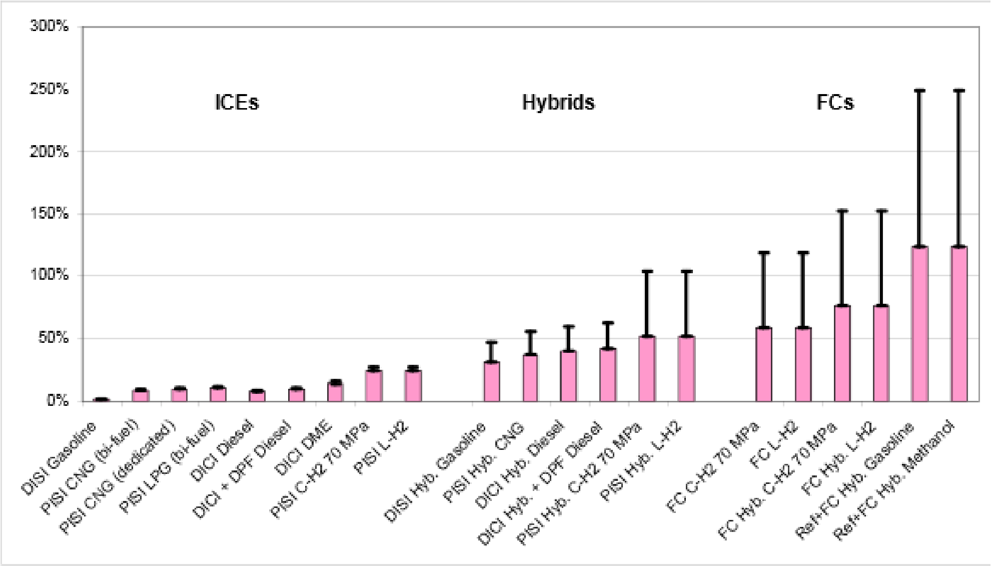


Figure 3.7: % increase of vehicle retail price compared to gasoline PISI vehicle

Source: CONCAWE, EUCAR, JRC, 2011

4 POLICY OPTIONS AND CONCLUSIONS

The policy options laid out in this final chapter focus on issues that are particularly critical for the future competitiveness of CO_2-derived methanol, which can be summarized as follows:

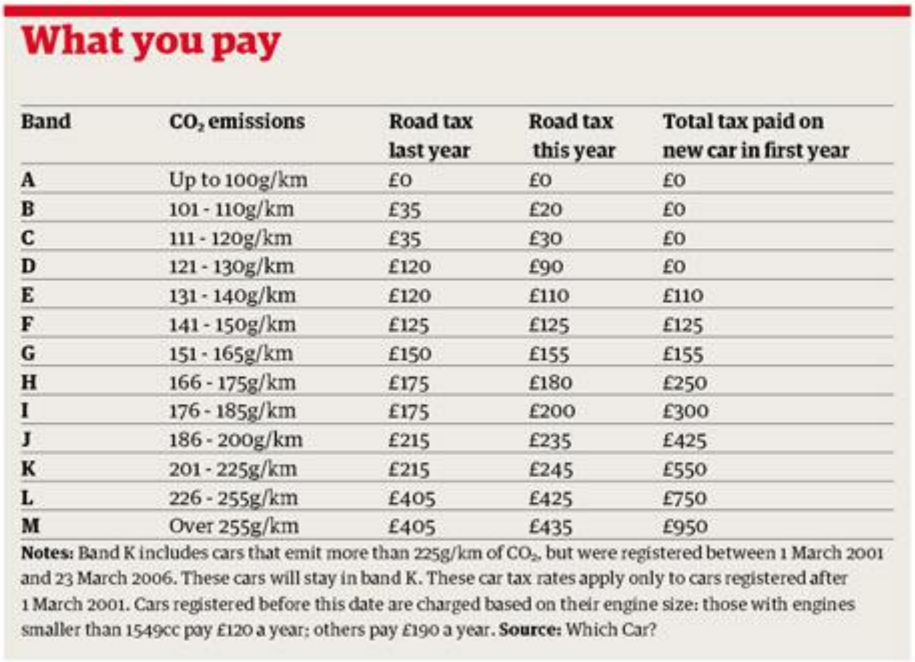
1. The level of priority awarded in transport policy to environmental considerations – first of all CO_2 abatement - and to security of supply concerns.
2. The uncertainty of future technology developments in the transport sector and the need to avoid stranded investments in the medium and long-term.
3. The need for bringing down the costs of captured CO_2 and stimulating its potential uses, among them methanol production.
4. Improving the competitiveness of methanol fuel cells while respecting the free market rules.
5. Considering the need for diverse solutions for different types of transport fleets and the high likelihood of competition for fuels between all transport sectors.

4.1 *Policy Option n° 1 - The market-driven approach*

Since there is no clear picture for the moment as to which alternative fuels and powertrain technologies will ultimately prevail in the market, the option of creating a "level playing field" for all technologies – as proposed by the promoters of the Open Fuel Standard Act in the US – is appealing, as it would oblige the car industry to put a substantial number of vehicles in the market, which can run on natural gas, hydrogen, biodiesel, methanol, as well as flexible fuel or plug-in electric drive vehicles, among others. Proponents argue that this legislation would leave the decision on the type of car and fuel used to the final customer. The US methanol producers support this initiative, but some shortcomings of this policy initiative should be considered.

As shown in the interim report, both hydrogen and methanol produced from CO_2 are still far from being competitive fuels, so that they are unlikely to gain market shares in the next decades, unless there is a drastic increase in prices for gasoline and conventional diesel. Open standards could increase the "food or fuel" dilemma associated to the use of first generation biofuels, i.e. biocrops, and the competition for land and water resources. It is also unclear how other environmental impacts of the production and use of different fuels would be accounted for.

A second critical point for this strategy is to assure that customers are well aware of the advantages and disadvantages of different fuels in terms of performance (km/l) and environmental impacts, among them CO_2 emissions, so they can make informed choices. This has considerable implications for policy making, since the numerical evidence for comparing different fuels and car performance is not presently available, as the second interim report of this study has shown. Even values given by car makers for CO_2 emissions from cars and fuels already in the market have been questioned repeatedly (ICCT 2012). Getting the right values directly affects consumer purchases and calculations, as CO_2 emission levels are frequently used by authorities to define the taxes to be paid by the vehicle owner.



What you pay

Band	CO_2 emissions	Road tax last year	Road tax this year	Total tax paid on new car in first year
A	Up to 100g/km	£0	£0	£0
B	101 - 110g/km	£35	£20	£0
C	111 - 120g/km	£35	£30	£0
D	121 - 130g/km	£120	£90	£0
E	131 - 140g/km	£120	£110	£110
F	141 - 150g/km	£125	£125	£125
G	151 - 165g/km	£150	£155	£155
H	166 - 175g/km	£175	£180	£250
I	176 - 185g/km	£175	£200	£300
J	186 - 200g/km	£215	£235	£425
K	201 - 225g/km	£215	£245	£550
L	226 - 255g/km	£405	£425	£750
M	Over 255g/km	£405	£435	£950

Notes: Band K includes cars that emit more than 225g/km of CO_2, but were registered between 1 March 2001 and 23 March 2006. These cars will stay in band K. These car tax rates apply only to cars registered after 1 March 2001. Cars registered before this date are charged based on their engine size: those with engines smaller than 1549cc pay £120 a year; others pay £190 a year. **Source:** Which Car?

Figure 4.1 - Taxes related to CO_2 emissions from private transport

Source: The Guardian[15]

4.2 Policy Option n° 2 – Regulatory push for CCU

Should Europe choose to set very clear rules for competition between different types of fuels and vehicle technologies, based on a comprehensive and comparable well-to-wheel life-cycle analysis and considerations of security of supply, this would favour CO_2 recycling. It would also imply embracing the idea of CO_2 as an important future prime material and setting up a powerful CCU industry, similar to the Chinese approach, once CO_2 capture costs can be brought down to a competitive level (estimated at around 20€/t of CO_2 captured) and once the environmental and energy balance of methanol production from CO_2 has been considerably improved.

The advantage of this strategy lies in the opportunity of exploring additional potential markets for captured CO_2 – not only road transport – and the chance for European technology leadership and exports. The risks associated to this strategy are the need for sustained investment in R&D and the uncertainties about the time to market of CO_2-derived and competitive products. However, some of the ideas included under policy options 3 and 4 (focussed on methanol) may be valid for defining a broader and long-term European strategy for CCU.

The idea of stimulating research on different options for obtaining value from CO_2 was raised during the expert workshop celebrated in Brussels and credit must be given for that to the Centre for Low Carbon Futures (2011).

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[15] http://www.theguardian.com/money/2010/apr/17/road-tax-carbon-emissions

4.3 *Policy Option n° 3 – Methanol islands*

Both the IRENA (2013) experts and the methanol industry agree that under very specific circumstances, such as in Iceland with its very low electricity prices, methanol produced from CO_2 is already competitive with gasoline. The analysis carried out in this project has identified further key elements for bringing down production cost for methanol from CO_2, such as using electricity from wind farms that cannot be evacuated to the grid or employing solar electricity generated in isolated, but sun-rich regions for hydrogen and methanol production. Another key factor is proximity of the CO_2 emission source to the hydrogen and methanol production sites, in order to avoid the elevated costs of transporting both types of gas. It can be concluded that there is an interesting potential for circular economy and industrial symbiosis concepts, which could be explored in large-scale demonstration sites.

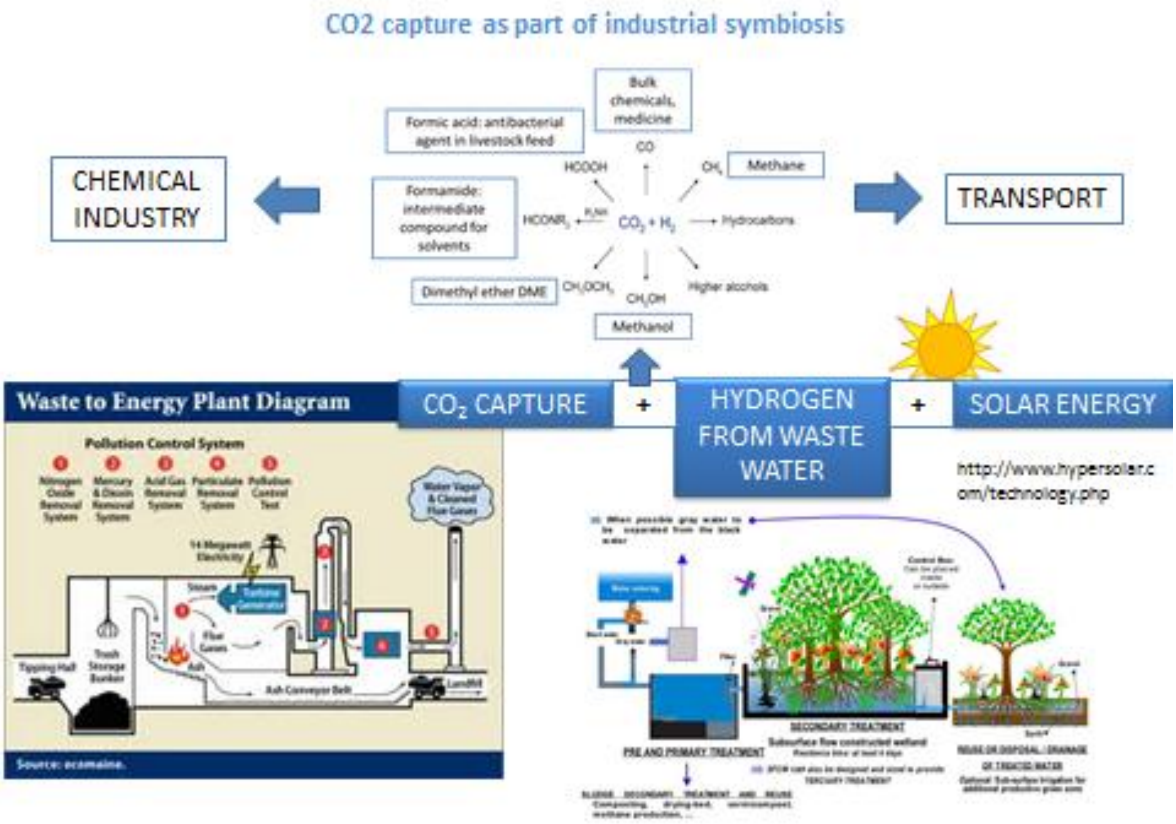

Figure 4.2 - Example of industrial symbiosis involving CO_2 capture

Source: Own elaboration

This strategy could be combined with a systematic exploration of market niches for methanol. The 2013 Fuel Cell Market Report, for example, shows that direct methanol fuel cells (DMFC) had a strong presence in small scale power applications, although they are now losing market shares to PEMFC.

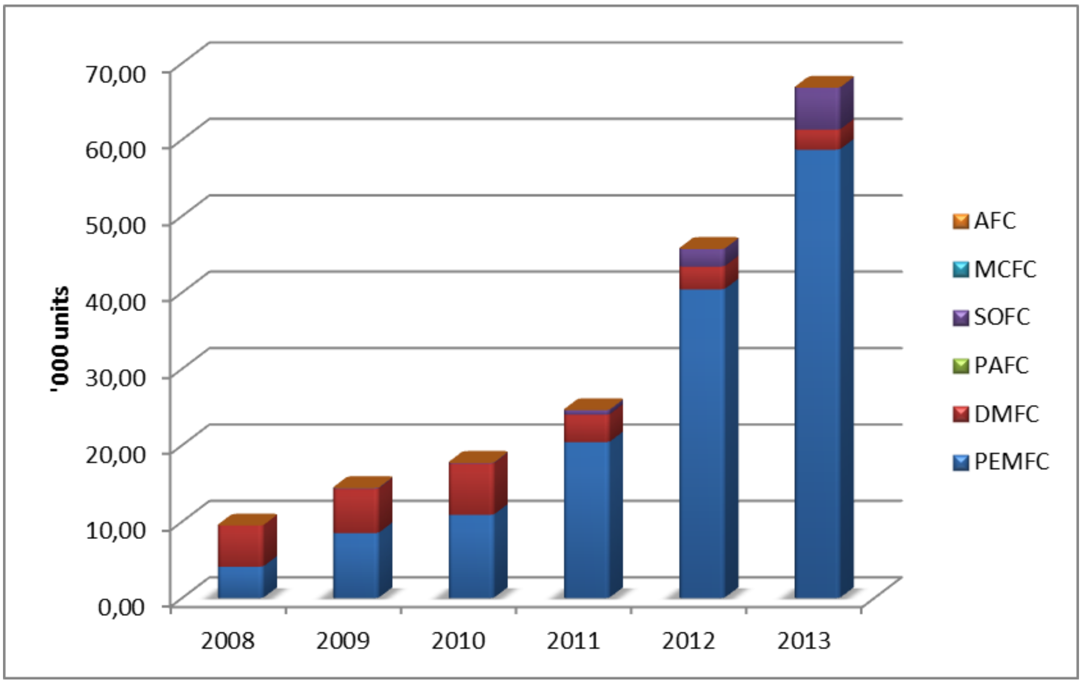

Figure 4.3 - Fuel cell shipments by type 2008 – 2013 for small generator and Auxiliary Power Units

Source: Own elaboration based on Fuel Cell Today 2013

The report, however, also indicates that some methanol fuel cell producers have closed deals with automobile producers such as Volkswagen, or with defence institutions to equip a limited number of vehicles with direct methanol fuel cells, which fulfil the function of range extenders for electric vehicles, and also for stationary fuel cells. Wartsila

offers methanol fuel cells to power commercial ships (Tiax 2012). Even though these are still very small market niches, and most of them are dependent on public purchasing strategies, expectations have been raised with regard to a possible use of DMFC in consumer electronics (Fuel Cell Today 2012) and in the oil and gas sector (Fuel Cell Today 2013).

This policy option would therefore combine smart strategies for bringing down the cost of methanol produced from CO_2 with the support of market innovations requiring the use of methanol fuel cells, matching growing demand with increased supplies. The advantage of such a strategy consists in limited initial investment needs and a greater independence from developments in the transport sector, which would allow for bridging the time necessary for bringing down the costs of methanol produced from CO_2 and improving the fuel cell technologies. Policy measures would have to respect free market rules, though, and implementation may therefore be complex.

4.4 Policy Option n° 4 – Scenario-driven transition strategies

A broader transition strategy for reducing dependence on oil-derived products in the European transport sector will necessarily have to look into all types of transport model and fuels, as well as mobility behaviours. The scenarios considered in this report mainly refer to the automotive sector and focus on private transport, but some reference has been found to the likely competition among different types of transport for a limited supply of fuels. It is the risk of increasing scarcity and dependence of the entire European transport sector that creates an obligation to carefully consider all potential alternative prime materials, including CO_2 captured from flue gases. The DG Move reference scenario assumes that prices for oil and coal will double between 2010 and 2050 in real terms, while price increases for natural gas are expected to be slightly lower (see Table 3.2). The implications of these price developments for energy consumption in the transport sector as a whole should be carefully evaluated. The present economic crisis has provided useful hints on the impact of increasing prices (or declining incomes) on the different transport sectors. The latest Eurostat figures, published in 2013, reveal that the road gasoline sector has reacted stronger to the crisis (from 2008 on) than the rest of the sectors and that, in the longer term, i.e. since 1990, its overall contribution to energy demand in transport has decreased.

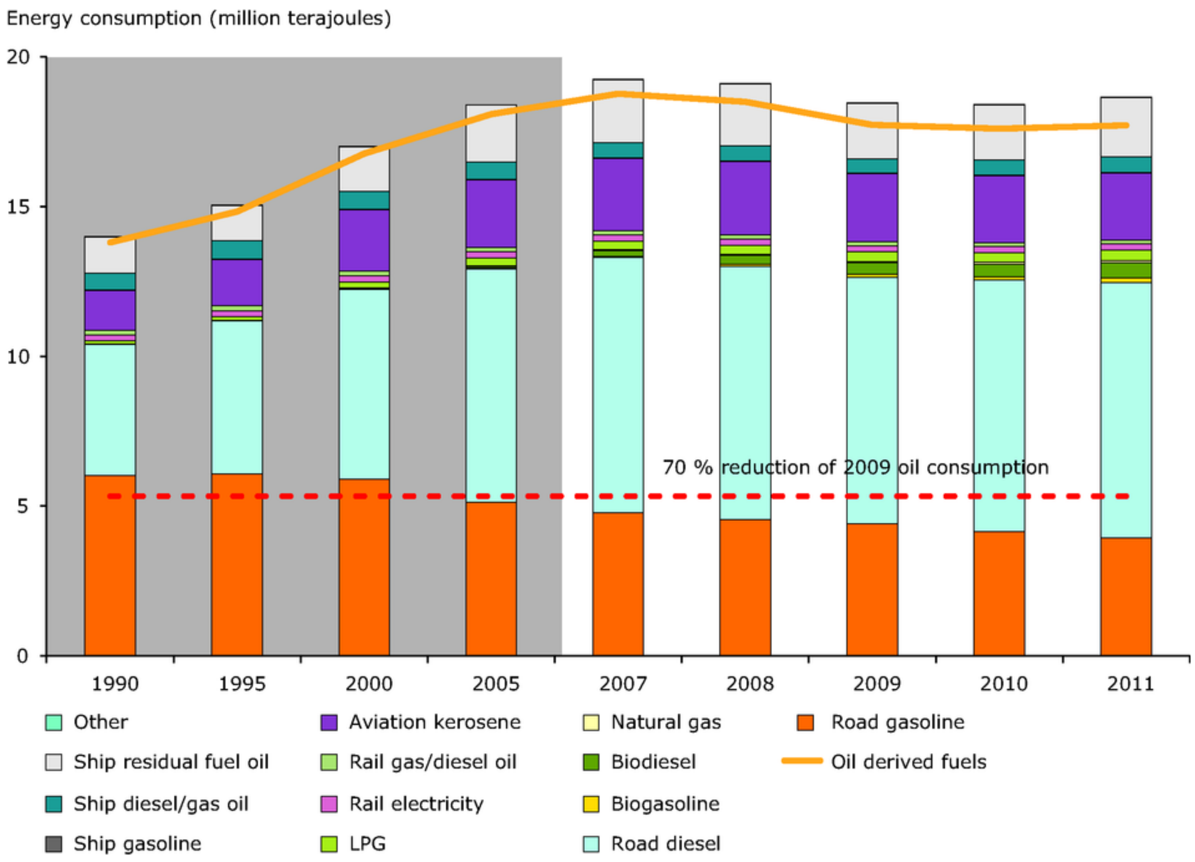

Figure 4.4 – Energy consumption for transport in the EU 1990 - 2011

Source: EEA[16]

The largest, long-term increases of fuel demand have come from the diesel road sector and aviation. For the first, DME seems to be a viable substitution option, according to truck makers such as Volvo (Greszler 2013), whereas the aviation sector – now also subject to CO_2 reduction objective – is still considering alternative fuels carefully. Some pioneer companies such as Clean Tech Aviation[17] are

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[16] http://www.eea.europa.eu/data-and-maps/indicators/transport-final-energy-consumption-by-mode/assessment-2. Accessed 19/2/2014

[17] http://ctdc.eu/clean-aviation-biofuel/ Accessed 19/2/2014

promoting blending strategies similar to those described for the road transport sector, which involve methanol from renewable sources.

If flexible fuel vehicles can raise methanol use in private transportation between 41.8 and 71.1 million tons and lead to the recycling of 68.7 to 104.3 million tons of CO_2, this could help the entire transport sector to better cope with increasing fuel demand and prices. But positive effects in terms of security of supply would even be greater, if further amounts of CO_2 were recycled similarly in other sectors (diesel road, maritime and, possibly, some aircrafts).

This policy option basically implies putting a price on energy security, which can be defined by evaluating the direct and indirect macroeconomic effects of rising transport prices throughout Europe. Higher fuel prices increase the price levels of all types of goods and affect the competitiveness of export-oriented companies, as well as especially vulnerable regional economies and consumer groups (ESPON 2010).

Putting a price on energy security does, however, not invalidate the need for finding more efficient conversion processes for alternative fuels, including hydrogen and methanol, nor for promoting the most suitable uses of all types of energy sources, recycled CO_2 included, so that energy remains affordable for all economic players.

5 REFERENCES CITED IN THE FINAL REPORT

- Bandose, A. and Urukawa, A., (2014), "Towards full one-pass conversion of carbon dioxide to methanol and methanol-derived products", Journal of Catalysis 309 (2014) 66-70
- Bechtold, R. et al (2007), "Use of Methanol as a Transportation Fuel", Methanol Institute, 2007
- Centre for Low Carbon Future (2011), "Carbon Capture and Utilisation in the green economy. Using CO_2 to manufacture fuel, chemicals and materials"
- CONCAWE, EUCAR and JRC (2011), "Well-to-wheels analysis of future automotive fuels and powertrains in the European context", WELL-TO-WHEELS Report Version 3c, July 2011
- CONCAWE, EUCAR and JRC (2013), "Tank-to-wheels analysis of future automotive fuels and powertrain in the European context"
- Dolan, G.A. (2013), "Methanol Fuel Drivers: Public Policy, Economics, Energy and the Environment", Presentation in the 20th International Symposium on Alcohol Fuels- ISAF 2013, Spier Estate, South Africa, 2013
- Dolan, G.A. (no date), "Methanol Transportation Fuels: A Look Back and a Look Forward", Methanol Institute
- ESPON 2010, "ReRisk Regions at Risk of Energy Poverty". Final report.
- European Climate Foundation (2010), "Roadmap 2050"
- European Gas Forum (2012), "Reducing the CO_2 emissions in the EU transportation sector"
- European Transport Group (2011a), "Future Transport Fuels"
- European Transport Group (2011b), "Infrastructure for Alternative Fuels"
- Fuel Cell Today (2012), "The Fuel Cell Industry Review 2012"
- Fuel Cell Today (2013), "The Fuel Cell Industry Review 2013"
- Greszler, A. (2013), "DME from Natural Gas or Biomass: A Better Fuel Alternative ",Volvo Group Truck Technology
- ICCT (2012), "Discrepancies between type approval and "real-world" fuel consumption and CO_2 values" ICCT Working Paper 2012-02
- James, B.D., Ariff, G.D., Kuhn, R.C. and Myers, D.B (2003), "DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low/Medium/High Production Rates", DOE, USA
- Kostka, G, and Hobbs, W., (2011), "Embedded Interest and the Managerial Local State: the political economy of methanol fuel-switching in China", Frankfurt School, Working Paper Series No.152, February 2011
- McKinsey et al (2010), "A portfolio of power-trains for Europe: a fact-based analysis: The Role of Battery Electric Vehicles, Plug-in-Hybrids and Fuel Cell Electric Vehicles"
- Methanol Institute (2010), "Contribution of the Methanol Institute to the EC Expert Group on Future Transport Fuels"
- TETRAPLAN (2013), "TranScenario Project" (DG MOVE), Final Report
- Tiax (2013), "Methanol as a Renewable Energy Resource", White Paper prepared for the Methanol Institute

- Yang, C-J and Jackson, R.B. (2012), "China's growing methanol economy and its implications for energy and the environment" Energy Policy 41(2012)878–884

6 COMPLETE LIST OF REFERENCES USED FOR THIS STUDY

- Abu Zahra, M.R.M (2009), "Carbon Dioxide Capture from Flue Gas. Development and Evaluation of Existing and Novel Process Concepts", Thesis, Technical University of Delft
- Adebajo, M.O. and Frost, R.L. (2012), "Recent Advances in Catalytic/Biocatalytic Conversion of Greenhouse Methane and Carbon Dioxide to Methanol and Other Oxygenates", book edited by Guoxiang Liu, ISBN 978-953-51-0192-5 (open access document)
- Andersen, L. (n.d.) "Methanol Synthesis on Danish Heat Plants". Available at http://www.fvu-center.dk/sites/default/files/3._praemie_methanol_1.pdf
- Ashley, A.E., Thompson, A.L. and O'Hare, D. (2009), "Non-Metal-Mediated Homogeneous Hydrogenation of CO_2 to CH_3OH", Angewandte Chemie International Edition, Volume 48, Issue 52, pages 9839–9843, December 21, 2009
- Atsonios, K., Panopoulos, K.D., Doukelis A., Koumanakos, A and Kakaras, E (2012), "Cryogenic method for H2 and CH4 recovery from a rich CO2 stream in pre-combustion CCS schemes", Proceedings Of Ecos 2012 - The 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems June 26-29, 2012, Perugia, Italy
- AutobloGreen (2009), "Toyota tops 2 million hybrid sales worldwide", Retrieved 2009-10-24
- Bandose, A. and Urukawa, A., (2014), "Towards full one-pass conversion of carbon dioxide to methanol and methanol-derived products", Journal of Catalysis 309 (2014) 66-70
- Barbarossa, V. and Vanga, G. (2011), "Alternative use of CO_2", Energia, Ambiente, Innovazione 6/2011
- Barton, E.E. Rampulla, D.M. and Bocarsly, A.B. (2008), "Selective Solar-Driven Reduction of CO2 to Methanol Using a Catalyzed p-GaP Based Photoelectrochemical Cell". J. Am. Chem. Soc. 2008, 130, 6342-6344
- Baskaya, F.S., Zhao, X., Flickinger, M.C. and Wang, P. (2010), "Thermodynamic feasibility of enzymatic reduction of carbon dioxide to methanol". Appl Biochem Biotechnol., 162 (2010) 391–398
- Bechtold, R. et al (2007), "Use of Methanol as a Transportation Fuel", Methanol Institute, 2007
- Bonaquist, D. (2010), "Analysis for CO_2 emission, reduction and capture for large scale hydrogen production plants", Praxair
- Bromberg, L. and Cheng, W.K. (2010), "Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation", Sloan Automotive Laboratory, Massachusetts Institute of Technology
- Cardenas Barrañon, C.D. (2006), "Methanol and hydrogen production. Energy and cost analysis", Master Thesis, Lulea University of Technology
- Centre for Low Carbon Future (2011), "Carbon Capture and Utilisation in the green economy. Using CO2 to manufacture fuel, chemicals and materials"
- Cerri, I., Lefebvre-Joud, F., Holtappels, P., Honegger, K., Stubos, T. and Millet, P. (2012), "Scientific Assessment in Support of the Materials Roadmap Enabling Low Carbon Energy Technologies", Publications Office of the European Union, 2012. 62 p. (E U R; No. 25293 EN)

- Chisti, Y. (2007), “Biodiesel from microalgae beats bioethanol”, Trends in Biotechnology Vol.26 No.3
- Clausen, L.R., Houbak, N, Elmegaard, B. (2010), “Technoeconomic analysis of a methanol plant based on gasification of biomass and electrolysis of water”, Energy 35, 5 (2010) 2338
- CO_2Chem (2012), “Roadmap for the future of CO_2Chem and CCU”
- Collodi, G. (2010)m “Hydrogen via Steam Reforming and CO_2 capture” Chemical Engineering Transactions, Volume 19, 2010
- CONCAWE, EUCAR and JRC (2011), “Well-to-wheels analysis of future automotive fuels and powertrains in the European context”, WELL-TO-WHEELS Report Version 3c, July 2011
- CONCAWE, EUCAR and JRC (2013), “Tank-to-wheels analysis of future automotive fuels and powertrain in the European context”
- Costentin, C., Robert, M and Savéant, J.M. (2012), “Catalysis of the electrochemical reduction of carbon dioxide”, Review Article, The Royal Society of Chemistry 2012
- Dave, B.C. (2008), “Prospects for methanol production” Bioenergy chapter 19. ASM Press 2008
- Dave, B.C., Rao, M.S., Burt, M.C. (2007), “Conversion of carbon dioxide to methanol in silica sol-gel matrix”, International patent WO2007/022504 (2007).
- Davidson, R.M., (2011), “Pre-combustion capture of CO_2 in IGCC plants”, IEA Clean Coal Centre
- de_Richter, R. and Caillol, S. (2011), “Fighting global warming: the potential of photocatalysis against CO_2, CH_4, N_2O, CFCs, tropospheric O_3, BC and other major contributors to climate change”, J. Photochem. Photobiol. C: Photochem. Volume 12, Issue 1, March 2011, Pages 1–19
- Dechema (2010), “Position Paper. Change in the Raw Materials Base”
- Dechema / VCI (2009), “Position Paper. Utilisation and Storage of CO2”
- DNV (2011), “Carbon Dioxide Utilization. Electrochemical Conversion of CO_2 – Opportunities and Challenges”. Research and Innovation, Position Paper 07 – 2011.
- DOE (2012), 2011 Fuel Cells Technologies Market Report, in collaboration with Breakthrough Technologies Institute, Inc., Washington USA.
- Dolan, G.A. (2013), “Methanol Fuel Drivers: Public Policy, Economics, Energy and the Environment”, Presentation in the 20th International Symposium on Alcohol Fuels- ISAF 2013, Spier Estate, South Africa, 2013
- Dolan, G.A. (no date), “Methanol Transportation Fuels: A Look Back and a Look Forward”, Methanol Institute
- EARPA (European Automotive Research Partners Association) 2006, “FURORE- Future Road Vehicle Research”, 2006
- ECOFYS (2012), “Renewable energy progress and biofuels sustainability”
- Esmaili, P. (2012), “Thermodynamic analysis of an integrated photovoltaic system for hydrogen and methanol production”. Thesis, University of Ontario Institute of Technology, June 2012
- ESPON 2010, “ReRisk Regions at Risk of Energy Poverty”. Final report
- EUCAR FUERO Workshop, Geiteborg, European Council for Automotive R&D (EUCAR), 2001 (www.eihp.org/public/documents/fuero)

- European Climate Foundation (2010), "Roadmap 2050"
- European Commission (2011), "European Workshop "CO_2: From Waste to Value". Report from the Workshop", Brussels, 30 March 2011
- European Commission, (28 March 2011) "WHITE PAPER _Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system", Brussels, 28 March 2011
- European Commission 2013, TranScenario Project (DG MOVE), Final Report
- European Gas Forum (2012), "Reducing the CO_2 emissions in the EU transportation sector"
- European Technology Platform for Zero Emission Fossil Fuel Power Plants (2011a), "The Costs of CO2 Capture"
- European Technology Platform for Zero Emission Fossil Fuel Power Plants (2011b), "The Costs of CO2 Transport"
- European Transport Group (2011a), "Future Transport Fuels"
- European Transport Group (2011b), "Infrastructure for Alternative Fuels"
- Eurostat (2012), "EU transport in figures - Statistical pocket book 2012"
- Finkenrath, M. (2011), "Cost and performance of carbon dioxide capture from power generation", IEA Working Paper 2011
- Florence, Gény (2010), "Can Unconventional Gas be a Game Changer in European Gas Markets?", The Oxford Institute for Energy Studies
- Folger, P. (2013), "Carbon Capture: A Technology Assessment", Congressional Research
- Fuel Cell Today (2012a) "Fuel Cell Electric Vehicles: The Road Ahead"
- Fuel Cell Today (2012b), "The Fuel Cell Industry Review 2012"
- Fuel Cell Today (2013a), "The Fuel Cell Industry Review 2013"
- Fuel Cell Today (2013b), "Methanol, clean fuel for the future?"
- Galindo Cifre, P. and Badr, O. (2007), "Renewable hydrogen utilisation for the production of methanol", Energy Conversion and Management 48 (2007) 519–527
- Ganesh, I. (2011), "Conversion of carbon dioxide to methanol using solar energy", Current Science, Vol. 101, No. 6, 25 September 2011
- Gerdes Kristin J. (2009), "Evaluating GHG Emissions and Transportation Fuels", National Energy Technology Laboratory (NETL)
- Gjernes, E., Helgesen, L. and Maree, Y. (2013), "Health and environmental impact of amine based postcombustion CO_2 capture", Energy Procedia 00 (2013) 000–000
- Global CCS Institute (2012), "Oxy Combustion with CO_2 Capture"
- Gravalos, I. , Moshou, D., Gialamas, T. , Xyradakis, P., Kateris, D. and Tsiropoulos, Z. (2010), "Performance and Emission Characteristics of Spark Ignition Engine Fuelled with Ethanol and Methanol Gasoline Blended Fuels", Technological Educational Institute of Larissa, Faculty of Agricultural Technology Department of Biosystems Engineering, Larissa, Greece

- Green, C.J., King, L., Mueller, S. and Cockshutt, N.A. (1990). “Dimethyl Ether as a Methanol Ignition Improver – Substitution Requirements and Exhaust Emission Impact. SAE paper 902155 October.
- Greszler, A. (2013), “DME from Natural Gas or Biomass: A Better Fuel Alternative”, Volvo Group Truck Technology
- Gu, Y., (2013), “Carbon Capture & Storage Policy in China”, Center for Climate Change Law White Paper, Columbia Law School
- Gupta, M., Smith, ML. and Spivey, J.J. (2011), “Heterogeneous Catalytic Conversion of Dry Syngas to Ethanol and Higher Alcohols on Cu-Based Catalysts”. ACS Catalysis, 1 (6): 641-656 JUN 2011
- Hamilton, M.R, Herzog H. J. and Parsons, J.E. (2009), “Cost and U.S. public policy for new coal power plants with carbon capture and sequestration”, Energy Procedia 1 (2009) 4487–4494
- Haumann, D., Göttlicher, G. and Muench, W. (2012), “Energy and greenhouse balance of photocatalytic CO_2 conversion to methanol”, EPJ Web of Conferences 33 02006 (2012)
- Haumann, D., Göttlicher, G., Osmancevic, E., Kuhn, T., Konrad, C. and Strittmatter, J. (2012), “ CO_2 Pipeline Transport from Germany to Algeria”. 7th Pipeline Technology Conference
- Honda Press Release (2012), “Cumulative worldwide sales of Honda hybrids passes 1 million units". Green Car Congress. Retrieved 2012-10-16.
- House, K. Z., Baclig, A.C., Ranjan, M., van Nierop, E. A., Wilcox, J. and Herzog, H.C. (2011), “Economic and energetic analysis of capturing CO2 from ambient air”, www.pnas.org/cgi/doi/10.1073/pnas.1012253108
- HybridCARS.com (2012), "December 2011 Dashboard: Sales Still Climbing”, Retrieved 2012-01-10
- ICCT (2012), “Discrepancies between type approval and “real-world” fuel consumption and CO2 values” ICCT Working Paper 2012-02
- ICO_2N (2011), “Perspective on conducting cost analyses of CO_2 capture technologies”
- Institute University of California (2010), “A realistic technology and engineering assessment of Algae biofuel production” Print. http://www.energybiosciencesinstitute.org/media/AlgaeReportFINAL.pdf
- International Energy Agency (2012), “CO_2 emissions from fuel combustion. Highlights”
- IRENA and IEA-ETSAP. “Production of Biomethanol. Technology Brief.” January 2013.
- ISIS 2012, in collaboration with Egis e Nestear: “Lyon-Turin ferroviaire, Economic and socio-economic studies of the Franco-Italian part of the international section”. Years 2010, 2012
- Izumi, Y. (2013), “Recent advances in the photocatalytic conversion of carbon dioxide to fuels with water and/or hydrogen using solar energy and beyond”, Coordination Chemistry Reviews 257 (2013) 171– 186
- James, B.D., Ariff, G.D., Kuhn, R.C. and Myers, D.B (2003), “DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low/Medium/High Production Rates”, DOE, USA
- Jiang, Z., Xiao, T., Kuznetsov, V. L. and Edwards, P. P. (2010), “Turning carbon dioxide into fuel”. Phil. Trans. R. Soc. A 2010 368, 3343-3364

- Kauw, M. (2012), "Recycling of CO_2, the perfect biofuel?", Master report, University of Groningen. Available for download at http://ivem.eldoc.ub.rug.nl/FILES/ivempubs/dvrapp/EES-2012/EES-2012-139M/EES-2012-139M_MarcoKauw.pdf
- Kostka, G, and Hobbs, W., (2011), "Embedded Interest and the Managerial Local State: the political economy of methanol fuel-switching in China", Frankfurt School, Working Paper Series No.152, February 2011
- Kumar, A., Ergas, S, Yuan, X., Sahu, A., Zhang, Q., Dewulf, J. Malcata, F.X. and van Langenhove, H. (2011), "Enhanced CO_2 fixation and biofuel production via microalgae: recent developments and future directions", Trends in Biotechnology Vol.28 No.7
- Lackner, K. S., Ziock, H.-J., and Grimes, P., (1999), "Carbon dioxide extraction from air: Is it an option?' Los Alamos National Laboratory Report number LA-UR-99- 583, 1999, as cited by Pearlson et al 2009
- Lackner, K.S. (2009), "Capture of carbon dioxide from ambient air", Eur. Phys. J. Special Topics 176, 93–106 (2009)
- Li, B., Duan Y., Luebke, D., and Morreale, B. (2013), "Advances in CO_2 capture technology: A patent review", Applied Energy 102 (2013) 1439–1447
- Liu, G. (editor) (2012), "Greenhouse Gases - Capturing, Utilization and Reduction", ISBN 978-953-51-0192-5
- Loveday, E. (2011), "Toyota sells 1 millionth Prius in Japan". Autoblog Green. Retrieved 2012-03-08.
- Lundquist, T. J., Woertz, I. C., Quinn, N.W.T. and J. R. Benemann (2010), "A Realistic Technology and Engineering Assessment of Algae Biofuel Production". Rep. Berkeley: Energy Biosciences Institute University of California, 2010. Print. http://www.energybiosciencesinstitute.org/media/AlgaeReportFINAL.pdf
- Maa, J., Sun, N, Zhang, X, Zhao, N, Xiao, F.,Wei, W., and Sun, Y., (2009)," A short review of catalysis for CO2 conversion", Catalysis Today 148 (2009) 221–231
- Marie-Rose, S.C., Perinet, A.L., and Lavoie, J-M. (2011), "Conversion of Non-Homogeneous Biomass to Ultraclean Syngas and Catalytic Conversion to Ethanol" in "Biofuel's Engineering Process Technology", Dr. Marco Aurelio Dos Santos Bernardes (Ed.), ISBN: 978-953-307-480-1, InTech, Available from: http://www.intechopen.com/books/biofuel-s-engineering-process technology/conversion-ofnon-homogeneous-biomass-to-ultraclean-syngas-and-catalytic-conversion-to-ethanol
- Markovic, N.M. (2013), "Electrocatalysis. Interfacing electrochemistry", Nature Materials | Vol 12 | February 2013
- McKinsey (2008), "Carbon Capture & Storage: Assessing the Economics"
- McKynsey et al 2010, "A portfolio of power-trains for Europe: a fact-based analysis: The Role of Battery Electric Vehicles, Plug-in-Hybrids and Fuel Cell Electric Vehicles"
- Methanol Institute (1992), "Technical Bulletin No7, Emission and Air Quality Modelling Results from Methanol/Gasoline Blends in Prototype Flexible Variable Vehicles"
- Methanol Institute (2010), "Contribution of the Methanol Institute to the EC Expert Group on Future Transport Fuels"

- Milici, R. (2009), “Coal-to-Liquids: Potential Impact on U.S. Coal Reserves”, Natural Resources Research, Volume 18, Number 2 / June 2009.
- Misra, RD and Murthy, MS. (2011), “Blending of additives with biodiesels to improve the cold flow properties, combustion and emission performance in a compression ignition engine. A review”, Renewable & Sustainable Energy Reviews, 15 (5): 2413-2422 Jun 2011
- Mondal, M. K., Balsora H. K, and Varshney, P. (2012), “Progress and trends in CO_2 capture/separation technologies: A review”, Energy 46 (2012) 431-441
- Mori, K., Yamashita. H. and Anpo, M. (2012), “Photocatalytic reduction of CO2 with H2O on various titanium oxide photocatalysts”, RSC Adv., 2012, 2, 3165-3172
- Nazimek, D. and Czech, B. (2011), “Artificial photosynthesis – CO_2 towards methanol”, IOP Conference Series: Materials Science and Engineering 19 (2011)
- NETL National Energy Technology Laboratory (2013), “Carbon Dioxide Transport and Storage Costs in NETL studies”
- Nichols, W. (2012), "Ford tips hybrids to overshadow electric cars". Business Green. Retrieved 2012-10-16.
- Nowell, G.P (1994). “On the road with Methanol: The Present and Future Benefits of Methanol Fuel”, The Methanol Institute http://www.afdc.energy.gov/pdfs/2474.pdf
- Nuwan, H.P., De Alwis, S., Mohamad, A.A. and Anil K. Mehrotra, A.K. (2009), “Exergy Analysis of Direct and Indirect Combustion of Methanol by Utilizing Solar Energy or Waste Heat”, Energy & Fuels 2009, 23, 1723–1733
- Obert, R. and Dave, B.C. (1999), “Enzymatic conversion of carbon dioxide to methanol: enhanced methanol production in silica sol-gel matrices”, J. Am. Chem. Soc., 121 (1999) 12192–12193
- Ogden, J. M., Steinbugler, M.M. and Kreutz, T. G., (1998) “A comparison of hydrogen, gasoline and methanol as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development”. Elsevier, 28 September 1998
- Olah, G. A., Goeppert, A. and Prakash, G. K. S (2009), “Chemical Recycling of Carbon Dioxide to Methanol and Dimethyl Ether: From Greenhouse Gas to Renewable, Environmentally Carbon Neutral Fuels and Synthetic Hydrocarbons”. J. Org. Chem., 2009, 74 (2), 487–498
- Olah, G. A., Goeppert, A. and Prakash, G. K. S (2011), “Beyond Oil and Gas: The Methanol Economy”. Book edit by John Wiley & Sons. August 2011
- Olajire, A. A. (2010), “CO_2 capture and separation technologies for end-of-pipe applications. A review”, Energy 35, Issue 6, June 2010, Pages 2610–2628
- Olivier, J.G., Janssens-Maenhout, G. and Peters, Jeroen A.H.W. (2012), “Trends in global CO_2 emissions. 2012 Report”, PBL / JRC
- Panahi, P. N., Mousavi, S. M., Niaei, A., Farzi, A. and Salari, D. (2012), “Simulation of methanol synthesis from synthesis gas in fixed bed catalytic reactor using mathematical modelling and neural networks”, International Journal of Scientific & Engineering Research Volume 3, Issue 2, February-2012
- Parsons Brinckerhoff and Global CCS Institute (2011), “Accelerating the Uptake of CCS: Industrial Use of Captured Carbon Dioxide”

- Patzek, T. and Croft, G. (2010), "A global coal production forecast with multi-Hubbert cycle analysis". Energy 35 (2010) 3109-3122.
- Pearson, R.J., Turner, J.W.G. and Peck, A.J., (2009), "Gasoline-ethanol-methanol tri-fuel vehicle development and its role in expediting sustainable organic fuels for transport", Lotus Engineering, Norwich, Norfolk, UK
- Pearson, R.J., Turner, J.W.G., Eisaman, M.D., Littau, K.A. and Taylor, G. "Sustainable Organic Fuels for Transport (SOFT) – A Concept for Compatible Affordable Mobility Using Carbon-Neutral Liquid Fuels". Available at http://www.ecolo.org/documents/documents_in_english/Methanol-Lotus_SOFT_09.pdf
- Pedersen, T.H. and Schultz, R.H. (2012), "Technical and Economic Assessment of Methanol Production from Biogas", Master Thesis, University of Aalborg, Denmark
- Pongrácz, E., Turpeinen, E., Mäyrä, O., Leiviskä, K. and Keiski, R. (2009), "Chemical utilization of CO2 in dry reforming and methanol synthesis". In: Paukkeri, A.; Ylä-Mella, J. and Pongrácz, E. (eds.) Energy research at the University of Oulu. Proceedings of the EnePro conference, June 3rd, 2009, University of Oulu, Finland. Kalevaprint, Oulu, ISBN 978-951-42-9154-8. pp. 79-82.
- PWC 2012, "Too late for two degrees? Low carbon economy index 2012"
- Reda, T., Plugge, C.M., Abram, N.J. and Hirst, J. (2008), "Reversible interconversion of carbon dioxide and formate by an electroactive enzyme". Proc. Natl. Acad. Sci. USA., 105 (2008) 10654–10658.
- Richard L. Bechtold, P.E. Study carried out for the: New York State Energy Research and Development Authority (1997), Alternative fuels for Vehicles Fleet Demonstration Program. Volume3, Technical Reports. http://docsfiles.com/pdf_alternative_fuels_and_vehicles_on.html
- Rihko-Struckmann, L.K., Peschel, A., Hanke-Rauschenbach, R. and Sundmacher, K. (2010), "Assessment of Methanol Synthesis Utilizing Exhaust CO_2 for Chemical Storage of Electrical Energy", Ind. Eng. Chem. Res. 2010, 49, 11073–11078
- Rogers, H. V. (2012), "Gas with CCS in the UK – waiting for Godot?" The Oxford Institute for Energy Studies, NG 66, September 2012
- Rosetti, I. (2012), "Review Article. Hydrogen Production by Photoreforming of Renewable Substrates", ISRN Chemical Engineering, Volume 2012 (2012), Article ID 96493
- Rubner, J. (2010), "CO_2 seperation", Spring 2010
- Sakakura, T., Choi, J.-C. and Yasuda, H. (2007), "Transformation of carbon dioxide", Chem. Rev., 107, 2365-2387.
- Schmitz, M., Kluczka S. and Vaessen C. (2010), "Methanol from CO_2 and Solar Energy - A Literature Review". 18th World Hydrogen Energy Conference 2010 - WHEC 2010. ISBN: 978-3-89336-652-1
- Sen, C. (2012), "Algae Based Carbon Capture and Utilization feasibility study- initial analysis of carbon capture effect based on Zhoushan case pre-study in China", Master Thesis, Royal Institute of Technology, Sweden.
- Sileghem, L., and Van De Ginste, M. (2010), "Methanol as a Fuel for Modern Spark-Ignition Engines: Efficiency Study"

- Simons, K. (2010), “Membrane technologies for CO_2 capture”, PhD Thesis, University of Twente, The Netherlands
- Sing, S. F., Isdepsky, A. Borowitzka, M.A. and Moheimani, N.R. (2011) "Production of Biofuels from Microalgae." Mitigation and Adaptation Strategies for Global Change 18 (2011): 47-72. Springer Science + Business Media. Springer, 26 Apr. 2011. Web. 15 July 2013.
- Singh, B. (2010), “Environmental evaluation of carbon capture and storage technology and large scale deployment scenarios”, Thesis, NTNU
- Smith, C., (2013), “Coal Research and Development”, Statement before the Committee on Science, Space and Technology, Subcommittee on Energy- U.S. House of Representatives
- Söderbergh, B., Jakobsson, K. and Aleklett, K. (2009), “European energy security: The future of Norwegian natural gas production”, Energy Policy, Volume 37, Issue 12, December 2009, 5037-5055.
- Steinberg, M. (1995), “The Carnol Process for CO2 Mitigation from Power Plants and the Transportation Sector”. Brookhaven National Laboratory, 1995
- Stevens, Paul (2012), “The ‘Shale Gas Revolution’: Developments and Changes”, Chatham House Briefing Papers, August 2012
- Styring, P., Jansen, D., de Coninck, H., Reith, H., and Armstrong, K. (2012), “Carbon capture and utilisation in the green economy”, The Centre for Low Carbon Futures 2011 and CO_2Chem Publishing 2012
- TETRAPLAN (2013), “TranScenario Project” (DG MOVE), Final Report
- Tiax (2010), “Methanol Fuel Blending and Materials Compatibility Report”
- Tiax (2013), “Methanol as a Renewable Energy Resource”, White Paper prepared for the Methanol Institute
- Toyota Press Room (2013), "Toyota cumulative global hybrid sales pass 5M, nearly 2M in US". Green Car Congress. Retrieved 2013-04-17
- Tuyen, M. (2009) “Electrochemical reduction of CO2 to methanol” Thesis, Louisiana State University, 2009
- VDKI Verein der Kohlenimporteure (2012), “ANNUAL REPORT2012. Facts and Trends 2011/2012”. Available for download at http://www.verein-kohlenimporteure.de/download/2012/VDKI_JB_2012_GB.pdf?navid=15
- Wadia, C., Albertus, P. and Srinivasan, V. (2011), “Resource Constraints on the Battery Energy Storage Potential for Grid and Transportation Applications”, *Journal of Power Sources,* Volume 196, Issue 3, p. 1593-1598
- Wang W., Wang S., Ma X. and Gong J. (2011), “Recent advances in catalytic hydrogenation of carbon dioxide”. Chem. Soc. Rev., 2011, 40, 3703-3727
- Wu, H., Huang, S. and Jiang, Z., (2004), “Effects of modification of silica gel and ADH on enzyme activity for enzymatic conversion of CO2 to methanol”. Cat. Today, 98 (2004) 545–552
- Xia, L. (2008), China DME market outlook. Proceedings of the 3rd international DME conference & 5th Asian DME Conference. Shanghai, China, September 2008

- Yang, A. and Cui, Y. (2012), "Global coal risk assessment: data analysis and market research", World Resources Institute Working Paper, November 2012
- Yang, C-J and Jackson, R.B. (2012), "China's growing methanol economy and its implications for energy and the environment" Energy Policy 41(2012)878–884
- Yang, Z-H., Vivian R. Moure, V.R., Dean, D.R. and Seefeldt, L.C. (2012), "Carbon dioxide reduction to methane and coupling with acetylene to form propylene catalyzed by remodeled nitrogenase", 19644–19648 | PNAS | November 27, 2012 | vol. 109 | no. 48
- Yu, C-H., Huang, C-H. and Tan, C.S. (2012),"A Review of CO_2 Capture by Absorption and Adsorption", Aerosol and Air Quality Research, 12: 745–769, 2012
- Zangeneh, F.T., Sahebdelfar, S. and Ravanchi, M.T., (2011), "Conversion of carbon dioxide to valuable petrochemicals: An approach to clean development mechanism". Journal of Natural Gas Chemistry, 20 (3): 219-231 May 2011
- Zhai, H. and Rubin, E.S. (2011), "Technical and Economic Assessment of Membrane-based Systems for Capturing CO_2 from Coal-fired Power Plants", Presentation to the 2011 AIChE Spring Meeting, Chicago, March 13-17, 2011
- Zhen, H. et al (2010), 4th International DME Conference, Stockholm 6 -9 September 2010

As Europe's access to fossil fuels becomes more limited and expensive, the issue of alternative sources of fuel arises. This study considers the obstacles in place to using carbon dioxide to produce methanol, and the feasibility of using methanol in car transport. Over the long term, methanol could help reduce dependence on fossil fuels and counteract risks to security of supply, but considerable research is needed to make carbon dioxide an attractive raw material. Policy options are considered to reduce the costs of alternative fuels.

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