7th Conference on Applied Infrastructure Research (InfraDay)
October 10th – 11th 2008, Technical Unity Berlin

Climate Policy and Innovation in Vehicle Technology – the case of hybrid electric vehicles

Author:

Claus Doll
Fraunhofer-Institute for Systems and Innovation Research
Breslauer Str. 48, 76139 Karlsruhe, Germany,
T: +49-721-6809-354, F: +49-721-6809-135,
E: claus.doll@isi.fraunhofer.de

Date: October 5th 2008

1 Introduction

The current debate on climate gas emission targets and on CO2 emission limits of motor vehicles call for advanced technical as well as non-technical concepts. Among the latter traffic demand management, pricing and regulatory measures, including speed limits and infrastructure access control, provide possible solutions. Bud addressing peoples' daily decisions and behaviour patterns requires continuous monitoring and re-adjustment of measures as people try to maintain their style of living. Many attempts in local transport policy trying to convince travellers of the advantages of public transport underline the strong resistance to accept travel alternatives.

Technical solutions constitute an important component in solving future climate and environmental problems caused by transport (King 2008). Once developed and introduced into the market new motor technologies, vehicle construction standards or materials are available for future vehicle generations. Technological and political solutions do not exclude, but complement each other. The successful introduction of the German motorway toll for heavy goods vehicles for instance combines the technical standards for exhaust emissions (Euro-Standards) with differentiated pricing tools.

However, technical improvements may lead to rebound effects as less fuel consuming cars may encourage people to drive more (de Haan et al. 2007).

One of the intensively discussed technical solutions is combined fossil fuel and battery powered acceleration systems. These hybrid electric vehicles (HEVs) allow driving quietly and locally emission-free because the internal combustion engine is run in a more favourable load range, while the highly efficient electric motor supports at low speeds and in acceleration phases. Further reductions in fuel consumption are achieved by down sizing the combustion engine and by recuperating brake energy back into the battery. However, the actual environmental and energy advantage strongly depends on driving styles and driving cycles.

This paper constitutes a summary of a case study on future markets for hybrid propulsion technologies carried out within the study “future markets environmental technologies” for the German Federal Environment Agency (UBA) in 2007 (FhG-ISI 2008).

2 Objectives and methodologies of the paper

Considering hybrid propulsion systems a core element of future innovative vehicle concepts the paper aims at testing whether European car manufacturers have the potential to make up for the advance of Japanese and US companies and where and under which conditions future markets for the technology may establish. The paper presents a case study on “future market: hybrid propulsion technology” carried out by Fraunhofer-ISI within the study “Innovative Environmental policy in core fields of activity” on behalf of the German Federal Environment Agency (UBA) in November 2007. Objective of the paper is to investigate the innovation dynamics in the field of hybrid technologies and to assess the innovation potential and the market power of important competing countries.

- Section 3 discusses the current state of hybrid propulsion systems, technological options and its benefit for society and the environment. Applications currently in use and potential new fields of applying the technology in cars, buses, lorries or trains are briefly presented in the chapter.
- In Section 4 innovation potentials are derived by patent analysis using the databases of the European Patent Agency (EPA) and the World Patent Office (WO). Search strategies have been defined for the three major components of hybrid vehicles: combustion engines, electric motors and energy storage devices. By time series of patent applications from 1991 to 2005 the “relative patent share” of the most relevant competing countries is computed and compared to other core technologies (traditional combustion and fuel cell vehicles).

- Section 5 deals with the economic power of the competing countries, which is derived by analysing trade flow data taken from the UN ComTrade data base and computing the revealed comparative advantage (RCA) for the competing countries. Combining both, innovation potential and economic power in a particular technology filed provides a powerful indicator on which level within the innovation process the respective country is situated.
- Section 6 finally draws conclusions on sensitive and likely future markets for hybrid electric vehicles and the role European manufacturers and policy makers can – or should - play in this technology.

3 The hybrid propulsion technology

In the definition of this paper hybrid vehicles are defined as vehicles which are powered by both, an internal combustion engine plus a battery powered electric motor. Other forms of hybrid solutions are possible, such as the combination of fuel cell and electric motors or the combination of different fuels, but here we concentrate on hybrid electric vehicles (HEVs) and particularly on hybrid electric passenger cars.

Currently, hybrid cars lead the eco rankings of independent consumer organisations due to their commonly high fuel efficiency. Hybrid cars have the potential to be more fuel efficient than common cars as the electric motor serves the drive train under conditions where combustion engines work inefficiently. This is particularly the case at low speeds or when accelerating. Further, the battery of the electric motor can make use of brake energy (recuperation).

The energy saving potential very much depends on the driving cycle. While ordinary cars use more fuel in city traffic than on inter-urban roads, hybrids are more fuel efficient in urban traffic. Outside urban areas the combustion engine is more efficient than the electric motor and is thus used, but the heavy battery has to be moved around with the car.

Among current models the TOYOTA Prius is the obvious market leader, followed by the Honda Civic Hybrid with big distance. In the USA in 2006 262 thousand hybrid vehicles were sold, of which 107 thousand were TOYOTA Prius' and another 63 thousand other TOYOTA models. Table 1 presents the sales volumes and the fuel efficiency by driving pattern of current hybrid car models in the USA.

Table 1: Sales and fuel consumption indicators for some hybrid models (USA 2006)

Market and model	**Fuel consumption outside urban areas**	**Fuel consumption s in urban areas**	**Vehicles sold in the USA 2006**
	l/100 km		Units
TOYOTA Prius	4,6	3,9	106'971
TOYOTA Highland	8,8	7,6	31'485
TOYOTA Camry	6,2	5,9	31'341
TOYOTA total			**169'797**
HONDA Accord	8,2	11,8	5'598
HONDA Civic Hybrid	4,6	4,8	31'253
HONDA Insight			722
HONDA total			**37'573**
FORD Mercury Marriner	10,3	13,1	
FORD Escape+Marriner	8,2	7,2	**22'549**
LEXUS GS450h	8,4	9,5	1'784
LEXUS RX400h	8,8	7,4	20'161
LEXUS total			**21'945**
OVERALL			**261'864**

Source: http://hybridreview.blogspot.com/2007/01/hybrid-car-sales-in-2006.html

Hybrid vehicles consist of four major components. For further details please refer to Ahmed (2004), Bak (2005), ^Chan (2002), Stan (2005), Franke (2004), Power (2007), Mohrdiek (2007), McLean and Lave (2002), Neunin (2007) or other works on vehicle propulsion technologies. :

- The internal combustion engine. This may be diesel or gasoline powered. But commonly gasoline engines are used as they are more complementary to electric motors across all engine speeds than diesel engines. In most cases combustion engines are downsized in hybrid drive trains.
- Electric motors are constantly energy efficient across a wide range of engine speeds while combustion engines are less efficient at low speeds. Electric motors can thus either support the internal combustion engine while starting or accelerating the vehicle, or may fully take over vehicle propulsion in certain situations.
- Electric energy storage on board is one of the key issues for designing hybrid vehicles. Due to safety reasons contemporary models use nickel-metal hybrid (NMH) batteries. But advances in the safety and durability of lithium-ion batteries promise an extended range of the electric power train and thus more efficient hybrid

or pure battery powered vehicles. The plug-in hybrid concept uses the electric motor for driving purposes only and fuels the battery via the electricity grid network.

- The transmission system and the on-board electronics to regulate and combine the two power sources of a hybrid vehicle are critical. Using epicyclic or planetary gears the power of both engines can be run in parallel. In contrast, serial concepts simply use the combustion engine to fuel the battery through an on-board power generator. More advanced concepts use hub motors directly at the wheels to further increase the efficiency energy efficiency.

It is stated by the automotive industry, that most of these components will be round in virtually all contemporary vehicle designs. In particular power management on board and more efficient batteries serving the increasing number of in-vehicle electronic devices are to be named here.

Hybrid technologies are frequently considered an intermediate step towards fully electric powered vehicles or fuel cell cars (Demiodöven and Deutsch 2004, Romm 2004). The have the charm of not being restricted to a particular technology, but can make use of improvements in battery as well as in common combustion engine technologies. The plug-in technology is further promoted by the power generation industry via the vehicle-to-grid concept (Brooks 2002). This should help to temporarily store supply peaks in the grid network, e.g. caused by renewable energy sources such as wind or solar power.

Besides less fuel consumption across the whole driving cycle hybrid vehicles emit less exhaust emissions and are, depending on their configuration, able to drive completely emission-free on parts of their journey. Further, they are quieter in start and acceleration phases. This makes them particularly attractive for use in urban areas. These obvious advantages have to be balanced against the production and disposal externalities of the battery and, in case of plug-in hybrids, the efficiency of electric energy generation (Grünwald 2007, de Haan et al. 2006).

4 Innovation potentials

The first patent worldwide for a gasoline-electric powered vehicle was applied in 1905. Its goal was not to increase fuel efficiency, but to enhance the acceleration power up to 10 seconds from 0 to 40 kph. But the development of internal combustion engines went on quickly and fuel efficiency was not an issue for customers at that time. Thus, the first hybrid model offered in 1914 in the USA was not successful on the market.

Further serious developments of hybrid models were pushed forward in the early 1990 in Europe, but due to the market entry of clean diesel technologies and stagnation in battery technology this stand of car development was given up by European manufacturers. Driven by the enormous air quality problems in the big metropolitan areas of Japan and the US and the non-acceptance of diesel as a car fuel in these countries, TOYOTA developed and successfully introduced the first serial hybrid electric car, the Prius.

To explore the innovation dynamics in this applied technology field we have analysed the patents applied for several components of hybrid cars at the European Patent Agency (EPA) and the World Patent Office (WO). We have concentrated on components of hybrid cars as the hybrid concept itself is a modular technology for which no all-embracing patents can be expected. Concerning the components we have concentrated on the three key elements

- Electric motors
- battery technology and
- combustion engines

For transmission or gear systems and power regulation electronics no specific patents have been found and it can be suspected that the innovation dynamics in these areas is less expressed as for the key elements considered here.

The patent search strategy has been defined on the basis of patent classes using the nomenclature of the international patent classification (IPC). Search worlds have not been used as applicants formulate the patent description commonly in rather general terms to broaden the possible fields of application. As further applicants in some cases try to “hide” their patents by allocating them to less appropriate patent classes the search strategies have been verified by intensive sample tests.

Figure 1 presents the relative development of patent applications for components and entire systems of hybrid car technologies in Europe and worldwide from 1991 to 2004. The development of the curves shows that the hybrid technologies as a border technology between the traditional fields of combustion engines, electric motors and energy storage devices shows a much more dynamic development than its single components. The development shows two peaks in the mid 1990s were in particular in Europe the industry was still not focussed on diesel technologies, and around 2001 when TOYOTA finally developed the Prius.

Figure 1: Index of patent applications of hybrid vehicle technologies and their components (1991 = 100)

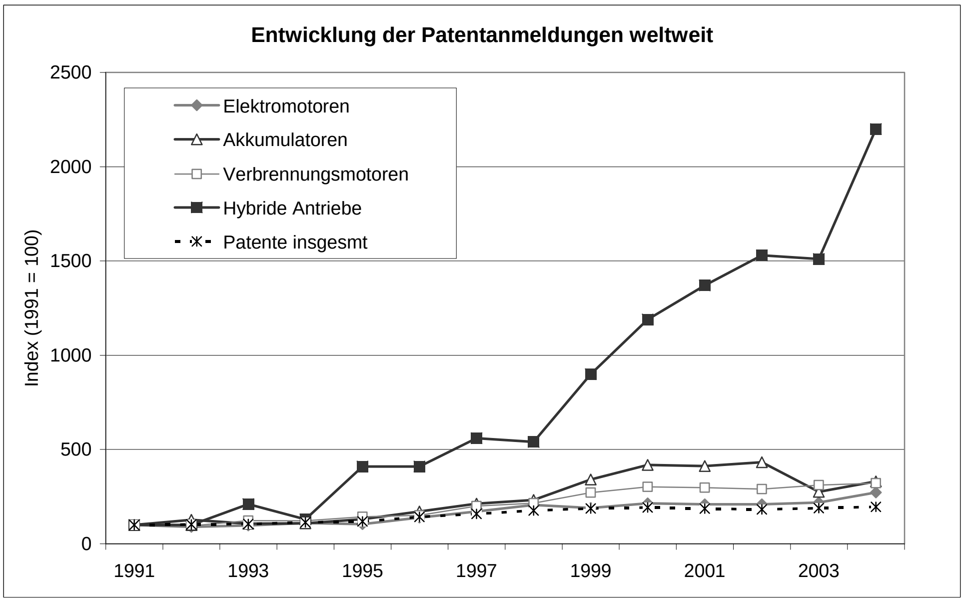
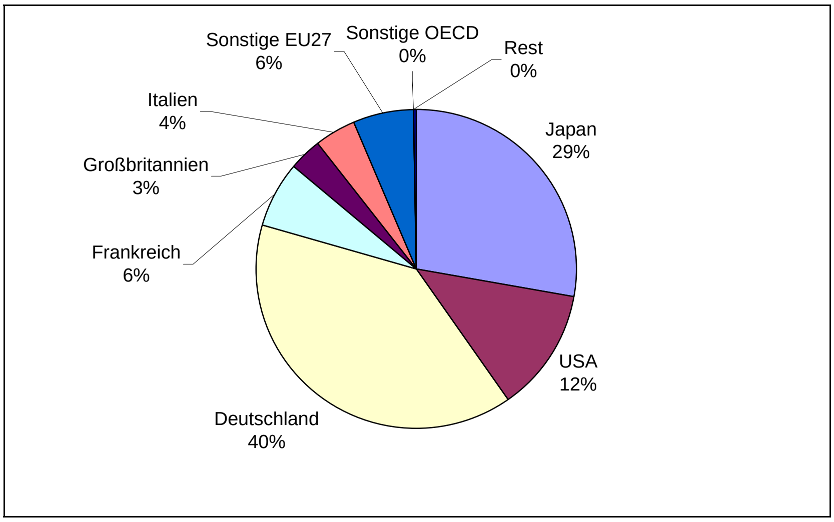


Figure 2 shows the distribution of patent applications for hybrid systems and their components by country. While the production of hybrid vehicles and the most critical components, such as batteries, takes place in Japan and the US (FhG-ISI 2006), the high share of Germany (40 %) of all patent applications in the field is explained by the development in electric motors, break systems for energy recuperation and combustion engines. Altogether, EU27 countries hold around 60 % of patents for hybrid propulsion systems and their components in the major international patent agencies. Europe thus seems to be in a good position for the future development of new vehicle concepts.

Figure 2: Patent applications of hybrid propulsion systems worldwide by application country 2000 – 2004



The “Relative Patent Application” (RPA) is a measure for the specialisation of the research and development activities of countries in particular technologies. It basically relates the ratio of the patents applied in the technology field *T*, $P_{T,C}$ to all patents P_C in the country *C* to the respective ratio of patent applications of all countries. The values are transformed by the arccot-function and multiplied by 100 to yield in workable value ranges. Formally:

$$RPA = 100 \cdot arc\cot\left(\frac{P_{T,C}/P_C}{P_T/\;P}\right)$$

A RPA of 0 means a average specialisation of the country’s RTD activities compared to all other countries, while values close to -100 indicate no specialisation in the technology field and +100 indicate full concentration of national RTD activities in this area.

The results of the RPA indicator for hybrid technologies and their components are depicted in Figure 3. Comparing the specialisation of countries in the late 1990s and the first half of the current decade, a number of European countries, Canada and Russia have focussed their RTD activities more towards technologies relevant for hybrid propulsion systems. Only Switzerland, Sweden, France and Germany show declining specialisation indictors. As these include the big vehicle manufacturing countries in the EU the outcome of the RPA indicator here seems to support to reflect well the loss in interest of European car manufacturers in hybrid concepts since the late 1990s.

Figure 3: RPA of hybrid propulsion technology and its components 2000 – 2004 in comparison to 1995 – 1999 by country

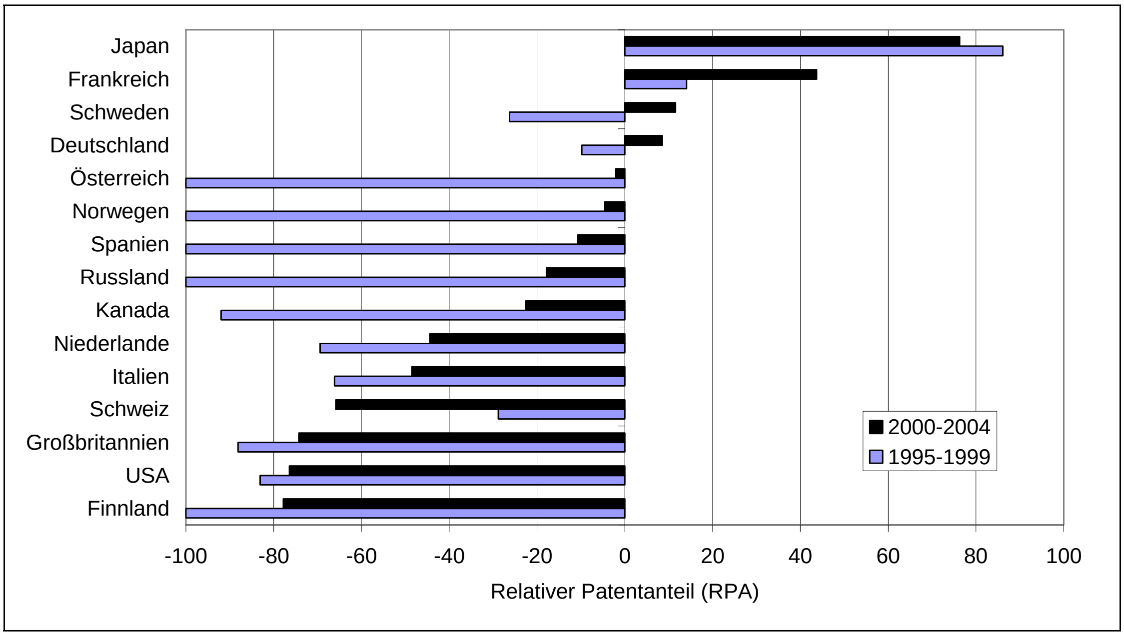
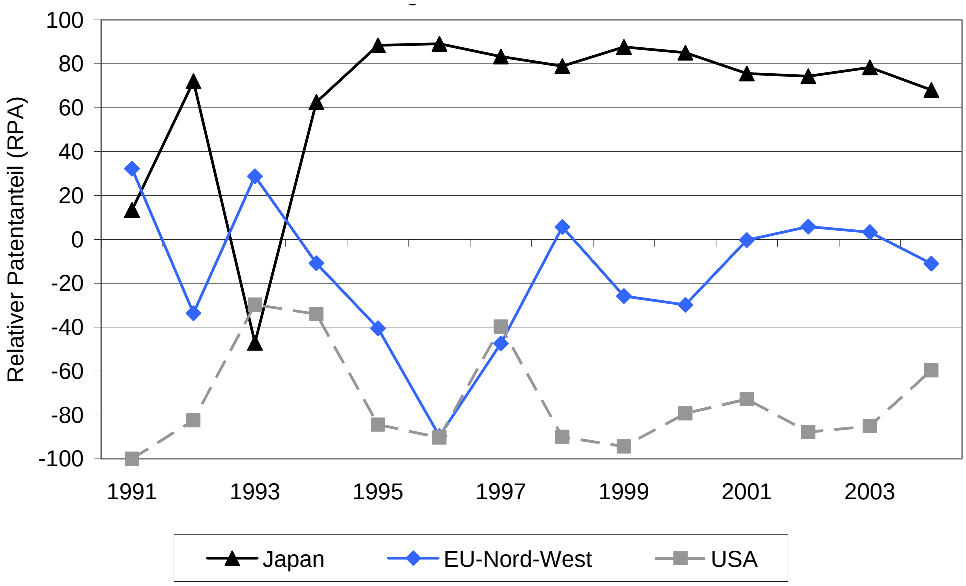


Figure 4 explicitly compares the RPA indicator for Japan, the USA and the north-western states of the EU, including France, Germany, the UK and Sweden. Here the rise in competences for hybrid technologies in Japan and the declining specialisation of the US gets very obvious. Europe's role, however, is not so clear. There seems to be a stabilisation at a medium level since the end of the 1990s.

Figure 4: Relative patent shares of hybrid propulsion systems for selected world regions over time



All in all the numerical analysis reveals the leading role of Japanese car manufacturers as concerns hybrid technologies and their components. But the figures also show that Europe's position in this potentially important future market is not too bad.

5 Markets and competitors

Estimating the potential size of sales markets for hybrid electric vehicles is difficult as their benefits for the users depend on a number of factors, such as

- Fuel and electric energy prices (compare e.g. EIA 2007 or Mantzos and Capros 2006)
- driving habits, in particular urban and inter-urban trips
- policy and fiscal incentives, such as lower road charges, special treatment in environmental zones, etc.
- technical progress, in particular in battery technology
- future of competing concepts, such as clean diesel, electric vehicles or fuel cells

To get an idea of future markets we have asked a number of car manufacturers on their expectations. Table 2 gives an impression of the expectations of German auto companies. Astonishing is the rather low number of (10 % to 15 %) expected for Europe. This is explained by the popularity of the clean diesel concept in Europe, while diesel as a car fuel is still not accepted by US or Japanese consumers. Given the big size of China the expected 5 % market share would end in an enormous market for hybrid vehicles in total numbers (Ballagheer 2006). In particular for developing countries the concept is considered inappropriate due to the complex technology. For other than car markets compare e.g. Green et al. (2006).

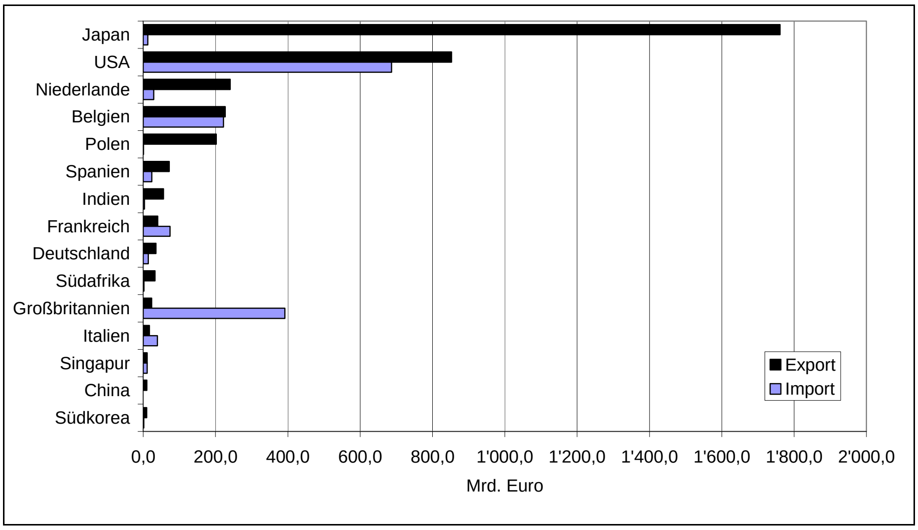
Table 2: Potential market shares of hybrid vehicles until 2020

Country	Potential market share until 2020
Europe	10 – 15 %
USA	20 %
Japan	30 %
China	5 %

Source: Informal statement of selected German car manufacturers

From the UN ComTrade database Figure 5 shows the exports and imports of electric powered vehicles in 2004. While Japan and – astonishingly – a number of other countries like the Netherlands, Poland and Spain, do only export electric vehicles, the trade flows of the US are balanced, but the UK appears the biggest net importer. This can be explained as hybrid vehicles are exempted from the London congestion charge introduced in 2003 in inner London. The simple message arising from the latter result is that policy settings are of utmost importance for creating lead markets for new technologies, such as hybrid electric vehicle propulsion systems.

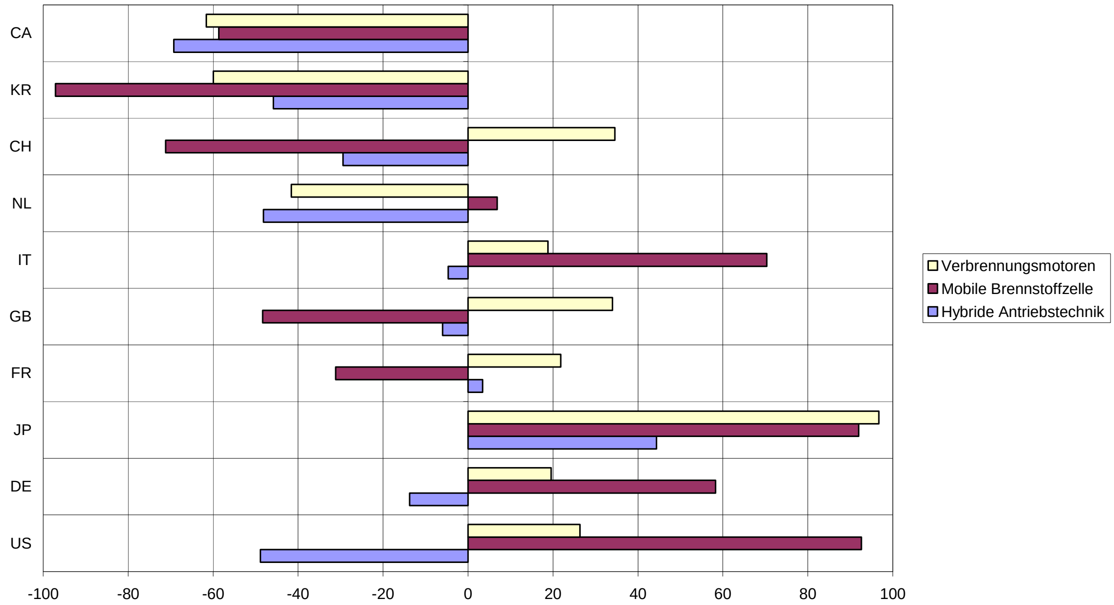
Figure 5: Exports and Imports of vehicles with electric propulsion of the 15 most export-intensive nations in 2004



Similar to the Relative Patent Application (RPA) the "Revealed Comparative Advantage" (RCA) indicator expresses the relative export power of a country with a given product type compared to the relative export power of all countries worldwide. Figure 6 compares the RCA indicator for selected countries between hybrid technologies, fuel cell technologies traditional combustion engines. There seems to be some correlation between the RCA for combustion engines and hybrid technologies which indicates that combustion engines dominate the patents found for hybrid systems.

European manufacturers depend strongly in imparts of high-end batteries from Japan or the US. Electric motors and break systems are partly imparted and partly produced in Europe. The least import dependency is considered for gear systems and combustion engines. The European industry is thus only in one out of several components for hybrid vehicles dependent on imports, but on the other hand only very little of Europe's current competences in car manufacturing have the potential for major exports abroad. The highest potential is considered for combustion engines. These expectations have been collected through a series of interviews with German car manufacturers and industry associations.

Figure 6: Revealed Comparative Advantage (RCA) for components of hybrid propulsion systems for the 10 most export-intensive countries compared to fuel cell technologies and traditional combustion engines



To conclude: markets are potentially, big and policy has the power to create sufficiently large application fields or lead markets. Good examples are the London congestion charge; the free access of hybrid vehicles into inner Athens or the Californian zero emissions vehicle policy. Although European auto industries are well prepared to gain a share of hybrid markets, their dependency on imports of batteries and the missing of sufficiently big markets in Europe to guarantee stable sales numbers are a challenge for the future.

6 Findings

Hybrid electric vehicles are highly energy efficient in urban areas, while they can not compete with other available technologies on inter-urban roads. Given their higher purchase costs, hybrid cars are particularly suitable to reduce energy consumption and climate gas when used in commercial urban vehicle fleets. Good practice examples are taxi or urban delivery fleets. For this purpose the technology should be supported by policy measures in big agglomeration areas.

Through interviews with industry people and politicians we have collected the following list of strengths, weaknesses, opportunities and threats Europe faces as it comes to the development and successful market introduction of hybrid electric vehicles. From this simple SWAT analysis and the previous elaborations a number of conclusions are derived. They are elaborated throughout the following paragraphs.

Table 3: SWOT-Analysis for hybrid propulsion systems

Strengths	Opportunities
• Powerful car manufacturing industry • well skilled engineers • excellent staring position in some components, e.g. combustion engines and car electronics • Leading position in hybrid systems for special and heavy goods vehicles	• ambiguous environmental policy of the European Union • growing cities worldwide plus growing concern of citizens for environmental problems and well-off consumers • rapidly growing energy prices
Weaknesses	**Threats**
• general back-log in developing hybrid vehicle propulsion systems • no competence in the field of rechargeable batteries • different environmental and transport policies in EU member states.	• strong competition by catching-up countries • shortage of specialised employees • declining demand due to demographic change • further preference of consumers towards diesel technologies in cars

The technology dynamics of hybrid propulsion systems appears more intensive than the dynamics of its core components: combustion engine, electric motors and energy storage technology. Due to its higher price and the more expensive maintenance the destination countries of the technology are most likely located in North America, Europe, Japan, Australia and the metropolises of South America and Southeast Asia. However, estimates of future market potential widely diverge.

With regard to technology, Japan, the United States, France and Sweden are the most important competitors for Germany. European producers, however, are completely dependent on imports and lag sufficient technology competence in key areas, namely in the field of battery technology. Due to specific preconditions and national incentive systems, the competing countries are on different stages of the development processes. Important is the disapproval of diesel for cars in Japan and the USA but also tax incentives and special conditions for hybrid cars, e. g. the Congestion Charge incentives and special conditions for hybrid cars, e. g. the Congestion Charge in London.

Although Japan appears as the technology leader in the field of hybrid electric vehicles, Germany holds 40 % and the EU 27 60 % of the worldwide patent applications of hybrid propulsion systems and their components. These figures indicate a nameable technological and economic potential of Europe, and especially of Germany, in the field of hybrid propulsion technology, which are the result of the productive and internationally very successful car industry on the one hand and of the high specialization in some key components on the other hand.

Also the ambitious environmental policy of the EU as well as of individual member states constitutes a potential advantage. But the different developments in environmental and transport policies are a retarding factor regarding the creation of a standardized large European market for alternative vehicle concepts. Creating reliable incentive systems for clean vehicle technologies across Europe would create a sufficiently large market, allowing European car manufacturers to build up own competences and production capacities for alternative propulsion systems. Challenges in this process are the technology advance of US and Asian manufacturers and the foreseen lack of qualified engineers in Europe.

Due to still existing problems with battery capacities or fuel cells, hybrid electric vehicles will play a major role for particular market segments and as a transition technology to totally emission-free propulsion technologies. Moreover, clean diesel technology slowly gains acceptance in the US. Depending on driving patterns and driving habits this concept can even be superior to hybrid electric systems as it does not require heavy batteries and the maintenance of the vehicles is simpler.

References

Ahmed, M. A. H. (2004): Bewertung von alternativen Antriebskonzepten in Fahrzeugen mit unterschiedlichen Einsatzcharakteristiken. Univ. Dissertation and der Fakultät für Maschinenwesen der Technischen Universität Dresden, Sept. 2004.

Back, M (2005): Prädiktive Antriebsregelung zum energieoptimalen Betrieb von Hybridfahrzeugen. Schriften des Instituts für Regelungs- und Steuerungssysteme, Universität Karlsruhe (TH), Band 02. Universitätsverlag Karlsruhe.

Brooks, A. (2002): Vehicle-to-Grid Demonstration Project: Grid Regulation Ancillary Service with a Battery Electric Vehicle. Schlussbericht an das Kalifornische Air Ressources Board und die kalifornische Environmental Protection Agency. San Dimas, Dezember 2002.

Chan, C. C. (2002): The State of the Art of Electric and Hybrid Vehicles. IEEE Proceedings, Ausg. 90 Nr. 2, Februar 2002.

Demiodöven, N. and J. Deutsch (2004): Hybrid Cars Now, Fuel Cell Cars Later. Science 305, 974 (2004).

EIA (2007): Annual Energy Outlook 2003: Projections to 2030, US Energy Information Administration, Washington D.C., January 2007.

FhG-ISI (2006): Foresight and Assesment for Environmental Technologies. Work Package 1 Identification and Characterisation of Environmental Technolgies. Task 1.1 und 1.2. Karlsruhe, 4./ 5. Dezember 2006

FhG-ISI (2008): Zukunftsmarkt Hybride Antriebstechnologie. Case Study on behalf of the German Environment Agency (UBA).

Franke, F. (2004): Mit dem PRIUS in die Zukunft, Hybrid-Technologie für das 21. Jahrhundert. Motorbuch Verlag Stuttgart.

Gallagher, K. S. (2006): Round Table on Barriers and Incentives for Hybrid Vehicles in China. Belfer Center for Science and International Affairs und China Automotive Technology and Research Center. Bejing, Mai 2006.

Green, D. L., K. G. Duleep and W. McManus (2004): Future Potential of Hybrid and Diesel Powertrains in the U. S. Light Duty Vehicle Market. Studie im Auftrag des US Department for Energy. Washington D.C.

de Haan, P., M. G. Müller and A. Peters (2006): Does the Hybrid Toyota Prius Lead to Rebound Effects? Analysis of Size and Number of Cars Previously Owned by Swiss Prius Buyers. Ecological Economics 58 (2006), pp. 592 – 605. Elsevier.

King (2008): The King Review of low-carbon cars. HM Treasury, London, 2008.

Power, J. D. (2007): 2007 Alternative Powertrain Study. J. D. Power Associates, Westlake Village, USA

Mantzos, L. and Capros, P (2006): EU (2006) European Energy and Transport Trends to 2030 – update 2006. Bericht an die Europäische Kommission, Mai 2006.

McLean, H. L., Lave, L. B. (2002): Evaluating automobile fuel/propulsion system technologies. Progress in Energy and Combustion Science. Pergamon. September 2002.

Mohrdieck (2007): Alternative Drive Trains for Sustainable Mobility. 4. Braunschweiger Symposium „Hybrid Vehicles and Energy Management" 14./15.2.2007

Naunin, Dietrich (2007):Hybrid-, Batterie- und Brennstoffzellen-Elektrofahrzeuge : Technik, Strukturen und Entwicklungen. 4. Aufl., Expert-Verlag, Renningen.

Romm, J. (2004): The Car and Fuel of the Future. Energy Policy 34 (2006), pp. 2609 – 2614. Elsevier.

Stan C. (2005): Alternative Antriebe für Automobile. Springer-Verlag Berlin, Heidelberg.

Grünwand (2007): Perspektiven eines CO2- und emissionsfreien Verkehrs – Kraftstoffe und Antriebe im Überblick. Büro für Technikfolgenabschätzung beim Deutschen Bundestag. Berlin.