CODEN:LUTEDX/(TEIE-5268)/1-98/(2009)

Industrial Electrical Engineering and Automation

Power Sources for Hybrid Electric Vehicles

Stefan Skoog

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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Stefan Skoog
Department of Industrial Electrical Engineering
Lund University, Faculty of Engineering

A thesis submitted for the degree of
Master of Science, Electrical Engineering

Presented 2009-09-02

Abstract

This thesis has been carried out to investigate a few areas concerning electric and hybrid electric powered land vehicles. The main objective has been to analyze the efficiency of such power trains to compare them with canonical combustion engines, both in a tank-to-wheels basis and a well-to-wheels basis. One of the question formulations is if an electric or plug-in hybrid electric vehicle charged by public electricity generated by a fossil plant will result in any environmental alleviation at all, in excess of reducing the local tailpipe pollution. To establish reasonable figures about a car's energy consumption in dynamic drive cycles such as the NEDC and the US06, a comprehensive simulation model has been used. The simulation results are presented as an analysis of waste energy, directly leading to an estimation of the potential of hybrid electric locomotion as a method to save energy and thus fuel. To form an overview about the new emerging market of hybrid electric vehicles, some of the topical key power train components are briefly discussed; combustion engines, electric machines, supercapacitors and batteries. The overview is rounded off with a brief discussion about motives behind the popularity of hybrid propulsion as well as some economical aspects from an end user point of view.

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

Max Planck

Acknowledgements

This thesis has been carried out at Semcon Automotive AB, Gothenburg in January to June 2009. The project I worked in concerned the implementation of hybrid propulsion in a passenger car. I would like to thank my tutors Frank and Henrik, and all the other energetic and inspiring people I've worked with at Semcon within this project: Marcus, Gordon, Richard, Pete, Patrick and yes, Martin, you finally get your credits too!

Back in Lund, I appreciate the support from my tutor Bengt Simonsson at the Department of Industrial Electrical Engineering and Automation. I would also like to thank Professor Mats Alaküla from the same department, whose teaching has spiritized me to pick this very thesis subject.

Dr. Rolf Egnell, Department of Energy Sciences, Combustion Engines, has supplied me with valuable information concerning primary energy converters discussed in section 5.2. I deeply appreciate his input.

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Chapter 1

Introduction

1.1 The Definition of a Hybrid Vehicle

Hybrid (electric) propulsion is a very topical subject, despite the fact that it has existed for over 100 years. At the time of writing, there are many development projects in progress, aiming to implement hybrid propulsion into everything from light urban transportation vehicles to heavy engineering vehicles. As explained in section 2.1.2.3, the cars on the market today belong to the third generation of hybrid propulsion systems, which is more comprising and prosperous than never before.

The definition of a hybrid vehicle is the usage of more than one unique propulsion system. To benefit from the key features, at least one of the power sources should have bi-directional energy flow capability. This allows energy saving concepts such as regenerative braking. The most common hybrid power trains can be strictly divided into a primary and a secondary energy converter; this is closely studied in chapter 5.

Many benefits of hybrid propulsion were discovered back in the turn of the century, though it was first when environmental discussions were aggrandised together with rocketing oil prices in the 70's that hybrid propulsion really got attention. A line in a patent filed in the early 80's (44) sums it up quite well:

> *"This system combines the speed and power advantages of an internal combustion engine with the economy and non-polluting nature of storage batteries and electric motor drive."*

1.2 Aim of Thesis

This thesis is intended to give a detailed energy analysis of the energy-saving potential of electric and hybrid electric vehicles. A well-to-wheel approach has been applied do motivate electric propulsion as global energy-saving concept. In the middle section of the report, hybrid electric powertrain components and their potential are presented from a technical point of view. The last chapter features a brief market overview from a technology aspect.

1.3 Delimitations

This report will only consider light vehicles, mainly cars, propelled by mechanical torque provided to the wheels. A wide selection of energy sources are studied, however, only generally accepted energy sources are considered. The main aim of this thesis is thus personnel cars. Commercial vehicles and sport utility vehicles will also show up as production examples of new technology. Driving habits in the European and US market are based on observations made in the last few years, and are assumed to be constant since then.

1.4 Methodology

The main work behind this thesis has consisted of scrutinizing the market for hybrid and electric vehicles, and to some extent light commercial vehicles, to catch up trends, upcoming products and active actors. At the same time, a great opportunity to actively work in a live project involving hybrid propulsion was offered. This was a unique opportunity to host discussion with colleagues about the potential and limiting features of hybrid cars and its components. The third major component in this work is a series of simulations to evaluate the energy efficiency of locomotion in personal cars.

1.5 Criticism of Sources

Hybrid propulsion is a very topical and live subject, and the market for all the sub components making up a hybrid vehicle is not yet mature. A lot of actors on this new market segment want to embellish their own products, leading to confusing and in some cases unrealistic technical specifications. This phenomenon is especially applicable for the new lithium ion battery market. To address this, a rather comprehensive mapping of the market was done, which is to some extent presented in section 6.1.

1.6 Literature Overview

Despite the modest popularity of hybrid propulsion the last 80 years, until just a few years ago, there has been a huge interest for this topic in the academia. Owing to this fact, a large amount of research has already been done, which is easy accessible through engineering research societies such as SAE (Society of Automotive Engineers) and IEEE (Institute of Electrical and Electronics Engineers).

On the subject of analysing hybrid propulsion systems and its components, excellent work has been done at the Department of Industrial Electrical Engineering and Automation Lund University, for example by Jonansson (56; 57), Ottosson (76), Bergh (17) and Andersson (12; 13).

An excellent source of reliable raw data is the U.S. Department of Energy (DoE) through Energy Efficiency and Renewable Energy (EERE) office, Vehicle Technologies Program, the Alternative Fuels and Advanced Vehicles Data Center (AFDC), the Fuel Economy program and the Advanced Vehicle Testing Activity.

Concerning the environmental debate, many of the estimations in chapter 4.1 relies on LCA analysis from public energy generation. Such studies are found in Spadaro et al. (52), Jacobson (53) and Vattenfall (18). Further on, the U.S. Department of Energy (DoE) Argonne National Laboratory Transportation Technology R&D Center offers a great tool for LCA analysis for vehicles; The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. The International Energy Agency, Hybrid and Electric Vehicle Implementing Agreement is also a rich source for information.

1.7 Physical Units

In general, a consistently use of SI units only is preferred in physical calculations and estimates as in this work. However, due to the vast amount of influence from U.S. research, automotive- and energy industry practice, a number of exceptions have been made. Table 1.1 shows the most important exceptions. Conversion tables are supplied when needed in the report.

Table 1.1: Non-SI units used in this thesis

Measure	*SI unit*	*Alternative unit*
Energy	Joule (J)	kilowatt hour (kWh)
Power	Watt (W)	horse power (hp)
Weight	kilogram (kg)	pound (lb)
Volume	cubic meters (m^3)	liter (l), gallon (ga)
Length	meter (m)	mile (mi)
Velocity	meters per second (m/s)	miles per hour (mph), kilometers per hour (km/h)
Primary Fuel Economy	-	liters per 10 km miles per gallon (MPG)

1.8 Main Results

Chapter 2 deal with the background and history of hybrid propulsion. Chapter 3 explains a simulation method to deduce the amount of energy required by a normal passenger car in everyday conditions, and its following results. Chapter 4 uses the results in chapter three to form a discussion about energy efficiency in transportation and motivate why hybrid propulsion really is a catch. Further on, this chapter also analyzes the efficiency of pure electric propulsion in areas with fossil based electric power generation. Chapter 5 briefly discusses the different key components that are relevant when implementing hybrid electric propulsion in land vehicles. Chapter 6 presents a market overview and some analyses of the market potential in hybrid vehicles.

1.9 Author's Opinion

At present, hybrid cars represent 2.3 % of all new light-duty vehicle sales (32), and virtually all analysts agree on a dramatic increase in electric and hybrid electric propulsion in vehicles the upcoming decade. This is certainly an interesting age for this subject.

Hybrid propulsion is a broad collection of technologies that are proven to be desirable by both customers and manufacturers. The only thing holding it back from being deployed in as good as all land vehicles is the standardization of components to dramatically reduce prices, and maturity of the technology to prove its safety and robustness properties. Several events worldwide indicates that (hybrid) electric propulsion really is the technology of the future. For example, US Department of Energy is granting some \$2.4 billion to support infrastructure to manufacture battery electrical vehicles (30). Norway (91) and Israel (29) have made statements about phasing out gasoline cars entirely within a few decades, to replace them with electric vehicles. Several extensive projects are being deployed around the world to establish the infrastructure for electric vehicles; one example is *Better Place* (3).

Most of the big car manufacturers have, at least not until recently, shown much interest in making products that are particularly energy efficient. They really have had no reason so far, because the problem of paying for the running costs in form of gasoline and maintenance of advanced mechanical components (combustion engines, etc.) lies in the hand of the end consumer. This concept has worked ever since the modern car was introduced in the early 20th century, and no actor has had any incentive to change it.

In the last few years, a fast growing interest from major stakeholders has developed in, as far as possible, getting rid of petroleum based fuels for transportation purposes.

Chapter 2

Background

2.1 History

To be able to understand the future, one must master the past. This section presents a brief history about what's relevant for hybrid electric vehicles: electricity and the car.

2.1.1 A Brief History of Electric Propulsion

In 1819, Hans Christian Ørsted discovered that electricity was closely connected to magnetic fields, a phenomenon that was apart confirmed by Michael Faraday, Joseph Henry and Francesco Zantedeschi around the year of 1830. Though, neither of them successfully managed to create any rotating electric motor through their experiments. A self-taught blacksmith Thomas Davenport created a fully functional electric motor in 1834 (51; 72), for which he was granted a patent (33) three years later. Due to the high costs of electric primary batteries, this motor did not become commercial successful until 50 years later. Short after Davenport's patent, there were ideas and patents about electrical railway cars (Henry Pinkus (51)), but they also failed at that time due to the absence of good power electric generators. In 1857, Professor Page made a five miles run in the Washington area on a pure electric battery powered locomotive. Sadly, the batteries were far from practical enough to make this a commercial solution. Not until the end of 1870s, when the generators ('dynamos') been perfected, the great idea of electric trolleys were actualized in many different locations in Europe (Berlin, Budapest) and in the U.S (New York-area, Chicago, Stockbridge (MA), New Orleans). At this time, 1870-1890, enterprises that today are recognized as General Electric (US), Westinghouse Electric (US), Siemens (Europe) and AEG (Europe) emerged and led the development in this area of technology. During the end of 1880s, electric trolleys were getting really popular, and the first commercial power plants were built to power the cities, where Edison's incandescent lamp had become widely used at this time. Nikolas Tesla invented the electric multiphase motor and got it patented in 1888 (92) (Figure 2.1), roughly the same time as Mikhail Dolivo-Dobrovolsky also made great contributions to the same area, including three-phase transformers.

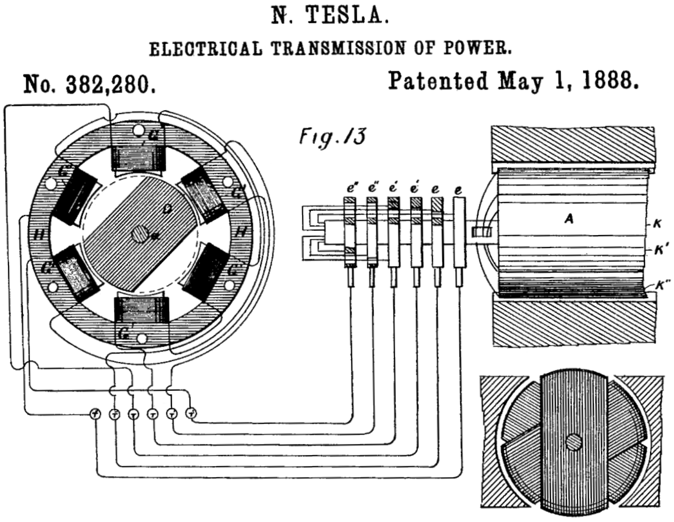


Figure 2.1: Nicolas Tesla's three-phase electric induction motor patented in 1888 (92).

These technologies eventuated in power distribution by alternating current, enabling electric power to be transmitted long distances with low losses. This allowed large centralized power plants to be built far away from the energy-consuming factories, for example the Folsom hydroelectric power plant (1895, Sacramento, CA) and Niagara hydroelectric plant (1896) (72). This time era is referred as *the second industrial revolution*.

2.1.2 The Birth of the Automotive Vehicle

The very first vehicle powered by a machine, a steam powered carriage with very limited performance, was developed somewhere between 1670 and 1770. In the 1820s, some more or less successful steam powered vehicles were built (Gurney steam car, William

James), and the concept slowly ameliorated for the next 80 years. Steam powered cars had their highest popularity around the shift into the 20th century. After ca 1912, they faded out due to the improvements of the gasoline powered car.

The first electric vehicle was most likely built by Davenport 1934 (see section 2.1.1). The applications for this quite new invention was very limited at that time, because the only available source of power was the primary battery (non-rechargeable), which was invented in 1802 by William Cruickshank (1). Half a century later, in 1859, Gaston Plant invented the secondary (rechargeable) lead-acid battery. The lead-acid battery was improved by Henri Tudor in 1886 to a fully commercially viable product. The rechargable battery made the market for electric cars flourish. Soon, specialized patents for automotive applications, *"the horseless carriages"* started to show up, for example the first in-wheel electric motor (77) (1890). The popularity of the electric car was increasing. The first recognized electric vehicle, *William Morrison's electric auto*, carried 350 kg of rechargeable batteries, making it capable of 22 km/h for up to 80 km with its 3 kW electric motor mounted on the front wheels.

2.1.2.1 The Age of Electric Cars

The turn into the 20th century, the electric vehicles held more than one third of the automotive market share. At this time, there were more electric vehicles on the street of New York than gasoline powered. The World War 1 kept the oil prices high (see figure 6.1) until the 1920's, making the electric propulsion a favorable alternative. The electric vehicles at this time offered cleaner operation than horse carriages, more quiet and safe than gasoline cars, and much quicker startup times than those few steam powered vehicles still in use.

Since the 1920's, except for the 70s, little happened on the electric vehicle market. In 1990, California Air Resources Board (CARB) introduced the *Zero Emission Vehicle Program*, which trigged the major car manufacturers (GM, Ford, Toyota, Honda, Nissan, etc.) to develop electric prototype vehicles. The most storied of those cars is the *GM EV1*. However, the vast majority of those vehicles were only demo products, and only a few models were launched as commercial products.

2.1.2.2 The Internal Combustion Engine

In parallel with steam powered cars and electric vehicles, the *internal combustion engine* was developed during the late 19^{th} century; the first reported successfully designed internal combustion engines was built in the mid 19th century. In 1876, Nikolaus August Otto patented his progress with a four-stroke internal combustion piston engine, nowadays known as the Otto cycle. Daimler and Maybach did significant improvements to Otto's design in 1885, and successfully finished the first practical four-wheeled gasoline powered car the year after. At the same time, Karl Benz patented the first gas-fueled car, after experimenting with Otto's invention in combination with the carburetor (5).

The gasoline powered vehicle gained popularity due to its superior range compared to the electrical vehicle. However, the early gasoline powered cars were bulky, loud and the needed manual cranking to start the motor, which was both dangerous and inconvenient for most users. At this time, electric cars offered superior comfort as safe, quiet and clean vehicles. Unfortunately, electric cars always suffered from a very high cost due to the problems with mass production of the big traction battery. The gasoline car had a big advantage here. Henry Ford introduced a very effective assembly line for the Ford Model T in 1914, which made gasoline powered vehicles drop radically in price thanks to mass production. Together with the introduction of the electric starter around 1919, exonerating the end user to manually crank the engine, the gasoline based car gained domanation in car sales. From now on, as good as all gasoline cars were also equipped with a lead-acid battery, but ironically, it's main purpose was to crank start the gasoline engine.

2.1.2.3 The Hybrid Electric Car

The first known hybrid electrical vehicle was made by an automotive company in Germany, Lohner, around year 1900. The car, Lohner Mixte was equipped with two or four in-wheel electrical motors. One of the main contributing engineers at Lohner was Ferdinand Porsche, later the founder of the company with his name. This car won many competitions thank to its amazing top speed of 60 km/h. Of course, the range was very limited despite the almost 1000 kg heavy lead-acid battery. Lohner also built a version of this car with a combustion engine powering a generator to drive the wheel motors (series hybrid). The car was sold in thousands with various powertrain configurations;

front wheel-drive, rear-wheel drive and all-wheel drive, with battery power and with on-board generator.

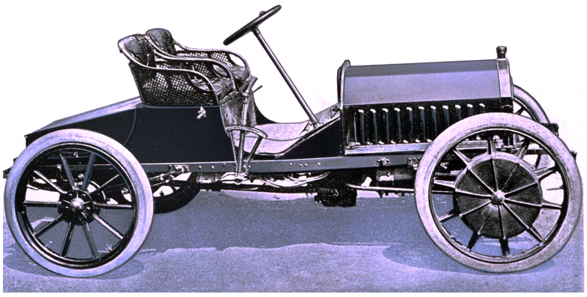


Figure 2.2: Lohner-Porsche "Mixte" (15)

The obvious advantages of an electrical powertrain, combined with a combustion engine to increase the range, triggered a wave of patents in the start of the 20th century. For example, Lars G. Nilson of New York filed a patent for a *"Electrogasolene-Vehicle"* (71) in 1902, which explains the topology of what we today call the series hybrid electrical vehicle. Another patent among the very first ones on hybrid propulsion was submitted by Henri Piper 1905 (78). Hybrid vehicles were popular in the same time period as electric vehicles. The cheap gasoline cars swiped the hybrids from the market around the late 1910's.

2.1.2.4 Modern Electric Propulsion

The market and development of both electric and hybrid electric vehicles practically stood still from 1920 until the 1970s. In the 1970's oil crisis, there were anew some few tries on pure electric vehicles. Though, they never got accepted before the crisis was over. At the same time, the ideas of the first modern hybrid cars started to show up, triggering a wave of patents being filed.

In the 1970s, the induction motor (IM) was improved from Tesla's early design, to become a robust, high-efficient, high-power source of torque. Along with the IM, sophisticated power electronics for efficient control of both DC- and AC-motors started to evolve. Thanks to this, the idea of regenerative breaking was described in a patent (46) filed 1967. At this time, a new wave of patents were issued, explaining different types of control systems for combustion engines in combination with electric motors and a battery for traction, i.e. what we today call the *hybrid electric vehicle*. In 1968, Michel N. Yardney file a patent (98) containing statements widely accepted today:

> *"The exhaust fumes generated by the combustion of hydrocarbon fuel pollute the air and are therefore considered harmful to public health. On the other hand, conventional batteries available for use in automotive vehicles do not have the storage capacity for powering such vehicle on long-distance travel"*

The solution to this problem, according to Yardney's patent, was a car that should run in pure electric mode in city traffic, and use the combustion engine only outside the city.

After this invention, a few contributions worth mentioning was a patent (50) of a car with a combustion engine powering the front wheels, and an electrical motor powering the rear wheels through a continuous variable transmission, which also feature a charging system for the batteries from the power grid. This is what we today recognize as a *plug-in parallel hybrid electric vehicle*. In 1979, Fields and Metzner (43) applied for a patent describing a *"Hybrid car with electric and heat engine"*, a control system for a parallell hybrid electrical vehicle that can be easily operated and didn't demand any particularly extra knowledge from the driver. This is a key feature to make the hybrids available to the broad market. In 1981, a patent (84) was filed for a series hybrid system using AC machines (generator and motor) to maximize the efficiency of the ICE by providing a more suitable load point. This is one of the big advantages in hybridization, explained further in Chapter 5. The wave of innovations around 1970, and the renewed view of hybrid propulsion as a more efficient and environmental friendly locomotion alternative, made up the second generation of hybrid vehicles. Despite the academic popularity, no broadly commercialized vehicles were introduced.

In 1990, California Air Resources Board (CARB) introduced the *Zero Emission Vehicle Program*, which trigged the major car manufacturers (GM, Ford, Toyota, Honda, Nissan, etc.) to develop electric prototype vehicles. The most frequently mentioned of those cars is the *GM EV1*. However, the vast majority of those vehicles were only demo products, and only a few models were launched as commercial products.

2.1.2.5 Summary

Hybrid propulsion has already gone through two generations, and the cars on the market we see today belong to the third generation of hybrid vehicles. The first generation was the early hybrids of Lohner-Porsche-type (Figure 2.2), which used the hybrid propulsion primarily for quiet operation and ease of power train configuration. The second generation that emerged in the early 1970s, used the hybrid configuration to increase fuel economy and drastically lower emission levels of the combustion engine. The third generation of today indeed also uses the hybrid configuration to increase fuel economy, but the components today are much more complex and efficient due to the availability of power electronics with high power semiconductors and alternating current electric machines.

2.1.3 Early Researchers

Hybrid and electric propulsion is considered a high-tech subject. Without brilliant researchers in the subject, this technology would not exist at all. During the last half century, many bright people have contributed knowledge and enthusiasm to revise the hybrid car. The two bright researchers that are briefly presented in the following section have made great impact on the entire automotive segment concerning hybrid propulsion.

2.1.3.1 Victor Wouk

Dr. Victor Wouk (1912-2005) (25), also known as *the grandfather of electric and hybrid vehicles* (20), made major contributions to electric and hybrid vehicles during the 60s and 70s. Wouk's most famous project went under the name *Petro-Electric Motors* (61), which consisted of a successful implementation of parallell hybrid with a rotary engine. The fuel consumption was cut in half (80) and the emissions were reduced to under a tenth of what was standard of that time. Alas, after several years of intense promoting these ideas in the automotive industry without any response, Wouk turned to other chores such as correspondence and standardization.

> *"The hybrid is the way to go if we must reduce automobile pollution and reduce automobile fuel consumption a large amount in a short period of time."*

Victor Wouk in the 1970s
"The grandfather of modern hybrid programs"

Figure 2.3: Victor Wouk and one of his hybrid prototype cars

2.1.3.2 Andrew Frank

Dr. Andrew Frank, also known as *the father of modern plug-in hybrids*, built a plug-in hybrid vehicle for the first time in 1972 as a university student project (19). His creation performed just fine, but the topology (parallel hybrid) was way ahead of the available technology (batteries and electronics). Luckily, Dr Frank has continued to build hybrid cars of different types as research projects during his career (54). With a dozen of finished hybrid cars in his curriculum, he ought to be the most experienced hybrid car developer in modern time.

2.2 Hybrid Propulsion in Heavy Vehicles

Hybrid propulsion is very suited to be implemented in heavy vehicles, such as commercial land vehicles. However, this report will only briefly cover this area.

2.2.1 Early Adoption

The concept of mixing internal combustion engines (ICEs) with electrical motors in different topologies is neither new nor unacquainted in the automotive sector. Heavy construction vehicles such as off road dump trucks, boats, submarines and railway engines (see figure 2.4) have already used motor-generator solutions together with combustion engines for a long time. Military prototype vehicle are also adapting the use of hybrid electrical propulsion (88), offering better fuel economy and the ability to quiet and redundant operation through electric-only propulsion.

2.2.2 Observed Performance

Several independent successful field evaluations of hybrid buses in public transit have been made in different places (Sweden (59), Seattle (23), New York (22)). The latter two shows a long-term evaluation between 2004 and 2006 of public transit in Seattle and New York city traffic. A hybridization of the bus fleet lowered the fuel consumption by 21 %, in some cases down to 50 %, and also lowered the total operational cost (maintanance and purchase) by 15 %. Hybrid propulsion is certainly eligible for commercial vehicles. These field test are among the most extensive made so far, but as good as all field tests agree on drastically lowered fuel consumption and most often a better drive experience through lower emissions and noise. The first fleets of distribution trucks in North America also feature a 30 % improvement in fuel economy (45).

2.3 Related Projects

2.3.1 Lobby Organizations

The widespread interest of electric and hybrid vehicles has trigged a large number of independent organizations to gather devotees and to spread information about the subject. They often offer comprehensive data on the subject, but the objectiveness must of course be regarded. Table 2.1 summarizes a few of the organizations.

2.3.2 The Solar Car

Palmer Louis, Switzerland, built his own solar powered vehicle, The Solar Taxi (4), and traveled around the globe (53451 km) in 534 days during 2007 and 2008. The vehicle is powered soley on solar power, Palmer claims. The car is equipped with 6 m^2 solar cells, but is also recharged over night from the grid. The use of grid power is justified by generating solar power into the grid at a stationary solar plant back in Switzerland.

Figure 2.4: Heavy vehicles with electric propulstion systems

Table 2.1: Some lobby organizations in (hybrid) electric vehicles

Organization	*Web Resource*
The California Car Initiative	http://www.calcars.org
Electric Auto Association - Plug in Hybrid Electric Vehicle	http://www.eaa-phev.org
Electric Drive Transportation Association	http://electricdrive.org
Hybrid Cars	http://www.hybridcars.com
Autoblog Green	http://www.autobloggreen.com
Green Car Congress	http://www.greencarcongress.com

2.3.3 Project Better Place

The US/Israeli entrepreneur Shai Agassi, leader of the project *Better Place* (3) is currently in an alliance with Renault-Nissan to make pure electric cars to put out on the market in 2010, and achieve large-scale production in 2011. The Project symbolizes a new business model to make ordinary people afford electric vehicles with the same performance as the old gasoline car they are used to. Better Place is currently beeing applied in limited areas such as Israel, Denmark and more.

> *"The car **is** the biggest solution for climate changes,*
> *not the biggest problem."*
>
> Shai Agassi, 2008 (75)

Chapter 3

Vehicle Simulations

3.1 Introduction

Cars are, or should be, bodies that are designed to move efficiently on land through displacement of the tropospheric air and overcoming of surface friction. To get a fundamental understanding of the physical properties and energy requirements of longitudinal movement in cars, a model has been used to evaluate these properties with realistic drive conditions. The model is based on differential equation solving through Matlab ® Simulink ® and is prior developed at the department of Industrial Electric Engineering and Automation (IEA), Faculty of Engineering (LTH), Lund University. The work in this thesis has provided further improvements of the model in order to reach the consequent results.

3.1.1 Objectives

The simulations are done as a pre-study to get a profound insight in the energy requirements of locomotion, primarily concerning cars and personal transportation. The objectives are to show the potential of pure electric- or hybrid electric powertrains in terms of energy efficiency.

3.2 The Model

The model, as seen in figure 3.1, is developed for Matlab ® Simulink ® and cover a wide range of physical properties of four-wheeled vehicles, from small cars to heavy trucks by just changing the associated input parameters. The primary scope of use is to evaluate the longitudinal vehicle behavior through standardized drive cycles. The basic physical properties such as weight, air drag, roll drag, engine and gearbox specifications are easily configured through initialization scripts. The scripts allow batch simulations to be executed in order to explicitly compare the result from different vehicles and drive cycles.

Each sub-model represents physical components such as engine, brakes, gearbox, road, driver, etc. The model is centralized around the fundamental physical laws including units of force, mass, distance and torque leading to power, speed and energy when relating to time.

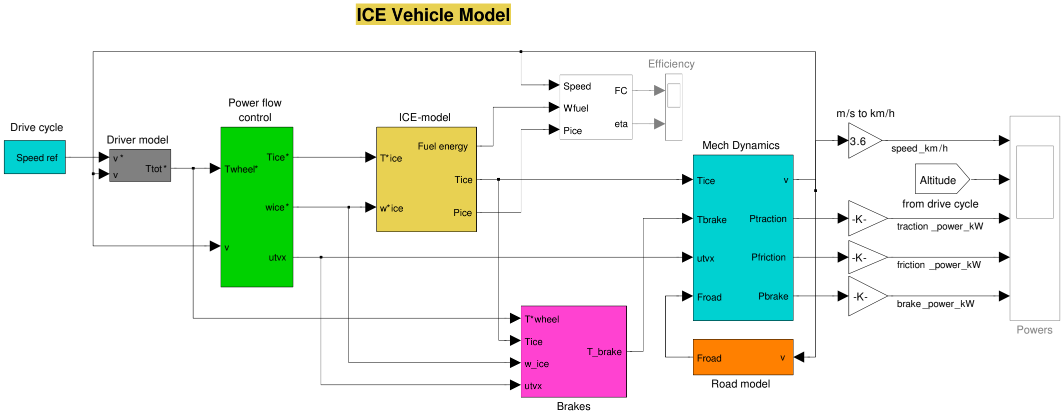


Figure 3.1: Top level of the simulation model. Each block consists of a number of subsystems that represents the real physical properties of the power train.

3.2.1 Limitations in the Model

Despite the flexibility and comprehensiveness of the model, it has a few limitations. The vehicle dynamics does only cover for longitudinal behavior along the velocity reference, and does not consider the dynamic friction effects of curve taking nor the tire slip during heavy acceleration and retardation. The combustion engine models are based on measured data from ordinary personal car or light commercial vehicle engines. However, the model treats all working points as steady state and thus rejects the transient response that naturally exists in combustion engines of the prescribed type. To adress this in the model, a low pass filter is implemented at the torque reference signal.

3.2.2 Basic Physical Properties

The simples accurate physical model to represent braking forces of a car (see figure 3.2) is through Newton's laws of motion as presented in formula 3.1.

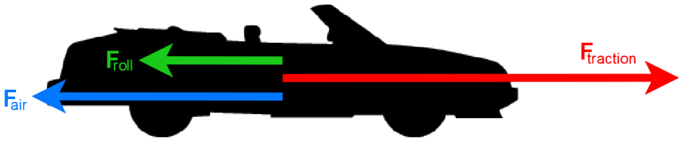


Figure 3.2: Basic forces acting on a rolling car

$$F_{brake} = F_{roll} + F_{air} \tag{3.1}$$

$$F_{roll} = C_r \cdot M_v \cdot g \tag{3.2}$$

$$F_{air} = \frac{1}{2} \cdot \rho \cdot C_d \cdot A_v \cdot v^2 \tag{3.3}$$

Where F_{brake} is the total braking force, C_r is the roll resistance, M_v the vehicle mass, g the gravitation constant, ρ the air density, C_d the air drag, A_v the frontal area, and v the vehicle speed. To operate in steady state velocity, the traction force must exactly equal the braking force. The sum of the traction force and the braking forces, F_{tot}, results in a change of speed according to Newton's law of motion:

$$F_{tot} = m \cdot a = m \cdot \frac{dv}{dt} \tag{3.4}$$

Steady state operation (constant speed) implicates fairly straight-forward calculations, and can be made by hand. However, braking forces are dependent upon the speed, and realistic driving require dynamic changes in speed. This makes the basic relationships more suited to be evaluated in an automatic computer model.

3.2.3 Drive Cycles

To specify a realistic drive pattern in real traffic situations, two different drive cycles are used throughout the simulations. The New European Drive Cycle (NEDC, see figure 3.3) represents city driving, including one short piece of highway driving. The US06 (figure 3.4) represents more intense highway driving.

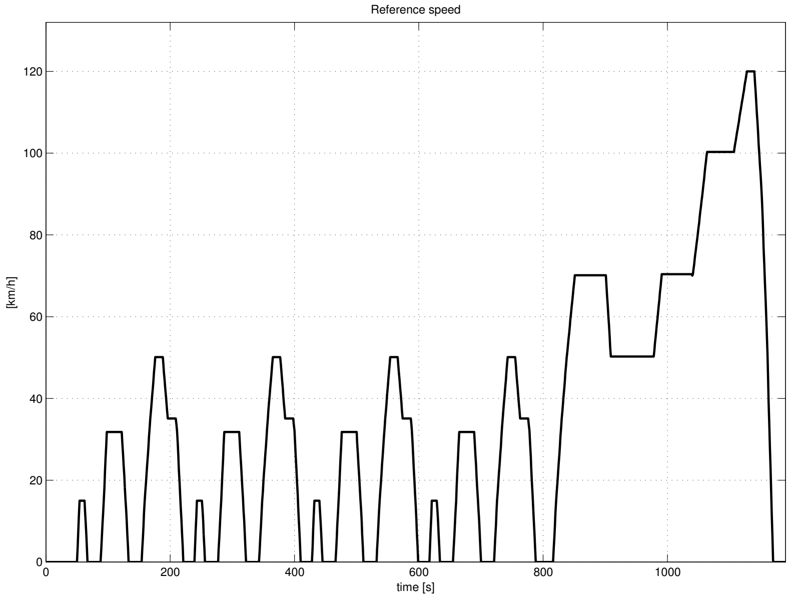


Figure 3.3: New European Drive Cycle (NEDC)

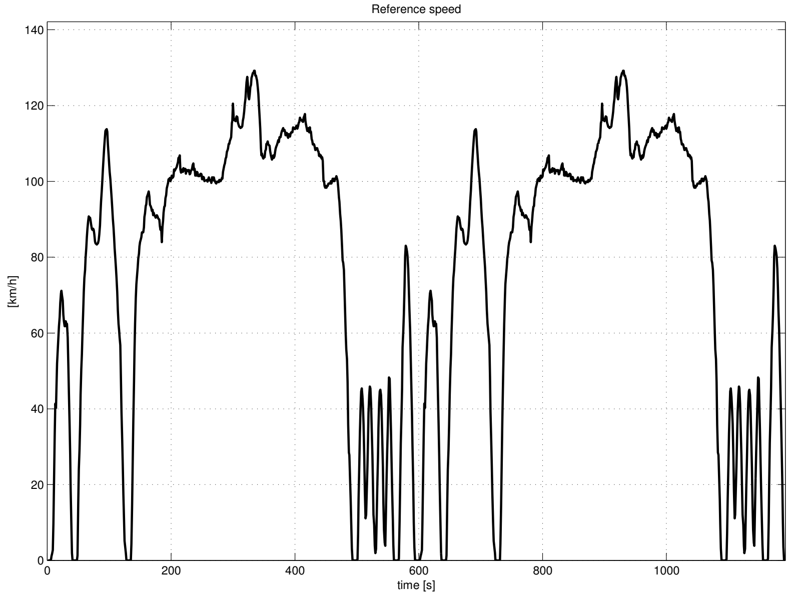


Figure 3.4: US06 Drive Cycle

3.2.4 Reference Car

To run the simulations with realistic results, a reference car must be specified with its basic physical properties. The data used in the simulations (see table 3.1) are chosen to represent a larger variant of a Toyota Prius, an aerodynamically slim and low-friction modern car. Auxiliary loads have been added to represent a reasonable traffic situation. Such auxiliary components can be head lights, minor cabin heating or cooling, audio and media systems, and so on.

Table 3.1: Specifications for the Reference Car

Specification	*Symbol*	*Value*
Vehicle weight	M_v	1600 kg
Drag coefficient	C_d	0.26
Frontal Area	A_v	2.55 m^2
Wheels		
Rolling resistance	C_r	0.010
Radius	r_w	0.30 m
Gearbox		
Numer of gears	n_{gear}	6
Efficiency	η_g	0.97
Max shift time	t_{gmax}	0.5 s
Engine		
Max power	P_{max}	100 kW
Max rate of spin	ω_{ICEmax}	6000 RPM
Max efficiency	η_{ICEmax}	34.3 %
Fuel		Gasoline
Fuel energy density	ρ_f	31.4 MJ/l
Auxiliaries		
Electric loads	P_{el}	500 W
Mechanical loads	P_{mech}	150 W
Generator efficiency	η_{el}	0.5

3.3 Cases Studied

The primary goal was to investigate the required mechanical energy, as well as the average traction force, to complete two common drive cycles. As the basic simulations are executed with a classic internal combustion engine installed in the simulated vehicle, the real efficiency of the gasoline engine is also of interest in this study.

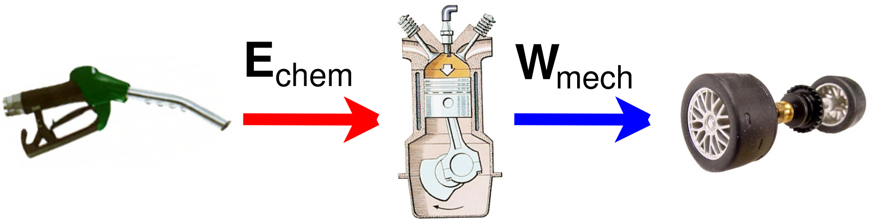


Figure 3.5: The explicit difference of mechanical energy and chemical energy.

The first study is focused entirely on the energy, power, and force required to propel the reference vehicle's glider through the current drive cycle. The result will establish the requirements of an arbitrary power source in the car. Measurements are done pre-transmission, directly on the engine output shaft, to include the powertrain losses and auxiliary loads, but make the results independent of the primary engine type itself.

The second study is made with the measurements at the primary energy input of the combustion engine, i.e. the gasoline. Powertrain losses from gearbox, idle power consumption and auxiliary power consumption are therefore included in these results (see figure 3.5). The chemical energy is traced and categorized into the different scopes of use. The steady state efficiency map of the used gasoline engine is shown in figure 3.6. The simulation model chooses the best suited load point for the combustion engine by choosing a suitable gear for each reference speed and torque.

3.3.1 Definitions of Measurement Results

Before presenting the results, there are a few figures to clarify. The reader should be aware of the meaning of some physical measurements to be able to follow the reasoning in the upcoming section: Energy Efficiency, Tractive Force, and Locomotion Efficiency.

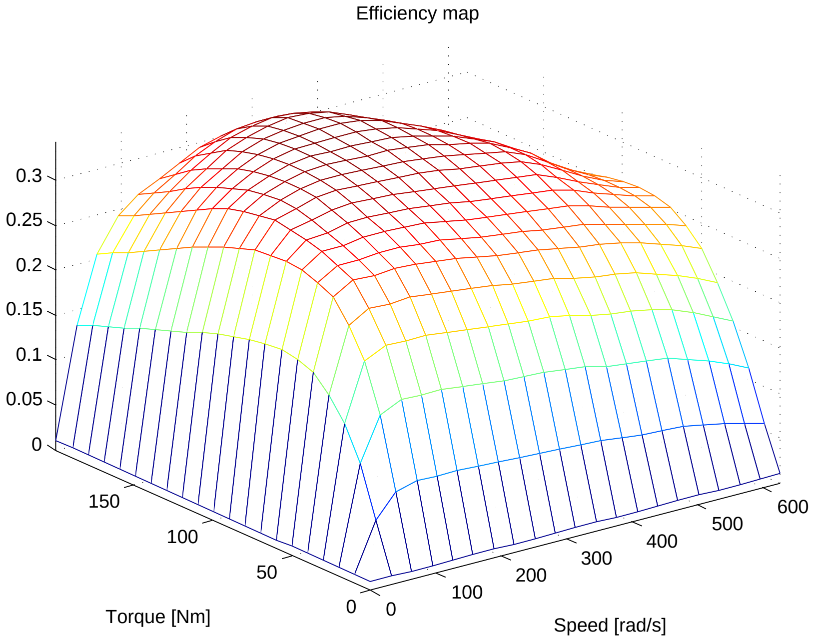


Figure 3.6: The efficiency map of the gasoline engine used in the simulation model.

3.3.2 Energy Efficiency

In the automotive sector, it is very common to mention the fuel consumption or fuel efficiency of a particular car, termed in liters/10 km or miles per gallon (MPG) respectively. However, these units become rather futile when the primary fuel no longer is based on fluid hydrocarbons such as gasoline or diesel. Especially electric vehicles are in need of another method of measuring the energy consumption or energy efficiency respecting the locomoted distance. Looking at standard SI units, energy ($Joule$) per distance ($meters$) appears to be a suitable unit. Since the energy business prefer the alternative unit watt hours (Wh) for measuring energy, de facto unit has become Wh/km or $Wh/mile$ among OEMs. See table 4.1 for some example figures.

3.3.3 Tractive Force

The composed unit for energy consumption in the previous section, Joule per meter (J/m), is the exact same physical unit as mechanical force, measured in the SI-unit Newton (N) (equation 3.5). The conversion factor and some topical figures from this work are presented in table 4.1.

$$Tractive\ Force = \frac{Energy}{Distance} = \frac{Power}{Speed} \tag{3.5}$$

The average tractive force is a powerful number to measure how efficient a car's glider (chassis and body) can move through a drive cycle. Intuitively, the tractive force should be measured as the mechanical power related to the speed at the output axle to the driving wheels, presuming optimal ground contact through the wheels.

3.3.4 Locomotion Efficiency

The locomotion efficiency is defined here as the quotient between the output energy used for actual traction and the input primary energy. The input primary energy could be the chemical energy in gasoline supplied to an internal combustion engine, or electric energy charging the batteries of a plug-in hybrid vehicle. The locomoton efficiency never exceed the maximum efficiency of the combustion engine, in fact, it is most often in the range of 40 % - 80 % of the peak ICE efficiency.

$$\eta_{loc} = \frac{E_{traction}}{E_{input}} \tag{3.6}$$

The average locomotion efficiency (η_{loc}), the average mechanical traction force (F_{trac}) and the fuel energy consumption (E_{fuel}) are connected according to:

$$E_{fuel} = \eta_{loc} \cdot F_{trac} \tag{3.7}$$

3.4 Results

Four main cases evaluated in total. Mechanical energy at the drive shaft and chemical (fuel) energy entering the combustion engine is carefully traced for each of the two drive cycles. Table 3.2 summarizes the most interesting numbers for all cases.

3.4.1 Mechanical Energy

The analysis of mechanical energy, pre-transmission, is particularly interesting since it is independent of the choice of engine in the car, presupposing the engine is strong enough to fulfill the power and torque requirements of the drive cycle. The results from this

Table 3.2: Simulation Reults

Case	**Data**	
	NEDC	US06
Traveled Distance	11.0 km	25.8 km
Elapsed Time	1190 s	1190 s
Average Speed	33.3 km/h	77.9 km/h
Locomotion Efficiency	18.7 %	24.5 %
Average Developed Tractive Force	474 N	720 N
Average Engine Output Power	5500 W	16700 W
Total Required Mechanical Energy at Engine Shaft	6.60 MJ	19.9 MJ
Total Required Input Chemical Energy	35.3 MJ	81.2 MJ
Total Brake Energy	1.65 MJ	5.94 MJ
Total Idle Energy	7.00 MJ	9.70 MJ
Optimal Load Point Potential Savings	9.08 MJ	13.4 MJ

case are later used to assess the energy requirements of a car with electric propulsion. In short terms, it represents the mechanical force required to make the specified car glider overcome the braking forces (roll- and air drag) and reach the predetermined speeds of the drive cycle.

At first, the results are compared with independent sources to verify the equitableness of the numbers. The main result shows that the deduced average tractive force indeed is resonable when compared to commercial electric vehicles, see table 4.1.

The first interesting outcome from the simulations is the low average output power requirement: 5.5 kW and 16.7 kW for the NEDC and US06 drive cycle respectively. This is to compare with the installed engine power; 100 kW. The observation partly motivates the low average efficiency (18.7 % / 24.5 %) compared to the peak efficiency (34.3 %) of the combustion engine. Most internal combustion engines have a very limited efficiency at low loads, as illustrated in section 5.2.1.

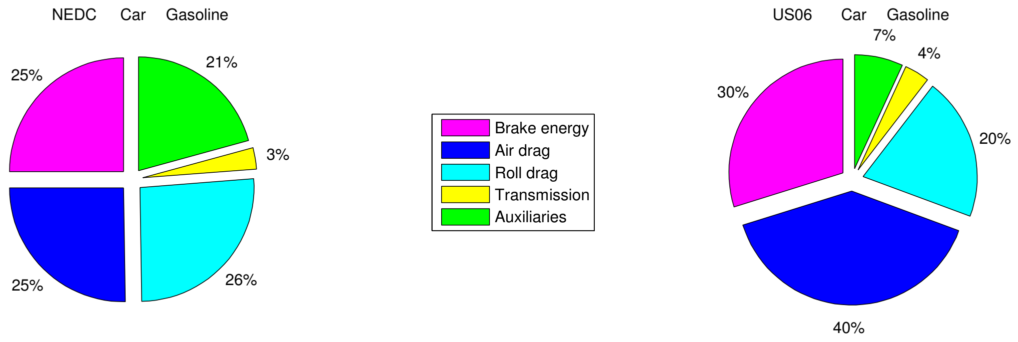


Figure 3.7: Mechanical energy distribution required in NEDC (left) and US06 (right) drive cycles.

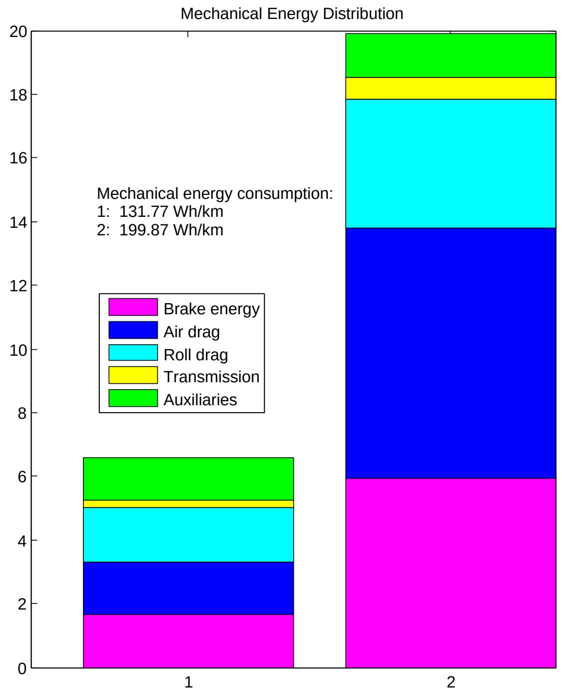


Figure 3.8: Mechanical energy in MJ required to finish the (1) NEDC and (2) US06 drive cycle respectively.

Figure 3.7 shows a graphical representation of the energy distribution after one completed drive cycle with the reference car. In the city-like drive cycle, NEDC, the energy loss is almost equally shared between air drag, rolling friction, brake energy, and auxiliary devices. Remarkable is that the auxiliary devices consume one fifth of the total energy, even though the drive pattern is rather active. The highway driving in the US06 cycle requires more power over all, hence minimizing the share of auxiliaries. The air drag consumes a bigger share, which is expected due to the higher vehicle velocity. Figure 3.8 shows the same result as in figure 3.7 but in absolute measures.

3.4.2 Chemical Energy

Similar to the mechanical energy analysis in the previous section, the chemical energy at the input to the combustion engine is declared and categorized into its end usage, see figure 3.9 and 3.10. The distribution diagram in figure 3.9 clearly shows the potential in hybridization. Some of the categories may deserve an explanation.

Thermal loss is the amount of chemical input energy *not* converted to mechanical energy at the motor output shaft, i.e. pure losses due to friction and other parasitic losses in the realization of the thermal cycle.

Idle represents the amount of input energy that could be saved if the motor was instantaneous shut down as soon as the traction torque demand from the driver was below a threshold close to zero. Since the engine does not deliver any useful mechanical power for locomotion in idle mode, the efficiency is theoretically zero. The idle-category could therefore be included in the thermal loss-category.

The rest of the categories and its relative distribution are identical with the previous section, mechanical energy. Noticeable by the chemical energy distribution is that the pure thermal loss represents an equal share in the two drive cycles. Though, the end locomotion efficiency is significantly different. It seems like the reduced idle power alone accounts for the increase in total fuel efficiency in the US06 cycle.

The average corresponding force from the fuel entering the engine during the both drive cycles is fairly equal in magnitude (ca 880 Wh/km), despite the significant difference in actual performed traction force. The answer to this is the low total efficiency at the NEDC as seen in table 3.2.

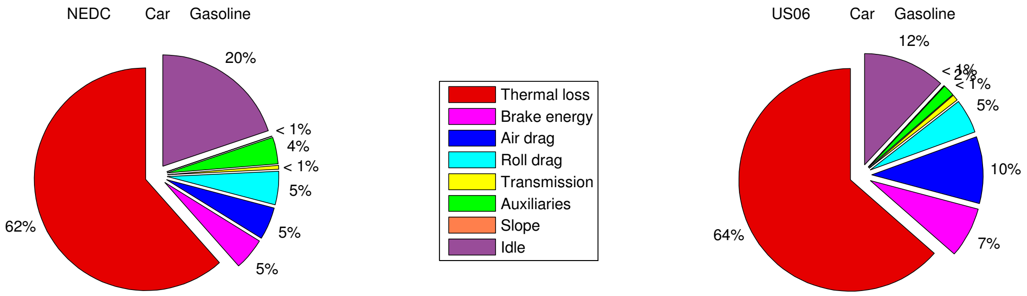


Figure 3.9: Chemical energy distribution required in the NEDC (left) and US06 (right) drive cycle.

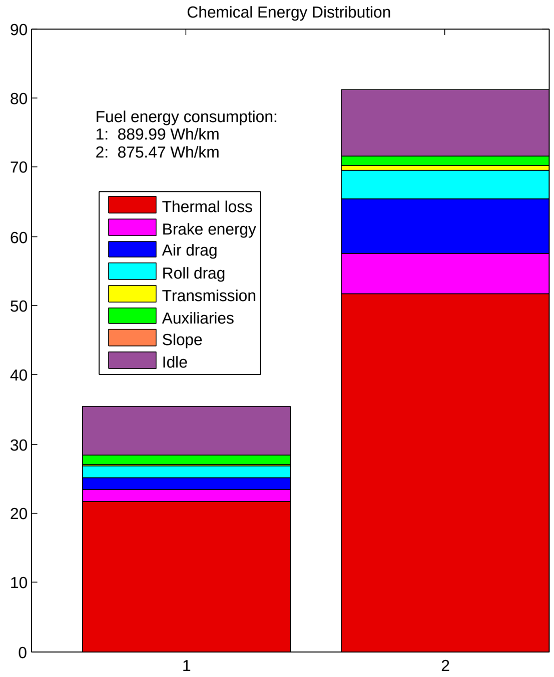


Figure 3.10: Chemical energy in MJ required to finish the (1) NEDC and (2) US06 drive cycle respectively.

3.4.3 Potential of Hybridization

The outcomes of the simulations show the quantity and quality of the losses in a normal reference car. By relating the losses in different categories to the useful output energy, an estimation of fuel saving potential for hybrid electric vehicles can be estimated, see table 3.3. Remarkable is how an lossless hybrid propulsion system could save up to 50 % fuel in intense highway driving as represented in the US06 drive cycle. In terms of energy savings, a pure electric vehicle also has most of the properties presented in table 3.3. For example, an electric propulsion system has very little or no idle power consumption. Regenerative braking is rather easy to implement if the main traction motor already is electric. Lastly, electric motors have high or very high efficiency in all load points, comparing with combustion engines.

Table 3.3: Potential of Hybridization

Feature	**Potential Fuel Savings**	
	NEDC	US06
Regenerative Braking*	25 %	30 %
Idle Elimination	20 %	12 %
Optimized Load Point*	32 %	19 %
Total	41 %	50 %

* A lossless secondary propulsion system is supposed

3.5 Conclusions

The drive cycle has great impact in the efficiency of the internal combustion engine. A drive pattern with high continuous load toque favors the efficiency of the combustion engine, but will at the same time result in a higher average traction force, thus still increasing the fuel consumption.

Hybridization has a great potential to recover large amounts of energy wasted by the combustion engine, in terms of idle elimination and optimization of load point. The results also show the big potential of regenerative braking by electric motors when driving in realistic conditions represented by the two drive cycles. The results, especially those presented in table 3.2, are verified to be reasonable compared to similar authentic studies, for example as presented in (64, p40) and (10).

3.6 Further Use of Simulation Model

The simulation model used in this chapter has great future potential. Only the basic features of the original model are used in this work, with some improvements to explicate the output date. The full model, however, is designed to simulate advanced hybrid systems, as in ref (56) and (85). Thanks to the high modularity of the model, it can easily be modified to model virtually any type of vehicle with any type of motor, tracing a vast number of parameters. The strength of the model is the representation of standard gasoline and diesel engines as well as electric traction motors, making easy to setup models for common hybrid topologies.

Chapter 4

Energy Analysis

4.1 Energy Consumption

4.1.1 Introduction

Transportation requires energy, but how much does this correspond in relationship to everyday activities? In the previous chapter, the mechanical and chemical energy to propel a passenger car was deduced through a simulation model (section 3.4), applied through pre-defined drive cycles.

A direct thought of analyzing the transportation energy demands is if we really have to strain the atmosphere by releasing fossil based green house gases for this purpose. What alternative energy sources do we have as options for locomotion except fossil fuels? Today's cars and trucks are usually powered by gasoline or diesel. Since the oil is expected to run out in a few decades (21), it is highly apposite to evaluate other energy sources for propulsion.

4.1.2 Situation Today

The driving habits for personal cars, the car fleet itself as well as the choice of primary propulsion differ in the three regions of interest; Sweden, EU and the US. The following section clarifies the numbers used for estimations later on in this chapter.

4.1.2.1 The U.S. Car Fleet

Motor vehicles account for about half of U.S. petroleum usage, and about three-quarters of this fuel goes to the 220 million cars and light-duty trucks in the nation's passenger vehicle fleet, accounting for 25 % of all CO_2 emissions in the U.S (53). By traveling $4.2 \cdot 10^{15}$ meters ($2.6 \cdot 10^{12}$ miles), these vehicles burn about $4.92 \cdot 10^{11}$ liters ($1.3 \cdot 10^{11}$ gallons) of gasoline and diesel fuel each year (38; 64), or about 2,271 liters (600 gallons) per vehicle on average annually. In terms of fuel consumption, U.S. passenger vehicles in the fleet average 1.18 l/10km or almost 20 miles per gallon (MPG), which includes the 22.1 MPG averaged by cars and the 17.6 mpg averaged by light trucks (64, page 9). This result in an average US car traveling 57 km (36 miles) every day, consuming 6.7 liters (1.8 gal), measuring up to 235 MJ (65 kWh) (see table 4.2). The motorization in the U.S. is 776 cars per 1000 inhabitants (6).

4.1.2.2 The European Car Fleet

The EU car fleet by 2006 was powered by 67.7 % gasoline, 31.4 % diesel and 0.9 % other fuels (6). Noticeable by this fleet is that cars in general are smaller and more energy efficient than their US counterparts. The motorization in the EU15/EU27 is 508/446 cars per 1000 inhabitants (6). Unfortunately, further accurate statistics are not as forthcoming as for the US or Swedish market.

4.1.2.3 The Swedish Car Fleet

The Swedish car fleet has some protruding data. The average engine power (102 kW) is the second largest in the EU (81 kW) (14) for new registered cars, resulting in one of the world's thirstiest car fleet. With a total number of 4.2 million cars (6), traveling an average of 15,180 km per car and year (83), consuming in average 0.84 l/10 km gasoline and 0.68 l/10 km diesel (89). The share of diesel powered cars is low in Sweden compared to the EU average. Averge emissions over all new sold cars is 181 gCO_2/km, the EU25 average for new cars is 160 gCO_2/km (2006) (70). The amount of registered hybrid cars at the end of 2008 was 13,483 (83) and 129 pure electric vehicles. The motorization in Sweden is 461 cars per 1000 inhabitants (6).

4.1.3 Locomotion Power

The primary goal of a car is to move the driver and possibly any passengers. This requires a specific input of energy from the prime mover in the car, as explained in chapter 3.

Table 4.1: Overview: Automotive Average Tractive Force

Situation	**Required Tractive Force**		
	(kJ/km) or (N)	(Wh/km)	(Wh/mile)
Unit Conversion	1.000	0.278	0.447
	3.600	1.000	1.609
	2.237	0.621	1.000
Simulation results:			
NEDC, "City Driving"	475	132	212
US06, "Highway Driving"	720	200	322
OEM Tractive Force Assessments:			
Tesla Roadster @ highway (86)	671	186	300
Tesla Roadster @ city (86)	335	93.2	150
Smart Ed (63)	268	74.5	120

4.1.4 Perspective

In a power consumption point of view, it is interesting to compare car transportation with other high-power activities relevant for as good as all people. Household electricity is a pertinent example of such activity.

4.1.4.1 US Household Energy

Official U.S. statistics (37) states that the average household electricity consumption was 936 kWh per month in 2007. This corresponds to an average power of 1.28 kW (see table 4.3) or average daily energy usage of 31 kWh (see table 4.2). The average price for household electricity was 0.11 USD/kWh at the same year.

4.1.4.2 Swedish Household Energy

The corresponding number for Swedish households (68; 69) is 5.0 MWh/year for electricity only and 20 MWh/year including heating and hot water, resulting in 14/55 kWh/day or 570/2300 W with and without heating respectively (see table 4.2 and 4.3).

Table 4.2: Overview: Automotive Energy Requirements

Situation	**Energy** [MJ]	[kWh]
1 liter of gasoline	32.56	9.044
1 liter of diesel	35.87	9.963
One tank (45 l) of gasoline	1465	407
Average Household Electricity		
US household per day	111	31
SE household per day	50-198	14-55
Average US car gasoline energy consumption per day (38; 64)	235	65
Kinetic energy		
1300 kg car @ 50 km/h	0.125	0.035
1300 kg car @ 100 km/h	0.502	0.139
4500 kg truck @ 50 km/h	0.434	0.121
4500 kg truck @ 100 km/h	1.736	0.482

4.1.5 Kinetic Energy

An ordinary car has a mass of approximately 1300 kg, which corresponds to a kinetic energy of 502 kJ at a speed of 100 km/h (see table 4.2). The required power of a similair car is 10.28 kW according to table 4.3. Thus, the kinetic energy of this particular car corresponds to 49 seconds of driving at constant velocity of 100 km/h. This figure gives an appreciation of the potential of brake energy recapturing systems. In ordinary cars, all the energy generated by the propulsion system to accelerate the car is lost in the friction brakes when decelerating.

4.1.6 Vehicle Dynamics Improvements

There are several methods to reduce vehicle power consumption except for hybridization of the power train. As presented in formula 3.1, the most natural way to increase locomotion efficiency is to reduce the brake friction forces; air drag and rolling resistance. It is indeed possible to build a very low drag vehicle with, for example, three wheels, and an aerodynamically slimmed glider. Such vehicles has existed for a long

Table 4.3: Overview: Automotive Power Requirements

Situation	**Required Power**
Reference	
Average US Household	1,280 W
Average SE Household	570-2,300 W
Car Auxiliaries Systems	
Full beam lights	200 W
Air condition (27)	200-6,000 W
Power Audio System (peak) (66)	1,500 W
Car Ancillary Systems	
Electric Brake (peak) (66)	2,000 W
Electric Steer (peak) (66)	1,200 W
Traction Power:	
NEDC, average power	4,220 W
US06, average power	14,970 W
Reference Car (94) :	
GM EV1 @ SAE J1634 drive cycle	5,280 W
GM EV1 @ 45 mph (72 km/h)	5,810 W
GM EV1 @ 60 mph (97 km/h)	10,280 W

time, but never succeeded to reach a wide customer basis. An example of a low-drag vehicle today is Aptera, which also features hybrid electric propulsion. However, ultra-slimmed vehicles have never, and probably will never, been accepted as replacements to the big square boxes with wheels that people are widely inculcated to define as cars today. Commencing from what cars look like today, Kirchain et al. (60) present how minor improvements can decrease the braking forces on the car glider. A 10 % reduction in vehicle aerodynamics provides a 3 % fuel economy increase. Further on, a 10 % mass reduction provides 2-8 % better fuel economy, depending on tires and road friction.

4.1.7 Auxiliary Devices

Cars today use their installed power to much more than for traction purposes. Well-recognized auxiliary units today are power steering, air condition, multimedia entertainment system, electric heating, etc. One of the bigger challenges in electric and hybrid electric vehicles is cabin climate control. Electric vehicles do not have the vast amounts of waste heat as ICE cars have. Air condition becomes an even bigger problem, because the large amount of power required to cool air. Electric air condition modules are already available on the automotive market. A typical maximum power consumption of a such product can be as high as 6 kW (27), which is higher than the average power needed for traction at the NEDC drive cycle (4 kW) (see section 3.4.1). Ironically, the auxiliary devices in a modern premium car today are destined to consume more power than the average traction power generated in reasonable city driving, see table 4.3.

4.1.8 Ancillary Devices

Ancillary devices are those which are necessary to upkeep the functionality of the internal combustion engine, for instance water pump, oil pump, ignition system, etc. It turns out that the cars today still have a lot of unnecessary pump losses. Just by regulating the oil pump, fuel efficiency can increase by 2 % (24) through the standard drive cycle (NEDC).

4.1.9 Power Management

In a hybrid vehicle, there are more than one source of energy available. The total system efficiency is a key matter, and dependent on the efficiency of each component in the power train. One common component for all hybrid topologies is a Power Management Controller (PMC), which is the unit for central intelligence in means of controlling the power flow of the drive train. In highly electrified power trains, the overall system efficiency could be further increased by letting the PMC control auxiliary devices through Power Scheduling. Tests have shown that just by scheduling one of the most power consuming auxiliary component - the air conditioning - in a hybrid car equipped with *"stop & go-technology"* (idle elimination), fuel savings of 9 % can be achieved during a regular summer day (NEDC) and without affecting the driving behavior (82).

4.2 Energy Sources for Transportation

In times when the availability of energy becomes limited due to economical, enviromental, and political reasons, it is highly topical to consider the eligibility of other sources than the ones we are currently using. Electric and hybrid electric vehicles feature several benefits concerning energy consumption and environmental strain.

Electric propulsion:

- Eliminates the tailpipe emissions
  - leads to cleaner traffic-intense areas; cities and highways
  - inaugurates the possibility to apply carbon capturing storage on the primary fuel conversion
  - dramatically increase the possibility for renewable primary power sources
- Increases the locomotion efficiency
  - decreases the total energy usage
  - leading to lower end emissions over all
- Simplifies the powertrain (when mature)
  - leading to fewer service intervals
  - reducing the amount of oils and lubricants

4.2.1 Current Situation

The world transportation is 95 % powered by oil products. Natural gas has some 3 % cover, coal and electricity together cover 2 %, renewable power sources are statistically negligible (8).

4.2.2 Steps of Hybridization

It is no doubt that fossil fuels harm the environment. In a long-term perspective, oil and other fossil fuels should be phased out as a primary source in transportation. However, this is not done over a night. Shifting in a new type of technology in a huge business as the car industry demands enormous effort, where the technology itself is the easy part, compared to the achievement of changing the attitude of both manufacturers and end users. Therefore, big changes are always implemented gradually. Hybrid electric vehicles are perfect bridge between classical internal combustion cars and electric cars, which can be implemented gradually. Here's an example of how hybridization is likely to be phased in on the mature market:

1. Reduce the consumption of fossil fuels by increasing the efficiency of the combustion engine.
2. Let the electric part of the propulsion system be able to operate independent of the combustion engine to allow electric-only operation.
3. Enable the electric storage system to be charged from external sources, i.e. the power grid, creating a plug-in hybrid.
4. Phasing out combustion engines and/or replace it with other high primary energy power sources such as fuel cells.

At the moment of writing, hybrid cars on the market fulfill step one, and are gradually adopting step two. So far, only concept cars fulfill the third step.

4.2.3 Cars Powered by Electricity

At the time when external charging becomes available by plug-in hybrids, it is crucial to control from which sources the electric power is generated. Globally, 65 % of all electricity is generated by combustion of fossil fuels, where 63 % originate from coal, 29 % natural gas and 9 % oil (7). The supply chain for a grid charged electric vehicle becomes rather extensive, and the question is if a vehicle powered by a world mix of electricity has a potential to lower the emissions at all. The following section will lead to the answer.

4.2.4 Energy Efficiency

One way to measure the suitability of an energy source is to consider the total efficiency from well to wheels. Two particularly interesting cases have been compared in the study presented in figure 4.1. A classical car powered by a combustion engine fueled

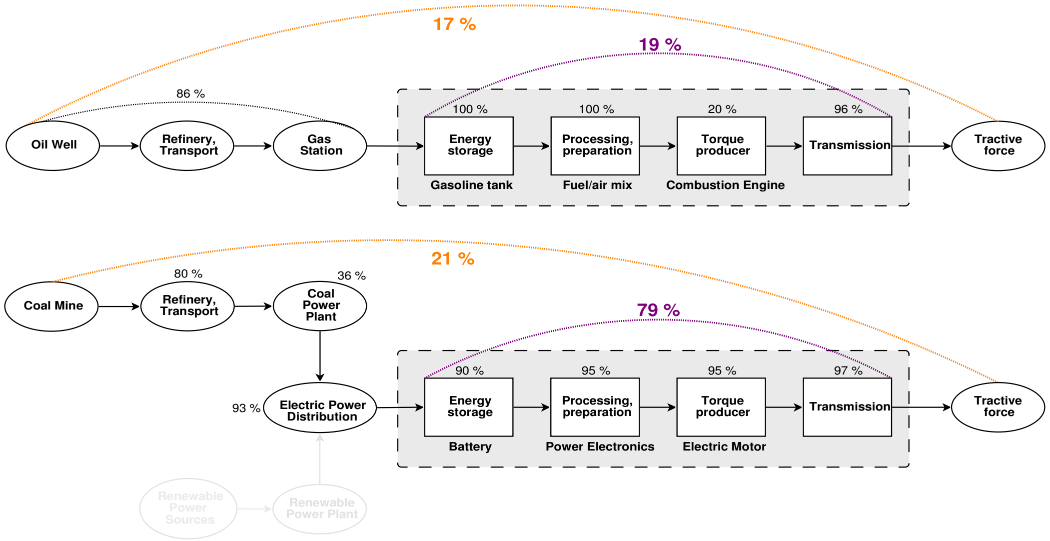


Figure 4.1: Energy efficiency study: Direct fossil powered ICE car versus indirect fossil powered modern electric car.

by gasoline, meets a modern electric vehicle charged via the public grid by electricity generated by a fossil powered power plant.

Power generation from fossil fuels has limited efficiency due to material constrains when realizing a thermodynamic process. This is true for both combustion engines in cars as well as for power plants for public electricity generation, but larger plants tends to archive considerably higher efficiency. The efficiency of converting and transporting crude oil to the local gas station where one can fill up the car's gas tank is 86 % according to (73; 95). The power plant efficiency is adopted from (7) to represent the US average coal plant, which also is very close to the world average. The average internal combustion engine efficiency is set from the results in section 3.4. The efficiency of the electric car components are intended to represent a modern electric vehicle with a high-efficient motor- and power electronic converter system together with high performance lithium-ion batteries. The figures are adopted from what discussed in chapter 5, and verified to be reasonable compared to Åhman (10). The energy saving effect of regenerative braking has not been considered in the calculations.

The conversion efficiency of the electric power plant becomes a very critical factor in the overall efficiency assessment of the electric vehicle. In fact, this number is very diverse for different countries and regions. Some extreme cases are worth mentioning, as seen table 4.4. The critical part is that a gasoline powered car actually could be more energy efficient than an electric vehicle if the electricity is generated by a low-performance fossil plant.

4.2.4.1 Worst Case Electric Power Generation

If, for example, an electric car as specified in figure 4.1 is charged by electricity generated *solely* by *fossil power* in India (motivation: table 4.4), the electric vehicle would actually become less efficient (16.4 %) than the assessed equal internal combustion car (17 %) as seen in figure 4.1. Luckily, India also has a 20 % share of renewable energy, which will be in favor for the electric car and actually change the conditions, resulting in the electric car being a slightly better alternative in terms of reducing the emission of green house gases.

4.2.4.2 Other Cases of Electric Power Generation

In regions which are known for a high density of cars, such as USA, Germany and Japan, the electric car efficiency, *not* concerning the share of renewable power, would eventuate as 21.7 %, 22.9 % and 25.2 % respectively. This presupposes the same figures for efficiency in the refinery process and electric power distribution for all of these regions. Also, the same type of driving habits is indirectly assumed through the car's internal efficiency assumptions.

4.2.4.3 Non-polluting Sources of Electricity

A considerable share of the world's electricity is generated by non-polluting technologies such as nuclear and hydroelectric power plants. The primary energy sources for nuclear and renewable sources (except maybe from solar power, see appendix A) are not directly comparable to any equivalent power source applicable for in-car use. A different method must be used in order to regard the positive effects on non-polluting electric power generation. A popular procedure to measure the environmental strain though emission of green house gases (GHG) is to establish life cycle assessments (LCA). The GHG assessments used in this work lean on three different studies, presented in table 4.5.

Table 4.4: Overview: Share and Efficiency of Fossil Power Plants

Country	*Fossil share*	*Efficiency* (7)	*(gCO_2/kWh)* (81)
Poland	95 %	36 %	665
Australia	92 %	33 %	
China	82 %	32 %	
India	80 %	28 %	
USA	71 %	37 %	605
Germany	61 %	39 %	453
Japan	60 %	43 %	
EU average (40)	48 %	35 %	430
Canada	27 %	38 %	
Brazil	$<$ 5 %	-	
Sweden	$<$ 2.5 %	-	51
Switzerland	$<$ 1 %	-	24
Norway	$<$ 1 %	-	7

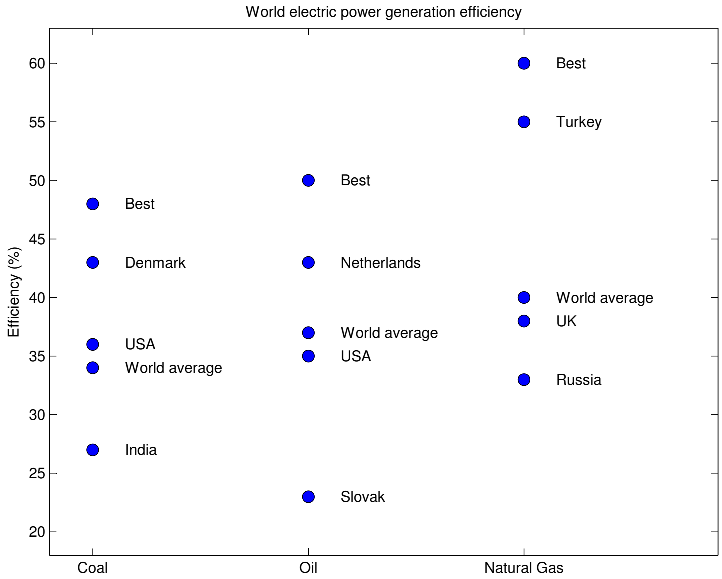


Figure 4.2: World public electricity power generetion efficiency from fossil fuels.

4.2.5 Electric Vehicle GHG LCA

To establish the indirect green house gas (GHG) emissions from electric vehicles, the following assumptions have been made:

- Required average traction force of an electric powered car is assumed to be 0.10-0.20 kWh/km, as presented in section 3.4 and table 4.1.
- Efficiency of the electric vehicle is 79 % (see figure 4.1)
- Electric power grid distribution efficiency is 93 % (see figure 4.1).

Respecting the limited efficiency of the electric cars (79 %, figure 4.1) and its supply chain (93 %, section 4.2.4), the numbers in the LCA analyses must be increased by a factor $(0.79 \cdot 0.93)^{-1} = 1.36$.

4.2.5.1 Electric Vehicle Indirect Emissions

It turns out that the *worst possible scenario* with the given data eventuates in an emision rate of 272 g/km for coal powered electricity generation with the LCA data given by Weisser (96), together with the car driving the US06 cycle with friction brakes only (no regeneration). The figure 272 g/km is equivalent with a gasoline car with a fuel consumption of 1.2 l/10 km (20 MPG). This is a rather high consumption, but not considerably higher than the US light car fleet current average of 1.1 l/10 km (22.1 MPG) (64). This result is also analogue with the low, but reasonable, worst-case efficiency estimation made in section 4.2.4.1.

As for a EU average, the sum of indirect and direct emissions for an electric car charged from the public electric grid, with the same conditions as above, result in 117 g/km. The US average of 605 $g(CO_2)/kWh$ for electricity generation would result in an electric vehicle running with 165 g/km. These numbers can be compared to the proposed emission levels regulations for EU in 2013 (see table 6.1): 120 g/km.

All the stated equivalent levels so far in this section have been worst-case estimations in terms of high emission levels. However, electric vehicles offer superior environmental performance when they are charged from public electricity generated by hydroelectric or nuclear power plants solely (motivation: table 4.5), resulting in emission levels of less than 1.0 g/km, which is far better than physically achievable by any car direct-powered by fossil fuel (0.004 l/10 km or over 5000 MPG). Such conditions exist in a few countries, as seen in table 4.4.

Table 4.5: Life-cycle assessments for public electricity generation

Power Plant	**LCA fossil CO_2 equivalent** $[g/kWh]$		
	Vattenfall (18)	Spadaro et al. (52)	Weisser (96)
Oil	910	149-246	800
Coal	690	206-257	1000
Natural gas	420	106-188	560
Solar photovoltaic	70	8.2-27	56
Bio-fuelled CHP	16	8.4-17	70
Wind power	10	2.5-9.8	14
Hydro power	5.1	1.1-6.3	4.0
Nuclear power	2.9	2.5-5.7	5.0

4.2.6 Future Scenarios

When oil becomes a scarce commodity, the price will rise and alternative fuels will fill its place. There is a range of possibilities to substitute the fossil based petroleum products for cars to run with their current internal combustion engines with minor or no modifications at all. Gasoline and diesel can be synthesized from both coal and biological waste. Ethanol can be produced from crops in large-scale. It is all just a matter of demand and fuel price. One of the most potential and long-term sustainable scenario would be electric vehicles charged by renewable power plants. The energy carriers (batteries) may be complemented by hydrogen and fuel cells, but that requires a series of major break-through in technology concerning efficient hydrogen generation. Hydrogen vehicles are not significantly more energy efficient or environmental friendly than classical internal combustion cars as long as the hydrogen is generated from electrolysis of water with electricity generated by the public electricity grid (95).

Chapter 5

Components

5.1 Introduction

This section will present some of the key components in hybrid electric vehicles concerning the generation and storage of energy for locomotion. Basic performance and key performance will be briefly evaluated for both novel and well-recognized motor types.

5.1.1 Hybrid Powertrain Topologies

It is assumed that the reader knows the common types of hybrid powertrain topologies when reading this chapter. This thesis does not include the walkthrough of the different topologies. For more information, the reader is recommended to refer to *Jonasson, Strandh, Alaküla* (55) and *Jonasson* (56).

5.2 Primary Energy Converters

The primary energy converter in a hybrid powertrain is defined as a unidirectional converter, most often between a chemical primary energy storage and mechanical traction.

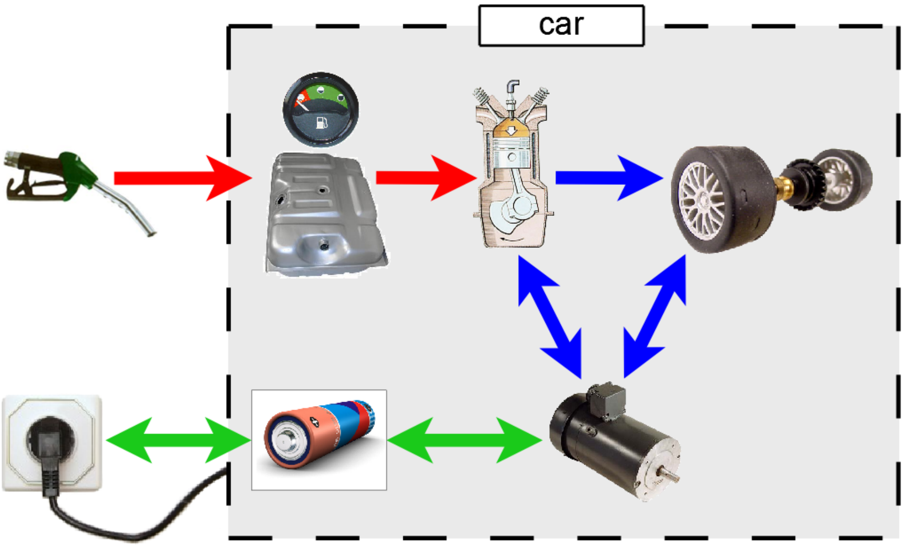


Figure 5.1: Energy flow with hybrid propulsion: Primary (red arrows), secondary (green arrows) and mechanical (blue arrows) energy defined.

5.2.1 Otto Engine

The most recognized combustion engine in cars is the Otto engine, more often than not powered by gasoline. The Otto engine is a flexible thermodynamic cycle that can run on gasoline, ethanol and similar fuels. This technology has been used widely for well over 100 years now, and the performance in terms of reliability and efficiency has increased. Though, the average efficiency in end applications such as cars is still very limited. Figure 5.2 shows that efficiency is dropping quickly outside a limited area of load. The Otto engine is nowadays a complex machine, leading to high maintenance requirements. Another obvious drawback concerning the efficiency is the requisite of idle running even when not developing any useful mechanical output torque.

The average power consumption for normal drive cycles, as specified in chapter 2, is 4 kW to 15 kW. A power output of 4 kW corresponds to an BMEP of under 2.0 bar at rotational speeds over 1000 RPM, leading to a very unfavorable load point with under 20 % efficiency (see figure 5.2). Further on, a 15 kW power output would result in 3.0 bar at 2600 RPM (typical highway cruise situation), which also results in a fairly low efficiency of about 25 %.

5.2.2 Diesel Engine

The Diesel engine is by far the most common combustion engine in heavy vehicles, and also in car in certain regions. Overall, the Diesel engine shares the drawbacks of the Otto engine, complexity, idle power consumption, and a bulky installation with all ancillary systems. However, modern diesel engines with exhaust aftertreatment are cleaner and more efficient (see figure 5.3) that an Otto engine with the same specifications. The primary market disadvantage of Diesel engines over Otto engines is the installation cost, as presented in figure 6.3, as well as the requirement of exhaust aftertreatment.

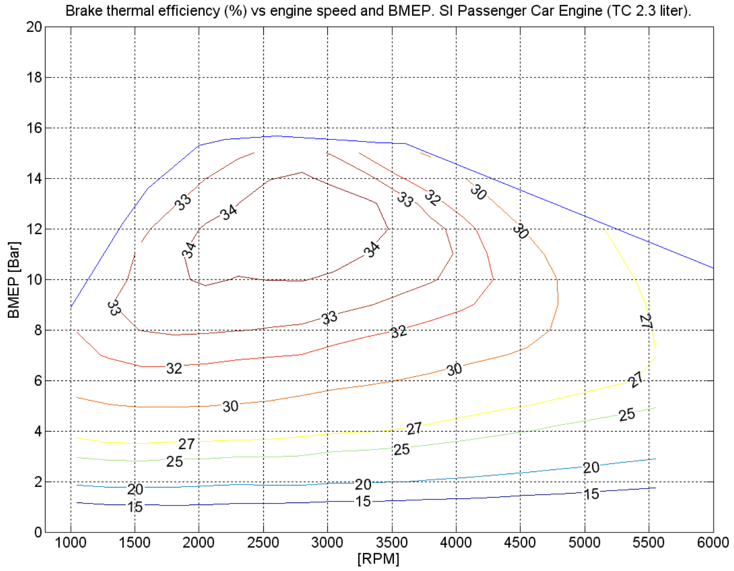


Figure 5.2: Performance of a general turbo charged Otto engine for automotive usage. BMEP (y-axis) is proportional to mechanical output torque. Source: (97)

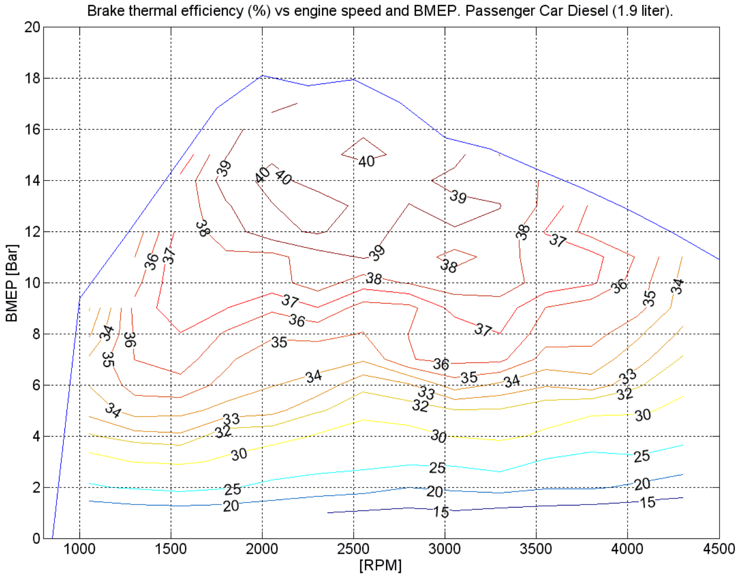


Figure 5.3: Performance of a Diesel engine for automotive usage. BMEP (y-axis) is proportional to mechanical output torque. Source: (97)

5.2.3 Rankine Engine

Also known as the steam engine, the realization of the Rankine cycle can be based on both a piston engine and a turbine. This process is known to be the most robust and scalable, wherefore it is used in as good as all large scale power plants. The external combustion makes this heat engine very fuel flexible. Realizations of Rankine engines have been implemented in cars successfully. Already in the 1970's, formerly SAAB-Scania implemented a piston based Rankine engine in a car as a research project to investigate the potential increase in fuel efficiency. Today, compact, portable and high-efficient Rankine piston engines are available from the same inventor (79).

The efficiency profile for a calculated automotive Rankine engine, as seen in figure 5.4, has some very noticeable distinguished features. Very high torque can be delivered at low rotational speed, and a very high maximum rotational speed can be achieved. Most important, the maximum efficiency is derived at low torque, where most load situations occur in light vehicles. Another feature is the fact that a steam piston engine theoretically does not need to run in idle mode, which gives even more efficiency improvements by natively support idle elimination.

5.2.4 Brayton Engine

Also known as the *gas turbine*, *microturbine*, *JET* or *turbo generator*, the Brayton engine features high power to weigh ratio desirable in portable applications as in cars. The Brayton process is fuel flexible and can be made very clean with exhaust aftertreatment. However, it features rather high idle consumptions and prefers to operate at high rotational speed to achieve a plausible efficiency, as illustrated in figure 5.5. The Brayton engine is probably best suited to work together with a high-speed generator in a series hybrid powertrain, as sucessfully accomplished by Volvo in the late 90's with the *HSG concept hybrid bus* (59).

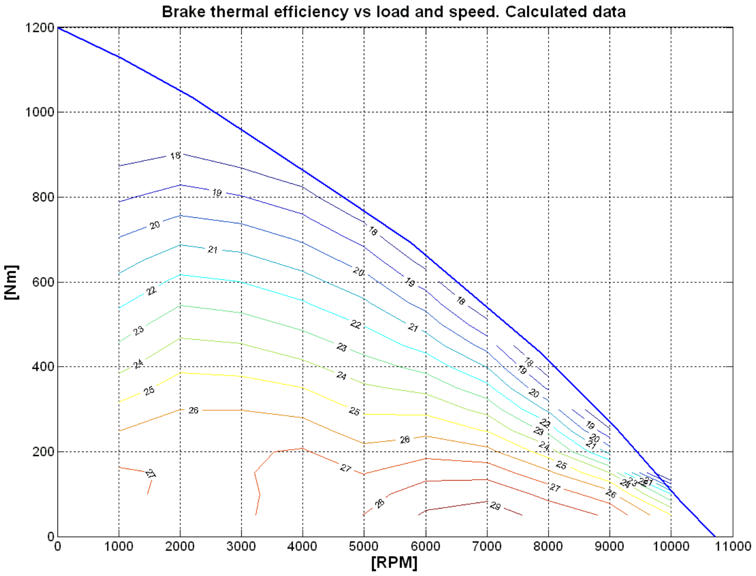


Figure 5.4: Performance of a Rankine engine for automotive usage (calculated). Source: (97)

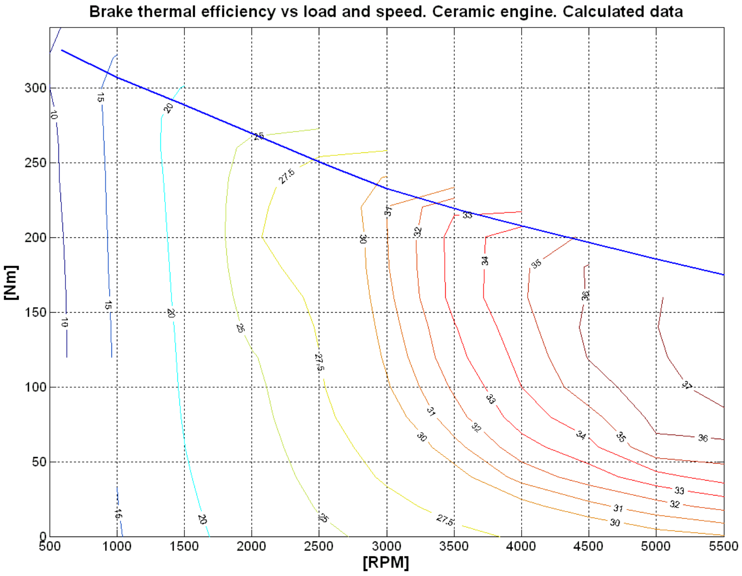


Figure 5.5: Performance of a Brayton engine for automotive usage (calculated). Source: (97)

5.2.5 Stirling Engine

The Stirling engine is also a valid candidate to power a car. Due to external combustion, it can be very fuel flexible and run on most fuels that feature a clean open-air combustion. The efficiency profile for an automotive Stirling engine, as shown in figure 5.6, is somewhat similar to a Diesel engine. The Stirling engine offer very high torque at a low rate of spin, but it normally requires help i the start-up procedure through ancillary components. This type of engine is also known for its great potential of quiet, vibration-free and emission-free (with the right fuel mix) operation. Extensive development projects have been carried out with Stirling engines for automotive use in the 1980s (42). The results were good, delivering 30 % better fuel economy over a comparable spark ignition engine. Another famous hybrid implementation with Stirling engines is the Swedish Gotland submarines, as seen in figure 2.4.

5.2.6 Fuel Cell

The fuel cell is a beheld technology to be used as primary energy converter in cars. The technology promises a relatively silent and high efficiency operation, thus clean, electric output from a chemical input. The ideal primary energy source for a fuel cell is hydrogen, although hydrocarbons and alcohols can also be used through a lossy reforming, leading to reduced system efficiency (see figure 5.7). Fully functional hydrogen fuel cell cars already exist, for example the *Honda Clarity*. The problem of efficient generation of hydrogen and a fully functional infrastructure to distribute it to end customers still prevails.

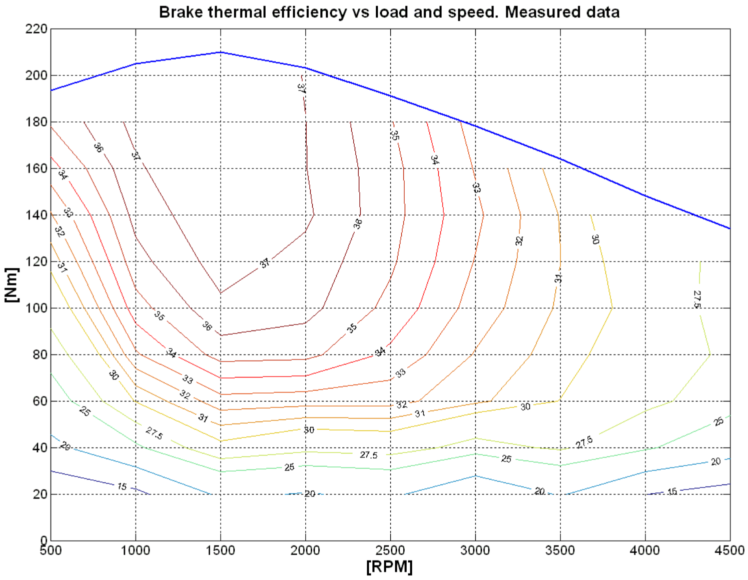


Figure 5.6: Performance of a Stirling engine for automotive usage (measured). Source: (97)

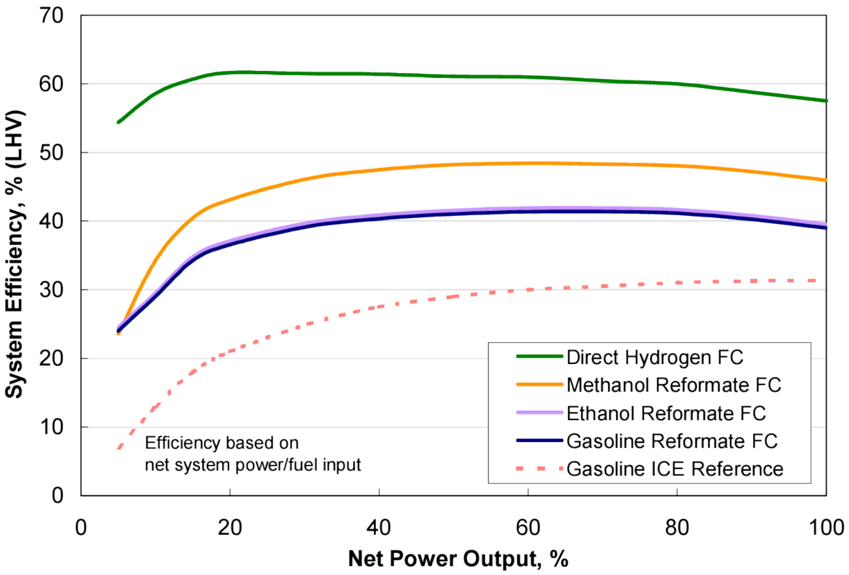


Figure 5.7: Performance of a Fuel Cell for automotive usage (calculated). Source: (62), with permission.

5.3 Secondary Energy Converters

The secondary energy converter can both generate torque from the secondary storage and revert the process by generating secondary energy from mechanical torque. An illustration of this can be seen in figure 5.1.

This section will very briefly mention the four main candidates applicable as traction components in automotive use. For a more comprehensive walkthrough, the reader is recommended to refer to (41) and (65).

5.3.1 Direct Current Machine

The direct current (DC) machine is a group of self-commuting electric machines with the primary windings in the rotor (anchor). The stator of the DC machine can be either permanent magnetized or energized through series or parallel magnetization windings. Therefore, it can be run on both DC- and AC current. Efficiency is normally high (over 90 %) in high power motors. Controlling the DC motor is fairly simple, and the installation price is comparatively low. However, the DC motor suffers from high maintenance due to the brushes.

5.3.2 Permanent Magnetized Synchronous Machine

The permanent magnetized synchronous machine (PMSM) has a great potential as a traction motor. It features high power density, very high efficiency and it is rather robust. The most common setup is a multi-pole, three-phase, high-speed, high-voltage (over 100 V) machine controlled by advanced power electronics. The PMSM can be built in many different configurations, allowing low-speed high-torque direct-drive traction motors to be implemented directly in the wheel of some land vehicles. The major drawbacks are the price of the magnets, and the advanced power control needed for dynamic operation.

5.3.3 Induction Machine

The multiphase alternating current asynchronous induction machine (ACIM) is by far the most common high-power electric motor type in the industry. It is very robust and needs very low maintenance, and completely lacks permanent magnetic fields. With the help of advanced power electronics, it is also well suited as traction motor in automotive applications with high efficiency. The major downside is the low power density compared to its competitors mentioned above.

5.3.4 Reluctance Machine

The polyphase switched reluctance motor (SRM) is not too common as traction motor in automotive application, although it has some appealing features; high power density and very high robustness. With the correct power electronics, the efficiency will also be high over a wide speed range (39). The major drawback is the high toque ripple, which induces vibrations and noise in adjacent mechanical components.

5.4 Secondary Energy Storage

5.4.1 Electro-static Storage

Also known as supercapacitors, electro-static storage has the ability to store electric energy through the physical property known as capacitance. Supercapacitors is a somewhat new technology which has gained much attention with the rise of popularity of "cleantech". Super capacitors can increase both the efficiency and performance in hybrid electric vehicles.

5.4.1.1 Electric Properties

The basic concept of capacitance is the separation of electric charges through two isolated bodies, creating a static electric field.

$$C = \epsilon_S \frac{A}{d} \tag{5.1}$$

Where C is the capacitance, ϵ_S is the static permittivity of the isolating material, A is the area of the two terminals, and d the distance between the two terminals. The amount of energy stored in a capacitor is:

$$W = \frac{1}{2} C V^2 \tag{5.2}$$

Where W is the stored electric energy, C is the installed capacitance, and V is the terminal voltage. The amount of energy dynamically stored by a capacitor is determined by the voltage, and the maximum allowed voltage is limited by the materials and internal structure of the two capacitor plates.

The ideal capacitor is represented in electronic circuitry, however, in a high-voltage high-power application like electric drive trains, it is neccessary to use an expanded representation. An adequate representation of the capacitor would be a damped three pole network to account for the highly distributed material properties of high-performance capacitors (66).

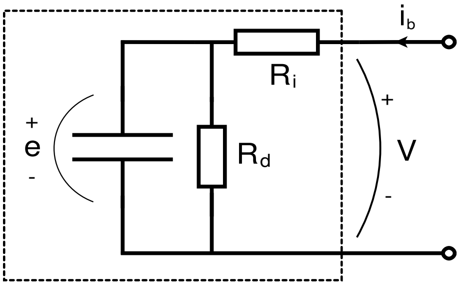


Figure 5.8: A basic realistic model of a high-power capacitor.

The model in figure 5.8 is a simplified circuit which is accurate for short time periods, under a few minutes, for a single super capacitor cell such as Maxwell MC-series (3000 F @ 2.7 V = 10.9 kJ = 3.0 Wh) (90). For longer time frames, a slightly more extended model must be used to cover for internal leveling out effects in the super capacitor. The equivalent series resistance, R_{ESR} , limits the imput and output current due to the internal thermal losses it will cause. The discharge resistance, R_d , will drain power from the capacitor with a time constant of roughly one year for the stated example cell. Supercapacitors are usually low voltage, a few volts per cell (67), which speaks for modular design to make them wearable in high-power design as electric power trains (see figure 5.9). When capacitors are connected in series to form modules, a load-balancing circuit is required to prevent individual cells from over-charging. Commercial modules available today offer active load balancing, active cooling and even digital interface for real-time diagnostics and control. Because the strong relationship between capacitor voltage and its state of charge, it is expedient to use a DC/DC-converter to manage the power flow between capacitor banks and a fixed high-voltage DC-link. This kind of setup also offers the ability to arbitrarily control the energy flow in and out from the capacitors.

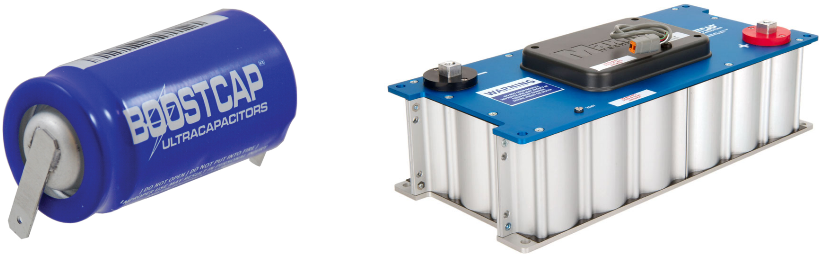


Figure 5.9: Left: Supercapacitor cell. Right: High-power module from Maxwell Technologies. Pictures are not to scale.

5.4.1.2 Applications

The types of supercapacitor applicable to electric drive trains is featured by a very high power density, they have the ability to store large amounts of energy in short time intervals with low losses. On the other hand, the energy density is rather limited, making them expensive and bulky as unique energy source in electric power trains. This property makes them very suitable to use as distributed energy buffers in electrical energy systems, to cancel sags and dips caused by parasitic resistance in energy sources and inductance in long cables. Supercapacitors in combination with batteries offer increased performance in terms of temperature stability and handling of strong surges that otherwise can reduce the lifespan of batteries. A bank of supercapacitors significantly decreases the peak power requirements for the assisting battery or fuel cell.

5.5 Electro-chemical Storage

Also known as batteries, electro-chemical storage has the capability to convert electrical energy to chemical energy for storage, and vice-versa. The fundamental principle has been known since the end of 1800s when Alessandro Volta invented the voltaic cell, although galvanic cells has probably been used far earlier than that. The basic idea of a voltaic cell is to offer an electrochemical reaction which can store electrical energy. In this section, only secondary batteries (rechargeable) are considered.

5.5.1 Electrical Model

A battery cell or module can be modeled electrically by a Thevenin equivalent as in figure 5.10.

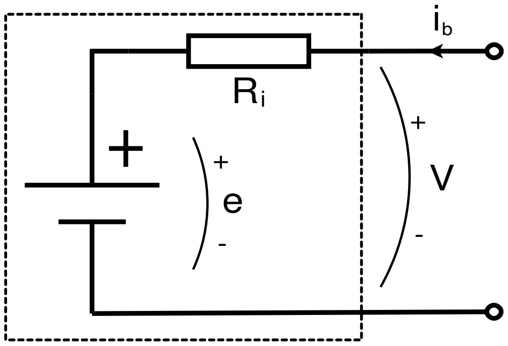


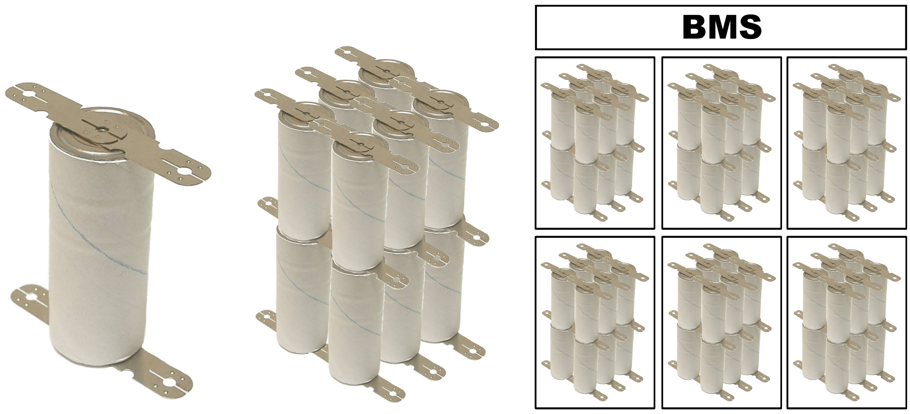
Figure 5.10: Basic electric battery model, a Thevenin equivalent.

Where:
P is the power drawn from the battery
i_b is the current flowing into the battery
e is the cell internal voltage
V is the effective voltage at the output terminals
R_i is the Thevenin equivalent internal resistance.

The battery voltage, e, and the internal resistance, R_i, are dependent on many factors. The parameters are dependent on the battery's State of Health (SoH), which is a collection of properties such as age, temperature, charging history, charge acceptance, etc. The performance is also dependent on the current State of Charge (SoC) (76), which is a measure of how much potential energy the battery contains (56). The manufacturing process of battery cells also introduce a slight variation in the parameters, which leads to issues when interconnecting cells.

5.5.2 Battery as the Modular Unit

A battery is a combination of one or more identical voltaic cells. Each cell has a set of specifications that will define the batteries capabilities. With today's commercially applied chemistries, the cell voltage typically reaches from 1.2 V to 4.0 V. A hybrid electric vehicle battery pack is a large unit compiled of hundreds or thousands of voltaic cells. Most battery units can be broken down in packs, modules and cells as illustrated in figure 5.11. Each level has a certain setup of performance parameters and market-like actors such as OEMs and distributors.



(a) Cell (b) Module (c) Pack

Figure 5.11: The modularity of batteries, illustrative.

5.5.3 Basic Properties and Performance

The four most interesting parameters to compare when choosing a battery is (76, p.21):

- *Energy density*

  Measured in kWh/kg (or SI units: J/kg). A measure of how much energy a battery can hold per weight unit.

- *Power density*

  Measured in W/kg, an important figure in smaller HEV batteries and powerful electric traction components.

- *Cycle life*
  The number of charge-discharge cycles the battery can sustain, keeping the capacity above 80 % of its original rating (41). Another important related measure is the *Depth of Discharge* (DoD), which is a measure of how much of the battery's specified energy content that should be converted for each cycle. For li-ion batteries, the normal depth of discharge (DoD) when measuring cycle life is 80 % (93). The DoD used when testing the cycle life can be different for other battery chemistries, and it is very important to take these details in consideration when comparing different battery types.

- *Cost*
  Of course, the battery cost is important. A pertinent method to measure a battery's cost is to take the specified energy content into relation, leading to the units such as $\$/kWh$ or EUR/MJ.

5.5.4 High Power Batteries

Batteries are primarily high energy storage systems. When exposed to high power surges, their performance is generally reduced due to the limited speed of reaction of the internal chemistries, according to Peukert's law (16). This is partly why it is harder to manufacture a battery for high power, rather than high energy applications. The electric time properties respecting time, that is power versus energy, can be illustrated using the Ragone relationship. From this, a specific *time constant* of a particular storage device can be extracted (41, p.183). A Ragone chart is a powerful method to illustrate both power density, energy density *and* the time constant (the gradient), as seen in figure 5.12.

5.5.5 Battery Chemistries

There are plenty of different battery chemitries to choose from, all with different properties. This section briefly touches some om the most common battery chemistries that are applicable in (hybrid) electric vehicles.

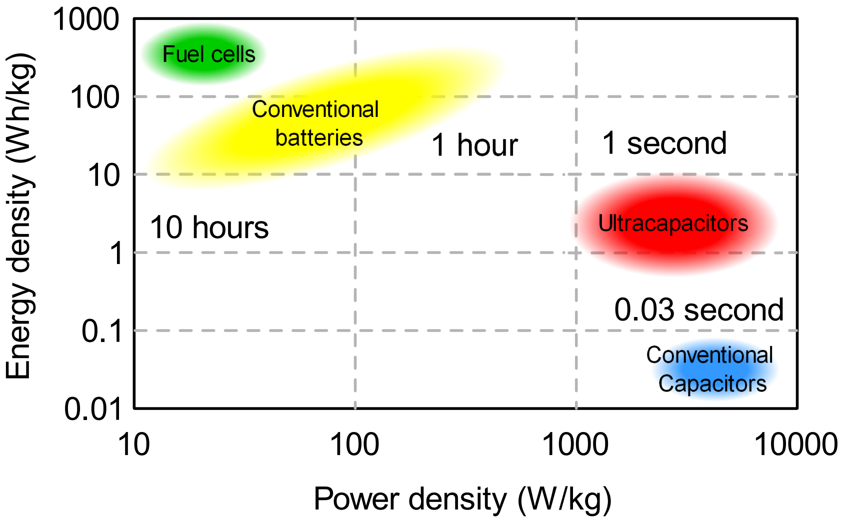


Figure 5.12: Ragone Chart for high-power applications. Source: Stan Zurek.

5.5.5.1 Lead Acid

The lead acid battery is the most common battery type in cars since early 20^{th} century (Section 2.1.2.2), for all applications. The lead acid battery has primarily serverd the electric crank motor in cars. However, that type of battery is not particularly well suited to serve as traction battery in (hybrid) electric vehicles. Special deep-cycle lead-acid based batteries exist that are specialized on tougher conditions, for example biopolar lead acid. The installation cost of general lead acid batteries is low, but since the life length is short in high power applications, the life cycle cost does not keep very low, see table 5.1

5.5.5.2 Nickel Cadmium

Nickel Cadmium (NiCd) batteries are used in many early electric vehicles due to it's good overall performance compared to lead-acid batteries. NiCd offer high energy density, high power density, and a good cycle life. However, the drawbacks are not negligible. NiCd is a wet battery, meaning it has to be continuously monitored and maintained to make sure the water level is good. Quick charging causes water loss, temperature elevation and build-up of hydrogen, which is a safety concern. Nickel is a costly metal and also highly toxic, implicating serious environmental impact if not taken care of properly when depleted. Escalating environmental acts makes this chemical unsuitable for new installations.

5.5.5.3 Nickel Metal Hydride

Nickel Metal Hydride (NiMH) batteries are by far the most commonly used battery type in hybrid electric vehicles today. NiMH was the strongest competitor to the NiCd-battery when it started to deprecate. NiMH has some confining properties which makes it unsuited for pure electric vehicles. The depth of discharge is very limited without subjecting the battery to excessive ageing. However, this is still a good and well-established battery technology for non-plug-in hybrid vehicles, where the state of charge can be strictly controlled. The NiMH battery will remain a good candidate for mild and medium hybrid vehicles until the li-ion battery demonstrates better performance in both price and reliability.

5.5.5.4 Lithium Ion

Lithium ion (li-ion) is a large family of a mere dozen of different similar chemistries, all using lithium as a key substance in the anode. The detailed discussion in chemistry is out of scope of this thesis, but the reader should bear in mind that the different chemistries can have rather different properties dependent upon the types of cathode, anode and electrolyte material used. Li-ion batteries have been used widely in portable applications such as cell phones and laptop computers for many years, but these specific battery variants are not necessarily appropiate to build packs to use in electric vehicles. Over all, the upcoming li-ion batteries promise significantly higher performance than other chemistries to a price that is long-term fencible. Table 5.1 shows that high-end li-ion batteries today offer three times better energy density than corresponding lead acid batteries, at the same time as they offer superior cycle life. At the time of writing, many of the promising new li-ion variants are still under development and it is therefore too early to perform a benchmark. The lack of test standards between different batteries also makes it tough to compare the real performance from different manufacturers.

5.5.6 Battery Cycle Life

The life cycle of the battery is a crucial parameter, since it is normally shorter than the expected life cycle of the rest of the car. It is important to regard not only the installation cost of the battery, but also the life time with respect to the performance and price. Table 5.1 shows a compilation of battery chemistries with typical performance for automotive battery packs. Unfortunately, accurate and comparable figures for battery capacity and especially cycle life are hard to come by. Part of this depends on the new emerging market segment of high-energy batteries is not standardized yet. As seen in table 5.1, the cheapest battery chemistry by installation cost is not necessary the cheapest choice respecting its life cycle.

Table 5.1: Battery cycle life and weighted cost

Chemistry	Wh/kg	W/kg	$Cyclelife$*	$\$/kWh$	$\$/kWh$ life storage**
Lead Acid	35	110	0.4-1.0k	150	0.10-0.26
NiCd	50	175	1.5-2.0k	600	0.21-0.28
NiMH	70	300	1.5k	250	0.12
NaS	110	100	600	250	0.29
Li-ion	60-200	100-10k	300-4k	300-1k	≈0.07-0.70

** DoD* $\geq$ *70 %*

*** Life time storage price = (Cost*DoD)/(kWh*NoC)*

5.5.7 Battery Cost

Lithium based batteries seems to be the most promising choice to use as traction battery in (hybrid) electric vehicles. The market is not yet mature for mass production of high-energy lithium based batteries, which imply small volumes leading to high prices. Many elaborate market analyses have been done to try to estimate the future price of li-ion batteries. Anderson (11) suggest a baseline scenario for complete *battery packs* starting with today's (2009) prices at $\approx$ 800 USD/kWh , reaching 500 USD/kWh in 2020 and 350 USD/kWh in 2030. However, the price evolution is very sensitive for raw material costs and the rate of consumer acceptance of electric vehicles. The barrier 500 USD/kWh is important to gain market acceptance of all-electric personal vehicles under reasonable scenarios, as discussed section 6.2 and figure 6.2.

Looking at the life-cycle breakdown estimation in table 5.1, the cost per stored kWh of mobile electricity is in the same magnitude of the average price for a residential electricity in the US: 0.1136 USD/kWh as for 2008 (37). This again confirms that the main problem in an electric vehicle is the storage of electricity traction energy, rather than the price for the resource itself.

5.5.8 Battery Management

The variations in performance between cells caused by temperature differences, manufacturing imperfections, etc, together with high current charging and discharging, can lead to electrical imbalances which decrease the battery performance as much as 25 % (87). To solve this, an active Battery Management System (BMS) is needed to monitor, control and balance the cells. A BMS consists of hardware and software to measure and balance the battery to protect it from unsafe operation, to track the state of charge (SoC) and state of health (SoH), to provide data for optimal charging and discharging. Some of the parameters a BMS preferably has to track is cell/module voltage (with high precision), battery current (and total accumulated charge), temperature and pressure (for NiMH).

5.6 Summary

This chapter featured an overview of a set of previously known technologies that deserves to be brought up for discussion in the new generation of hybrid electric vehicles we are facing. For example, it is no longer certain that a classic piston based Otto or Diesel engine is the best choice of power source along with an electric propulsion system. Gas turbines, Stirling engines, steam engines, and rotary Otto engines have been proven worthy candidates during earlier trials. The same applies to batteries; there is not one single of energy storage that will fulfill the requirements from all hybrid vehicles. Batteries might as well be combined with supercapacitors in performance hybrids. The only thing certain about the hybrid technology right now is that there is much more interesting choices of components to see.

Chapter 6

Market Overview

6.1 Introduction

It is a fairly extensive work and a somewhat valorous to claim to have a complete mapping of a whole new market segment. The following presentation is only intended to give a coarse overview of some of the actors to gain insight in the properties of their products.

6.1.1 Disclaimer

This section is intended to give a rough snapshot over selected parts of the hybrid vehicle component market as of spring 2009. The overview is by no means complete and should not be used for commercial purposes.

6.2 The Popularity of Electric Vehicles

As written in history section (2.1.2.5), two waves of popularity for the electric and hybrid electric vehicle have already passed. Between the two last peaks in interest of hybrid electric propulsion, it has been practically silent about this technology. One very plausible explanation to this is the oil price, as seen in figure 6.1. The popularity of hybrid electric vehicles correlates with high oil price. It turns out that the broad market is not particularly interested in alternative propulsion as long as the oil price is stable at a low level. Since alternative vehicles with the same performance always will cost more in purchase (see figure 6.3), it is hard to motivate end users to such investments without additional incentives.

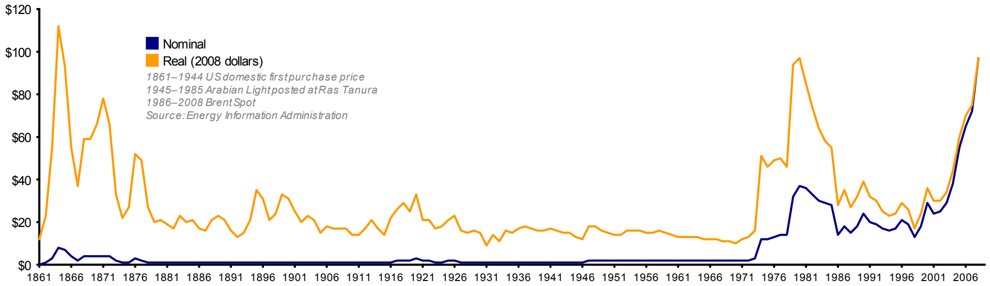


Figure 6.1: Long-term history of oil prices in the U.S.

The Boston Consulting Group (47) has made an study about the Total Cost of Ownership (TCO) for cars under realistic condition, dependently on the oil price, presented in figure 6.2. The graph shows how tough it is to motivate electric vehicles, and even hybrid electric cars by just thinking in economic terms in the eyes of the end user (cost of ownership). Even with the high oil price peaks of 2008, the electric vehicle with limited range per charge due to small battery, is barely cheaper in TCO than a modern gasoline car. The latter case with the limited performance electric vehicle is based on the estimated battery price in 2020 (see section 5.5.7) with wide market acceptance of (hybrid) electric vehicles, which of course is a sensible factor. With these figures, it is obvious that the incentives for a growing marked for cars with hybrid propulsion presupposes substantially higher oil prices through taxes or through a short of oil supply. The governments play an important role in leading the way with these kinds of actions, by offering tax reliefs on environmentally friendly cars.

Another break-down study by Arhur D. Little (figure 6.3) shows why hybrid gasoline cars can be more popular than ordinary diesel cars in USA, while diesel hybrids practically do not exist on the market (yet) despite their great potential. As opposed to in Europe, US car buyers prefer hybrid electric propulsion in front of diesel engines. It turns out that the cost of purchase, which is based on the cost of manufacturing, is so critical for the market adoption. A hybrid gasoline vehicle is cheaper to manufacture than a car with diesel-only propulsion, which will strongly reflect on the consumer end price. The combination with a diesel engine and electric propulsion has some great potential from a technical point of view, but the economical aspect of as little as 10 %

higher installation cost can become a major obstacle in marketing.

Further on, figure 6.3 also shows how much more expensive fuel cell and pure electric propulsion are than the well-recognized gasoline and diesel engines. For comparison, it is only the direct hydrogen powered fuel cell car that offer substantially better fuel economy than other alternatives, but lacks the infrastructure for its fuel.

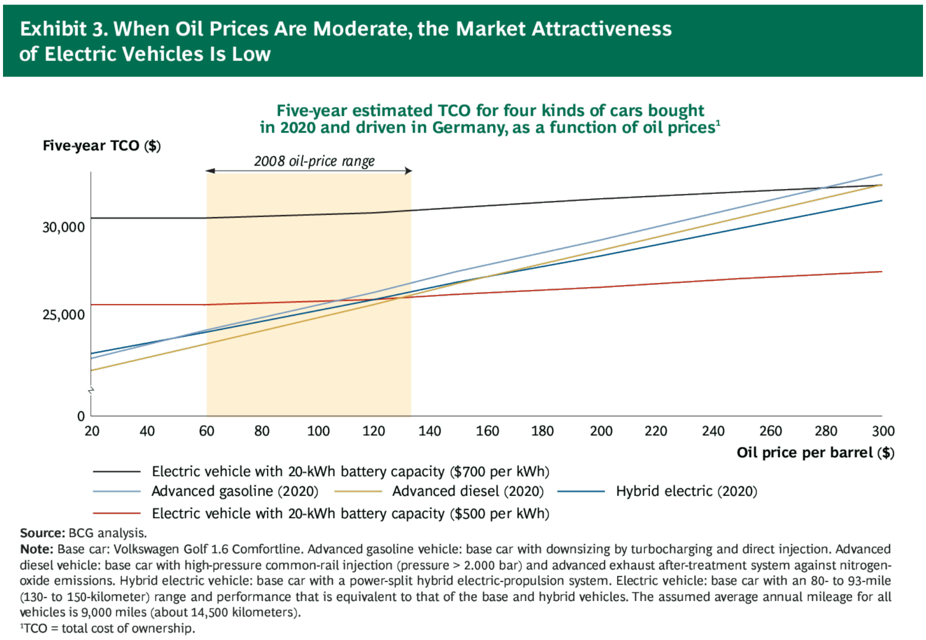


Exhibit 3. When Oil Prices Are Moderate, the Market Attractiveness of Electric Vehicles Is Low

Source: BCG analysis.
Note: Base car: Volkswagen Golf 1.6 Comfortline. Advanced gasoline vehicle: base car with downsizing by turbocharging and direct injection. Advanced diesel vehicle: base car with high-pressure common-rail injection (pressure > 2.000 bar) and advanced exhaust after-treatment system against nitrogen-oxide emissions. Hybrid electric vehicle: base car with a power-split hybrid electric-propulsion system. Electric vehicle: base car with an 80- to 93-mile (130- to 150-kilometer) range and performance that is equivalent to that of the base and hybrid vehicles. The assumed average annual mileage for all vehicles is 9,000 miles (about 14,500 kilometers).
[1] TCO = total cost of ownership.

Figure 6.2: Total cost of ownership of a near future car. From (47), with permission.

6.3 On EU Emission Regulations

According to EU regulation No443 (74), the carbon dioxide emissions from cars sold in the European Union must meet certain levels, based on an average number over the manufacturer's fleet. Table 6.1 summarizes the stated emission levels. Car manufacturers which do not fulfill those levels must pay a penalty. These figures are significativ to the estimations done in section 4.2.5.1. According to the previous results, a pure electric vehicle powered by public electricity would result in indirect emissions of 165 g/km with the 2008 US grid mix and 117 g/km with a EU grid mix.

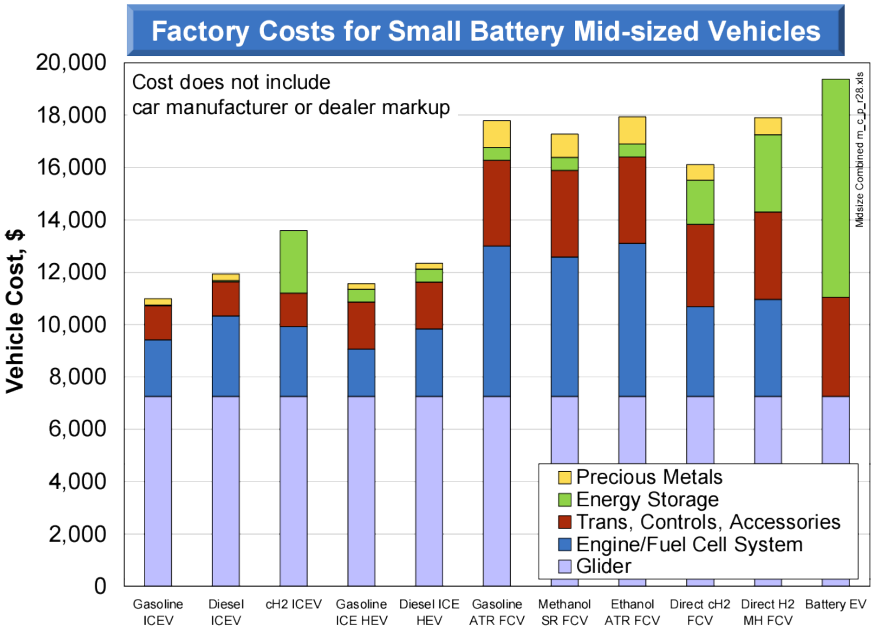


Figure 6.3: Factory costs for midsize cars with different propulsion systems. From (62), with permission.

Table 6.1: European Emission Performance Standards

Year	**Emission Level**	**Estimated Equivalent Gasoline Consumption**	**Note**
2008	140 g/km	0.60 l/10 km	Established 1998
2009	140 g/km	0.60 l/10 km	Japanese and Korean Automobile Manufacturers' Association
2013	120 g/km	0.51 l/10 km	Phased in between 2012 and 2015
2020	95 g/km	0.41 l/10 km	Preliminary

6.4 Market Relationships

A scrutinizing study has been done, leading to a flowchart (see appendix B) representing many of the promulgated business relationships in the automotive area concerning development of electric and hybrid electric vehicles. The primary interest is concentrated upon the relationship between actors in battery development and technology consultant companies towards the bigger automotive companies as well as smaller development projects. It turns out, not particularly surprising, that a small number of actors that are involved in most of the projects concerning electric and hybrid propulsion. Very few projects can claim that their specific solutions are unique down to the details. The flowchart in appendix B shows the co-occurrence of many of those actors as a snapshot of the market in spring 2009.

Chapter 7

Conclusions

7.1 Summary

Chapter 1 tells the story of what has already happened in the world of electric propulsion. Hybrid electric propulsion is not a new concept, and it has already been popular in two waves, and the hype we experience now ought to be the third in order. Chapter 3 shows through a series of simulations that hybridization could offer 41-50 % fuel savings in an optimal implementation and under realistic drive cycles. Chapter 4 used the results from the simulations and put them in a more everyday energy perspective. Power and energy saving methods are discussed and it turns out that for city driving, auxiliary functions can consume more energy than actual useful traction energy.

Section 4.2 analyzes the sources and efficiency of energy utilization in and around cars. Estimations show that an electric vehicle is more than 4 times more energy efficient than a gasoline car on a tank-to-wheels basis. However, on a well-to-wheels basis, the electric car is barely 20 % more efficient than a gasoline ditto when the electric power plant is fossil fueled with an world average operational efficiency. This last example is among the worst cases for the electric vehicle, and for all other cases it's environmental alleviating effects is not challenged in terms of indirect locomotion emissions.

Chapter 5 presents some topical primary energy converters for hybrid electric vehicles, and concludes that the contemporary popular Otto engine is not necessarily the best combustion engine to use in future propulsion systems. Section 5.4 briefly analyzes the properties of suitable secondary energy storages: batteries and supercapacitors. It is told that the upcoming Lithium-ion batteries are a promising, but not yet mature, product to power the next generation of hybrid and electric vehicles.

Chapter 6 ends with a light market analysis and an ascertainment that selling cars is much more about the consumer price tag and politics than technical performance.

7.2 Looking into the Future

Hybrids represent well over 2 % of the light vehicle sales in the US market today. Realistic forecasts show that more than one in 20 new vehicles sold in the US and Canada will have a hybrid gas-electric powertrain by 2012 (48). The European market is expected to grow even quicker due to more extensive environmental and regulatory pressures. Nissan Renault SA and Nissan Motor Co. foresee a big push by automakers to bring pure electric vehicles to market, predicting that 10 % of all vehicles globally will be electric by 2020 (48).

Big industrial actors in Germany are investing 360 million plus 60 million in federal funding to develop the next generation lithium-ion batteries to be used in the future car fleet (Project LIB 2015) (28). The German federal government aims for 1 million electric and plug-in hybrid electric vehicles on the road by 2020, that's 2,2 % of the total country car fleet (31).

This is certainly an interesting time era to experience.

7.3 Generating Energy for Electric Vehicles

As discussed in chapter 4, the source of electric energy is important in the discussion of the environmentally friendly car. In a free market, the cheapest source of energy will dominate as electric power generation. However, the current situation is heavily regulated by laws to inhibit pollution.

The current situation is rather interesting, inasmuch the huge shift of interest in power generation from heavy polluting fossil fueled plants to environmental friendly and renewable sources. Future technologies such as carbon dioxide capture and storage (CSS) may make coal power anew as a topical source of electricity. This scenario has the potential to result in a solution where a fleet of plug-in electric vehicles is charged by coal fired power plants that capture the carbon dioxide emissions and dispose them safely into mountains. The outcome of these types of solutions is very sensitive to politics and economics, which are out of scope of this thesis. More information can be found in Hansson (49).

7.4 Getting Electric Vehicles to the Market

Electric vehicles is not a new technology, they have been around longer as gasoline powered cars. Modern efficient electric cars are equipped with sophisticated power trains and control electronics. The main problem is indubitably the extra cost of the batteries today. It is estimated that a HEV will have additional end consumer costs of 2-5 kUSD due to batteries (54). This is a major problem in car industry, since a great majority of prospective car consumers only are interested in the purchase price when choosing a new car model (9). Consumers are also unwilling to accept compromises of EVs such as maximum range, even though today's EVs offer a range that is big enough for most people's driving habits.

The main cost-related problem is still the batteries, and all other additional non-direct related costs to shift technology, to offer an electric vehicle to the broad market. People will not simply buy a more expensive car with shorter range, unless they are forced to. This is where governments play the vital role. Without their acts to increase the incentives for private actors and OEMs to the advantage for electric vehicle propulsion, this technology will never be anything else than an option for a smaller enthusiast market (47).

7.5 New Business Model

Project Better place has the business model to offer relatively cheap electric vehicles, by selling the cars without batteries. The batteries are then rented to the customer only as a source of power, where you pay only for the amount of energy you use, i.e. when you recharge the battery. In this way, by paying the equal amount of money per traveled distance for an electric vehicle as you did for your old gasoline car, the difference goes to funding the expensive battery. This can be a way to push an early adoption in a wide segment of customers.

Appendix A

A Solar Powered Car

A study is performed to evaluate the appropriateness of photovoltaic (solar) cells on passenger cars.

A.1 Reference Car

A reference car has been used, defined after the simulations done in prior works. The average motor power is 5.5 kW and 16.7 kW for city driving (NEDC) and highway travel (US06) respectively, as established in earlier simulations. This is valid for a quite average medium sized modern passenger car. An area of 2.0 m^2 is assumed to be available for solar cells on the roof of the car.

A.2 Reference Solar Cells

Solar cell efficiency, input light to electric energy, vary from 6 % to 41 % depending on the technology used in the photovoltaic cells. The efficiency of commercial available solar cells is a trade-off between cost, area and power demand. The most efficient solar cells tend to require more energy to manufacture than they can produce under their entire lifetime.

Today's low-cost, easy accessible (wafer-silicon PV) solar cells perform 12 % - 18 % light-to-electricity efficiency under standard conditions, meaning under an irradiation of 1.0 kW_{light}/m^2. The manufacturing cost is typically 2 USD/W according to (36), however, the cheapest available solar cells is just under 2 USD/W (2). Solar cells require power electronics to maximize the energy output, which tend to double the total system cost (58). The energy payback time of a solar cell with this technology is 2-3 years if set up to absorb the US average available sunlight (35). The expected lifetime for a solar cell from the wafer silicon family is 20-30 years with negligible reduction in efficiency. The required solar cell power converter electronics is assumed to be 90 % in the calculations, and the solar cell efficiency is set to 14 %.

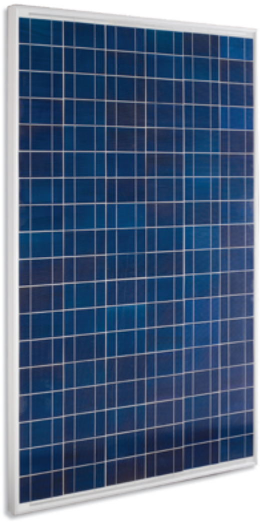


Figure A.1: A typical solar cell.

A.3 Reference Solar Insolation

The European Commission provides an excellent tool to examine the irradiation in Europe and Africa called PVGIS (26). With this tool, the user can get an estimation of the solar irradiance under different conditions. For a car, only the horizontal irradiance is interesting. Table A.1 shows some example of solar power input on some locations for horizontal insolation. Sources are (26) for Europe and Africa, and (34) for US locations.

Table A.1: Solar insolation with horizontally aligned solar cells

Location	**Solar insolation**		
	Per day $kWh \cdot m^{-2} \cdot day^{-1}$	Peak power W/m^2	Average year power W/m^2
Lund, SE	2659	800	111
London, UK	2698	956	112
Stuttgart, DE	2948	978	123
Washington, US	3600	-	150
New York, US	3800	-	158
Rome, IT	4041	990	168
Lisbon, PT	4475	915	186
California, US	4900	1000	204
Arizona, US	5600	-	233
Khartoum, SD	6736	1048	281

A.4 Calculations

The electric power output from a solar cell array is calculated according to equation A.1.

$$P_{out} = P_{in} \cdot A_{cell} \cdot \eta_{cell} \cdot \eta_{PE} \tag{A.1}$$

Where P_{out} is the output power in Watts, P_{in} the solar irradiance at the working inclination in W/m^2, A_{cell} the area of the photovoltaic cell, η_{cell} the photovoltaic cell's efficiency and η_{PE} the power electronic converter's efficiency. If the power is changed to energy (in Wh), the equation is valid for day average energy calculations, giving the result in $Wh \cdot m^{-2} \cdot day^{-1}$.

A.5 Reference Cases

The average American car uses about 65 kWh of gasoline per day. An electric vehicle is just over 4 times more energy efficient, tank-to-wheels, leading to the comparable number 15 kWh of required electric energy to perform the same locomotion per day. The average traction power needed to finish the New European Drive Cycle is 5.5 kW. The US06 cycle demands 16.7 kW in average for the stated reference car.

A.6 Optimal Realistic Case

Assuming Los Angeles, CA, US as the location of benchmarking, the horizontal insolation is typically 1000 W for roughly 5 effective hours per day. It is assumed that the solar cells atop of the car always are exposed fully to the sunlight.

Using equation A.1, a day's charge would give 1235 Wh, corresponding a day average power of 51 W, or an instantaneous effective electric power of 252 W during sun hours. This can be compared with the reference figures for traction power in the previous section A.5. The energy output from the solar cells corresponds to roughly 8 % of the required traction energy per day for an average American car under these conditions. In other words, the reference car would be able to drive $6 - 9$ km per day of charge with solar cells only.

A.7 Non-optimal Cases

Few urbanized places have as good insolation as California, as in the previous case. Table A.1 shows that most northern European countries only offer half of the insolation, leading to longer energy pay-off for the solar cells. Further on, these regions have the most of the insolation concentrated in the summer months.

Even if the insolation is strong, the car's roof must be exposed to direct sunlight as good as all day, which is not particularly feasible in city environment with high shading buildings, parking garages and vegetation in parking lots.

A.8 Conclusion

The use of solar cells on cars brings few benefits in an energy point of view. An investment in solar cells is much more suited to be installed on land, on top of buildings, and plugged in to the public grid to deliver the generated electricity. A better choice would then be to charge a plug-in (hybrid) electric vehicle through the same public grid. A land installation also benefit from the possibility to physically align the solar cells to maximize the exposure, passively and actively, leading to a 8 - 60 % gain in energy generation for the same setup of panels.

Another issue is that solar cells are expected to have a 20 - 30 years calendar life, which is considerably longer that the 6 - 10 years expected by the average car. In a non-optimal implementation such as cars, the solar cell may not reach it's energy pay-off within the car's life time.

Appendix B

Light Hybrid Vehicle Market Overview

A market overview has been put together out from promulgated company relationships. The complete overview is inserted at the back of this report in the printed version only.

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