FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Study of Real-Time Estimation Techniques Related to the Autonomy of an Electric Vehicle

Pedro Rodrigues Pacheco

Integrated Masters in Electrical and Computer Engineering
Report in the Scope of “Master Thesis Preparation” Course

Supervisor: Rui Manuel Esteves Araujo (PhD)

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Chapter 1

Work Done and Document Structure

At the beginning of the “Master Thesis Preparation” course, which will be labeled as "PDI" for now on, a reunion with the master thesis proponent was scheduled to both familiarize with the proposed problem and elaborate a work plan for the PDI course. The “work plan”, which has now been transformed into “work done” is itemized in section 1.2. That work plan was exploited and gave information to the Gantt chart represented in figure 1.1 present in section 1.3.

1.1 Objective of the Document

This report, in the scope of the PDI course, has as objectives, to compile in an organized manner, the motivations for the topic of the master thesis, a bibliographic review, a state of the art survey, a detailed characterization of the problem concerned in the aforementioned thesis and a work plan for the “Master Thesis” course. The work plan includes the technologies and tools which will be used.

1.2 Itemized Work Done

At the beginning of the course “Master Thesis Preparation” a work plan was done. It suffered numerous iterations. In 1.3 a Gant diagram shows the work done in the “Master Thesis Preparation”.

- Justify the interest in the electric vehicle;
- Characterize the most important energy sources;
  - State of the art of each energy source
  - Focus on the essencial characteristics of an electric vehicle
  - Promote an analysis for each type of energy source supported on models

- Study of some operations modes for an electric vehicle
  - Energy and power flux
- Hybridization fundamentals
- Study of Power structures applied to the electric vehicle
  - Topologies for energy source interface
  - Topologies for traction interface
- Control structures for power electronics applied to the electric vehicle
- Arrive at a model and a transfer function of the power electronics system
  - System linearization
  - Study the achieved transfer function
    - Steady state analysis
    - Transient response analysis
- Development of a potetially optimized controller
- Study of the possibility of a dynamic controller
- Study of State-of-Charge estimation methods

1.3 Gantt Diagram

The next figure, 1.1 is the Gant diagram of the work done in “Master Thesis Preparation” course.

1.4 Document Structure

Apart from this chapter, this report will approach in chapter 2 some of the motives for the effort and studies in electric vehicles, touching some aspects like the CO2 emissions and threats to the electric production and distribution system. In chapter 3 many references are visited to attain information about portable energy sources 3.2, sources hybridization 3.3, power electronic structures 3.4 and SoC determination methods 3.5. The last chapter, 4 is a work plan in which the objectives of the mater thesis are approached and scheduled.

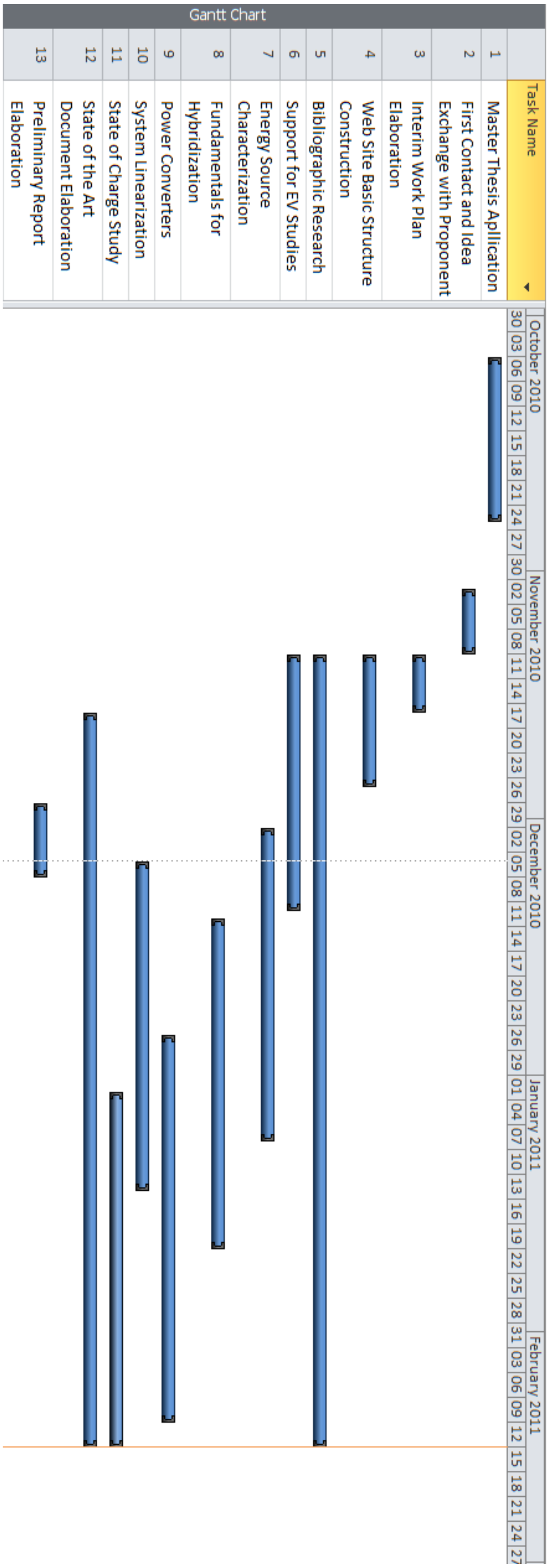


Figure 1.1: Gantt Chart

Chapter 2

Motivations and General Framework

Paradigmatic changes happen in people's mean of transportation since the beginning of times. The invention of the wheel, the first horse tamed, the usage of chariots and the internal combustion engine were historical modifications that brought the world close to the probable next step, the electric vehicle.

Mostly since the later part of the 18th century, with the United Kingdom's industrial revolution, mankind became more and more dependent of fossil fuel. Those dependencies brought environmental, social and political issues that have wormed deeply in modern society.

2.1 Environmental Impact

Human activities are affecting the global eco-system. Among all the factors that increase CO2 emissions, like population pressure or land usage, the most influential is without doubt combustion of fossil-fuel [12].

For the first time CO2 emissions from Annex I countries1 were surpassed by those from non-Annex I countries2. That change happened in 2008, that was also the year that Annex I countries first fell below 1990 CO2 emissions threshold. This trend can be explained by the recent financial crisis, economic slowdown and "price signal received by consumers after the high energy prices observed in 2008" [13].

Non-Annex I trends of CO2 emissions are in a continuous growth, on the other direction are Annex I countries that are consistently reducing CO2 emissions [13]. Figure 2.1 shows the global change of CO2 emissions worldwide.

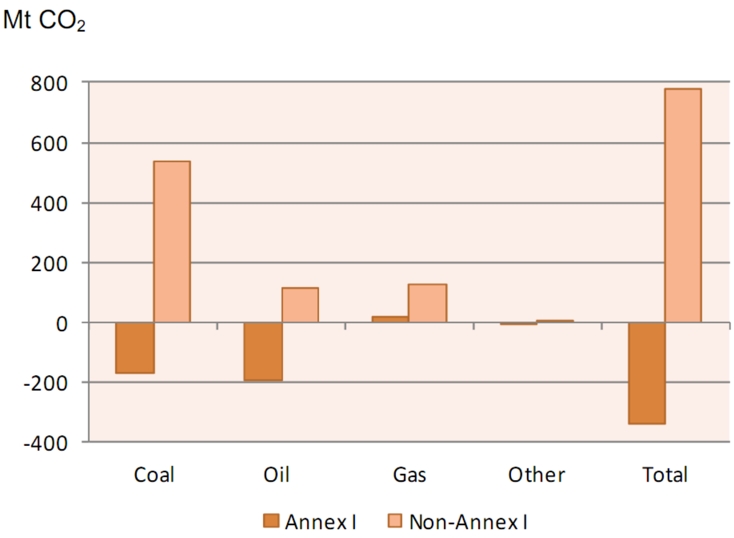


Figure 2.1: Global Change in CO2 Emissions (2007-2008)

2.1.1 CO2 Emissions by Fuel

Having 2008 as a reference we can see in “CO2 Emissions from Fuel Combustion Highlights” [13] that 43% of CO2 emissions were due to coal combustion, 37% from oil and 20% from gas. The next figure, 2.2, illustrates those numbers and shows trends since 1971 to 2008.

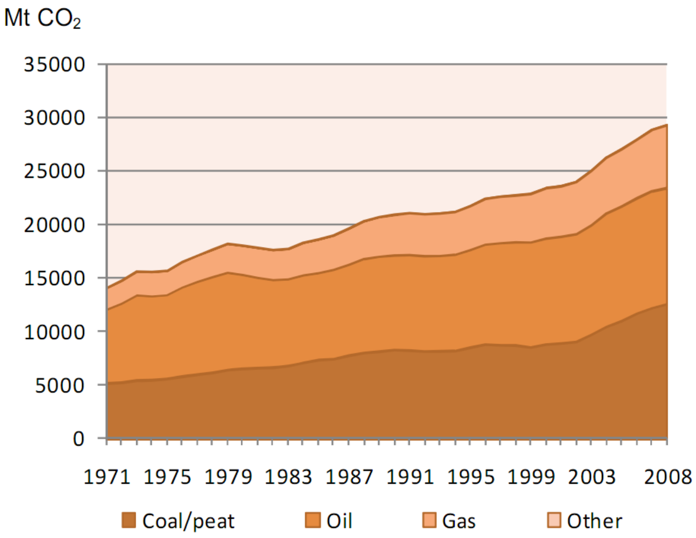


Figure 2.2: Trends in CO2 Emissions from Fuel Combustion

Now we can turn our attention to CO2 emission by sector, analyzing data from [13] it is possible to conclude that “the combined share of electricity and heat generation and transport represented two-thirds of global emissions in 2008”. The next chart, inserted in figure 2.3 expresses those values visually.

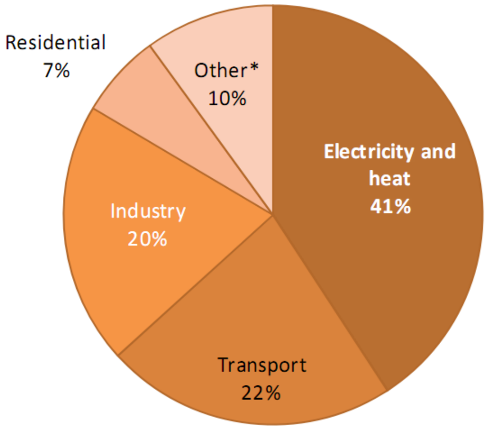


Figure 2.3: CO2 Emissions by Sector

Some conclusions can be achieved, the most important one is that the generalized entry in the market of the EV tends to reduce directly a great slice of CO2 emissions, the one named in the pie chart as “Transport” since most of the emissions are directly related to road transportation, the main target of the EV as seen in figure 2.3. Furthermore, global demand for transportation is, as WEO 2009 predicts, likely to increase by 45% until 2030 [13].

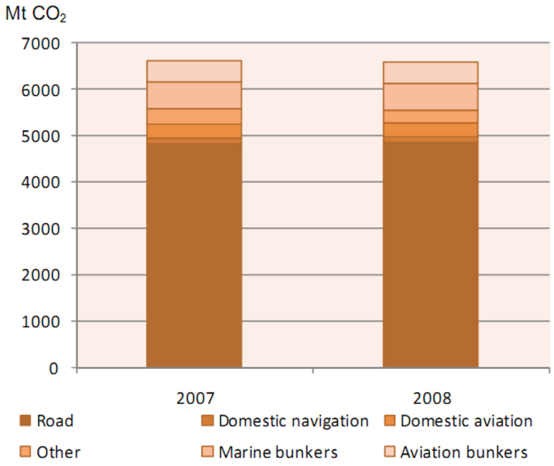


Figure 2.4: CO2 Emissions in the Transport Sector in 2007 and 2008

There are obviously some setbacks in the entry of the EV in the international scene. Looking at the figure 2.4 a major problem is identifiable, an increase in emissions due to energy generation would happen.

A solution to that problem is needed. Policies can encourage a shift to new low-carbon emitting energies. With those policies came the increase in the last decade of renewable energy production [13]. As an example, there is an European Directive released in 2009 that sets ambitious targets for all countries in the EU, those targets will make the share of energy consumed from renewable sources to reach 20% of all the energy consumed, those values are set to achieve by 2020 [14].

2.1.2 Emission Trading Schemes

Giving the time needed for CO2 to disperse in the atmosphere, stabilizing the concentrations of greenhouse gases at a given level would require either a great reduction in emissions or an as soon as possible decrease of emission.

Some protocols were enabled complementing various national and community measures in order to achieve a recommended level to greenhouse gases concentrations. The Kyoto Protocol of the UNFCCC is by far the most evident multinational effort to mitigate climate change. "Having entered into force in February 2005, the Protocol commits industrialized countries (as a group) to curb domestic emissions by about 5% relative to 1990 by the 2008-12 first commitment period."[13] With this "as a group" clause economic transactions of emission allowances started among Protocol country members. "The Kyoto Protocol implies action on less than one-third of global CO2 emissions as measured in 2008."[13].

Some of non-participant countries in the Kyoto Protocol elaborated a protocol of their own. An example of those initiatives is the Western Climate Initiative, a collective emission system composed by 11 US states and Canadian provinces. "A number of other trading schemes are also under consideration."[13]

2.2 Socio-Economic Impact

A paradigmatic change such as EV worldwide dissemination must have a major impact on both economic and social structure. A great number of studies were done so we can have some perspective over the future changes in the world socio-economic structure.

2.2.1 Commercial and Industrial Changes

The scenario of world fossil-fuel combustions free is almost a utopia, but the EV proliferation gets us closer to that objective and brings up some problems related to companies that make a living either selling or producing products for ICE vehicles. In spite of those problems, some benefits are obvious, like the emergence of companies specialized in products needed for a functional EV.

To analyze the EV market entry impact, USA can be used as an example, because, being a country with a high fossil-fuel dependency, the industrial structure around petroleum and petroleum products is deeply cemented.

We can conclude from the data available in figure x that battery manufacturing companies tend to grow significantly in order to attend EV products demand. On the other hand, the petroleum and petroleum products are industries with a major setback in revenue. Those abrupt changes have obvious implications in human resources e.g. employment and import policies [1].

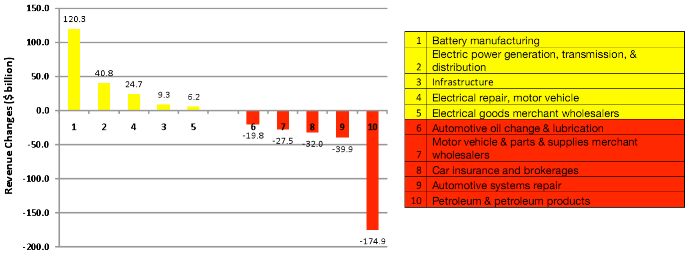


Figure 2.5: Top 10 Industries Direct Gains and Losses [1](edited)

2.2.2 EV and PHEV Market Penetration

A high EV market penetration would be a threat to electric power systems stability, so a good judgment about the share of EV and PHEV being used at the time is crucial. According to [15], EV and PHEV are going to grow in the next few years, bringing a huge new load to power generating and distribution systems. The worst case scenario to the electric power system is a high penetration rate of the EV and PHEV. Two market penetration scenarios were presented in [15], sales based on national announcements in figure 2.6 and sales targets if national targets growth rates extend to 2020 in figure 2.7.

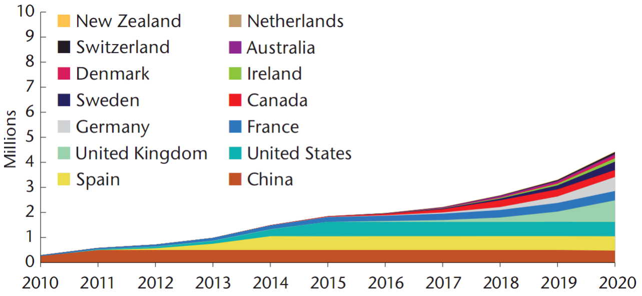


Figure 2.6: National EV/PHEV Sales Targets Based on National Announcements 2010-2020

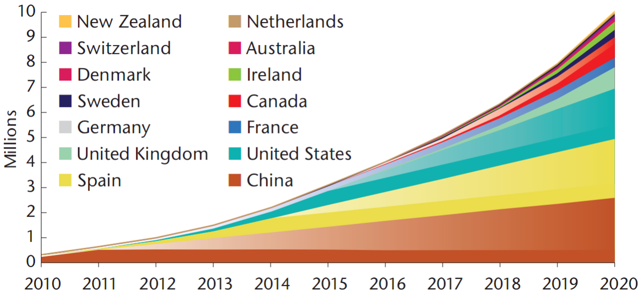


Figure 2.7: National EV/PHEV Sales Targets if National Target Year Growth Rates Extend to 2020

According to an interview to Joao* Dias, an economic adviser in the Prime Minister's office, at 20 October 2010 to Reuters, Portugal has an aim of 750000 EV and PHEV on the road, around 10% of all road vehicles, by 2020.

2.2.3 Energy Related Importation and Exportation Changes

Focusing the attention on Portuguese importation/exportation balance, we can see a continuous crescendo of energetic related importation, and worst, the commercial balance between exportation (assumed all FOB) and importation (assumed all CIF) is decreasing. The next figure 2.8 subtracts FOB to CIF and relates that value as that year GDP percentage [2].

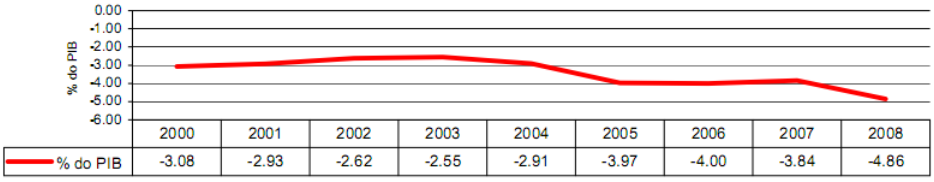


Figure 2.8: (FOB - CIF) as percentage of GDP [2]

To have a good idea of how the EV dissemination nation-wide (in Portugal) would change Portuguese importation/exportation balance an energetic of importations and exportations characterization is needed. Figure 4 explicitly shows the relation between each product quantities with intra-EU estimated data for 2008. The figure was edited in order to translate it to English language.

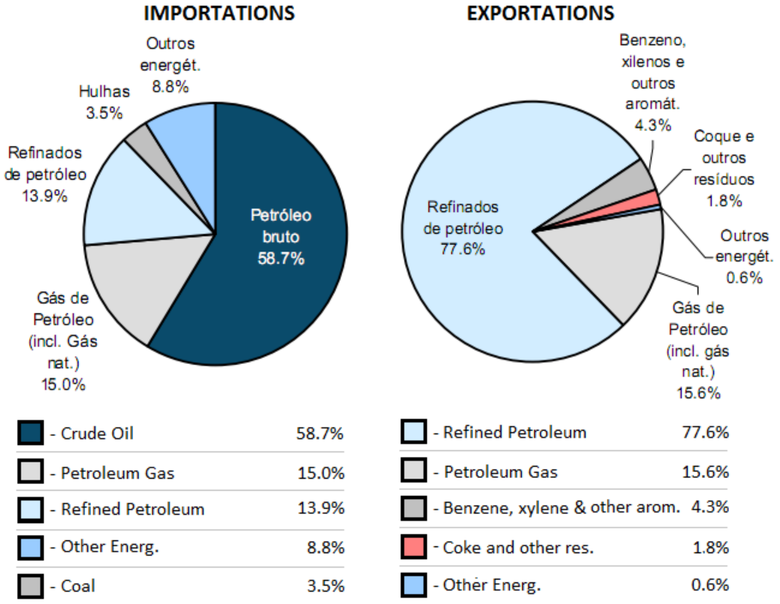


Figure 2.9: Energetic products transacted by Portugal in 2008 relative weight (edited) [2]

Now is possible to understand the EV implication on the economy of a country such as Portugal knowing that 12.5% of all importation is to crude oil and refined petroleum [2] with a good slice of that going directly to the transportation sector. That slice would definitely decrease, reducing substantially importation and opening doors to a widely use of emerging renewable sources of electricity. These exportations are only 6% of the total exportations of the country which is much less than the importations as viewed above in the document [2].

2.3 Technologic Impact

History tells us that most of technologic advances come from one reason, need. With the possibility of a high demand of products associated with the EV in the future it is only normal that a raise of some economic and academic interest happen. It is from that mutual interest that technology usually evolves.

2.3.1 Academic and Industrial Effort

The need for a versatile transportation sector with much less CO2 emissions brought the public attention to the EV.

A great number of universities all around the world are studying the electric vehicle and many times with companies or government support and funds.

A paradigmatic example of the visible EV technologic impact and attempt of being a magnet of innovative research, is ITS (Institute of Transportation Studies) UC Davis (University of California, Davis), with more than 60 affiliated faculty and researchers, 100 graduate students, and a $6 million annual budget, acquired by partnering with industry, government, and non-governmental organizations [16].

2.4 Impact on Electric Power Production and Distribution System

In this part there is a need to focus in a single country that has a well-developed and economically healthy [17] electric power system in order to detain all the information needed to achieve pertinent conclusions. Portugal will be the country used for the study due to its electric power distribution system characteristics, renewable energy sources development state and extrapolation capability to most of the EU-25 member states with no nuclear power production.

2.4.1 Current Power Production Capability

To assess the Power System capability to accept a high market penetration of the EV is important to understand what the current power generation capability is. Figure 2.10 is based on values shown in reference [18] and shows the installed power by source in Portugal at the end of 2009.

In reference [18] we can see that the total of installed power is 16738 MW. In spite of that value, many of the sources are related to meteorological events. More than 40% of these capacities are not always available due to their time dependency.

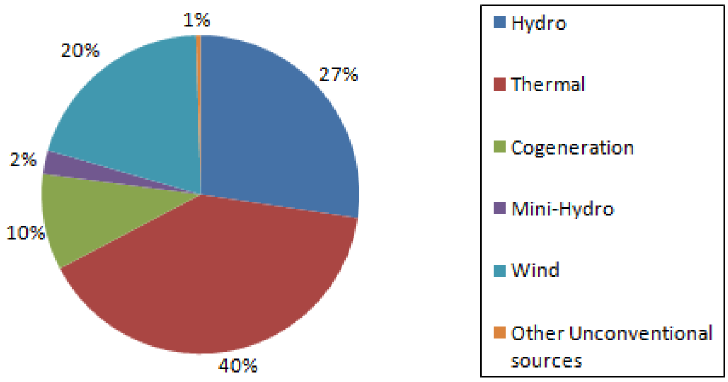


Figure 2.10: Portuguese installed capacity by source in 2009

2.4.2 Expected Power Production Capability by 2015

The installed power upgrade is nowadays underway in Portugal, many hydro plants are being constructed and are expected to be functional by the year 2015, like Alvito and Foz do Tua with a combined capacity of 476MW. Production reinforcements are being held at Venda Nova II upgrading it to Venda Nova III with an increase to 736MW installed power also expected to be functioning by 2015. Many wind turbines are being deployed as well. The next figure shows the expected Portuguese installed capacity by source in 2015.

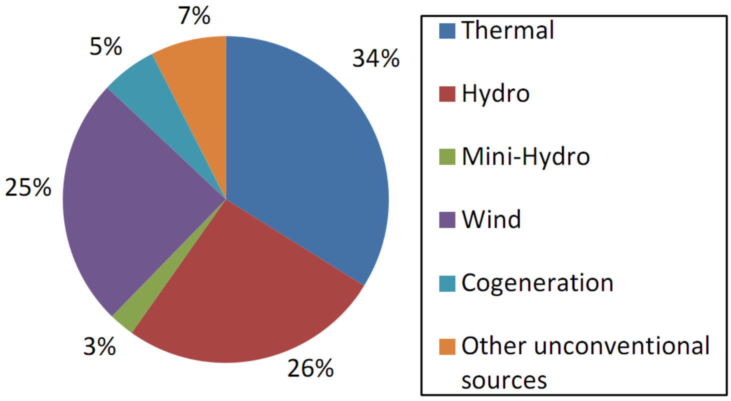


Figure 2.11: Expected Portuguese Installed Capacity by Source in 2015

Problems inherent to time constraining energy sources tend to grow. By 2015 the share of hydro and wind production is expected to break the 50% threshold.

2.4.3 Threats

Like every other technology entering the world market, it has some risks, in this section will be approached the challenges that companies responsible by production and distribution of energy will face during the EV dissemination (e.g. EDP and REN respectively).

2.4.3.1 Power Production System Stability

An unregulated entry of EV in the electric power system could get catastrophic very quickly. In [3] analytical approaches were made in order to assess the security of energy supply. Those studies came up with pertinent results for Portugal. The proposed methodology in [3] uses a modeled generation system and a monthly affectation of hydro systems. To combine those models with sources/loads which strongly depend on the time, like wind generation, unconventional sources and EV charging models, FFT was used. Two scenarios of EV battery charging were used. The first one is the dumb charging scenario, where the vehicle battery charging follows the natural behavior of Portuguese population, which is visible in the load diagrams showed in figures 2.12 and 2.13. No political or economic measures are used in this dumb charging scenario.

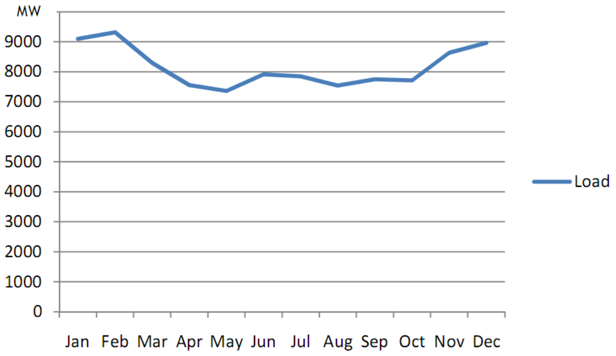


Figure 2.12: Portuguese System Mean Load Monthly Variation

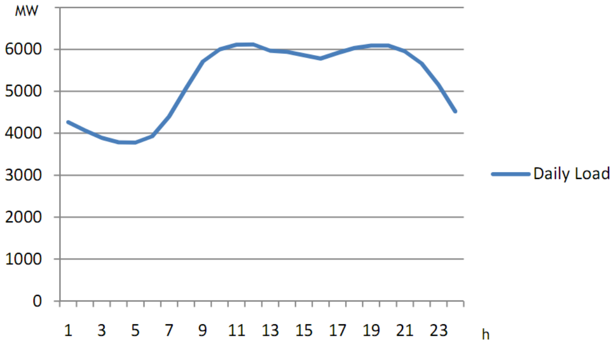


Figure 2.13: Portuguese System Mean Load Daily Variation

The next figure, 2.14 is merely illustrative of a dumb charge behavior and may not be representative of the Portuguese case.

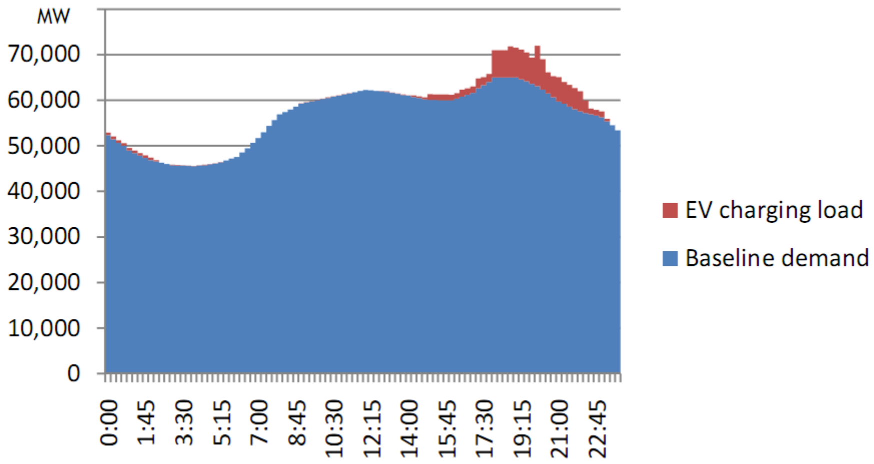


Figure 2.14: Dumb Charge Example [3]

The results of simulations were expressive in both LOLE and LOLF assessments.

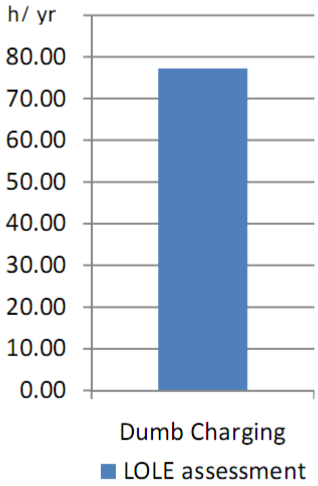


Figure 2.15: LOLE assessment for Portuguese System (edited) [3]

In a dumb charging scenario is expected that the system cannot supply the total demand for 77h in a year, this scenario affects in a drastic way Portuguese security of supply. Figures 2.15 and 2.16 shows the high influence of the dumb charging in the reliability indices with system failures occurring more than 35 times in a year.

These assessments prove that an unregulated EV entry in the electric network can be translated as a major threat to the system stability.

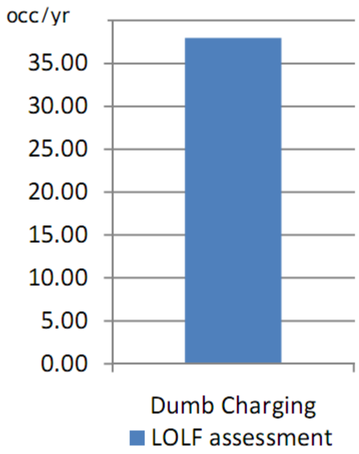


Figure 2.16: LOLF assessment for Portuguese System (edited) [3]

2.4.3.2 Challenges with Transmission and Distribution

“The transmission and distribution grid today serves a critical role in delivering electricity from generation sites to population centers”[19]

Usually the place where energy is consumed is not the same where it is generated, hence there is a necessity of a transmission and distribution grid. Thus the state of that grid will influence directly the quality and reliability of delivered power.

The Portuguese company responsible for energy distribution and transport is REN (Rede Electrica Nacional). This company has high quality of service standards, thus has a continuous improvement policies [18]. The main challenges of this kind of companies worldwide will be to keep the quality of service high, developing ways to predict congestions in some branches of the grid.

2.4.3.3 In Short

All these threats to the electric power system come from the peaks of energy needed to charge batteries. The energy usage efficiency of those batteries is then crucial. Managing the energy and power flow inside the EV can directly affect the electric power system positively.

2.4.4 Opportunities

The need for a “green” possibility for medium distance locomotion brought the spot light to the electric vehicle, with those lights investment is often a consequence, leading to revenue and intellectual knowledge.

2.4.4.1 Electricity Selling Revenue

It is clear that electric vehicle usage will increase electric consumption, thus more selling opportunities. According to “Impact of Widespread Electric Utility Business - Threats and Opportunities” [19], having an EV driving 33 miles per day at 0.35kWh per mile and average retail price of 11.36 cents/kWh it translates into an additional revenue of $480 per annum for every EV in service.

A similar approach can be used to Portugal. Assuming that the battery charging of every vehicles are made in the valley zone of the load diagram with bi-hourly contract, a wage of 0.0850€/kWh can be achieved, this means an additional revenue of 358€per annum per EV. Assuming Portuguese perspectives of 750000 EV by 2020 are correct it implies a gross revenue rounding 260M€per year.

2.4.4.2 Increase of Installed Capacity Usage - Valley Filling

The concept of Valley Filling is the assumption that some loads can be programmed to absorb power in periods of non-peak demand.

Many policies can be done to achieve this load profile, one of the most compelling is wage reduction in non-peak demand. Since is predictable that most of recharges of EVs will occur during late evening and overnight, an increase of wage from 16:00 to 18:00 and a low wage from 20:00 to 6:00 could shift loads to a better period for the electric power system.

A question must be answered now, “Why do the Valley Filling concept increase the installed capacity usage?”.

Looking at figure 13 we can see a lack of demand 23:00 to 7:00. Some power sources are continuously active due to time needed to be deployed. Sources with time dependencies, in order to have efficiency must be active for periods when energy generation is possible, those time intervals can coincide with lack of demand periods. In short, during valley hours is possible that the power generated is more than the power dispatched. Nowadays excess of power is used to pump water backwards to the bayou in hydro plants, in order to transform electric energy in potential/kinetic energy. Even with pumping methods there is excess of power at occasions, thus that power is usually sold at very low prices or even given. With EV charging batteries in lack of demand periods installed power capacity would be used in a more efficient manner, minimizing investment in power upgrades and maximizing installed power use.

In [3] valley filling using EV battery charging is named “smart charging”, the next figure, 2.17is illustrative that behavior.

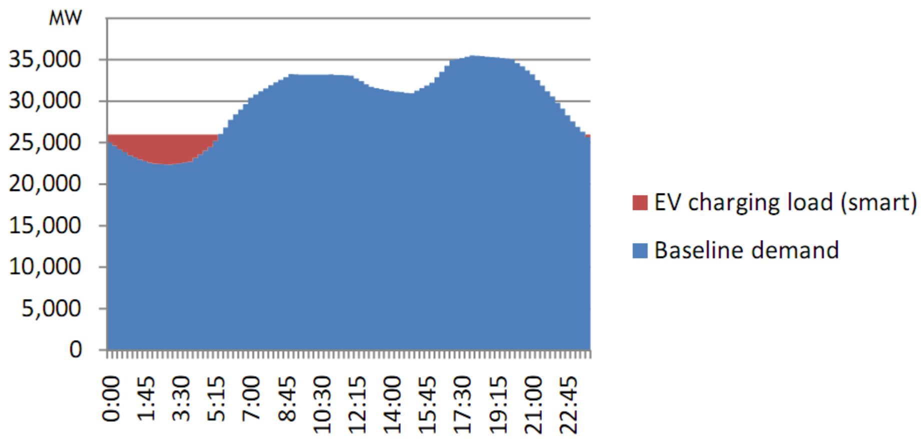


Figure 2.17: Illustrative representation of a valley filling with EV [3]

2.4.4.3 Vehicle to Grid (V2G)

“Vehicle-to-Grid (V2G) has been hyped as one of the most promising opportunities of the EV revolution.” [19]

The idea behind V2G technology is that utility firms will be able to manage plugged-in EV batteries to be used as distributed storage to serve as back-up capacity to help meet unusual demand spikes.

With dynamic pricing the EV owner could profit by plugging it in during the afternoon. These policies could encourage EV fleets in companies. Another possibility is the previously referred valley filling.

However, the authors believe that some issues may prevent V2G from becoming a reality in the next decade. Unproven economic justification for utilities and consumer, the complexity of knowing when to draw power from the vehicle, lack of support for smart grid technology and the need for development and wide scale installation of bi-directional power converters. But one of the most important issues brings batteries and battery management to the spot light. The early development stages of battery technology makes unlikely that either the car manufacturer or the utility will risk interconnections [19].

Contributions in battery technology and knowledge are crucial to a steady progression towards the, for now utopic, V2G reality.

2.4.4.4 In Short

Is noticeable that the EV entry brings many opportunities to the electric power system, but in order to achieve good results a good knowledge of battery and battery management is mandatory.

Chapter 3

State of the Art

In order to achieve good results in a bibliographic review, reference organization is mandatory. The citation manager used, EndNoteX4, presented in the course in which this document is inserted, was an excellent help to keep organized journal articles, web pages and many other kind information.

3.1 A Digest of the Present Electric Vehicles

The reality of the electric vehicle has been changing in the past few years throughout the world. Many companies historically related to internal combustion means of transportation, predicting that the electric vehicle will appear as a viable alternative to usual locomotion systems, are approaching their technology to fully electric vehicles.

In the last few years a great effort to maximize the autonomy of those electric vehicles, aimed as one of the main obstacles to their generalized adoption in general population. Battery technology is not fully developed, hence to use state of the art batteries, the ones with higher energy density, the price is high, thus raising the final value of the car. As a result of that recent effort some big automotive brands made big advances in their vehicles autonomy, thus are finally able to commercialize their fully electric means of transport. Other companies are now in the concept car step.

Focusing our attention on light vehicles, we can see that some major brands are leading the way to a high penetration of electric vehicles worldwide. Brands like Nissan, Renault and Fiat, already came up with fully functional plug-in electric vehicles commercializing them in some countries, Portugal is one of them.

The European Car of 2011 award winner (for the Car of the Year web site) is the Nissan LEAF has an AC synchronous motor that produces 80kW (109hp) from 2730 to 9800 rpm. This Nissan state of the art vehicle, as stated in [20], gets his power from a “new-generation”[20] battery that brings the Nissan Leaf autonomy to values from 75Km (worst case scenario), passing through around 160Km (US LA mode), to 220Km (best case scenario)[21].

But for now, the state of art electric vehicle is Tesla Roadster, from Tesla Motors, with an AC induction motor producing 288hp at 4400-6000 rpm [22]. The range is specified in [22] as 245 miles, around 392 Km (combined city/highway EPA cycle).

3.2 Energy Sources

Throughout the world the crescent attention to the electric vehicle as a mean of transportation brought scientific interest and government and industrial investments to the energy source sector inside the electric vehicle [5]. One can notice that attention by observing the join-ventures of well-known manufacturers all around the world. Some examples of those collaborations are AESC (2007), a Nissan, NEC and NEC Tokin association, SB LiMotive (2008), a Bosh and Samsung SDI team play [5]. Obviously the energy source requirements for an EV differ from others like HEV or PHEV. This section will only discuss the energy sources of interest for the EV.

3.2.1 Batteries

“A battery is a device that provides a source of electrical energy to an external circuit by direct internal conversion of chemical energy.” [5] Many technologies of batteries are available or in development, all of them use the basic concept of electrochemical oxidation-reduction reaction of its active materials to generate electrical energy. For many different reasons some technologies are not suitable for electric vehicles applications, hence only the fully developed or assured technologies will be addressed in this part. The big diffusion of the battery technology made standardization a necessary measure to take. Among many national institutes some international organizations like the International Electrotechnical Commission (IEC) and the International Standards organization (ISO) came up with some battery standards.

3.2.1.1 Basic Concepts

In order to understand the battery as a whole some basic concepts must be absorbed.

The output voltage of a single cell is, in theory, function of the materials used in the cathode and anode, the composition of the electrolyte and the cell temperature. This voltage is similar to the open-circuit one. When connected to a load, internal polarization effects impose a voltage drop top the cell terminals.

The energy output is, usually a low percentage of the theoretical one, this is mainly due to lack of stoichiometry balance in the active materials and to the non-null end-voltage (voltage of the cell when totally discharged) in a totally discharged battery. As stated in [5], the energy output can be from 16 to 37 percent of the theoretical one. The actual energy output leads to an important concept named specific energy. It relates the total output energy with the weight of the cell or group of cells (Watt-hour/kilogram). Another important parameter that one should be acquainted with is the capacity of a battery. The capacity is the amount of electrical energy that a cell can deliver at a constant temperature when discharged at a constant rate, this is measured in Ampere hour (Ah). A high discharge rate imposes a low capacity. One can now use the battery capacity to extrapolate some performance parameters. "The life cycle of a battery is the number of cycles that a battery can perform before its nominal capacity falls below 80 percent of its initial rated capacity"[5]. A high depth of discharge is a factor that can worsen the life cycle expected of a battery and that life cycle behaves, in almost all batteries, with a quasi-logarithmic function of the depth of discharge. One of the main performance indexes is the specific power (Watt/kilogram). This shows the power that can be used as work in a time instant.

3.2.1.2 Primary Batteries

"These batteries are not capable of being easily or effectively recharged electrically and, hence, are discharged once and discarded." [4] Usually these kinds of batteries have as their general advantages the commonly inexpensiveness, lightweight package power source. Having a good shelf-life, high energy density, moderate discharge rates, almost no maintenance and ease of use, primary batteries are the used for a wide range of applications going from portable electronic and electric devices to toys and backup memory. A particular case of a primary battery is a "Reserve Battery", according to [4]. This sub-type of battery is designed to a very particular objective, to "meet extremely long or environmentally severe storage requirements that cannot be met with an "active" battery designed for the same" [4]. All of these properties make this kind of battery a good emergency backup as a primary energy source, extending, in case of need, the electric vehicle autonomy. In 3.1 some primary battery technologies are shown in terms of its specific energy and energy density, the main characteristics disered for a backup energy source.

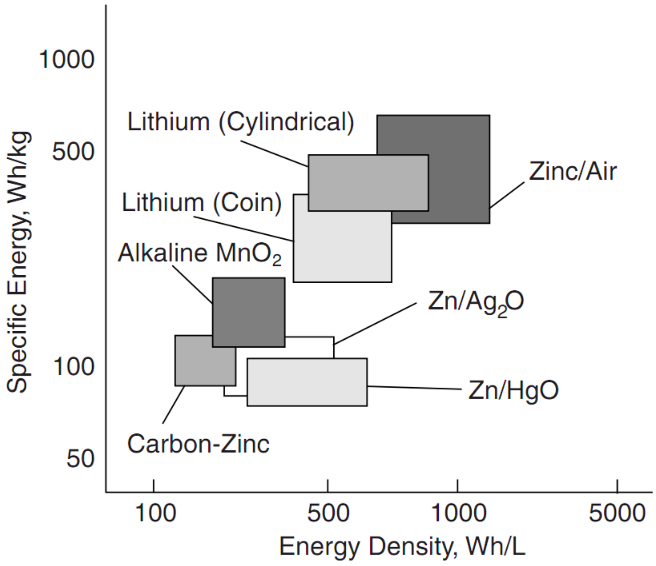


Figure 3.1: Some Primary Battery Technologies [4]

3.2.1.3 Secondary Batteries

"These batteries can be recharged electrically, after discharge, to their original condition by passing current through them in the opposite direction to that of the discharge current." [4]

This kind of battery is characterized by a high power density, high discharge rates, flat discharge curves and good low-temperature performance. The energy density is lower than in the case of primary batteries, poor charge retention and some capacity lost on standing makes secondary batteries a bad choice if storage is needed.

All these characteristics make secondary batteries a good choice in two major types of application, as an energy storage device (i.e. Uninterruptible Power Sources, Stationary Energy Storage, Electric Vehicles and Aircraft Systems), or just like a primary battery, only with the attribute of being recharged instead of being disposed of [4].

According to [5], some types of secondary batteries are not suitable for electric vehicle applications. Hence between a large number of technologies only the fully developed and assured technologies will be treated in this part, Lead-acid, Ni-MH, Li-ion, Li-po. Due to cadmium toxicity Ni-Cd batteries will not be regarded in this part.

1. Lead-Acid (LA)

   The lead-acid battery was invented in 1859 by Raymond Gaston Plante and continues to be the most deeply cemented technology for SLI applications with many suppliers worldwide. Its low internal impedance, high current delivery and tolerance to overcharging procedures make this kind of battery a good solution for automotive SLI applications. Due to its bulkiness, low energy density, specific energy, charge efficiency (about 70%), specific power and life cycle, this technology is not suitable for a primary energy source of an efficient electric vehicle. Moreover, when charged with a high current, the lead-acid battery overheats making it not appropriate for fast recharging.

   With an enhancement of this type of battery in mind some developments were made to improve some shortcomings of this classic technology.

   One of the most known developments of lead-acid batteries are Valve Regulated Lead Acid (VRLA), introduced in 1970's, designed to prevent the electrolyte evaporation, spillage and gassing. These batteries are considered either as gel type VRLA or Absorbed Glass Mat (AGM) VRLA. These preventions impose some enhancements in robustness, with a higher resistance. No enhancements in specific power or energy density are described in [5].

   A more recent development to lead-acid batteries named Bipolar Lead-Acid involve a stack of bipolar electrodes connected in series, improving the power level delivery, offering an increased energy density and quadrupling the power density, in relation to the classical lead-acid batteries. The next figure, 3.2, took from [5] offers a quantitative relation between the classic Lead-Acid battery and the one described in this paragraph, a Nickel-Metal Hydride is also compared.

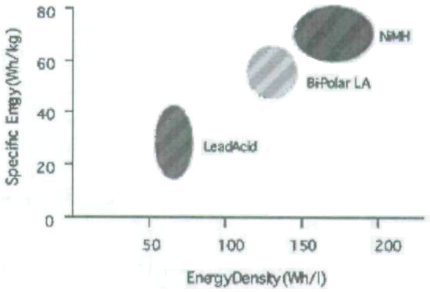


Figure 3.2: Bi-polar battery energy respect to lead acid and NiMH batteries [5]

2. Nickel-Metal Hydride (NiMH)

   Over 2 million hybrid cars use the Ni-MH batteries, a technology developed throughout the years with its origin in 1967 in the Battelle Geneva Research Center, with a Ti-Ni alloy for the negative electrode and a NiOOH for the positive electrode. The battery used nowadays in hybrid cars like, Prius and Lexus Highlander from Toyota, Altima from Nissan and others, is an improved version of the one invented in Switzerland. Ovonics altered and improved the Ti-Ni alloy and licensed the Ni-MH batteries in 1986.

   Many advantages came with this type of battery, a high energy density and cycle life together with the low internal impedance and wide operating temperature made it an interesting solution. Some shortcomings still exist, a very high self-discharge rate, a coulomb efficiency with typical values of about 66 percent [5] and, depending on the application, a full power delivery that can go down to 50 percent DOD, prevent this technology from a wider application window in electric vehicles.

   In [6] some recent advances in NiMH batteries are shown. Ovonics driven by research of advances materials for the electrodes of the NiMH battery, came up with an extended power through more cycles. In the next figure, 3.3, took from [6], those improvements are shown.

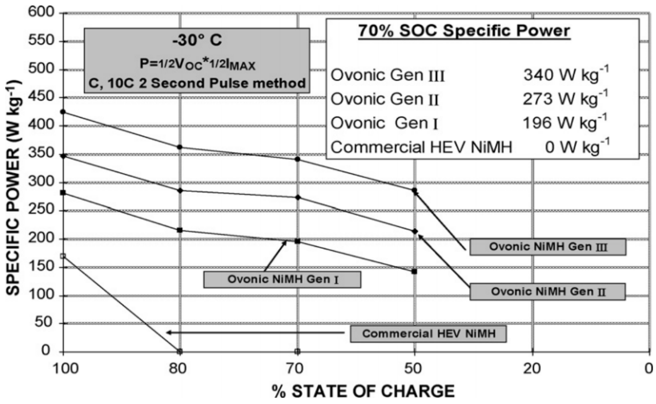


Figure 3.3: Improved NiMH specificc power at -30 C [6]

Figure 3.4, extracted from [5] shows the targets for the specific energy and power of the next generation NiMH batteries when compared to Lithium based batteries. The proximity of those two technologies in terms of specific power and energy is orienting the research of NiMH batteries to a competition for the electric vehicle battery market. Even with some disadvantage of those performance parameters, the cost and safety of NiMH can make this technology competitive.

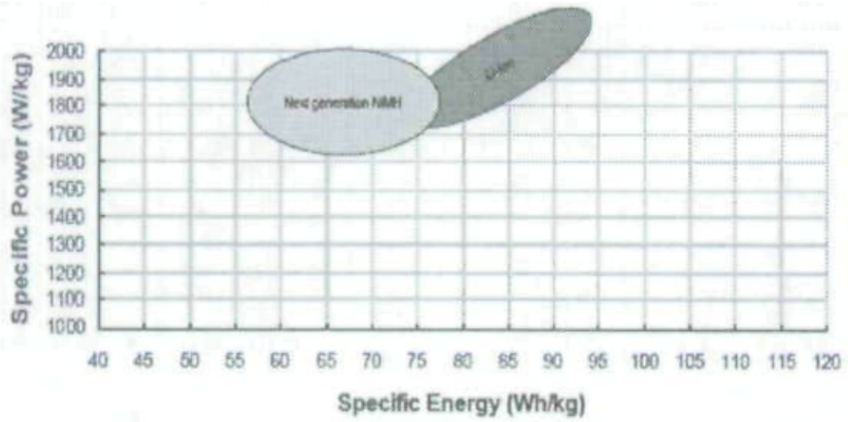


Figure 3.4: Targets in specific energy and power of next generation of NiMH batteries related to Li-ion batteries [5]

3. Lithium-ion (Li-ion)

   The typical lithium cell is composed by a carbon based anode and a lithium compound, such as Lithium Cobalt Dioxide or Lithium Manganese Dioxide cathode (other chemistries are possible). The electrolyte cannot be an aqueous material, since Lithium reacts violently with water. In this kind of battery the electric energy is generated when the lithium ions inserted of extracted into “the crystalline lattice of the host electrodes without changing their crystal structure”[5].

   The performance factors of Li-ion batteries make them an attractive solution for automotive applications. A high cell voltage (3.6V), a very high specific power and energy density, a low weight, the possibility of faster charging without damaging the battery cells, a coulomb energy of almost 100 percent and a long cycle life, make this technology competitive even with their high initial costs, the need for protective circuitry, degradation with high temperatures and high internal impedance when compared to other secondary battery technologies [5].

   In the recent years many companies and research institutions are directing their effort to create the next generation lithium based battery. The research is dealing not only with the electrodes, but with the electrolyte material as well. The variations to the classical Li-ion cell started with three variations of the materials used. The most mature of those first generation technologies is the Lithium Cobalt, this combination of materials made a battery with very high energy density, long cycle life and good typical cell voltage (3.7V) but, due to the toxicity of Cobalt the application capability in the automotive industry is limited. The other two variations in materials are in the Lithium Manganese battery, with higher typical cell voltage (3.8V) but less energy density (about 20% less), and in the Lithium Nickel battery, with lower typical cell voltage (3.6V) when compared with Lithium Cobalt type but higher energy density (about 30% more when compared to Lithium Cobalt batteries). The research did not stop with these three types of Li-ion batteries and many variations of materials were tested. The tradeoff is shown in the next table, 3.1.

Table 3.1: Tradeoff Development in Li-Ion batteries [11]

Name	Description	Automotive Status	Power	Energy	Safety	Life	Cost
LCO	Lithium cobalt oxide	Limited auto applications (due to safety)	Good4	Good4	Low2,4 Mod.3	Low2,4	Poor2,3
NCA	Lithium nickel, cobalt and aluminum	Pilot1	Good1,3	Good1,3	Mod.1	Good1	Mod.1,3
LFP	Lithium iron phosphate	Pilot1	Good1	Mod.2,6	Mod.1,2,4	Good1,4	Mod.1 Good2,3
NCM	Lithium nickel, cobalt and manganese	Pilot3	Mod.3	Mod.3 Good7	Mod.3	Poor.3	Mod.3
LMS	Lithium manganese spinel	Devel.1	Mod.2	Poor.1,2,3	Excel.1 Good2	Excel.1 Mod.6	Mod.2
LTO	Lithium titanium	Devel.3	Poor.3 Mod.7	Poor.3	Good3	Good3	Poor.3
MNS	Manganese titanium	Research1	Good1	Mod.1	Excel.1	Unkwn.	Mod.1
MN	Manganese titanium	Research1	Excel.1	Excel.1	Excel.1	Unkwn.	Mod.1

3.2.2 Supercapacitors

When compared to normal capacitors (i.e. electrolytic), the supercapacitor has much more capacitance, hence a higher energy storage capability. Contrary to common thinking, the supercapacitor is constructed much like a battery, being a basic cell composed with two electrodes, a separator and an electrolyte. The decomposition voltage of the electrolyte determines the working voltage of the supercapacitor that depends greatly of the environment temperature, current intensity and lifetime required. There are three main supercapacitor technologies using two types electrolytic material, one organic, with high working voltage, high energy density, wide temperature range and good compactness, and one aqueous, with low decomposition voltage and a narrow temperature range [5].

1. Double-Layer

   This kind of technology “is based on an electric double layer phenomenon” [5] . The main convenience of this form of supercapacitor is its possible high capacitance (several thousands of Farads), that is mostly dependent of the active surface of the electrodes. Since those electrodes are usually made of porous carbon, the active area is greatly increased, imposing a very high capacitance to the supercapacitor. “The research of materials is already open”[5]. The main difficulty is in cheaper materials problematic.

2. Pseudo-Capacitance

   In an ideal double-layer the capacitance is not dependable of the applied voltage, but in the supercapacitor utilizing the pseudo-capacitance technology, there are an interaction between the solid material and the electrolyte, imposing a voltage-dependent charge transferring behavior to the supercapacitor. This phenomena in which the charge transferred is voltage-dependent is the main basis for the name, pseudo-capacitance supercapacitor.

3. Hybrid Capacitor

   Also known as asymmetric supercapacitors, the hybrid capacitors are composed by one electrode of a double-layer carbon material, much like in the double-layer supercapacitor technology, and the other electrode of a pseudo-capacitance material (e.g. Nickel), used in the pseudo-capacitance technology. The devices using this hybrid technology have significantly higher energy density when compared to the double-layer one, but as a shortcoming, the charger/discharger characteristics are highly non-linear.

In the next table, 3.2, some performance indexes of some types of supercapacitors are shown. In 3.3 some supercapacitors actual performance indexes by manufacturer are compiled.

Table 3.2: Performance of the Different Types of EDLC [11]

Technlology Type	Electrode Material	Energy Storage Mechanisms	Cell Voltages	Energy Density Wh/kg	Power Density KW/kg
Electric Double Layer	Activated Carbon	Charge Separation	2.5 - 3	5 - 7.	1 - 3.
Advanced Carbon	Graphite Carbon	Charge Transfer or Intercalation	3 - 3.5	8. - 12	1. - 2
Pseudo-Capacitive	Metal Oxides	Redox Charge Transfer	2 - 3.5	10. - 15	1. - 2
Hybrid	Carbon/Metal Oxide	Double-Layer/ Charge Transfer	2 - 3.3	10. - 15	1. - 2
Hybrid	Carbon/Lead Oxide	Double-Layer/ Faradaic	1.5 - 2.2	10. - 12	1. - 2

In table 3.3 some supercapacitors actual performance indexes by manufacturer are compiled.

Table 3.3: Performance of the Different Types of EDLC [11]

Manufacturer	V	F	Wh/kg	W/kg
Maxwell	2.7	3000	5.52	13800
NessCap	2.7	5000	5.44	13000
BatScap	2.7	2600	5.3	18000
Vina Tech	2.7	600	5	4000
ApowerCap	2.7	450	5.89	24600
JSR Micro	3.8	2000	12.1	9000

3.2.3 Flywheels

The flywheel energy storage system is a rotational mechanical system that recurring to its high moment of inertia stores kinetic energy. This kind of device has often a power electronics interface to control the massive rotating cylinder supported by magnetic levitation in a low vacuum environment. The vacuum and the support by magnetic levitation tend to reduce rotational losses, hence preserving the stored kinetic energy.

$$E = \frac{1}{2} I_r \omega^2 \tag{3.1}$$

As we can see in equation (3.2.3), the moment of inertia and rotational speed are the key variables in this kind of system, thus a high speed and high moment of inertia is preferred. In 3.4 some materials that can be used to construct the flywheel are shown and related to their specific energy.

Table 3.4: Specific Energy of Different Material

Material	Specific Energy
High Strenght Aluminium	41.5 Wh/kg
High Strenght Steel	54.7 Wh/kg
Glass/Epoxy	144.4 Wh/kg
High Strenght Aramid/Epoxy	193.7 Wh/kg
High Strenght Glass/Epoxy	213.3 Wh/kg
High Strenght Carbon/Epoxy	356.5 Wh/kg

3.2.4 Fuel Cells

The fuel cell technology started with Sir William Grove in 1839, but mostly because electricity was not well known, this first attempt was not successful. This technology had its first success in 1932 by Francis Bacon and was used in the Apollo space program in 1950s. Since this application many manufacturers, including some of the major auto makers and government agencies made effort for an ongoing research and development of the fuel cell technology [23].

The electricity generation method of a fuel cell involves fuel in the anode, an oxidant on the cathode and a reaction in the electrolyte. The fuel cell is able to produce electricity as long as the flow of fuel is maintained [24]. The main advantages of this technology are in the quiet operation, durability, reliability, zero or low emissions and high conversion efficiency of fuel to electric energy.

There are some shortcomings to this technology, due to the relatively low energy density of hydrogen (2.6kWh/L) when compared to a fossil fuel like petrol (6kWh/L) big fuel tanks are needed [24]. Moreover, this technology has a relatively low response time and is very expensive ate the moment. The research and development nowadays is focused on hydrocarbon membranes to replace the current per fluorinated membranes [25].

In table 3.5 some fuel cell types are compared using the most significant parameters.

Table 3.5: Typical Characteristics of Fuell Cells

	Phosphoric Acid	Molten Carbonate	Alkaline	Solid Oxide	Direct Methanol	Solid Polymer
Temperature	150 - 210	600 - 700	60 - 100	900 - 1000	50 - 100	50 - 100
Density (W/cm2)	0.2 - 0.25	0.1 - 0.2	0.2 - 0.3	0.24 - 0.3	0.04 - 0.23	0.35 - 0.6
Life (kh)	40	40	10	40	10	40
Cost ($/kW)	1000	1000	200	1500	200	200

3.3 Sources Hybridization

The energy storage system of the electric vehicle is one its major drawbacks.

Nowadays and in the near future, the most viable energy sources to apply to electric vehicles are batteries, fuel cells, supercapacitors and flywheels. Batteries, in spite of being the most mature energy source, are bulky, heavy, and expensive and cannot deliver either the needed specific energy or specific power. Fuel cells are a proven technology but not a mature one, they offer a good specific energy, but are incapable of accepting regenerative energy. Supercapacitors, as primary energy source in a standalone application, are unable to deliver the required specific energy, but they have very good specific power characteristics. Flywheels are a technologically immature resource to be used as an energy storage system in an electric vehicle [trovao analysis].

The main objective of the researchers around the world studying sources hybridization is to take into use the best characteristics of the chosen energy storing devices, improving both vehicle driving range and cycle life of those devices.

With the energy storing elements described above, there are six possible types of hybridizations [chau]. The most common are the conjunction between fuel cells and supercapacitors, and batteries and supercapacitors. Other combinations are possible. The energetic flow assumptions that will be done next are supported in an effective power converter control and correct energy flow control (i.e. ESS).

1. Battery and Battery Hybrid

   In this combination of power sources two types of batteries are used. One provides high specific power, and the other provides high specific energy.

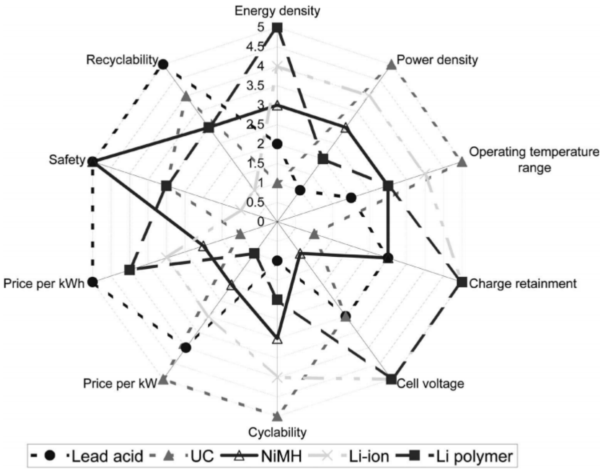


Figure 3.5: Comparison of attributes of various battery and UC technologies [7]

   Some of the most popular battery types are shown in figure 3.5, and is possible to gather sufficient data to state that the most effective battery and battery hybridization is with Li-ion to deliver power, accepting regenerative braking and Li-Polymer for a high driving range, since is the battery in figure 3.5 with most energy density. The Zn-Air battery has a very good energy density, but it is not rechargeable (or mechanically rechargeable), this property excludes it in most plug-in electric vehicle applications [26].

2. Fuel Cell and Battery

   Fuel cells and batteries combination is a good collaboration. In spite of not having the possibility for a regenerative braking system, Fuel cells have inherently a very high specific energy, thus a very high driving range is possible. To bridge the regenerative shortcoming of the fuel cells, a battery constructed to deliver a high specific power can be used. Using figure **??** again we can arrive at the conclusion that a Li-Polymer battery is a good choice when it comes to a high specific power, useful to either to absorb the downhill energy regeneration or regenerative braking and to provide instantaneous power to hill climbing or sudden acceleration.

3. Battery/Fuel Cell and Flywheel

   Once again, the batteries or fuel cells are used to provide the energy needed to obtain a high driving range and the flywheel technology provides the possibility of energy regeneration. Since flywheels are in their early stages of development is immature to take into account these combinations (Battery and Flywheel, and Fuel Cell and Flywheel) of power sources [trovao analysis].

4. Fuel Cell and Supercapacitor

   Using both fuel cell and supercapacitor technology the system is able to provide permanent and transient power as it is demanded by the load (i.e. the powertrain) [9]. This power sources interconnection is a reliable one. It has a very high driving range, due to the inherently good specific energy characteristics of the fuel cell technology and a very good power delivery and energy regeneration ratio, imposed by the very good specific power properties of the supercapacitor technology. This is, with the battery and supercapacitor, the most studied hybridization nowadays.

5. Battery and Supercapacitor

   With these two technologies working to the same objective, the possibility to absorb and provide both energy and power to and from the load, effective power source hybridization is possible. The battery is used, mainly, to provide the energy needed to a high driving range and the supercapacitor, with its very good specific power characteristics, provides the power peaks needed in some situations in an electric vehicle. The next table, 3.7, took from [5], shows power and energy characteristics of various types of both supercapacitors and batteries.

Table 3.6: Comparisons of the energy and power chatacteristics of Supercapacitors and Batteries [5]

Device techology	Nominal Cell Voltage	Wh/kg	W/kg 90%
Supercapacitors:			
Carbon/carbon	2.7	5	2500 - 5000
Hybrid Carbon	3.8	12	1635
Lithium-ion Batteries:			
Iron Phosphate	3.25	90 - 115	700 - 1200
Lithium Titanate	2.4	35 - 70	700 - 2260
NiCoMnO2	3.7	95	1700
Other Types of Battery:	1.2	46	400
Ni Mt Hydride HEV	2.0	26	150
Zn-Air	1.3	450	200-400

3.4 Power Electronic Structures

The power electronic structures usually present in an electric vehicle depend of designed power sources and powertrain. The usual topology of the converters is illustrated in the block schematic in figure 3.6. As represented in figure 3.6, the connection between the power source and the power train is made by a DC bus, hence if a proper control of DC bus voltage is done the two structures can be studied separately.

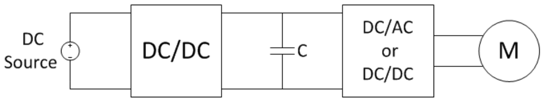


Figure 3.6: Basic power structure in an electric vehicle

3.4.1 DC/DC Power Converters Applied to Power Source

The most common power sources in an electric vehicle are direct current ones, imposing a DC voltage in the converter input and since the output, usually is a DC bus, a DC/DC power converter is the logical choice to interface the power source with the DC bus. A DC/DC converter is a switching device that converts a certain unregulated input voltage to a regulated one and there are various DC/DC topologies available. Many classifications can be achieved to DC/DC converters.

1. Hard-Switching Hard-switching power converters are not concerned with either voltage or current across the semiconductor. This usually degrades the power converter energetic efficiency, but typically simplifies the control strategies. Some new classifications can be integrated in the hard-switching one. This type of converter can be categorized in terms of its isolation and current directionality.

   Most of the classic basic converter topologies are non-isolated. Boost (step-up), Buck (step-down), buck-boost, SEPIC (single ended primary inductor converter), dual-SEPIC (zeta), and Cuk converters are all non-isolated. Isolated topologies for those basic power structures are available and, when the intended application is in electric vehicles, those are preferred mostly to provide safety for the loading devices [27]. Obviously the isolation parameter imposes some issues. It increases electro-magnetic interference, area, volume, weight and cost. Since a transformer is mandatory, leakage inductance appears, reducing the power converter efficiency.

   Current directionality must be analyzed in each case due to the many extensions available to the aforementioned classic topologies.

2. Soft-Switching

   The converters designed to switch their semiconductors at an instant in which their power is null are labeled as soft-switching converters. This name arises due to a theoretically loss free switching technique. “Most modern day DC/DC converters are soft-switched converters” [27]. The soft-switching are “generally classified as the resonant converter (RC), quasi-square-wave converter (QSC), quasi-resonant converter (QRC), multi-resonant converter (MRC) and zero-transition converter (ZTC)”[28].

   There is a common feature of all soft-switching converters. The existence of a resonant bank is mandatory to shape the current or voltage waveforms of the power converter in order to achieve the final objective of having a waveform (either voltage or current) passing through zero at time of the switch. According to [28], the zero voltage switching (ZVS) is usually preferred to zero current switching “because it can eliminate the major switching losses due to the discharging of its inherent junction capacitance”.

In electric vehicles applications the isolated are preferential and bi-directional topologies (for some power sources) are mandatory, the isolation parameter implies the use of a transformer and the current bi-directionality imposes the use of a topology that provides a way for the current to flow either to the load or to the source [27].

3.4.1.1 Multiple-Input DC/DC Topologies for Hybridization Purposes

Recently, the multiple-input (MI) DC/DC converters were developed to interface more than one power source with a single load. This concept fits in the hybridization profile, which is the diversification of the input power sources.

Several MI converters were in recent times proposed with the objective of combine various power sources. Among the topologies compiled in [8], each one has its own advantages and issues, leading to a difficulty in a choice for an appropriate topology for a specific application.

In the next figure, 3.7, the combination strategies are shown. From left to right, a combination sharing the output filter capacitor, a combination sharing some switches and energy transfer inductor and capacitor, and a magnetic-core sharing combination are presented.

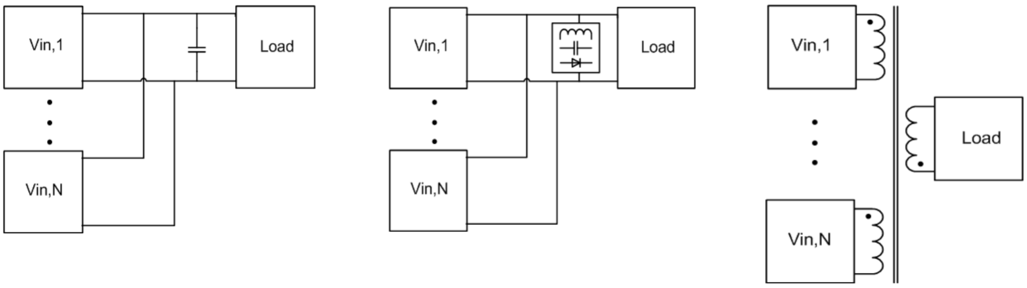


Figure 3.7: Combining methods of MI DC-DC converters [8] (edited)

These three main topologies have their benefits and shortcomings, which will be approached in this part.

1. Output Capacitor Sharing

   This MI technique must use a DC bus voltage control. It has the possibility to append the power source directly to the DC bus or use a power converter to match the voltage level required in the DC BUS, allowing the power source to have a different voltage level from the DC bus one. Providing that the BUS capacitor is capable of maintain a constant voltage (recurring to the DC BUS voltage control), there are no limits for the number of power sources that one can append to the DC BUS. The next figure, 3.8, is an example of this type of MI converter, which is approached in [9]. Increasing the number of power sources, an increase of control complexity appears.

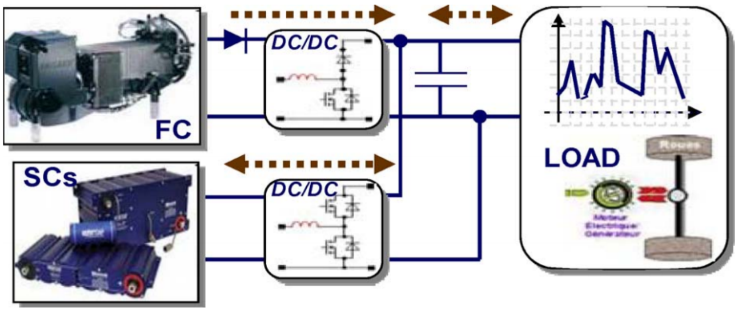


Figure 3.8: MI parallel structure for FC/SC hybrid power system [9]

2. Switching Device Sharing

   Multiple inputs aggregated to the same switches or energy transfer elements such as inductors or capacitors implement this kind of MI technique. Usually the shared components are used to interface the power source with the DC BUS while filtering or conditioning some waveforms. In [8], a MI-Cuk and a MI-SEPIC topologies are proposed.

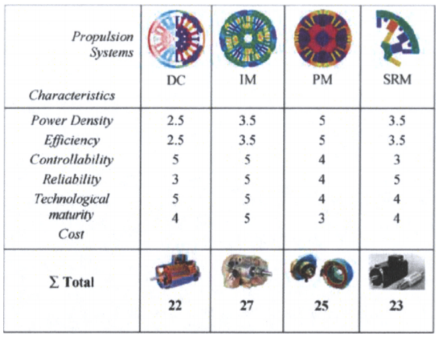
3. Magnetic Core Sharing

   Unlike the aforementioned MI techniques, this introduces a galvanic isolation, imposing the energy to be exchanged through the magnetic fields of a transformer. In spite of copper usage in transformers, bulking and increasing the weigh of the converter, input to output galvanic isolation is a very good attribute in electric vehicle applications. Modularity is extremely reduced, the number of inputs must be accounted in the first design of the converter, since appending another power source after the converter is produced implies a reconfiguration of the transformer, hence a new one. The abovementioned issues in the usage of a transformer are present in this kind of MI converters.

3.4.2 Power Converters Applied to the Traction System

The power converters to interface the DC BUS with the traction system depend on the type of motor used. There are some possibilities in which motor technology to use in a general purpose electric vehicle. A study in which powertrain to use in an electric vehicle carried out in [10] compared various motor technologies arriving at some interesting results represented in figure 3.9.

Both induction motor and the permanent magnet synchronous motor were best assessed, and both are AC fed. Hence an DC/AC (inverter) is needed to feed the motor from the DC BUS.



Propulsion Systems *Characteristics*	DC	IM	PM	SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	**22**	**27**	**25**	**23**

Figure 3.9: Evaluation of different traction systems for electric vehicles [10]

3.4.3 Challenges in DC/DC Converters Design

With the objective of finding solutions to reduce stresses in the converter elements and improve input to output efficiency, the DC-DC device should be totally safe for the electric vehicle passengers. Reliability in a wide range of temperature and respect for EMI standards regulation are important features for the power converters in an electric vehicle.

3.5 State-of-Charge (SoC) Determination Methods

The state-of-charge of a battery tries to answer a meaningful question. Many devices used nowadays have a battery as their primary energy source, thus knowing how long it takes until that device stops working is meaningful information. That information can be achieved through the SoC.

In electric vehicle applications a power source SoC is pertinent information to both the energy management system (i.e. ESS) and the electric vehicle passenger. The first due to energy control and the second to know what is the vehicle range. In both cases a real-time SoC estimation is important.

Many approaches to measure the SoC of a battery are proposed in literature, in this section different techniques will be overviewed and the most appropriate field of application for each method will be displayed.

3.5.1 Discharge Test

This test is the most reliable one on measuring the remaining capacity of a battery. The test consists in discharging the battery under controlled conditions. This kind of SoC estimation is time consuming for most applications and needs for the system function to be interrupted, hence its applicability on electric vehicles is not appropriate.

3.5.2 Ampere-hour Counting (loss calculations included)

Ah (Ampere hour) is the most common method to estimate the SoC of a battery, it uses the assumption that "the charge and discharge rate are directly related to the supplied or withdrawn current" [29], hence integrating the measured current the method gives as an output a SoC. Providing that the initial value for the SoC is known, the current integral is a direct indicator for the SoC.

There are issues to this method. Firstly, the current measurement must be a precise one otherwise that foul measurement can add up to a large error leading to an inaccurate SoC estimation. The second problem is related to the battery charging characteristics and its energetic losses. Not every current absorbed by a battery is used to charge it, some of that energy dissipated, generating energy losses.

In short, Ah method is an easy and reliable one as long as current measures are accurate and enough recalibration points are used [29].

3.5.3 Open Circuit Voltage

This method takes advantage of the linear relation between open circuit voltage and SoC. Usually this technique is used to calibrate other SoC estimation systems, this happens due to the applicability of this method, it needs relatively long rest periods to achieve a steady state value to SoC [29].

3.5.4 Heuristic Interpretations

Many approaches can be viewed in literature in means to interpret measured data in a heuristic manner. Those techniques use the electrical discharge/charge characteristics curves to calculate the SoC. For some methods a total charge/discharge curve is not needed.

One of the heuristic methods implement an approximation of the given battery to a linear model, hence a linear relationship between the SoC variation and the measurements made is achieved. This model was originally developed for photovoltaic applications with low SoC variations, hence imposing a point of operation to the system. In order to achieve the linear relationship this method use factors that do not describe physical parameters of the battery, but are calculated to describe a type of battery. This method is characterized as a high robustness in relation to measurement errors and wrong initial conditions.

The relatively recent artificial neural network technique, made possible to achieve a relation between input and output, even with non-linear systems, thus it can be utilized to replicate the behavior of any battery system providing that training data of a similar battery. The inherent SoC error strongly depends on the training method and if the battery used as training is of the same type as the one being measured. If training data is suitable for the battery that is being used, errors appear smaller and evenly distributed [29].

3.5.5 Impedance Spectroscopy

The research in this field is intense, but practical implementation of this method is rare. This method is used to inspect electrochemical processes via common measurements. Impedance spectroscopy is often used to attain the SoC but is also capable of extract information about battery state-of-health (SoH). This method can be supplemented by a fuzzy logic methodology so a relationship between model and impedance spectroscopy measurements can be achieved and therefore a value for SoC attained.

The curves acquired with this method are highly influenced by temperature, thus a temperature controlled environment is an important requirement to an accurate measurement. In order to attain the SoC convenient frequency ranges must be acquainted, because SoC varies only at low frequencies [29].

3.5.6 Internal Resistance

The value of the internal resistance depends heavily on the chosen time interval. Taking advantage of the fact that, in a small time interval (<10ms) only the Ohmic effects are measured and the SoC has a linear relation with the internal resistance of a battery, a proper SoC evaluation can be achieved. As an example, for a lead-acid battery, the change in the internal resistance variation from a full to a null SoC is of some m/omega per cell [29].

3.5.7 Kalman Filters

“A Kalman filter is an algorithm to estimate the inner states of any dynamic system. [29]”

Using the idea given by the last sentence, one can state that to use Kalman filters to achieve a value to SoC the battery can be considered the dynamic system and SoC one of its inner states. The estimation is only based on a model dynamic system. Some comparative studies were made to understand if this method is a reliable one. When compared to the Ah method little differences were attained. To apply the Kalman filter methodology to a system with higher dynamic, such as an electric vehicle, a model which is a simplification of the battery model must be used.

This method is a promising one, but further studies must be carried out to confirm the suitability of this method for high dynamic applications.

3.5.8 Summary Table

Table 3.7: Comparisons of the energy and power chatacteristics of Supercapacitors and Batteries [5]

Technique	Field Application	Advantages	Drawbacks
Discharge Test	All Battery systems Used for capacity determination in the begining of life	Easy and Accurate Independent of SOH	Offline Time intensive Modifies the battery state Loss of energy
Ah Balance	All Battery systems and most applications	Online, easy accurate if enough acllibration points are available and with good measurement	Needs a model for the losses Sensitive to parasite reactions Cost intensive for accurate current measurments Needs regular re-callibration points
Physical Properties of Electrolyte	Lead, possibly Zn/Br and Va	Online Gives information about SOH	Error if acid stratification Low Dynamic Problem of stability of sensors in electrolyte Sensitive to temperature and impurities
Open Circuit Voltage	Lead, Lithium, Zn/Br and Va	Online Cheap	Low dynamic Error if acid stratification Needs long rest times (current =0) for lead systems Problem of parasite reaction (e.g. Sb poisoning by lead)
Linear Model	Lead PV, possibility for other battery systems? (not tried yet)	Online Easy	Needs reference data for fitting parameters
Artificial Neural Network	All battery systems	Online	Needs training data of a similar battery
Impedance Spectroscopy	All systems	Gives information about SOH and quality Possibility of online measurement	Temperature sensitive Cost intensive
DC Internal Resistance	Lead, Ni/Cd	Gives information about SOH Cheap and Easy Possibility of online measurement	Good accuracy but only for low SoC
Kalman Filter	All battery systems Dynamic applications (e.g.HEV)	Online Dynamic	Needs large computing capacity Needs suitable battery model Problem determining initial parameters

Chapter 4

Work Plan

4.1 Objectives

Nowadays, electric mobility figures as one of the main challenges in Portuguese technologic development. Innovative technologic solutions are needed to create good conditions for a high penetration of electric vehicles in urban environments. Those ideas lead us to study many important features in an electric vehicle. Rigorous determinations of the state-of-charge of the batteries and estimative of the vehicle range are, therefore, main objectives. Thus a study of real-time algorithms for state-of-charge estimation is an important topic.

To achieve an effective knowledge of state-of-charge, all the system, including the power electronics, the controller and the power sources, must be understood. The next figure, 4.1, illustrates some of the systems that must be studied.

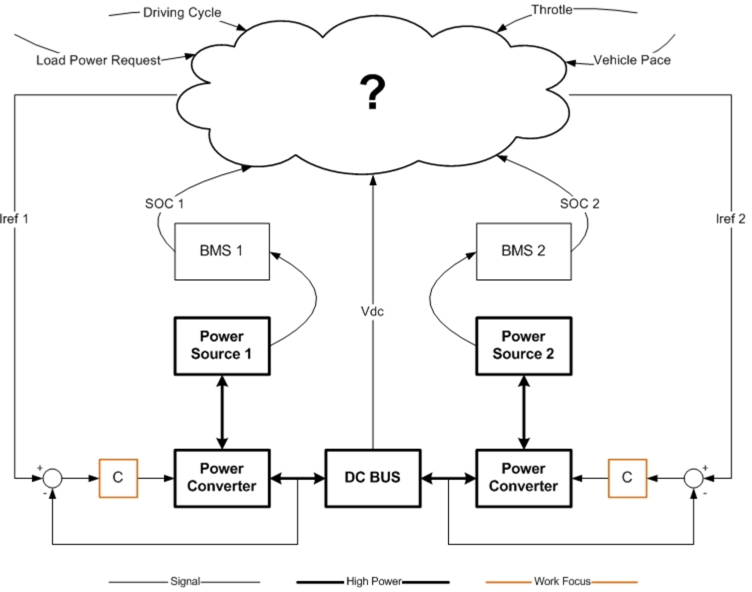


Figure 4.1: Gantt Chart

4.2 Itemized Work Plan

In order to achieve the proposed objectives, some general topics were elaborated to approach all the aspects in which the master thesis must be related.

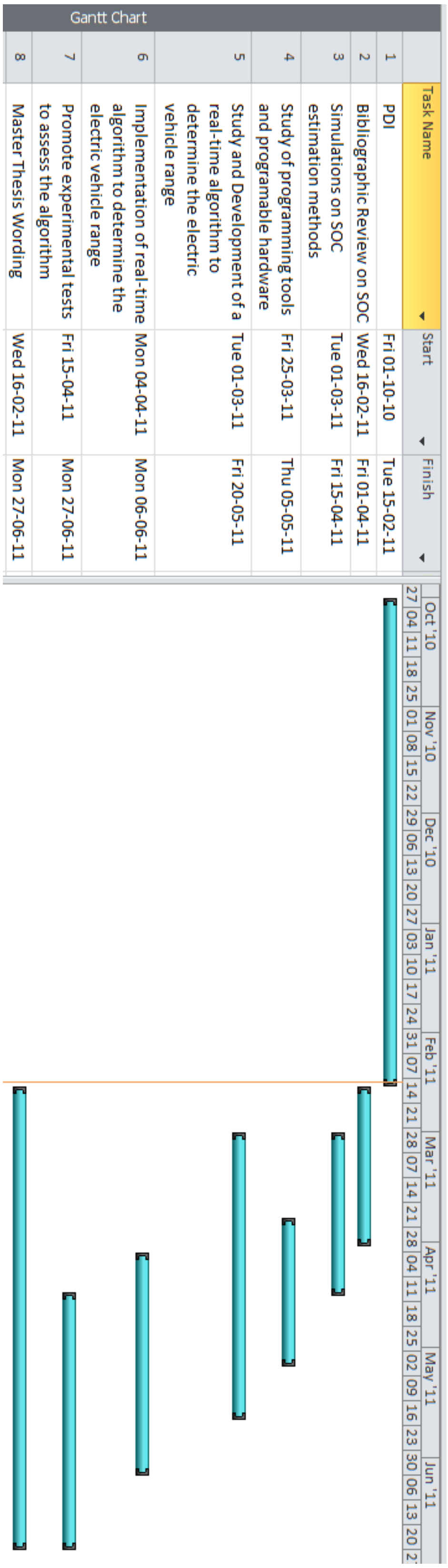
- Bibliographic review on SoC estimation methods
- Study based on simulations of already approached methods
- Study of programming tools and programable hardware
- Study, development and implementation of a real-time algorithm to determine an electric vehicle range
- Promote experimental tests to assess the behaviour or the algorithm
- Master thesis wording

4.3 Tools

During the master thesis some tools will be needed. Simulation based studies present in the thesis will be implemented in the MathWorks environment, MatLab, more properly in Simulink. LabView is powerful software from National Instruments which makes possible to implement various instrumentation and real-time strategies, hence this will be one of the tools used. Some software developing tools applied to embedded systems may be needed as well.

4.4 Gantt Chart

In figure 4.2 is a Gantt chart representing the proposed work plan for the "Master Thesis" course.



Gantt Chart

	Task Name	Start	Finish
1	PDI	Fri 01-10-10	Tue 15-02-11
2	Bibliographic Review on SOC	Wed 16-02-11	Fri 01-04-11
3	Simulations on SOC estimation methods	Tue 01-03-11	Fri 15-04-11
4	Study of programming tools and programable hardware	Fri 25-03-11	Thu 05-05-11
5	Study and Development of a real-time algorithm to determine the electric vehicle range	Tue 01-03-11	Fri 20-05-11
6	Implementation of real-time algorithm to determine the electric vehicle range	Mon 04-04-11	Mon 06-06-11
7	Promote experimental tests to assess the algorithm	Fri 15-04-11	Mon 27-06-11
8	Master Thesis Wording	Wed 16-02-11	Mon 27-06-11

Figure 4.2: Work Plan Gantt Chart

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