Invest in Sweden

Automotive Hybrid Technology Roadmap

Contents

1 Abstract

The aim with this report is to light up automotive hybrid technology know-how, experiences and R&D concerning vehicles in Sweden. The report starts with a brief introduction to the technology field and includes an explanation of key terminology. An outline of international hybrid projects as well as Swedish's are presented. This is followed by a summary of Swedish knowledge and research in the area.

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2 Introduction to Automotive Hybrid Technology

2.1 Definition

A hybrid is an offspring of two animals, plants etc of two different varieties. A more modern use of the term has come to include man made inventions as well;

… something (as a power plant, vehicle, or electronic circuit) that has two different types of components performing essentially the same function. (Your dictionary, 2001)

This implies that any vehicle, that combines two or more sources of power, is a hybrid. Power sources can be, for instance, ICE (Internal Combustion Engine), fuel cells, electric machines or muscle power. The intention is that this should lead to improved fuel consumption and lower emissions compared to conventional vehicles. (U.S. Department of energy, 2001 and How stuff works, 2001)

2.2 Motivations

Conventional vehicles are doomed to choose a load point that corresponds to the instantaneous demanded power. That means working at low efficiency when the power demand is low or fairly low. Furthermore has conventional vehicle no possibilities to avoid load points that have a disadvantageous fuel consumption or emission formation. When braking, there is no possibility to recover energy in a conventional vehicle. All kinetic energy will be lost.

The electric hybrid vehicles (HEV), on the other hand, have the advantage to alter its power sources or even better the possibility to combine them. This leads to the possibility to slow down the changes of load points for the ICE. By utilize pure electric mood, low ICE efficiency or load points that forms large amount of emissions are able to avoid, if the hybridization does not solve the problem. Further more makes the presence of battery it possible to regenerate braking energy.

A hybrid of today combines the extended range of a conventional vehicle with the environmental benefits of an electrical vehicle. This results in a vehicle with improved fuel economy and lowered, but yet not zero, emissions (How stuff works, 2001). The goal, to minimize the use of non-efficient operating points, is more or less easy to achieve depending on the chosen hybrid topology.

2.3 Short History

The first known converter of heat to mechanic energy is the Aeropile. It derives from ~10 -~75 A.D. The first steam engine was patented in 1698.

The first internal combustion engine was constructed in 1673. The engine had to be reloaded for every cycle. The first ICE using the two-stroke principle was built in 1860. The four-stroke engine was first presented in a patent filed 1862. In 1885 was the first diesel engine tested.

A Jesuit priest in Chine was the first to report of a car propelled by a steam turbine in 1670. The first European steam-engine car was French. This was in 1769. The first vehicle that was propelled by an ICE was presented in 1823. A boat was utilizing an ICE in 1832.

In 1894 were cars propelled by electric motors introduced, thirteen years after the first electric tram. These electric cars were utilizing rechargeable batteries.

The electric motor as well as the steam-engine was the most common way to propel vehicles in the beginning of the last century. The first hybrid vehicle was presented in the beginning of the last century.

The choice of ICE as the main power source in vehicles was not made until Ford begun to mass produce vehicles. The choice was probably due to better range and easier refueling.

2.4 Topologies

There are several alternatives to utilize when combining engines, motors, energy storages, clutches, gearboxes etc into a hybrid drive train. Thoroughly analyzed it turns out that there are two basic topologies: series and parallel. Other topologies can, *strongly simplified*, be considered as variants of these two basic concepts. Parallel and series topology, together with the power split topology (known from Toyota Prius) and finally also 4QT will be presented below. In (Harbolla, 1992) all together 18 topologies are presented, and there are yet other solutions.

Series Hybrid

The series hybrid has no mechanical connection between the ICE and the wheels. See Figure 2.1. The ICE load point can therefore be chosen freely, but at the expense of more energy conversions than with the parallel hybrid. The thermal energy is converted into mechanical energy in the ICE, and thereafter, in the generator, turned into electric energy. The generator charges the battery that in its turn supplies the power electronics for the electric traction motor(s). On its way the energy also passes power electronics twice, in the worst case. These many energy conversions cause the topology a significant reduction of the system efficiency. The ICE efficiency is depending on the low pass filtered power demand.

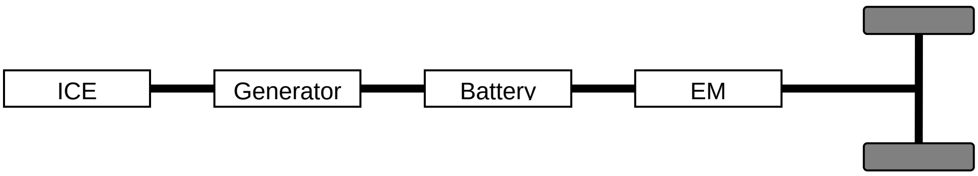

Figure 2.1: Series hybrid topology.

The electric machine used as the traction motor, has to be designed for peak power. The generator is designed for the ICE power. The simplest series hybrid vehicle is an electric vehicle, equipped with a range extender.

An advantage with the topology is that the ICE can be turned off when the vehicle is driving in a zero-emission zone, but this can be accomplished with a parallel hybrid as well. Yet another merit of the series topology is that the ICE and the electric machine can be mounted separately. This involves a possibility to distribute the weight of the vehicle drive system and in buses an opportunity to use low floor.

Parallel Hybrid

The parallel hybrid is a combination of two drive systems. The ICE is mechanically connected to the wheels via a gearbox. The low number of power conversions can potentially increase the efficiency of the vehicle as compared to a series hybrid. See Figure 2.2.

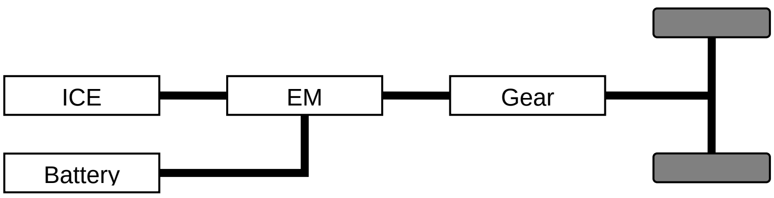

Figure 2.2: Parallel hybrid topology.

The load point, i.e. speed and torque combination of the ICE, of the hybrid can to some extent be chosen freely with the help of the electrical machine(s), i.e. the speed of the ICE is chosen with the gearbox and the torque with the electric machine(s). There are four options available: pure electric operation, pure ICE operation, electric operation while ICE is charging the battery and finally operation with all power sources. To achieve peak tractive power, both the ICE and the electric machines are used.

Power Split Hybrid

The Power Split Hybrid (PSH) has a blurred transformation between the series and parallel hybrid state. The PSH is even called complex, combined or dual hybrid vehicle. The PSH topology is shown in Figure 2.3.

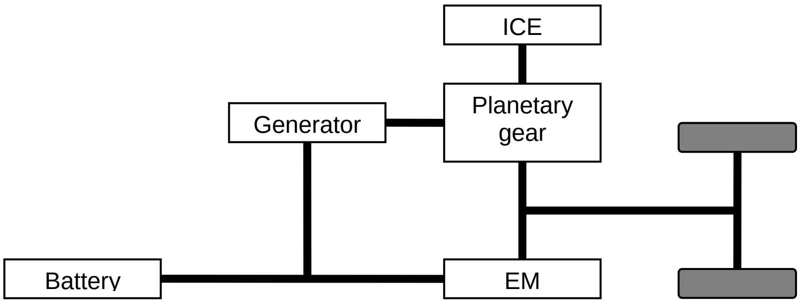

Figure 2.3: Power split hybrid topology.

A planetary gearbox (Figure 2.4) connects the two electrical machines and the ICE. The traction motor (electric machine 1) is connected to the ring wheel, the generator (electric motor 2) to the solar wheel and finally the ICE is connected to the carrier and thereby possible to switch off and the vehicle can operate in a pure electric mode. Owing to the connection of the sun wheel and the planet wheels the speed of the engine can simply be adjusted by varying the speed of the generator.

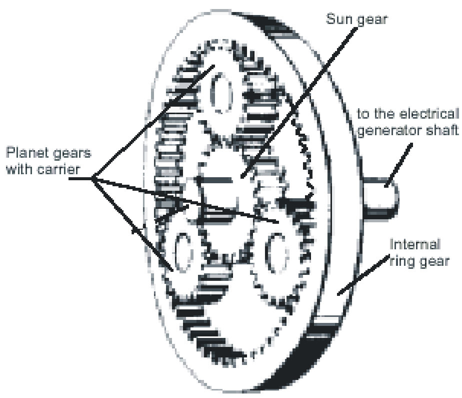

Figure 2.4: Planetary gear. The numbers of planet wheels are variable but influence the equations.

At most operating points some of the prime energy flows from the ICE to the wheels via the gearbox as in a parallel hybrid, and some flows via the electrical machines as in a series hybrid. The proportion between these two energy flows is speed dependent and at a certain speed it works as a pure parallel hybrid. In most other operating points it’s partially a parallel hybrid and partially a series hybrid. The latter means several conversions of the energy that flows the “series” way from the prime energy source to the wheels. This hints that it is difficult to get the system efficiency higher than the parallel hybrid efficiency.

There are many possible combinations of a PSH. While using reduction gears, CVT, advanced planetary gear, clutches and different numbers of motors the possible number of combinations grows rapidly. The drawback with the topology is that it can cause a power vicious circle that cost unnecessary high transmission losses.

Four Quadrant energy Transducer (4QT)

The four quadrant energy transducer is an electromagnetic propulsion system. It is intended to be used in hybrid vehicles. The 4QT consists of two electric machines, which are inserted in the transmission line of a vehicle, more precisely between the ICE and the wheel transmission. Both machines can operate as a generator. One of the machines is a double rotor machine (DRM) and the other has two shaft-ends in order to transmit torque through its rotor. This machine is referred to as the stator machine. To optimize the efficiency are both machines permanent magnet machines (PM). The two machines are integrated into one unit, which is referred to as the 4QT (Figure 2.5). There are different topologies when designing a 4QT. One example is the radial-radial flux topology. (Figure 2.6)

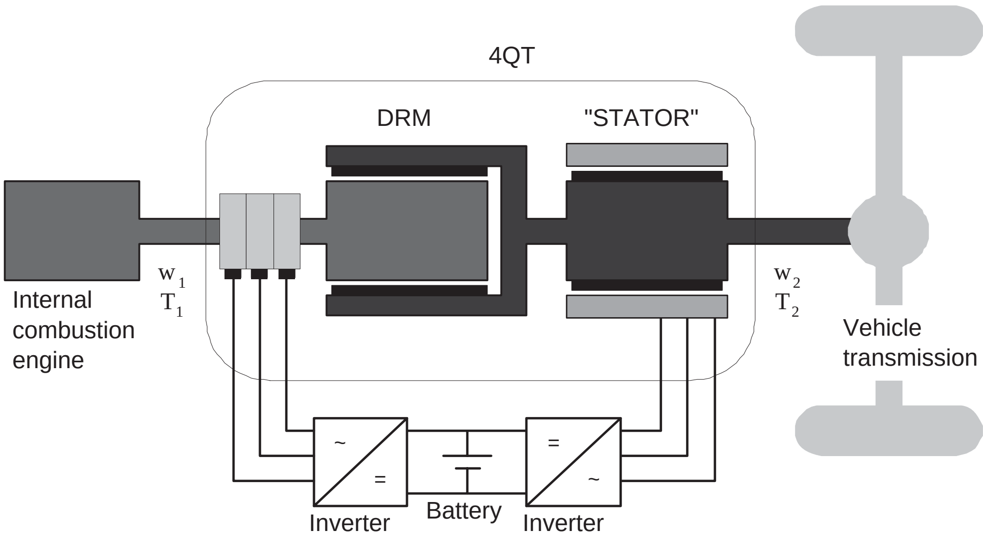

Figure 2.5: Scheme of the 4QT topology (Châtlet, 2005).

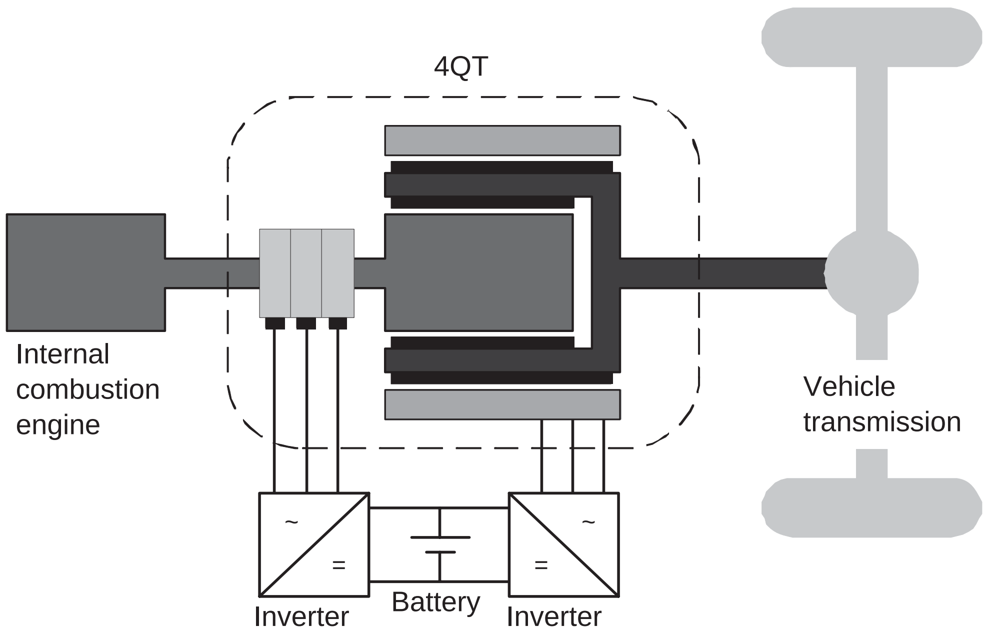

Figure 2.6: Scheme of the 4QT radial-radial flux integrated topology (Châtlet, 2005).

The idea behind 4QT is to allow the ICE to operate at a torque and at a speed , independently of the wheel transmission demand. The ICE is permitted to operate at the optimal operating line, i.e. at highest ICE efficiency at each speed. To achieve this DRM introduces a speed difference and the stator machine introduces a torque difference.

2.5 Degree of Hybridization

To define, categorize and better understand HEV there are some possible definitions to use. *The Order of Hybridization* is equal to the number of different systems that are necessary to build the specific drive train. A pure electric vehicle is of first order, a parallel hybrid with one engine and one electric motor is of second order and a power split or a strigear hybrid is of third order of hybridization (Baretta, 1998).

To get an indication of the range and performance of a hybrid vehicle the concept *the Electric Hybridization Rate* (EHR) can to be used. It is a ratio between the electric power and the total traction power, expressed in percentage. (Equation 2-1.) A higher ratio indicates that the hybrid is to a higher degree an electric vehicle, i.e. the hybrid is equipped with a large traction motor. (Maggetto – Kahlen, 1997)

$$EHR = \frac{electric\_power}{traction\_power} \tag{2-1}$$

A similar way to validate a vehicle is *the Combustion Hybridization Rate* (CHR). This concept renders the contribution from the ICE to the hybrid. The ratio is expressed in percentage and a higher value indicates that the vehicle tends to be a pure thermal vehicle. See equation .

$$CHR = \frac{thermal\_power}{traction\_power} \tag{2-2}$$

The sum of EHR and CHR is always one and each concept is just an indication whether the vehicle lends towards a pure electric or a pure thermal vehicle.

To investigate the relative contribution of each energy source to the traction system *the Ratio of Hybridization* (RH) has to be defined. As the systems contribute equally the rate is one. The concept is only valid for HEV of the second order. First order vehicles have the ratio zero. For hybrids more complex than of second order is the RH not useable, since it is not straightforward. (Van Mierlo, 2000) See equations 2-3 and 2-4.

$$\text{If } P_{el} < P_{th} \quad RH_{th} = \frac{P_{el}}{P_{th}} \qquad (2\text{-}3)$$

$$\text{If } P_{th} < P_{el} \quad RH_{el} = \frac{P_{th}}{P_{el}} \qquad (2\text{-}4)$$

The most basic definition of a hybrid vehicle is one that uses two methods of providing power to the wheels, but all hybrids are not equally created. They can be divided into degrees of hybridization such as *mild*, *full* or *plug-in*. In (Hybrid Center, 2006) five technology steps separate conventional vehicles from electric vehicles. A vehicle needs the first three steps to be a true hybrid. The forth and fifth steps create a potential for hybrids with superior energy and environmental performance. The steps are:

1. Idle-off capability
2. Regenerative braking capacity
3. Power assist and ICE downsizing (mild hybrid)
4. Electric-only drive (full hybrid)
5. Extended battery-electric range (plug-in hybrid)

In Table 1 the five steps are described further.

Table 1: Hybrid Checklist (Hybrid Center, 2006).

	The vehicle is a…			
If it…	Conventional vehicle	Mild hybrid	Full hybrid	Plug-in hybrid
Shuts off the engine at stop-lights and stop-and-go traffic	x	x	x	x
Uses regenerative braking and operates above 60 V		x	x	x
Uses an electric motor to assist a conventional engine		x	x	x
Can drive at times using only the electric motor			x	x
Recharges batteries using electricity from the wall plug and has a range of at least 32 km on electricity alone				x

Mild Hybrid

In a mild hybrid, the ICE shuts down whenever the vehicle comes to a complete stop and starts up again as soon as driving is resumed. The batteries in a mild hybrid are not able to run the vehicle in pure electric mode. Hence are the batteries smaller then in a full hybrid, which is able to run in electric mode. The power assist ability, combined with downsizing the engine, allows the vehicle to achieve the same performance as a vehicle with a larger engine while achieving superior fuel economy.

Another way of describing a mild hybrid is as a conventional vehicle with an oversized starter motor. Accessories can continue to run on electrical power while the engine is shut off in a mild hybrid. The motor is used for regenerative braking and to spin up the ICE to operating rpm speeds before injecting any fuel.

Full Hybrid

A full hybrid however, is able to run exclusively on electric mode during slower speeds and does not need to engage the ICE as long as there is enough power stored in the batteries. Full hybrids are sometimes also called strong hybrids. Batteries in full hybrids are consequently larger and more powerful than those on mild hybrids.

The greater flexibility of full hybrids allows the vehicle to spend more time operating its ICE only when it is as most efficient. At low speeds and at starts, the electric motor and batteries powers the car and at high speeds the engine takes over.

Plug-in Hybrid

A plug-in hybrid, or grid-connected hybrid or gasoline-optional hybrid or just PHEV, works pretty much the same as a conventional hybrid, but with one big exception: the battery pack is bigger

With the plug-in hybrid, it is *not* required to plug the car in, but there is the option. A conventional hybrid is not possible to plug in to the grid. As a result, drivers will get all the benefits of an electric car, without the biggest drawback: limited range. It is hereby possible to go electric for 90 percent of the average driving, i.e. the driving close to home. When the electric charge runs out, a downsized ICE kicks in and the car drives like a regular hybrid.

The advantages are several. The vehicle life time costs will be lower the more the vehicle is run in electric mode. Electric energy is cheaper and cleaner than fossil fuel and it is also available domestic. The electric mode allows a silent and zero-heat “foot-print” which is appreciated in military applications. Finally facilitates the PHEV to provide emergency backup power for a few home appliances at black outs.

(Main sources, Chapter 2.1-5: Ford vehicles, 2006, Hybrid Center, 2006, California Cars Initiative, 2006 and EV world, 2006)

3 Technologies and Industry Trends

As the name hybrid indicated there is a combination of traction systems. The most common power units will be mentioned below.

3.1 Energy Converters

Primary

Gasoline (Otto) Engines

The throttle, an air valve in the intake manifold that varies the flow of fuel to the combustion chambers of the cylinders, regulates the amount of the air/fuel mixture. The mixture is rich at idling speed (closed throttle) and at high speeds (wide-open throttle), and is lean at medium and slow speeds (partly open throttle).

An ignition system is used to ignite the mixture by means of using a spark plug mounted in one of the openings to the combustion chamber. It can thus be argued that the power output of gasoline engines is controlled with both the quantity of fuel and the quality of the air-fuel mixture.

A developed version of this engine, injects the fuel directly into the cylinders. This is referred to as GDI, Gasoline Direct Injection, and thus the inlet ports only convey air, and EGR (exhaust gas recirculation) if any, into the combustion chamber.

Diesel Engines

The other main type of reciprocating piston engine is the diesel engine. Diesel fuel is a petroleum oil fraction heavier than petrol. The diesel engine uses the heat produced by compression rather than a spark, from a sparkplug, to ignite the injected diesel fuel. The fuel is injected directly into the combustion chamber in the modern diesel engine. The lack of an electrical ignition system improves the reliability of the engine.

Diesel engines have no throttle and thus the power output is regulated with the quantity of fuel only. There is more air than needed for complete combustion present in the combustion chamber. The extra strength required containing the higher temperatures and pressures and lower speeds causes diesel engines to be heavier than petrol engines with the same power.

The increased fuel economy of the diesel compared to the petrol engine means that the diesel produces less carbon dioxide (CO_2) measured per covered distance. Unburnt carbon in diesel engine produces black soot in the exhaust. Other problems associated with the exhaust gases (high particulates including soot and nitrogen oxide) can be lowered with improved engine control.

Fuel Cells

Fuel cells are usually classified by the type of electrolyte they use. There are several different types of fuel cells, each using different types of chemistry. In principle it operates as electrochemical energy storage (battery), but does not need recharging. The fuel cell operates as long as it is supplied with fuel.

To be able to propel the vehicle the fuel cell system in a hybrid vehicle is in need of additional system components. The output voltage of the fuel cell stack varies with load. The voltage must therefore usually be conditioned to adapt to the system voltage. The same applies to secondary energy storages (e.g. battery). The electric power passes thereafter the electromechanical energy converter that finally feeds the mechanical power into the transmission system to the wheels.

Secondary

Electric Machines

Hybrid vehicles include at least one electric machine, but can include more. A power split hybrid demands two electric machine. It is also possible to include four, i.e. one on each wheel, known as wheel motors.

The requirements on electric machines are usually to have high torque density. This implies that the maximum torque should be high, at least at low speed, since is gives good starting properties. For example must an Integrated Starter Generator (ISG) be able to start the ICE, usually with at least 200 Nm of starting torque. This, as it at the same time, must not occupy more than a few centimeter of physical space, approximately where the clutch is located.

To create torque in the electrical machines that is most frequently used in traction system of vehicles, the interaction between an electric current and a magnetic field is utilized. The magnetic field is often accomplished with the help of permanent magnets. Such machines are called permanent magnet machines.

3.2 Energy Storages

Primary

As primary energy storages is possible to use not only gasoline and diesel, but also ethanol, DME, LPG, methane etc. Below follow some example, but there are still more available.

Diesel
Diesel is also a fossil fuel that originates from oil.

DME
DME, dimethylether, is a gas that originates from natural gas or biomass. It is possible to use DME in the diesel process without efficiency losses. DME also results in decreased missions of hydrocarbons, nitric oxides and particles compared to diesel.

Ethanol
Ethanol fuel is an alcohol, which is produced from biological material that is fermented. Alcohol results in decreased emissions of nitric oxides and particles compared to diesel. Ethanol fuel is considered as a renewable source of energy and at combustion does not contribute to increase the amount of carbon dioxide in the atmosphere.

Gasoline
A fossil fuel which originates from oil, i.e. it is a limited resource.

Hydrogen gas
Hydrogen does not result in carbon dioxide emissions and the particle emissions are lower than when using diesel for combustion. The consumption of energy at production is however large.

LPG
LPG, Liquified Petroleum Gas, is a secondary product when refining oil. It consists mainly of saturated hydrocarbons.

Methanol
Methanol is, as ethanol, an alcohol. It is mainly produced out of fossil gas. Alcohol results in decreased emissions of nitric oxides and particles compared to diesel.

Natural gas
Natural gas is also referred to as fossil gas and consists mainly of methane. It is extracted from a limited resource. Compared to diesel are the emissions of nitric oxide and particles decrease, but the hydrocarbons are slightly increased. The carbon dioxide emissions are more or less unchanged.

Secondary

It is very useful for a vehicle with large speed variations and many stop-and-goes to utilize secondary energy storage. An example is a vehicle in city traffic. The larger the relative ICE power the vehicle is equipped with, for instance in a heavy truck, the lower the use of secondary energy storage is, especially if there are few stop-and-goes as in highway traffic.

Electrochemical Storages

This group of energy storage systems contains what in everyday speech is known as batteries. Numerous battery types have been invented. All of these are not suitable for traction purposes and a limited number of them are mentioned below.

Lead-acid

Lead acid batteries were invented 1859 and are still today, probably, the most spread electric storage device for electric traction applications. In its basic form, the lead-acid battery consists of a negative plate made from lead metal and a positive plate made from brown lead dioxide, submerged in an electrolyte consisting of diluted sulphuric acid.

Lithium-ion

Lithium-ion, sometimes abbreviated as Li-Ion, are rechargeable batteries that are common in consumer electronics. They have one of the best energy-to-weight ratios, no memory effects and a slow loss of charge when not used.

Nickel-cadmium

In this battery, the positive electrode is made from nickel oxide and the negative electrode of cadmium. The electrolyte consists of a potassium hydroxie (lye) solution. Compared with a lead-acid battery, it has a higher energy density and a much higher power density. The latter makes it particularly suitable for traction applications. Nickel-cadmium batteries are capable of accepting high charge and discharge rates (up to 100%). Its energetic efficiency is lower, which means higher energy consumption on the grid and more maintenance. The main disadvantage of the nickel-cadmium battery is its price.

Nickel-metal Hydride

The nickel-metal hydride (NiMH) batteries are strongly related to the nickel-cadmium batteries, they use an alkaline electrolyte, and have replaced them in electric vehicle applications. This is due to is better performance without the toxicity problems with cadmium.

Sodium-sulphur

This is a battery with liquid electrodes and a solid electrolyte. It has an operating temperature about 350°C. It is essential that the battery is not allowed to cool below 200°C since the electrolyte then freezes solid. There are still problems concerning cycling life and safety that prevent commercialisation of this type of batteries.

Sodium-nickel Chloride

Sodium-nickel chloride batteries are also known as Zebra or Beta batteries. They are related to the sodium-sulphur battery, the negative electrode consists of sodium and the positive electrode of nickel-chloride instead of a liquid sulphur electrode as in the sodium-sulphur batteries. The melting point is lower, 160°C, and it becomes a powder, rather than a solid when freezing. Its operating temperature is 300°C.

Zinc-bromine

In zinc-bromine batteries a solution of zinc-bromide is stored in two tanks. The solution are pumped through a reactor and back in the tanks when the batteries are charged or discharged. The presence of bromide makes the batteries toxic and the need of pumps, reservoirs etc make them rather complicated.

Zinc-air

Zinc-air batteries are also called zinc-air fuel cells. They are powered by the oxidation of zinc with oxygen and are unable to recharge directly from the network. The zinc electrodes have to be regenerated through an electrochemical process. However, this process uses electricity. In practice, vehicles with this kind of batteries are equipped with a battery exchange system. The batteries have very high energy densities and are relatively inexpensive to produce.

Thermal energy storage

This storage is only relevant for regeneration and load-levelling in vehicles which make use of specialist prime movers such as the Stirling engine and the steam engine, or hybrids using them. It is however possible to engine heat from the ICE and make this heat available for rapid heating and demisting in the passenger department.

Electrostatic Energy Storage

Super Capacitor

Super capacitor, or also referred to as Ultra Capacitors, are capacitors with low maximum voltages. On the other hand do they have unusually high capacitance (for capacitors). To reach the demanded voltage level, for tractive energy storage in a hybrid vehicle, many cells are connected in series. To guarantee that a single cell is not overcharged it is possible to parallel connect the capacitors with resistors.

The most attractive capability with super capacitors, compared to electrochemical batteries, is the high power density. An important difference amongst those two is that the voltage varies strongly with the energy content in the super capacitor.

Electromechanic Energy Storage

Flywheel

The idea with a flywheel is to spin a wheel and hereby sore kinetic energy in the rotating mass. To transfer energy back and forth of the flywheel an electric motor is mounted of the rotating mass.

Compressed Air

Compressed air can either be charged or compressed as a way of dealing with regenerative braking. The compressed air is then utilized as energy storage. Experiments have been done with vehicles run on only compressed air and on vehicles run with gasoline and compressed air.

An air hybrid is a vehicle with an ICE that is modified to also work as an air compressor and an air motor. The engine is connected to two air reservoirs, normally the atmosphere and a high pressure tank. The main benefit of such a system is the possibility to make use of the kinetic energy of the vehicle otherwise lost when braking. Compressed air can also be externally charged.

Hydraulic Accumulator

The hydraulic accumulator operates in a similar way as a fly wheel. It stores energy during braking, low-speed or idling in a hybrid vehicle. It can then feed back power when high power is needed, e.g. during acceleration. Energy is stored in the accumulator by pumping oil at high pressure into a pressure-vessel. This vessel contains a highly deformable membrane, which separates the oil from highly deformable gas.

(Main sources, Chapter 3.2: Alaküla et al, 2004, and Westbrook, 2001)

3.3 Power Electronic Converters

Everywhere electrical energy has to be modified (voltage, current or frequency) power electronic converters can be found. The power rang vary therefore from milliwatts in cell phones to megawatts in power supply for trains. What can be called classical electronics, electrical currents and voltage, are used to carry information, whereas power electronics carry power. Hence becomes efficiency a key issue.

Almost any electric motor is power electronic controlled. The traction system of a hybrid vehicle demands several power electronic conversions. Secondary energy storages (batteries, super capacitors, fuel cells etc) are usually adapted to a dc link voltage via a power electronic converter.

Power electronic converters have a relatively high efficiency. They can have a peak at 97-98%, or higher. The losses consist of commutation and conduction losses. Commutation losses occur when the power electronic components are switching and the single components simultaneously is operating with high voltage drop and current for a short moment. The conduction losses, on its hand, occur when the converter current flow through any of the power electronic components, which exhibit a voltage in the range of a few volts.

3.4 Control

The vehicle will not operate if it is not controlled to do so, and the degrees of freedom increase in a hybrid vehicle. The goal in a hybrid vehicle is, for instance, to reduce fuel consumption and regulated emissions. The means available are many and the chosen solutions as well. The bottom line is that the vehicle has to be safe, an overtaking must be able to perform, the customer can expects some kind of drive experience and it must be reliable. The control of the included systems is crucial since they are mutual depending on each other.

3.5 Auxiliary Systems

The tractions system is far from the only power consumer on board a vehicle. The demands of comforts are steadily increasing. Some loads are today belt driven, others are electrically driven. To do the latter is connected with several advantages. The loads can be more freely distributed in the vehicle. This has a positive impact on weight, volume and packaging. The possibility to control the power consumption is bigger when using electric loads, the efficiency can be increased. Examples of auxiliary system that are affected are AC compressor, pneumatic system. Some auxiliary system does always have to be operating, such as the fuel pump. There is simply no room for controlling such system by switching them on and off.

3.6 Transmission

To transmit the mechanical power from the prime mover, i.e. ICE or electric motor, to some form of useful output device, a transmission or gearbox is used. The idea is to reduce an unsuitable high speed and low torque of the output shaft to a more useful speed and torque. Transmissions in vehicles include the ability to select one of several different gear ratios. In most cases is the idea to slow down the ICE output speed and increase the torque. The gear ratio should be chosen to allow the primary energy converter to produce the required power at the torque-speed combination that results in highest efficiency possible. This is especially important in an environmental friendly vehicle, such as the hybrid.

All conventional vehicles have a mechanical transmission, but all hybrid vehicles do not. If the hybrid vehicle has electrical wheel motors they can instead have an electric, not mechanical, transmission. Suck vehicles do exist on the market today. The most relevant transmission concerning hybrid vehicles will follow below.

Manual Transmission

Manual transmission is also known as stick shift, straight drive or standard transmission. Most often they feature a driver-operated clutch and a movable gear selector, but some do not. The most transmissions also allow the driver to select any gear at any time. Sequential manual transmission does however only allow the driver to choose the next highest, or the next lowest gear.

There are basically two types of manual transmissions, an unsynchronized system and a synchronized system. In the first system are the gears spinning freely and must be carefully operated by the driver to evade noisy and damaging gear clashes. The latter system will automatically mesh at gear changing and is known from rally cars.

Manual transmissions in passenger cars are, in general, available for four to six forward gear and one reverse gear. But there have been built transmissions with as few as two and as many as seven gears. Heavy vehicles have even more gears.

Automatic Transmission

The automatic transmission is a gearbox that automatically changes the gear ratio. Earlier where this transmission associated with reduced fuel efficiency. The transmission has been improved concerning this issue, but it has still a fuel penalty to pay compared to the manual transmission.

The transmission can be accomplished in many ways. The traditional is to use a hydraulic torque converter. Essentially replaces this converter the function of a clutch. While manual transmissions are characterized by gear ratios which are selectable by engaging pairs of gears inside the transmission, are automatic transmissions distinguishing-mark clutch packs that selects the gear ratio. Semi-automatic transmission is a transmission with clutch packs that allows the driver to select the current gear.

Manually Controlled Automatic Transmission

Most automatic transmissions also offers further control possibilities, except the obvious possibility to select forward, reverse and neutral gear. There is, for instance, throttle kick down. At kick down the transmission is downshifted to the next lower gear ratio. Normally is this only function up to a certain road speed. This is to prevent damaging the engine.

Some vehicles have the option to use full manual control that overrides the hydraulic controller. It is an optional mode where the driver has full control over gear shifting. In some cases is such a system completed whit control that will override the driver’s option if it will damage the engine.

CVT

Continuously variable transmission, CVT, changes gear ratio over a range rather than between gear ratios. The CVT compensates for changing vehicle speed very smoothly. It allows the ICE speed to remain in peak efficiency.

Planetary Gear

A planetary gear, or an epicyclic gear, consists of at least one outer gear, called planet gear. This is rotating about a sun gear. The planets are typically mounted on a movable arm, or carrier. The carrier may rotate relative the sun gear. The planetary gear can include an outer ring, an annulus that meshes with the gear. See also Chapter 2.4 and Figure 2.4.

Transmissions in Hybrid Vehicles

In hybrid vehicles the hybrid drive train provides new possibilities. It has been utilized by some manufacturer that has presented new transmission solutions such as shown in Table 2.

Table 2: Presented transmission solutions in hybrid vehicles.

AHS2 (advanced hybrid system) by GM, Daimler Chrysler and BMW (Daimler Chrysler, 2006)
BAS (belt alternator starter) by GM (GM, 2006)
IMA (integrated motor assist) by Honda (Honda Cars, 2006)
I-SAM (Integrated starter, alternator and motor) by Volvo (Volvo, 2006a)
THS II (Toyota hybrid system) by Toyota (Toyota, 2006)

(Main sources, Chapter 3.3-6 : Alakùla et al, 2004)

4 International Hybrid Projects

4.1 Private Cars

Most of the car manufacturer today has presented at least one concept car that includes hybrid technology in some way. The topologies, degree of hybridization, energy buffers etc varies considerably between the presented solutions. Far from all of them are available on the market however. The variety of solutions is an indication of that the technology is not quite completed yet.

Below are some of the hybrid vehicles available on the market, or introduced as concept cars, presented. See Table 3. Note that Table 3 to Table 6 is not intended to be absolutely complete.

Table 3: Hybrid personal cars, available or presented.

Chevrolet Malibu, Chevrolet Silverado Hybrid Truck, Chevrolet Tahoe Hybrid
Daihatsu Highjet
Ford Escape, Ford Mercury Mariner Hybrid
GMC Sierra Hybrid Truck, GMC Yukon Hybrid
Highlander Hybrid
Honda Accord Hybrid, Honda Civic Hybrid, Honda Insight Hybrid
Landrover Hybrid
Lexus GS450h, Lexus RX 400h
Nissan Altima
Porsche Cayenne Hybrid
Saturn VUE Greenline Hybrid
Suzuki Twin
Toyota Alphard Hybrid, Toyota Camry, Toyota Estima Hybrid, Toyota Prius
Twike

4.2 Trucks

Among trucks have some equipped with a hybrid drive train reached the market, see Table 4.

Table 4: Hybrid trucks, available or presented.

Eaton
Hino
Mack
Mitsubishi Fuso
Nissan Motor

4.3 Buses

Hybrid buses are not so common in the open market, even though there is a potential and an interest forthe technology. See Table 5.

Table 5: Hybrid buses, available or presented.

Allison Hybrid Bus
GM Hybrid Bus
Hino MIMR
Orion

4.4 Others

The advantages with hybrid technology are utilized in other applications. For instance in military applications are the ability of fuel reduction of highest interest, as well as the possibilities of noise reduction and the decreased wear and tear of components. Applications that include a lot of stop-and-go earn on the technology. Examples from such vehicles are presented in Table 6.

Table 6: Other hybrid vehicles, available or presented.

GM Hybrid Military Army Pickup	Military application
Hitachi	Construction
HMMWV	Military application
Komatsu	Construction
MP Hybrid	Military application
SmarTruck III	Military application
Stealth Hybrid Vehicle	Military application
The Shadow RST-V	Military application

5 Swedish Hybrid Projects

All major Swedish manufacturers within the automotive industry are doing R&D on hybrid vehicles. The extent of these efforts, and the chosen technical solutions, are business secrets. During the past decade some of these efforts have been presented to public, others are considered as mile stones in technology development within the companies. Below are hybrid projects that have been made public.

5.1 Private Cars

In March 2006 Saab Automobile presented a hybrid concept, Saab BioPower Hybrid Concept. It is a BioPower, a full hybrid vehicle using regenerative braking. The vehicle is a 9-3 convertible that is run on E100, i.e. 100 % ethanol, and is a 4WD equipped with 260 hp (191 kW). In addition there are two electric motors, the motor contributing with 38 kW and the starter/generator contributing with 15 kW According to (Auto motor & sport, 2006) the Saab hybrid is also a plug-in-hybrid, a fact Saab chooses not to publish, or comment, in connection with the exhibition.

Volvo Cars has on their hand presented a hybrid concept using four wheel motors. These motors are used as autonomous wheel corner, i.e. individual operation, steering and suspension at all wheels. A prototype is planned by 2009 at the latest. Before that Volvo Cars developed in its Dual Hybrid Electric System for Increased Efficiency and Economy (DESIREE) program two hybrid-electric concept vehicles. This was in the late nineties. Technologies from these concepts are later incorporated in Ford´s Escape HEV (Automotive Intelligence news, 2006).

Other technologies presented, that ought to be mention in this context, are from Saab their BioPower (run on E85, i.e. 85% ethanol, and/or gasoline), from Volvo Cars their Bi-Fuel (run on gas and/or gasoline) and Flexifuel (run on E85 and/or gasoline). They are not hybrids, but results in the endeavour to reduce the environmental impact.

Worth mentioning is the series hybrid vehicle presented by Solon in 1994. It was a series plug-in-hybrid, way before the concept was a reality. The vehicle was only produced in a limited prototype edition before economy issues put an end to the project.

5.2 Trucks and Buses

In March 2006 a hybrid technology for heavy vehicles was presented by Volvo Group. The concept was exhibited to the public in a buss and a truck. The fuel savings are predicted up to 35 %. The hybrid technology used is called I-SAM and is a combination of a starter motor, a propulsion motor and a generator. I-SAM co-operates with a diesel engine and uses regenerative braking. The presented hybrid topology is a parallel and is a full hybrid and includes new battery technology.

Volvo presented in 1997 the ECT (Environmental Concept Truck) and later also its successor Volvo FL6 Hybrid. They were series hybrid trucks equipped with a gas turbine and a diesel engine respectively. The trucks were able to run in pure electric mode. Bus concepts (ECB, Environmental Concept Bus) where also presented during this period. Volvo has presented a garbage truck too (Miljöfordon, 2006).

Scania has presented a concept for a series hybrid bus. The fuel savings are predicted to be 25% or more. The buses will utilize a diesel engine and super capacitors and has regenerative braking. Scania has also developed a prototype buss that used fuel cells. It was in 2001 and the concept included wheel motors and the batteries made it possible to utilize regenerative braking.

5.3 Others

There are other manufacturer and subcontractors that are into hybrid technology. For example investigates Bombardier to equip electric trains with combustion engines and super capacitors. The idea is to enable traffic without aerial conduit everywhere.

Interests for hybrid technology, and consequently R&D efforts, can also be found in connection with manufacturer of vehicles aimed at military vehicles, mining industries, wheel-mounted loaders, forestry work and ships, for instance.

(Main sources, 5.1-3: Saab, 2006, Scania, 2006, Volvo Cars, 2006, Volvo Trucks, 2006)

6 Swedish System Designers and Suppliers

Sweden has a long history of vehicle manufacturing. That implies an established network of subcontractors, education sites (to be separated from the universities), tests- and research institutes as well as laboratories. See for example (Fordons komponent gruppen, 2006), an interest organization for Scandinavian automotive suppliers.

Within the major Swedish manufacturers of civil vehicles SAAB, Scania, Volvo Cars and Volvo Group have a history of launch solutions in the leading edge. This implies a well-founded knowledge, R&D, laboratories etc in the sphere of industry.

Today, when the R&D resources are spread all around the globe, the know-how is spread in an extended network all over Sweden as well. This means that there is provided room for automotive suppliers, who are leading the progress.

The technology in automotive hybrid vehicles is, in most cases but not all, known. However, when used in new application new questions need to be solved. The knowledge needed for hybrid vehicles are sometimes already available, and sometimes available in other branches.

Traditional knowledge like ICE, transmission, control, packaging and weight issues are well developed in the vehicle industry. In adjoining businesses, such as trains and trams, knowledge about electric motors, inverters, power electronics and laboratory facilities to match, are already available in Sweden. Advanced knowledge about energy buffers is also accessible, even though on a smaller scale. There are small and medium-sized companies who are specialist in key areas.

A growing knowledge of hybrid technology is being developed in Sweden, as well as in the global automotive industry. The close collaboration between industry and universities facilitates a rapid progress.

The knowledge concerning automotive hybrid vehicles available in Sweden is schematically described in Figure 6.1.

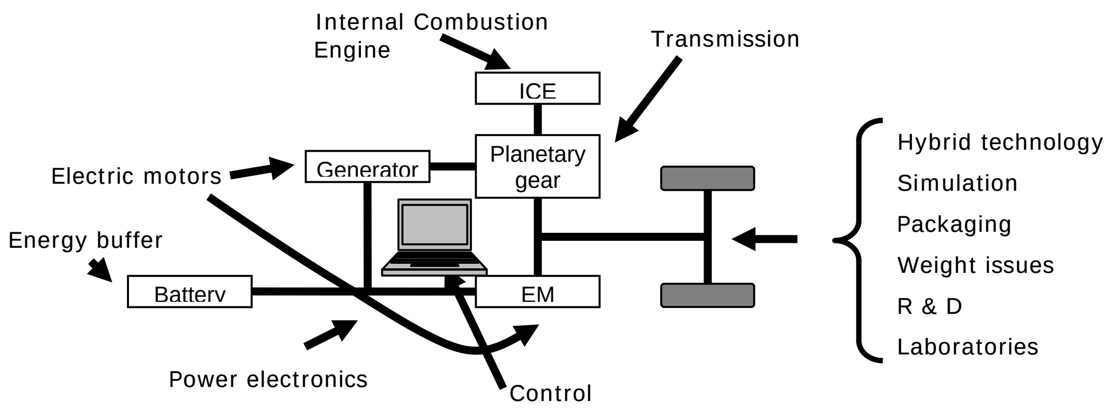

Figure 6.1: Available hybrid technology competence in Sweden.

A list of companies covering the area is not presented in this report. This is a dynamic field and new firms are set up, others are merged or taken over etc. Such a list would be out of date quite soon.

Below is nevertheless a structure presented. This is to be considered as a proposal for throwing light on Swedish know-how considering hybrid technology once it is completed with companies.

Hybrid Technology Structure

- Energy converters
  - Primary
    - Gasoline
    - Diesel
    - Fuel Cells
  - Secondary
    - Electric machines
- Energy storages
  - Primary
    - Diesel
    - DME
    - Ethanol
    - Gasoline
    - Hydrogen gas
    - LPG
    - Methanol
    - Natural gas
  - Secondary
    - Electrochemical
      - Lead-acid
      - Lithium-ion
      - Nickel-cadmium
      - Nickel-metal hydride
      - Sodium-sulphur
      - Sodium-nickel chloride
      - Zink-bromine
      - Zink-air
    - Thermal
    - Electrostatic
      - Super capacitors
    - Electro mechanic
      - Fly wheel
      - Compressed air
      - Hydraulic accumulator
- Power electronic converters
- Control
- Auxiliary systems
- Transmission
  - Manual
  - Automatic
  - CVT
- Weight issues
- Packaging
- Laboratories
- R&D
- Hybrid technology

7 Swedish Research

7.1 Green Car

The Program board for automotive research (PFF) is responsible for the *Green Car*, a collaboration programme for research and development of more environmentally adapted vehicles. The program is based on a contract between the Swedish government and the national vehicle industry.

The background of the *Green Car* is to face the increasing environmental demands and the tougher international competition within the vehicle industry. The complicated vehicle system of today results in new technical challenges, which requires leading competence within many more subject areas. One part of the programme includes an educational commitment with purpose of increasing access of vehicle engineers, and hopefully it also results in engineers with interdisciplinary education. Furthermore, the hope is that the commitment will initiate a deeper cooperation between universities in Sweden.

The Green Car National University Programme

The Green Car National University Programme has resulted in five new undergraduate courses, developed and performed commonly by five universities with participation from the vehicle industry.

All five courses are coordinated as a package, and when finishing the whole package a diploma will be received. The courses can also be taken separately. See Table 7.

Table 7: Courses within Green Car National Program

Vehicle systems for a better environment
Hybrid vehicle drive
The Combustion Process in Engines
Automotive control engineering
Environmentally friendly vehicle - project course

Center for Automotive Propulsion simulation (CAPSim)

The Swedish government is financing several different research programs concerning more environmentally friendly vehicles. The purpose is to create a solid ground for the Swedish automotive industry to cope with future demands on less pollutant and energy consuming vehicles. Two of these research programs have in a joint venture defined a simulation centre (Center for Automotive Propulsion Simulation, CAPSim). The two research programs involve several different projects dealing with issues related to fuel cells and hybrid electric vehicles, such as batteries, fuel cells, electric motors, internal combustion engines.

One of the objectives for CAPSim is to collect research results generated in these projects, in terms of physical or mathematical models, measurements, documentation and web-page links to national and international relevant information resources as well as offering competence and knowledge within the area of vehicle simulation, for both conventional and alternative powertrains, see Figure 7.1.

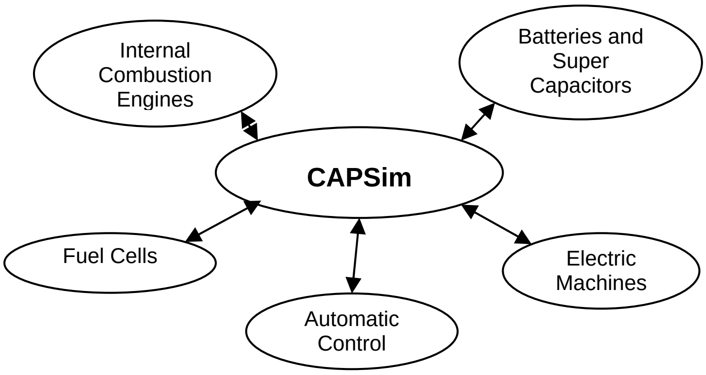

Figure 7.1: Sketch of how CAPSim cooperate with other research projects.

CAPSim has a homepage (http://www.capsim.se) that functions as a meeting place for exchange of models and ideas. Researchers involved in the programs contribute with models, measurement data etc via the CAPSim homepage. The models or measurement data are used for individual component studies or for complete vehicle studies. CAPSim has also developed a MATLAB/Simulink based simulation environment. The model library and the CAPSim simulation environment can be used for evaluating different powertrain configurations and the effect of different component sizes. The main evaluation criterion is fuel consumption and emissions.

The research activities deriving from Green Car (program I and II) is schematic described in Figure 7.2.

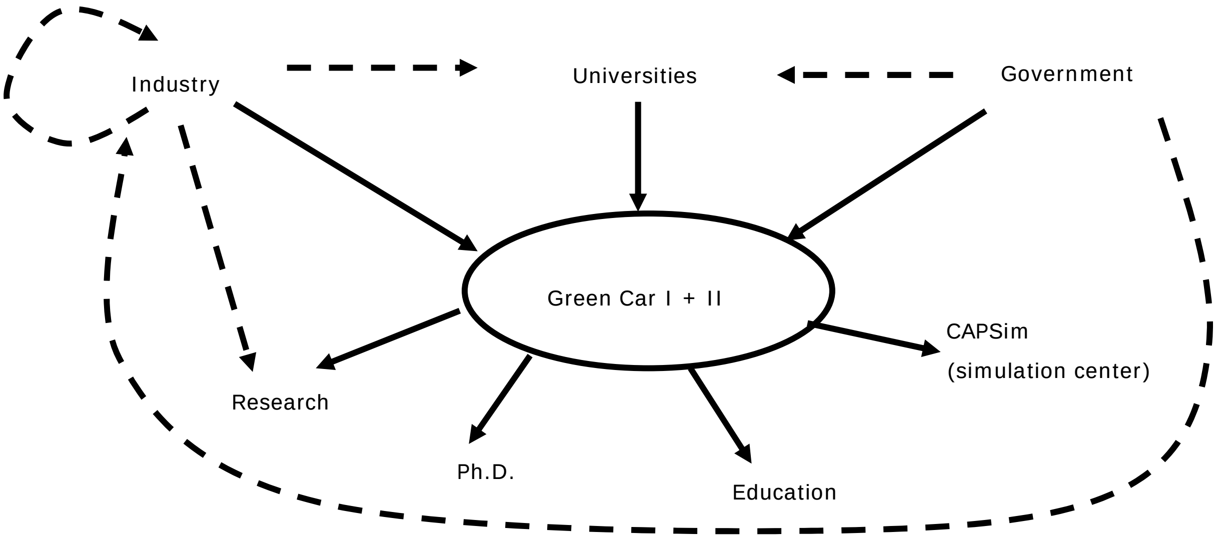

Figure 7.2: Flow of resources (economic and personnel) in Swedish R&D concerning Green Car program.

Swedish vehicle research is also receiving means from other financier such as the European Union and the Swedish Energy Agency (STEM) etc. There are also research institutes that make a contribution to Swedish R&D efforts. One example is the Industrial Research and Development Corporation (IVF).

7.2 Universities

In Sweden the following universities are involved in automotive hybrid technology related R&D, education and interchange with automotive industries and subcontractor in Sweden. See Table 8.

Table 8: Universities in Sweden involved in hybrid technology activities.

Chalmers University of Technology (Göteborg)
Halmstad University (Halmstad)
Linköping University (Linköping)
Luleå University of Technology (Luleå)
Lund University (Lund)
Royal Institute of Technology (Stockholm)
Uppsala University (Uppsala)

When using the technology structure in Chapter 6, and applying it to the Swedish universities, the result turns out like shown below.

Hybrid Technology Competence

Energy converters
- Primary
  - Combustion engines: *Chalmers University of Technology*, *Linköping University*, *Lund University*, *Royal Institute of Technology*
  - Fuel Cells: *Chalmers University of Technology*, *Luleå University of Technology*, *Royal Institute of Technology*
- Secondary
  - Electric machines: *Chalmers University of Technology*, *Lund University*, *Royal Institute of Technology*

Energy storages
- Primary: *Chalmers University of Technology*
- Secondary
  - Electrochemical: *Royal Institute of Technology*, *Uppsala University*
  - Electrostatic
    - Super capacitors: *Royal Institute of Technology*
  - Electro mechanic
    - Compressed air: *Lund University*

Power electronic converters: *Lund University*

Control: *Halmstad University*, *Linköping University*, *Lund University*

Hybrid technology: *Chalmers University of Technology*, *Lund University*, *Royal Institute of Technology*

7.3 Competence Center

In an evaluation report from spring 2006, a Swedish Competence Center for Hybrid Vehicles is discussed (Persson et al, 2006). The evaluation is aimed to focus on the research program concerning *Energy systems in road bound vehicles, 2nd phase*, but the evaluators choose to comment the plans of a national competence center. Their basic believe is that it is a good idea.

The evaluators point out some guidelines to enhance the success of such a center. They stress the importance of a seamless transfer of the cluster from the program into the center. They discuss the importance choice of geographic location too, especially since the competence within the automotive hybrid field is dispersed between several universities.

The report also refers to French authorities, who focused on three criteria when planning regional cluster. The criteria in focus were (Persson et al, 2006):

- ✓ Combination of firms, educational establishments and research centers in a given area.
- ✓ Partnerships between public and private organizations
- ✓ Critical mass – the ability to achieve international visibility.

Partly based upon this work the Swedish Energy Agency now plan to start a Competence Center for Hybrid Vehicles to develop hybrid technologies including plug-in and fuel-cell systems. This center shall supply the vehicle industry with competence and skilled personnel.

8 Conclusions

Automotive hybrid technology in Sweden is a dynamic area where the close collaboration between government, industries and universities has founded a broad competence. The know-how is spread all over the country, as well as into a diverged size of companies.

The selection of know-how includes, except the vehicle manufacturer them self, education, simulation center, laboratories, test sites and research institutes.

Within the field, there is a fundamental interest in collaborate to develop the knowledge. This concerns both industries and universities.

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10 Abbreviations

AHS2	advanced hybrid system
BAS	belt alternator starter
CAPSim	center for automotive propulsion simulation
CHR	combustion hybridization rate
CVT	continuously variable transmission
DC	direct current
DRM	double rotor machine
ECB	environmental concept bus
ECT	environmental concept truck
EGR	exhaust gas recirculation
EHR	electric hybridization rate
GDI	gasoline direct injection
HEV	hybrid electric vehicle
ICE	internal combustion engine
IMA	integrated motor assist
I-SAM	integrated starter, alternator and motor
ISG	integrated starter generator
IVF	Industrial research and Development Corporation
RH	ratio of hybridization
RH_{el}	electric ratio of hybridization
RH_{th}	thermal ratio of hybridization
P_{el}	electric power
P_{th}	thermal power
PFF	the Program Board for Automotive Research
PHEV	plug-in hybrid
PSH	power split hybrid
STEM	the Swedish Energy Agency
THS II	Toyota hybrid system
4QT	four quadrant energy transducer
4WD	four-wheel drive

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