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*Annex VII: Hybrid Vehicles  
Overview Report 2000*

# **Chapter 4: Components for hybrid vehicles**

*Worldwide developments and activities  
in the field of hybrid  
road-vehicle technology*

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## This report

This Overview Report on the status of Hybrid Vehicle Technologies and Programmes is the result of collaborative work carried out in phase I of Annex VII between June 1998 and June 2000. It incorporates the results of both Subtask VII/1 and Subtask VII/2 over this period. The main text is based on the information collected by the participants on the status of hybrid vehicle technology and the R&D and implementation projects and programmes in various countries. As the Topics that have been studied in Subtask VII/2 closely relate to the aspects that are analyzed in the Overview Report resulting from Subtask VII/1, the Topic Reports have been integrated into this report at the appropriate places. Whenever this is the case, authors of the Topic Report are clearly mentioned.

At the end of phase II an updated version of this Overview Report will be published, incorporating the Topic Reports on subjects studied in phase II.

The structure of the report is as follows:

Chapter 2 introduces the various hybrid drivetrain configurations which are being developed and studied by the light duty and heavy duty vehicle manufacturers in the world. Roughly spoken, one can divide hybrid drivetrain configurations using electrical storage devices into series-, parallel and combined hybrids. Furthermore, hybrids making use of a mechanical energy storage device are briefly discussed.

Chapter 3 takes a closer look at some concrete examples of hybrid vehicles that have been developed for different applications (two-wheelers, passenger cars, vans, buses and trucks) and discusses some trends. Different vehicle applications demand different hybrid configurations. On the basis of existing examples the choices made by the R&D community and automotive industry are illustrated.

Subsequently, Chapter 4 deals with the two main components that are specifically developed for hybrid vehicle applications: thermal energy sources and energy storage devices (i.e. batteries, supercapacitors and flywheels). An overview and analysis of the state-of-the-art of these components is presented and some general reflections on the latest developments are given. In a future version of this report more components for hybrid powertrains will be discussed.

Chapter 5 describes large programmes and projects on hybrid vehicles that are being carried out worldwide. These are on the one hand divided into governmental and industrial programmes and on the other hand split up for the three regions Europe, USA and Asia.

Based on the vast amount of data collected in Annex VII Chapter 6 analyses worldwide trends within the field of hybrid vehicle technology in a more statistical manner. Trends in R&D (for instance status of hybrid vehicles, components used within several hybrid vehicle configurations), market introduction and mass production are visualized. Furthermore time paths for the development and introduction of hybrid electric vehicles and fuel cell vehicles are discussed.

Chapter 7 is focused on energy and emission aspects of hybrid vehicles. This chapter is composed of various Topic Reports written by the Annex VII participants. Attention is paid to test methods for HEVs, energy consumption and emissions of hybrids and the perspectives for using alternative motor fuels in hybrid vehicles. As part of the discussion on energy aspects a comparative assessment is presented of different HEV configurations using the simulation tool ADVISOR.

The next chapter (Chapter 8) presents a study of the cost aspects of hybrids, fully based on a Topic Report devoted to this subject.

Chapter 9 concludes the report with some final remarks. A summary of the conclusions from the various chapters of this report can be found in the executive summary.

Finally in Chapter 10 a general overview is given of the information collected on hybrid vehicles (from human powered hybrid two-wheelers up to heavy duty vehicles) which are currently in the R&D or early commercial stage (prototypes, testing vehicles, concept cars). The overview is of course not complete. A selection is made of those vehicles that are attractive or illustrative by virtue of their technical innovation, or that are already in the (pre-) commercial stage. Apart from general vehicle data, some technical information of the driveline configuration is given (whenever available).

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## 4 Components for hybrid vehicles

### 4.1 Introduction

Hybrid vehicles to a large extent use components that can also be found in other propulsion systems: combustion engines, electric machines, power electronics and batteries. However, these components, by themselves or in combination with other components, can be optimized for their use in hybrid powertrain configurations. Combustion engines, for example, can be optimized for use in a restricted area of their engine map, while batteries in hybrids are being optimized for power density. This chapter gives a brief overview on the state-of-the-art and the latest development of thermal energy sources and energy storage devices for hybrid vehicles.

In a later version of this report (to be published at the end of phase II of the project) also developments in the field of electric machines and power electronics will be included.

### 4.2 Primary energy converters in hybrid vehicles

Generally speaking, the primary energy converter is the device that delivers the main part of the energy that is needed for propelling the vehicle under average driving conditions.

Depending on the powertrain structure, various primary energy converters can be distinguished:

- In a conventional, parallel hybrid or combined hybrid powertrain, the primary energy converter often is an internal combustion engine. The internal combustion engine may be augmented by means of electrical motors in starter-alternator and parallel hybrid form.
- In a series hybrid vehicle, the primary energy converter often is a generator set. Another name for this generator set is auxiliary power unit (APU). When it is a battery dominated series hybrid, the name range-extender is often used for the generator set. Normally speaking, a generator set consists of a thermal energy converter (internal or external combustion engine), coupled to a generator. This generator delivers electrical energy to the rest of the powertrain.

Various types of internal and external combustion engines can be distinguished:

- External Combustion Engine: Stirling engine
- Internal Combustion Engine: two types exist, a continuous internal combustion (gas turbine) and an intermittent internal combustion engine. This last category is the most well known one, with spark ignited and compression ignited engines as widely used examples.

Fuel cells are also primary energy converters. They convert chemical energy directly into electrical energy, and can be used in series-hybrid vehicles instead of a generator set. Fuel cells can also be used in a non-hybrid configuration (pure fuel cell vehicle) where the fuel cell directly powers the electrical drive without use of an electrochemical storage device.

For an overview of primary energy converters and their main characteristics see Table 4.1. For more details on the definition of hybrids see chapter 2.

**Table 4.1 Overview of primary energy converters and their main characteristics**

Type of primary energy converter			Operating principle	Advantages	Disadvantages	Remarks
<i>External Combustion Engine</i>			External heat generation, internal conversion into movement	Emissions Simple Universal Theoretical efficiency	Practical Efficiency Mass	e.g. Stirling engine
<i>Internal Combustion Engine</i>	<i>Continuous combustion</i>		Continuous heat generation, directly converted into movement	Mass Volume Emissions Vibrations	Costs Efficiency Dynamics	e.g. gasturbine
	<i>Intermittent combustion</i>	<i>Compression ignited</i>	Fuel/air mixture ignited by increase in temperature and pressure	Efficiency Robust Commodity Costs	Emissions Noise	i.e. Diesel engines, two or four stroked, reciprocating or rotating piston. Diesel, biodiesel, synthetic fuel or DME fuelled
		<i>Spark ignited</i>	Fuel/air mixture ignited by spark	Mass Volume Emissions w. cat Commodity Costs Full load efficiency.	Part load efficiency	i.e. Otto engines, two or four stroke, reciprocating or rotating piston. Hydrogen, natural gas, propane or gasoline fuelled
<i>Fuel cells</i>			Direct electrochemical conversion of fuel into electricity	Efficiency Emissions	Auxiliaries Mass Volume Fuel Costs	e.g. PEM-type for automotive application, hydrogen fuelled or other fuel with fuel reformer or direct internal reforming

Dependent on the hybrid powertrain configuration, the load pattern of a primary energy converter can differ significantly compared to that of conventional powertrain engines. The main differences are:

- Lower power requirements because of peak boosting by means of another energy converter in the hybrid powertrain;
- Smaller operating area due to total or partial uncoupling from road load;
- Less dynamic operation due to total or partial uncoupling from road load.

There are two main consequences because of these differences. Firstly, some energy converters that, e.g. because of unsuitable dynamic behavior, are not often used in conventional powertrains may become interesting in hybrid applications (gas turbines, Stirling engines, small fuel cells).

Secondly, in hybrid applications better known energy converters like spark and compression ignited engines are used in a different way than in a conventional powertrain. This means that they can be adapted and optimized for their use in hybrids. Some of the possibilities are mentioned in Table 4.2.

**Table 4.2 Possible adaptations and optimizations to an engine when used in hybrid applications**

	<b>Possible adaptations</b>
<b><i>Engine</i></b>	Downsizing
	Turbo-charging or supercharging
	Ignition timing
	Fuel injection shape, timing and duration
	Combustion chamber shape
	Valve train
	Thermal system
	Mechanical load optimization
	Exhaust gas recirculation
	No idling phase required
<b><i>Exhaust aftertreatment</i></b>	Oxidation catalyst
	Three-way catalyst
	NOx reduction catalyst
	Particulate filter
	Pre-heating
<b><i>Fuel</i></b>	Reformulated fuels
	Alternative fuels
<b><i>Integration</i></b>	With electrical machine(s)
	With hybrid control strategy
	Deleting auxiliaries

The lower power requirement in certain hybrid configurations means that the engine can be downsized in power. By doing this, the engine load can be relatively higher which yields in a net engine efficiency increase. Also turbo- or supercharging can be considered (high pressure, less dynamic requirements, peak efficiency in small operating area).

If the engine can be used in a smaller operating area, it can be easier to perform optimizations on the engine and its aftertreatment system. This can result in better fuel efficiency, emission and noise behavior. Also the secondary systems like the engine cooling can be specifically designed. All this results in a lighter, smaller and better performing engine.

#### **4.2.1 General design and development aspects**

In general, the following design and development aspects can be distinguished when using an engine for hybrid application:

- Determining the general specifications (e.g. power, efficiency, emissions, noise) of the engine, which depend on the vehicle's programme of demands and the chosen energy management strategy.
- Determining the engine operating points (torque and speed). This is dependant on the power control strategy and the consequences on emissions and efficiency when these operating points are changed (sensitivity).
- Optimizing the engine for these working point(s). This may include adapting the injection and ignition systems, the valve timing, and the intake manifold.
- Adapting the engine cooling system. This may comprise the redimensioning of the cooling system, the integration of the engine cooling system with other systems in the hybrid powertrain (cooling

of other components, dissipative electrical braking), incorporating engine and catalyst pre-heating possibilities, and ensuring passenger compartment heating when the engine is turned off.

- Adapting or developing the exhaust aftertreatment system (type, size, layout).
- Coupling of the engine to an electrical machine (stability control, mechanical interface, possibility of omitting the alternator, starter motor, and the flywheel).
- Ensuring satisfactory start/stop behavior (noise, wear, emissions, efficiency).

The part load efficiency of a spark-ignited engine can be as low as 0-25%. High load efficiency can be 25-40%, which means that by hybridizing SI engined vehicles a large fuel efficiency gain can be achieved. In contrast, CI engined vehicles have high peak efficiency (45%), and the efficiency does not fall off at the same fast rate outside the high load region as is the case for the SI engine. This means that hybridizing CI engined vehicles creates very fuel-efficient vehicles, although the relative gain is less than for SI engined vehicles.

#### 4.2.2 Fuel cells

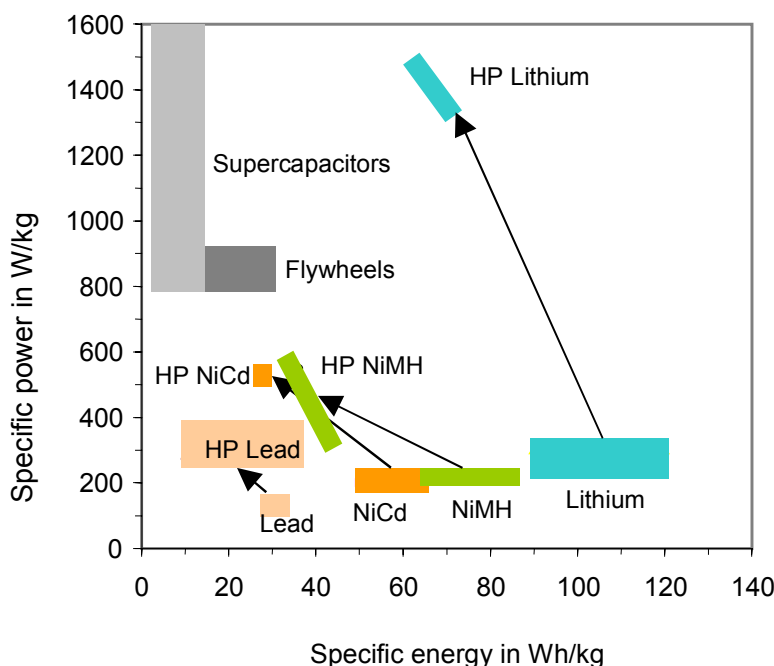
Finally, some words have to be spent on fuel cells as prime energy converter. Fuel cells combine hydrogen and air to produce electric energy and emit only pure water. The efficiency is high. In contrast to internal combustion engines, peak efficiency (around 60% for the fuel cell itself) occurs under low part-load conditions. Fuel cells are relatively easy to integrate in the hybrid-electric powertrain because of their electric energy output. In a non-hybrid configuration, without the use of a battery, the fuel cell system's output is directly coupled to the road load. In a series-hybrid configuration, with an electric energy storage, the fuel cell system's output is more or less uncoupled from the road load, while the battery provides the possibility of regenerating brake energy. Depending on the use conditions a hybrid fuel cell vehicle may be more fuel-efficient than a non-hybrid configuration. The presence of a battery allows the use of fuel cell systems (e.g. in combination with a fuel processor) with a slower response time. Optimizing efficiency in a hybrid configuration, however, requires the use of an overdimensioned fuel cell (peak efficiency at part load), which in combination with the added battery leads to high costs and high weight. On the other hand, operating a fuel cell minimized in size at high load to meet the average power requirement in a series-hybrid sacrifices efficiency.

#### 4.3 Energy storage devices

Batteries have been in use as an energy storage medium for a very long time in many applications, including conventional automobiles. In hybrid vehicles batteries as well as flywheels and supercapacitors can be used as an energy storage medium. Each system has its own characteristics and therefore has its own advantages and disadvantages. Roughly spoken, batteries (which store energy in an electro-chemical process) have a limited specific power (kW/kg) regarding absorbing and delivering energy compared to flywheels (which store energy mechanically) and supercapacitors (which store energy in a physical process). On the other hand, flywheels and supercapacitors have a more limited specific energy (kWh/kg) compared to batteries.

For a long time battery development for propulsion applications has been primarily targeted at increasing specific energy in order to be able to provide battery-electric vehicles with an acceptable range. In recent years a clear distinction can be discerned in battery R&D for battery-electric vehicle applications and R&D for hybrid-electric vehicle applications. Battery development for HEVs aims at increasing specific power while maintaining an acceptable specific energy. Specific power values comparable to those of flywheels and supercapacitors are found to be feasible.

Figure 4.1 reflects the differences in specific power and energy distribution of several relevant battery types specifically developed for both BEVs and HEVs. It must be stated that one should not look too closely to the quantitative values in Figure 4.1. These numbers are always debatable and quickly outdated. Moreover, the specific energy of both supercapacitors and flywheels tend to be less stretched out than given in the figure. For supercapacitors, a profound barrier seems to exist at 6 Wh/kg, whereas it is difficult for flywheels to contain more energy than about 20 to 25 W/kg. This is mainly due to a limitation of the maximum rotational speed (rpm) of the flywheel. However, the overall differences between different storage systems and between batteries for BEV and HEV applications are clearly depicted in the figure. From this figure it can be seen that lithium batteries seem the most promising (from an energy and power point of view) for use in advanced BEVs and HEVs. Reliability and cost aspects, however, could restrain the possible use of such batteries.



**Figure 4.1 Comparison of batteries specifically developed for BEV and HEV use**

Table 4.3 contains a list with the ‘most popular’ batteries for powering battery-electric and hybrid-electric vehicles, based on a recently published list by The Motor Industry Research Association (MIRA) and on data available at TNO.

One has to bear in mind that values presented have been accomplished under optimum laboratory circumstances. The maximum values are valid for periods longer than just a few seconds (during short time, much higher maximum values are attainable). Furthermore, these maximum specific energy and power values are not valid simultaneously. When discharged at the maximum power indicated in the table, the maximum amount of energy supplied by the battery is smaller than the value in the table and vice versa. Moreover, a spread to these values should be given, depending on specific applications and characteristics of the technology. Also, some battery types are relatively well developed, whereas other battery types are just in the first laboratory stage. Nevertheless, the values shown reflect a certain trend and relation in the state-of-the-art of battery development.

**Table 4.3 EV battery comparisons (based on data from MIRA and TNO)**

<i>Battery type</i>	<i>Maximum energy density (Wh/kg)</i>	<i>Maximum power density (W/kg)</i>	<i>Operating temperature (°C)</i>
Lead acid	35	150	Ambient
High power lead acid	20	400	Ambient
Advanced lead acid	60	350	Ambient
Bipolar lead acid	20	500	Ambient
Nickel cadmium	50	200	Ambient
Nickel metal hydride	80	170 to 200 @ 80 %	Ambient
High power Nickel metal hydride	40 to 50	300 to 500 @ 50 %	Ambient
Sodium nickel chloride	100	150	300
Lithium ion	150	200	Ambient
High power Li-ion	70	500 – 1000*	Ambient
Lithium polymer	150	300	Warm
High Power Lithium polymer	70	700**	Warm 90
Lithium metal	130	350	Ambient
Nickel iron	50	100	Ambient
Nickel zinc	70	200	Ambient
Sodium sulfur	110	200	350
Lithium iron sulfide	150	300	450
Zinc air	200	140	Ambient
Zinc bromide	80	80	Ambient

\* Test phase

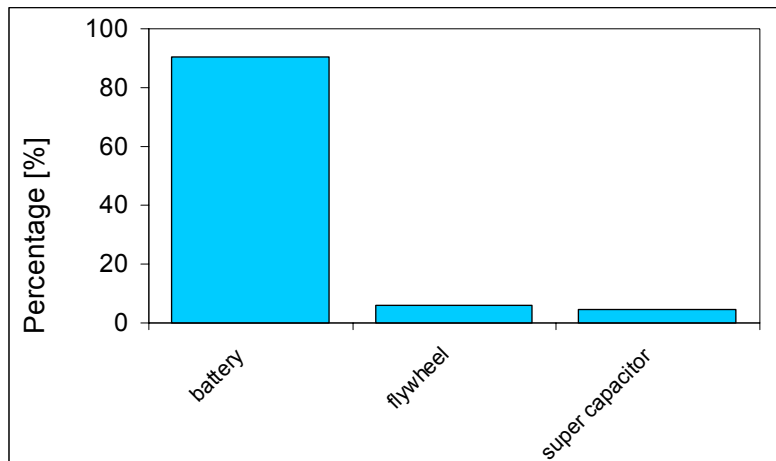
\*\* Average pack values (Avestor, Bolloré-EDF)

Currently, supercapacitors have a maximum specific power of about 1000 W/kg and a maximum specific energy of about 6 Wh/kg. Flywheels show comparable numbers: a maximum specific power of about 500 to 1000 W/kg (determined by the motor / generator choice) and a maximum specific energy of about 20 Wh/kg.

#### 4.3.1 Energy storage in HEVs

When regarding the type of energy storage device used in several HEVs nowadays, there seems to be a strong preference for the use of batteries.

Figure 4.2 shows the relative use of storage components in HEVs developed worldwide. HEVs in several stages of development (prototype, testing, demonstration, pre-commercial and commercial) are included in these statistics. It is shown clearly that batteries are used much more frequently than flywheels and supercapacitors.



**Figure 4.2 Storage components used in several HEVs (prototype, testing, demonstration and (pre-) commercial), derived from the Annex VII database**

Looking more closely into the data collected for this overview report, it is found that HEVs in the commercial or pre-commercial phase are always equipped with batteries, whereas vehicles in the test- or prototype stadium sometimes are equipped with a flywheel or supercapacitor. This basically reflects the early research phase in which supercapacitors or flywheels are situated.

Within the Japanese ACE project, several initiatives exist to test flywheels and supercapacitors, but only in prototype vehicles. A clear example of this is the Honda JVX concept car, presented in 1997, which was equipped with a supercapacitor. It is illustrative, however, that its commercial successor, the Honda Insight, is equipped with batteries. The same accounts for the Toyota Prius: the prototype version presented in 1995 was equipped with a supercapacitor whereas this vehicle at the commercial launch was equipped with a battery.

**Table 4.4 Examples of HEVs using a supercapacitor or a flywheel**

Hino (ACE-project)	Bus	Supercapacitor	Prototype
Nissan Diesel (ACE)	Bus	Supercapacitor	Prototype
Isuzu (ACE)	Truck	Supercapacitor	Prototype
Honda (ACE)	Passenger car	Flywheel	Prototype
Ford Synergy 2010	Passenger car	Flywheel	Testing
Honda JVX	Passenger car	Supercapacitor	Concept car

Table 4.4 shows some examples of HEVs equipped with flywheels or supercapacitors. As mentioned before, all these vehicles are in the development stage: prototypes, test- and concept cars.

A readers survey published in *Electric Vehicle Progress* in 1998, telling what they expect in terms of power sources that are, or will become, market feasible, resulted in the following table (numbers reflect percentages):

**Table 4.5 Survey under readers of EV Progress of expectations of power sources in the near future in EVs and HEVs (published in 1998)**

Power Sources	1998	1999-2001	2002-2004	2005-2009	Later or never
Near-term Batteries	57	29	4	0	4
Advanced Batteries	7	11	54	14	11
IC Engines for Hybrids	14	43	32	7	0
Fuel Cells	0	11	7	64	18
Supercapacitors	4	0	18	29	46
Flywheels	0	0	11	18	68
Others	0	0	4	0	7

This survey indicates that both supercapacitors and flywheels remain to be a ‘promise for the future’, but are not expected to play a decisive role in HEVs in the near future.

Another development, however, that may have interesting opportunities is the application of supercapacitors in combination with high energy-density batteries. This may yield a high energy and high power storage system with limited weight. Also in this combination battery life may be improved as higher power charges and discharges of the battery are avoided.

#### 4.3.2 Conclusions

Flywheel and supercapacitors seem to remain a ‘promise for the future’, whereas batteries appear the most utilized energy storage medium for HEVs at the moment and in the near future. There might be a role for supercapacitors, however, in combination with batteries or in applications with extremely low energy density demands. Flywheel application in hybrid vehicles is strongly limited at the moment and so far it is not clear whether there will be a significant role for flywheels in hybrid vehicles in the near future.

#### Literature

1. FT Automotive Environment Analyst, issue 49, February 1999, page 7
2. FT Automotive Environment Analyst, issue 37, February 1998, page 17-20
3. Electric Vehicle Progress, vol. 21,no. 4, February 15, 1999
4. Electric Vehicle Progress, vol. 21,no. 6, March 15, 1999
5. <http://evworld.com/>