NTNU
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Science and Technology

Electric Propulsion System for the Shell Eco-marathon PureChoice Vehicle

Controlling the lights and alternative storage devices such as batteries and supercapacitors

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Master of Science in Energy and Environment
Submission date: June 2008
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Problem Description

The PureChoice project is a group project between 13 master students from five different institutes at the Norwegian University of Science and Technology (NTNU). During the autumn semester this group of students has completed the first few phases of this development project towards a vehicle that will compete in the Shell Eco-marathon competition in Nogaro, France. Shell Eco-marathon is a competition where the goal is to design and build a vehicle that uses the least amount of fuel to travel the farthest distance. A good foundation has been made, and the master thesis is based on results from the project assignment.

The work in the master thesis takes place on four levels. All of them according to the rules specified from the Shell Eco-marathon organisation.

- The project in its complete form, inclusive involvement of the press and sponsors.
- The complete vehicle composed of the different individual parts.
- All the individual parts and their interface.
- External technical parts and organizational support when it comes to the building, testing and execution process.

The candidate must contribute on all four levels in addition to having an overall responsibility for his own task.

Main task for the candidate is to demonstrate different possibilities when it comes to controlling the lights in the PureChoice vehicle, and to make sure the vehicle has enough energy stored in alternative storage devices in order to have a fully functioning system when it comes to driving the vehicle and managing the safety system onboard. This implies:

- Performing a background research on the necessary components.
- Choosing and acquiring the right components.
- Performing laboratory tests and programming different devices to make sure they are working properly.
- Implementing the components in the final vehicle.

Assignment given: 22. January 2008
Supervisor: Lars Einar Norum, ELKRAFT

1 Preface

The PureChoice project is a group project between 13 master students from five different institutes at the Norwegian University of Science and Technology (NTNU). During the last two semesters this group of students has been designing and manufacturing their own fuel cell vehicle for their participation in the Shell Eco-marathon. Shell Eco-marathon is a competition where the goal is to design and build a vehicle that uses the least amount of fuel to travel the farthest distance. Several hundred teams from more than 20 countries compete every year, and are divided into two classes: Urban Concept and Prototype. The former is to be a city car, while the latter has no specific use specification.
The participating 13 students have different knowledge and interests. My main responsibility in this project has been the propulsion of the vehicle, a part I shared with two other students. The areas of responsibility were therefore divided in three parts, these being fuel cells and hydrogen, motor and controller and controlling the lights and alternative storage devices such as batteries and supercapacitors.

The report you are about to read describes two alternative solutions for controlling the lights in the vehicle, these being a self-manufactured controller card utilizing an Atmel microcontroller and Siemens's LOGO! Micro Automation module. Both of these solutions have been programmed and tested, and a comparison has been made regarding which of them that would fit better in the final vehicle.
The report also contains a literary study about batteries and supercapacitors. Based on this study the appropriate battery types and supercapacitor modules have been chosen, tested and utilized in the vehicle. Finally, the report gives a short introduction to DC/DC converters.

This has been a very demanding project and a large part of its success is due to the support from lecture holders and friends. I would hereby like to thank Bård Almås and Vladimir Klubicka for their help with acquiring all the necessary equipment and for showing me the manufacturing process when constructing PCB cards. Greatest thanks to Arkadiusz Kulka and Giupesse Guidi for their expertise and guidance in the matter of power electronics and supercapacitors. Additionally, I would like to thank Ivar Håkon Lysfjord and Samir Bahor for their friendship and our long lasting conversations. Finally, I would like to thank my supervisor, Professor Lars Norum, for his support in the project.

Trondheim, 16 June 2008

2 Abstract

This report is divided into six main chapters. It starts off with an introductory chapter explaining the different propulsion strategies that have been considered during the last semester, and the final propulsion system that has been decided upon. The final propulsion strategy has several demands when it comes to components that have to be implemented and what type of components they should be.
The main purpose for me in this project was therefore to meet these demands. Main demands for me were to demonstrate different possibilities when it comes to controlling the lights in the PureChoice vehicle, and to make sure the vehicle had enough energy stored in alternative storage devices in order to have a fully functioning system when it comes to driving the vehicle and managing the safety system onboard.

The report continues with five individual chapters explaining how these demands were solved and which components that have been considered and implemented in the final vehicle. All off the chapters start of with an introduction about the topic at hand. They then continue with an explanation about the different components used in the vehicle, and reasoning for why exactly these components were chosen. In order to determine how the components would function in the final propulsion system, laboratory tests were performed on all the involved parts, and these laboratory tests are described at the end of all the chapters.

This report includes both theoretical calculations and practical solutions.

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1. Introduction

1.1. Designing a Propulsion System for the PureChoice Vehicle

When designing the propulsion systems for vehicles, there are various storage devices available today, and therefore there are many possibilities to choose from. The energy providers available when manufacturing the hybrid vehicles include rechargeable batteries, fuelled batteries of fuel cells, solar cells, IC engines, supply lines, flywheels and capacitors. In order to form a hybrid electric vehicle, any two or more of these energy providers can be used. By utilizing two of the energy sources, there are over 21 combinations of hybrids. There are a further 35 combinations if three or more energy sources are combined [1]. It is therefore easy to understand that only one's imagination can be the restricting factor when designing the propulsion systems in a vehicle today. It is only a matter of thinking innovative and practical in order to come up with a new and groundbreaking idea with which one can change the traditional way of manufacturing and constructing.

In the design of the propulsion system for the Shell Eco-marathon vehicle, several storage devices have been considered. Since the main propulsion power would come from a fuel cell module and these in most cases need an alternative energy source to power up, there was the evident need of meeting this demand.
In addition we needed an energy source that could be used to run the additional electrical components such as hydrogen sensor, solenoid valves, controller card(s), electrical sensors, lights and the horn. One additional decision that had to be made was if it would be beneficial to have a hybrid operation where one would combine the fuel cell module with a supercapacitor module. The reasoning for the choice in this matter is presented below in Chapter 1.2.

Before considering which alternative storage of energy to use, it was important to always keep in mind the rules for the Shell Eco-marathon competition, and which possibilities were available. Below are extracts from three articles given in the "*Shell Eco-marathon General Rules and Regulations 2008*", which have been important when determining the propulsion system for the PureChoice vehicle. The articles have some restrictions that had to be followed.

Article 67: Make-Up
For all type of energy classes, stored electrical or pneumatic energy not replaced during the competition by the engine or the fuel cell may be used only for the self-starter, the ignition, the injector, the instrumentation and electronic management systems.

Article 68: On-Board Battery
Only one battery will be allowed. All additional sources of electricity (with the exception of hydrogen fuel cells) are forbidden.
For the fuel cells, the battery will be used only for the horn as well as the safety element of this one (Hydrogen Detector Emergency Shutdown valve / Relay, see article 76 Hydrogen).
For Urban Concept vehicles using hybrid technology, the use of a Super-Capacitor to store recovered electricity is strongly recommended (the storing of recovered electricity being permitted for hybrid vehicles). If a team chooses to use an electrical battery, it must be emptied before each attempt. In each case, two connectors will have to be installed outside the vehicle to allow the voltage measurement on the starting line.

Article 76: Batteries or super-capacitors
If an embedded electric storage device is part of the powertrain, it must be of capacitor type, referred to hereafter as super-capacitors. Other types of embedded electric storage device (Pb, NiMh, etc. batteries) are forbidden. The state of charge of the super-capacitor will be checked before and after each run by measuring the super-capacitor voltage. The voltage registered after the run must be at least equal to the voltage registered before the run. In the event of the contrary, the super-capacitor must be re-charged until their voltage is equal to the voltage registered before the run. The figure displayed by the flowmeter will then be picked up.
An external battery can be used on the starting line to start the fuel cell system.
As soon as the vehicle starts to move, this battery must be unplugged. The use of this external battery is permitted whether super-capacitors are used or not.
It is allowed to feed the hydrogen detector, the emergency shutdown valve and the relay by one additional battery.

Immediately after reading these articles it can be rather confusing to understand just how many batteries it is allowed to have onboard the vehicle. The Shell Eco-marathon committee has recently changed the rules regarding onboard batteries and what they allow to be used in the design of the vehicles. This led to much confusion in the participating teams, but eventually, after a long discussion with the French, it was clarified what in fact was possible to use. This being:

- One battery for the ignition, not carried on-board
- One safety battery, allowed on-board.
- If desired, a supercapacitor module for hybrid technology.

Article 76 informs us that it is possible to use an external battery to start up the fuel cell module, but which can not be used for the propulsion of the vehicle. By utilizing this opportunity, one would in fact save hydrogen needed to perform this task. Since this battery would not be carried in the vehicle and the weight therefore not being the main consideration, the focus was directed in acquiring a battery that was cheap, at the same time as it contained enough energy for the task.

As stated in the articles above, it is for instance allowed to have a separate battery pack which would make sure that the safety of the driver is maintained. Energy from this battery can be used for controlling the lights, the solenoid valves, the hydrogen detector and the horn, these being a part of "*the instrumentation and electronic management systems"* mentioned in article 67.

Since there were no given rules stating which batteries we had to use, a research about the different batteries was performed. Based on this research, the different batteries for the vehicle were chosen. For further information about the batteries and their use, see Chapter 4.

Since the supercapacitors are a new and hot topic today, a research of this device was performed. Although the supercapacitors might not be used in the vehicle, they were acquired and tested. This was done because there was a general interest in learning more about their operation and behaviour. For further information about supercapacitors and their use, see Chapter 5.

1.2. Choosing the Right Propulsion System

Several different propulsion strategies have been considered during the last year. Sometimes rules got changed or they were misunderstood, but most often it was because it was found out that some of the strategies considered would be too complicated to construct, or they would result in more losses than it was necessary. The uncertainty if one should use regenerative braking in the propulsion system also lead to additional strategies being considered. Some of the strategies considered are shown below in Figure 1 and Figure 2.

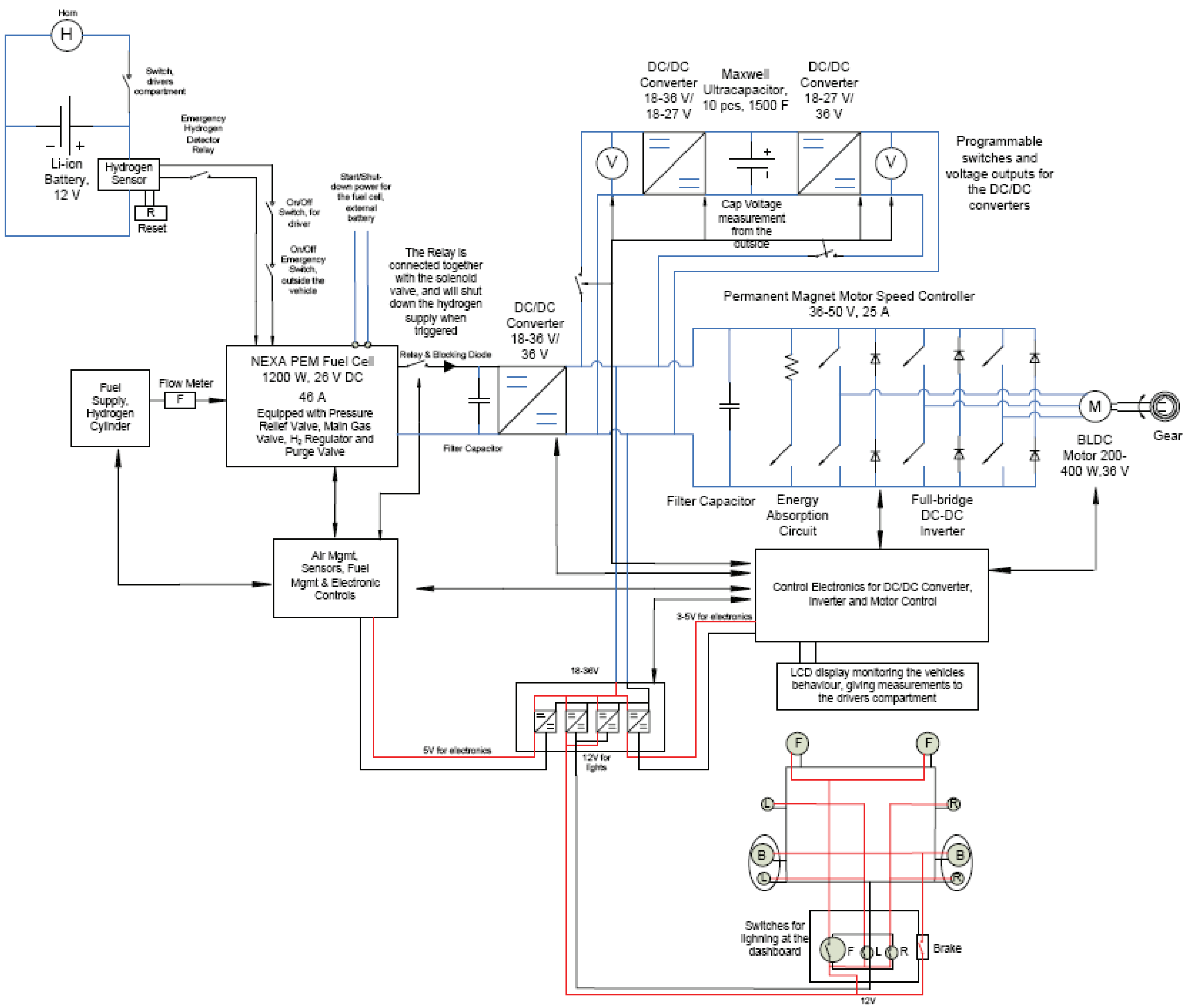

Figure 1: Control system with the ability for regenerative braking.

Figure 1 shows an early system, also containing a solution for regenerative braking. At this time in the project a DC/DC converter was needed between the fuel cell and the inverter in order to supply the inverter with a fixed voltage. Additional DC/DC converters would be used in order to store and use the energy due to regenerative braking. There was still some uncertainty about the rules regarding which components that could be supplied by the additional safety battery. In this system the lights and all additional control systems are using energy from the Nexa fuel cell. All of these additional components just bring unwanted losses to the total system.

As the vehicle was taking shape, it was easier for the propulsion group to start reasoning among themselves if the different strategies would work or not. One of decisions that had to be made was concerning supercapacitors and regenerative braking. Their employment would, in our case, only lead to many drawbacks, some of these being:

- Increased weigh
- Increased complexity, more demanding for the driver
- Utilizing them would not allow the use of a freewheel clutch in the vehicle
- Driving track is too flat, regenerative braking would not generate much energy

Although regenerative braking usually makes a propulsion system better and in conventional cars it is also able to generate a lot of energy when driving downhill, it was just not necessary in our case. Even though the supercapacitors were not used in the PureChoice vehicle, a lot of time was spent learning about how they work and on constructing a supercapacitor module. They will therefore also be presented in this report in order to give a short introduction, see Chapter 5.

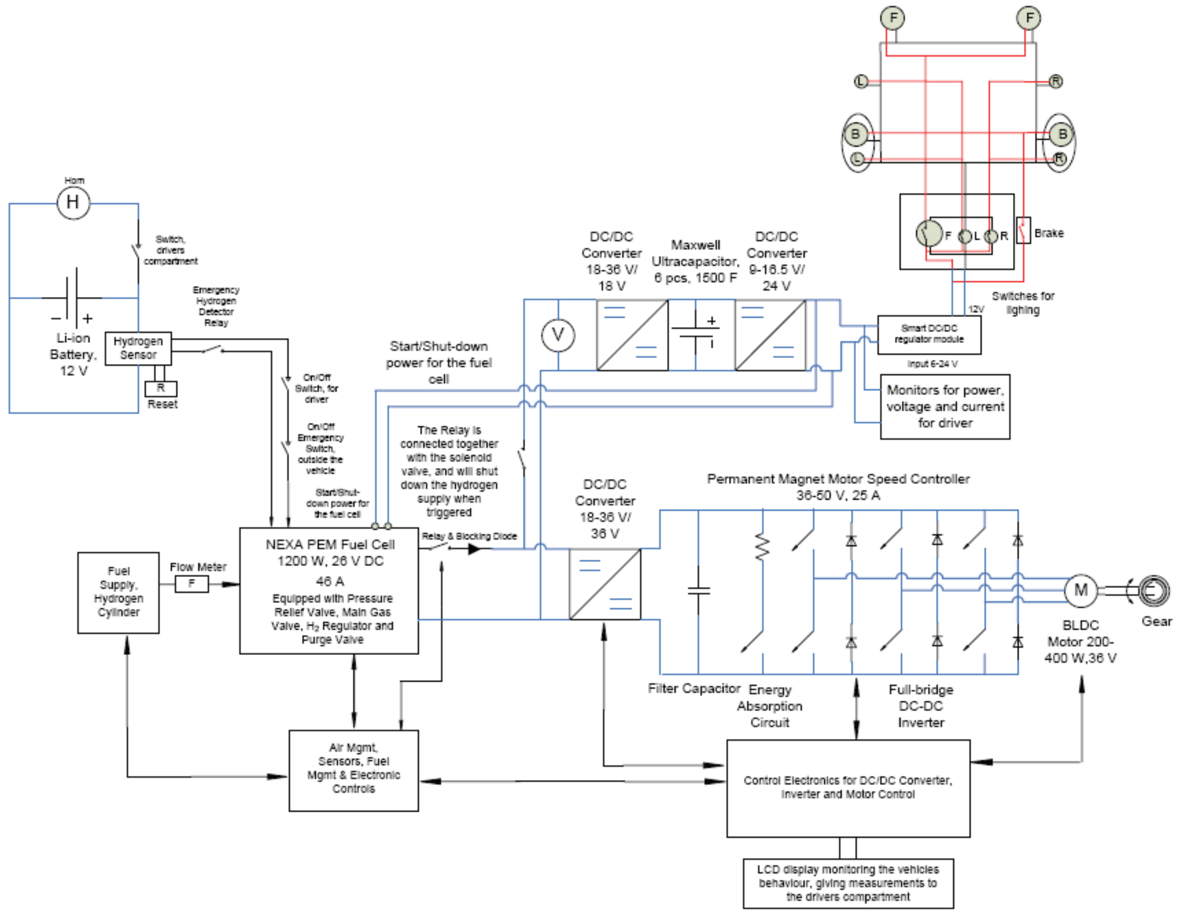

Figure 2: Control system without the ability for regenerative braking.

The second propulsion strategy was constructed when the decision not to use regenerative braking was made, see Figure 2. At this point there was still some uncertainty about the additional safety battery. It was not clear which components were included in the phrase "*the instrumentation and electronic management systems",* mentioned in Article 67 in the "*Shell Eco-marathon General Rules and Regulations 2008*" [2]. Maxwell supercapacitors would therefore be used to supply power to the lights, their control and any additional measurement devices. They could also be used to provide power to the fuel cell system in case it turned off during the race. A DC/DC converter is still used to supply the inverter with a fixed voltage.

Eventually, the propulsion system used in the vehicle today was constructed, see Figure 3. We focused on making a system that is as simple as possible. This has several benefits, the main being that at the same time as one saves energy, one also makes it easier for the driver to control the vehicle. It is also easier to detect faults in a simple system.

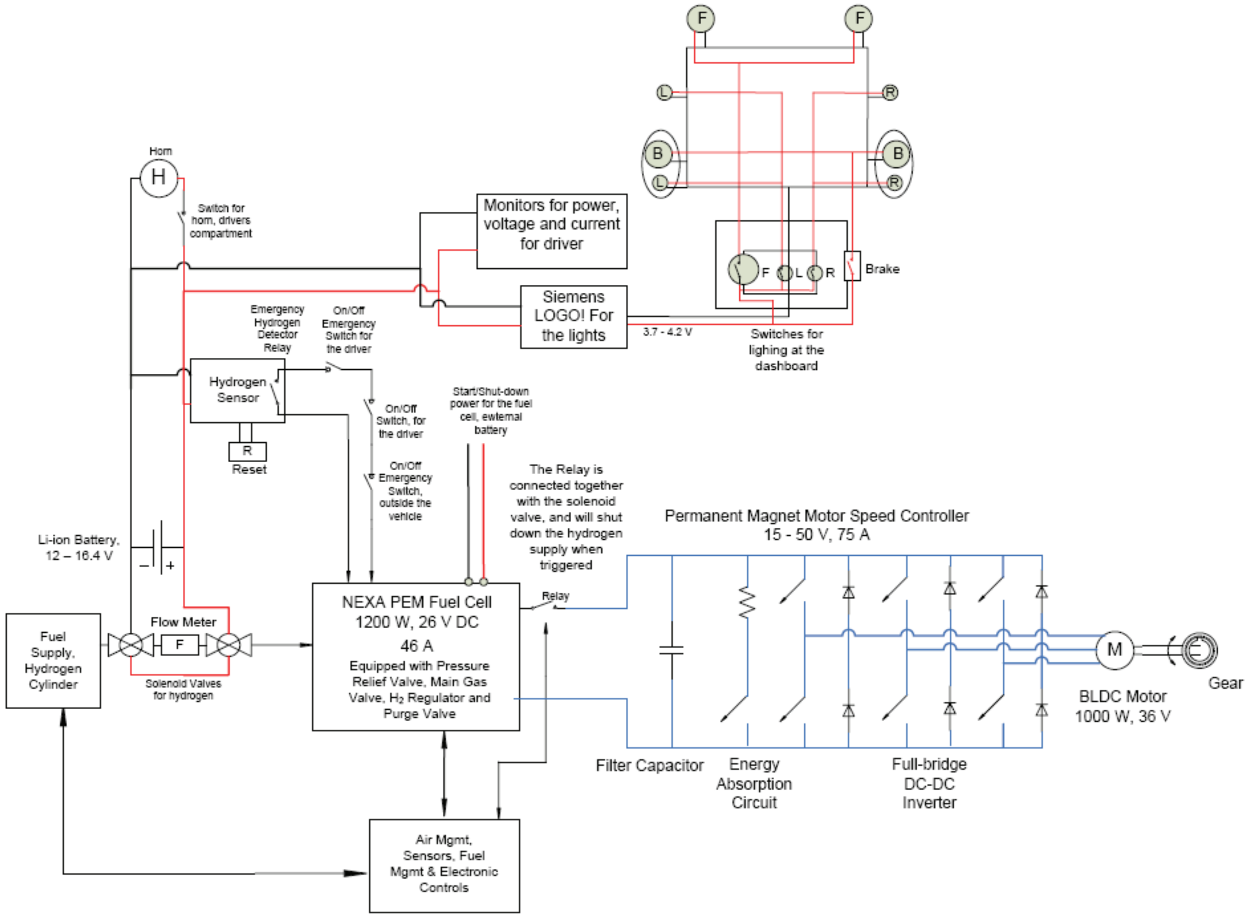

Figure 3: The final propulsion system in the PureChoice vehicle today.

Figure 3 shows a very simple system. Compared to the previous figures, all unnecessary components have been neglected. The DC/DC converter is neglected because an inverter accepting a wide range in the input voltage is being utilized, this way saving about 15 – 20 % of the energy from the fuel cell. At this point it was confirmed by the Shell Eco-marathon organization that the lights and their control, along with the solenoid valves, hydrogen detector, horn and any measurement devices all were included in the phrase "*the instrumentation and electronic management systems*". All of them are therefore now taking their necessary energy from the onboard Li-ion battery pack. As mentioned earlier, an external lead-acid battery pack is still being used to power-up the fuel cell system before start.

2. Designing a Controller Card for the Lights

Among many rules specified in the "General Rules and Regulations" for the Shell Eco-marathon competition, one of them is lighting of the vehicle [2]. Article 54 states that "the vehicle shall have a lighting system in proper working order for automobile road use, including:

- Two frond headlights
- Two front blinkers
- Two combined red blinker/stop lights in the rear
- The centre of each headlight beam shall be located at least 30cm to each side of the longitudinal axis of the vehicle" [2].

What article 54 does not require is in which way the lighting system shall be designed, and how strong the intensity of the different lights should be. This opens up many opportunities in how one wishes to construct the lighting system, and most importantly what kind of lights one wishes to use. There is the traditional way of making the system by using conventional light bulbs, relays, fuses and switches, but this way of constructing the system would lead to much weight and would in today's society and the opportunities given in the markets, be somewhat old-fashioned.
This is why the decision to use LED lights and control these by a self made controller card was chosen early in the project. There are several reasons for making this decision, the main reasons being that this solution would consume lesser energy, be lighter and be more advanced and up to date with the technology used in new vehicles by most leading car manufacturers in the world today.
Since constructing a controller card from scratch can be very time consuming and there is uncertainty if the outcome will be functioning correctly, an additional solution, plan B, has been constructed. This second solution is based on the Siemens LOGO! Micro Automation module and will be presented in Chapter 3.

2.1. Choosing a Program for the Design

Since designing and manufacturing a controller card is a new focus area for us, we needed to find a simple and easy accessible program with which we could work.
Contact was established with the Omega workshop at the university in order to have a conversation with them regarding which suggestions and recommendation they had for us.

Although there are many graphical design programs out in the market, the right one for us was the Cadsoft Eagle. This program was chosen mostly due to the easy and basic structure, but also due to the fact that it was easy accessible and widely used today.
An additional benefit by using this program was that one could find demo versions of the program on the producer's webpage. These versions did not have all the possibilities a full version usually contains, but it was enough for our use. With this in mind, the Cadsoft Eagle was acquired quickly and the process of learning how to use the program was started.

2.2. Cadsoft Eagle 4.16

In the design of the controller card, Cadsoft Eagle 4.16 (professional) was used. This is a combined graphical and text based design program, meaning that one can both ”draw” and “write” the commands one wishes to perform. Eagle is a cad program (computer-aided design), meaning that the user is designing with real measurements (here in millimetres or inches) in a xy-grid.
The design is split in three parts: Schematic, Layout and Library.

2.2.1. Schematic

It is in schematic that all the interconnections between the components takes place, see Figure 4. C3, L1 and the Tiny26L microcontroller are examples of some of the components. This is also where the components are given names and values. As indicated in Figure 4, it is easy to see that VCC is externally connected to AVCC, as desired by the microcontroller and indicated in Table 1.
The interconnection process can be very time consuming and it also requires full concentration by the designer. In addition to making sure the right components are connected together and at the right connections, it is important to keep in mind that the components used in the schematic later on need to be acquired and have to fit together with the desired design. The Cadsoft Eagle program has its own library, as explained later in Chapter 2.2.3, but this library often lacks the right components. It is very important, for instance in our case, to find the microcontroller and read the application note prior to the interconnection. This has to be done in order for the design to make sense for the final product. The Figure 4 beneath shows only a part of the total design constructed for the lighting in the vehicle. Complete solution and progress in designing the controller card is explained later in Chapter 2.4.

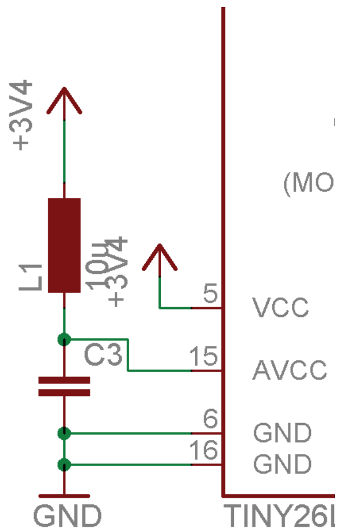

Figure 4: Part of the total controller card.

2.2.2. Layout

This is where the components added in the schematic are being placed on the card by the designer. Lines are being connected between the components, voltage layers are being made, the size of the card is being specified and explanatory text is being written to the card.
The layout editor keeps track of which components that should be connected together by indicating the connections by thin yellow lines. These connections are reflecting back to the schematic where the designer has indicated which connections he prefers for his design. What the layout editor does not do is to design the correct thicknesses of the signal lines immediately. One has to specify this oneself, or tell the layout editor how thick the connections should be depending on the current that will flow through them. Figure 5 and Figure 6 beneath are showing the difference between components before and after they have been connected.

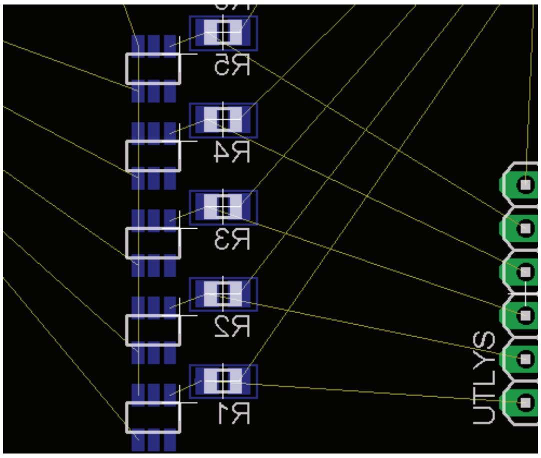

Figure 5: Connections indicated by thin yellow lines.

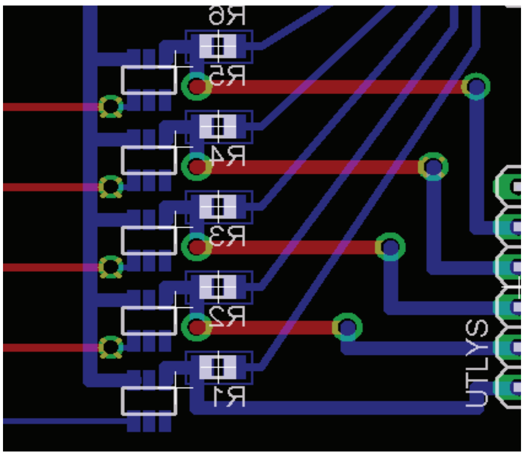

Figure 6: Connections designed with correct thicknesses of the signal lines.

Both figures show only a part of the total design constructed for the lightning in the vehicle. Complete solution and progress in designing the controller card is explained later in Chapter 2.4.

2.2.3. Library

The library is where the designer can go to find the components he or she wishes to implement on the card. The standard library in Cadsoft Eagle is in most cases not sufficient because the components one wants to use do not exist. By using the design feature in the library, the designer himself can construct the different components needed. If you are not an experienced user, this task can be time consuming.
Prior to the design of the component, one has to buy the component and read the application note. Most application notes include a paragraph about the mechanical data and the recommended pad layout, and this paragraph has also been used in the design of the different components. Unfortunately the relation between the bought product and the recommended pad layout are not always coherent with each other, and one has to further adjust the design. This is mostly due to the industrial way these components are being made. Although this is unfortunate, it is understandable that the large quantity of the components made can not always agree with what is specified.
In the process of making the control card for the lights, several components have been designed and added to the already existing library. One of the components constructed is the TEN 40 Traco Power DC/DC converter, see Figure 7. This component will be used to further explain the design process. For further explanation of this converter, see Chapter 2.3.2 or the application note [3].

Figure 7: TEN 40-2411 Traco Power DC/DC Converter [3].

1. Symbol for use in the Schematic

This is where the specifications for how the component should look like in the schematic are being made. There are two options for interconnection of different symbols, either by including all the signals in a block or by allowing each signal to have a "pin" which can be rearranged in the schematic. By adding a name and a value Cadsoft Eagle can automatically generate the text for use in the schematic, see Figure 8.

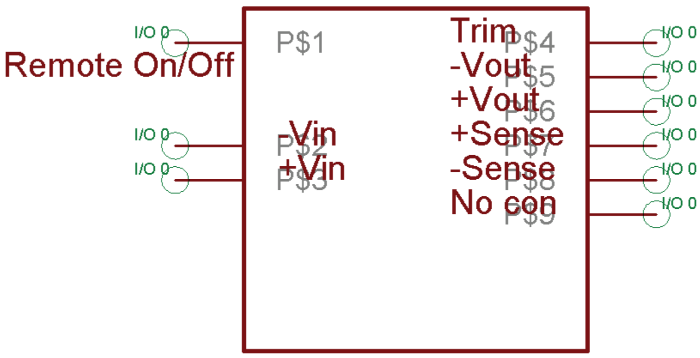

Figure 8: The TEN 40-2411 symbol.

2. Footprint for use in Layout

This is where the component is drawn with exact values to be able to fit on the final card. Figure 9 shows the footprint for the TEN 40-2411 converter. All the areas have names in order to be connected together with the pins specified in the first point. The TEN 40-2411 is a SMD (surface mount device). In addition, the designated pads have been made, because the converter has 9 pins that have to puncture through the final card in order to connect with the components on the back.

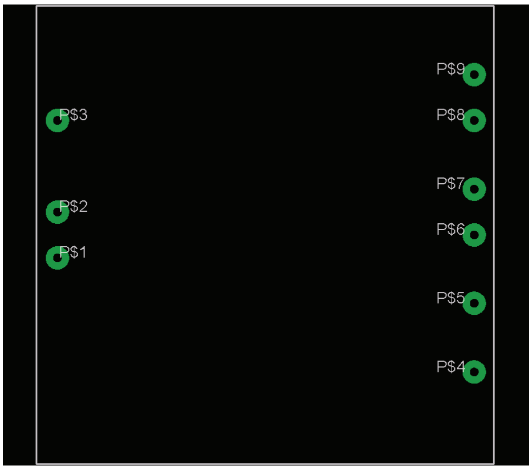

Figure 9: The TEN 40-2411 package.

3. Connecting the Symbol and Footprint by the Device Function.

The pins from the symbol have to be connected with their respective pads on the footprint. Considering the TEN 40-2411, the area by the name "P$3" connects to "P$1" and so on, see Figure 10. In this way the device will have the right size, at the same time as it can be connected to when designing in the Schematic.

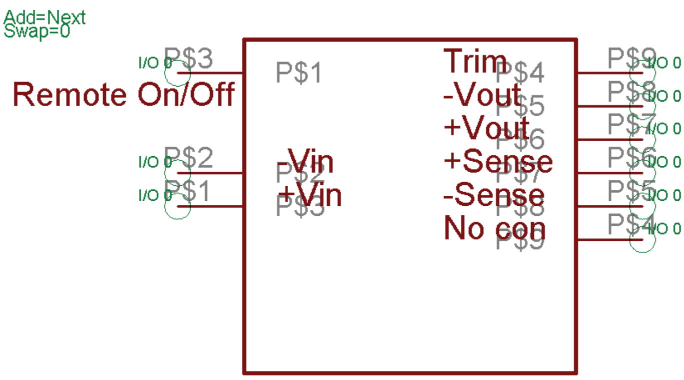

Figure 10: The TEN 40-2411 device.

2.2.4. Routing

When all the components are connected together in the schematic, then the traces in the layout editor can be stretched. This is called routing, as shown earlier in Figure 6. In most cases there are numerous components that have to be interconnected, making this task very time consuming. The solution to this problem can often be the Auto router. In most card-designing programs there is an Auto router addition, although this many times leads to more problems than actually solving them for the user. The Auto router follows the routs already laid out in the schematic, and is only restricted by two rules. These being how the Auto router is adjusted and which design guidelines that have been set.

Sometimes the Auto router can not stretch the needed traces. Often this is due to the fact that the contact points are not accessible; they can for instance be blocked by lines already connecting other components. The solution to this problem is to add layers to the card, meaning that a trace can be stretched to a different layer by means of via holes, to cross the hindering beneath, and then return to the original layer and the contact point. See Figure 11.

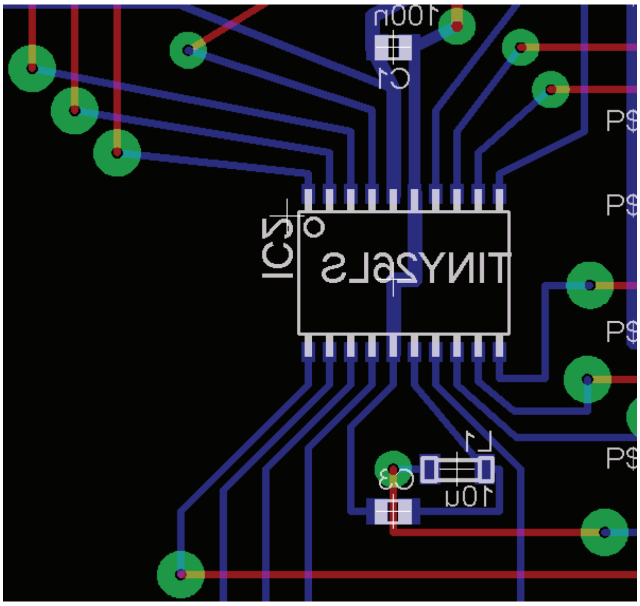

Figure 11: The routing around the ATtiny26L 8-bit AVR Microcontroller. Red traces are on the top, blue on the bottom and via holes indicate where it is necessary to drill in order to connect the two sides.

As mentioned above, the use of the Auto router is not only positive. Often the traces are being connected un-logically, with the consequence that the design becomes messy. In these cases, one has to use the rip-up function and stretch the traces oneself. The rip-up function allows the user to remove the traces laid by the Auto-router, in order to manually lay the trace. Even though this can be time consuming, manually laying the traces will give you a better and more organized product. In the construction of the controller card for the lighting of the Shell Eco-marathon vehicle, all the necessary routing has been made manually.

2.2.5. Dimensioning

Since an Atmel microcontroller by the type ATtiny26 is being used to run the operations of signal lights in the vehicle, it is important to specify how thick the traces should be between the different components. There has to be a difference between the signal traces to and from the controller compared to the traces carrying the current to the LED lights. The DC/DC converter used has a maximum current capability of 8A, even though not all of this current is necessary for the lighting. The main reason for this larger size is the efficiency the converter has, as explained later in Chapter 2.3.2.
The trace thickness is given by the cross section of the copper traces and the temperature difference between the trace and the environment in which the card is being used. Where it is possible, broader traces should be used. This reduces the impedance in the trace and makes the efficiency loss smaller. For calculation of the cross sections to the traces and their typical values, see Appendix A.

2.2.6. Via

For dimensioning via holes, one has to take in consideration the microcontroller being used. This means that the via hole can not be larger than what is possible when considering the distance between the signal traces. Where it is possible to use larger via holes, this has also been done. This is because these holes will later on be manually drilled out, and having a larger diameter to drill within will reduce the error of failure and damage to the final card. Where it was possible, additional copper was added to the via holes. This has been to make it easier to connect the pins with the tin when the soldering process is carried out.

2.2.7. DRC (Design Rule Check)

When designing a control card, there are several issues one has to consider. One of them being where the card is to be produced and what is possible to manufacture at the given site. These specifications are given design rules for the production of the control card. The design rules can for instance be the minimum size of the via holes, trace width and distance between the traces. These design rules can, if desired, be added in the design program used. After adding the design rules, the program can use these parameters to automatically generate the desired traces. Even though manual routing is performed, the same design rules need to be applied.

Since all the processes of making the controller card were performed at NTNU, it was necessary to consider what kind of equipment that was available and what kind of procedures it was possible to perform. These limitations needed to be maintained, they were crucial in order to have a successful final product.

2.3. Components used on the Controller Card

Several components have been acquired in order to be implemented to the final controller card, see Figure 12. These components have been acquired from either Farnell or Elfa. A short presentation of them will be given below, where the main focus will be on the Atmel microcontroller, which can be called the brain on the controller card. For additional information, their individual application notes can be addressed [4].

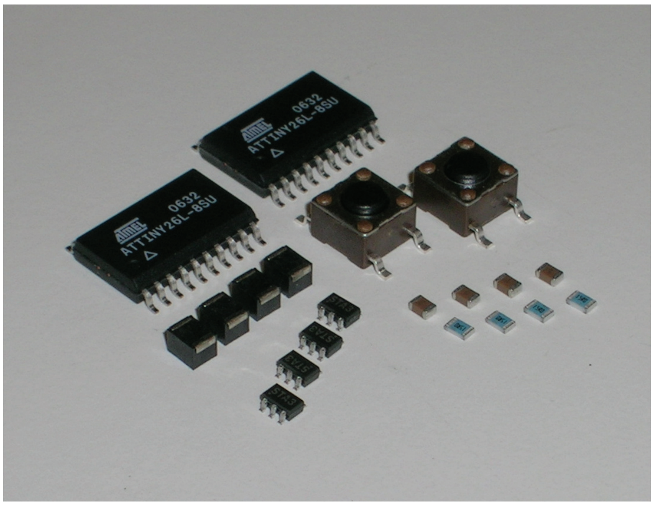

Figure 12: Components used on the controller card for lights.

2.3.1. ATMEL Microcontroller

With focus on microcontrollers, ASICs, nonvolatile memory and radio frequency components the Atmel corporation is a global leader in the design and manufacture of innovative integrated circuits. Providing complete electronic solutions that are smaller, smarter, more cost-effective and versatile than ever before Atmel enables its customers to lead the markets they serve [5].
Atmel`s low power, high performance AVR microcontrollers handle demanding 8- and 16-bit applications. To ensure fast code execution combined with the lowest possible power consumption, the AVR microcontrollers are equipped with a single cycle instruction RISC CPU, innovative picoPower technology and a rich feature set [5].

ATtiny26L 8-bit AVR Microcontroller

The ATtiny26L based on the AVR enhanced RISC architecture is a low-power CMOS 8-bit microcontroller. Compared to the conventional CISC microcontrollers, the RISC architecture is more code efficient and up to ten times faster. In one clock cycle it is possible to access the two independent registers in one single instruction execution. The device is manufactured using Atmel's high density non-volatile memory technology [5]. The main task for the microcontroller, when programmed, will be to receive inputs from switches at the steering wheel and the instrument panel, controlled by the driver and convert these into meaningful responses like putting on the blinking lights.

The ATtiny26L is a powerful microcontroller that provides a highly flexible and cost effective solution to many embedded control applications. Some of the features the ATtiny26L provides are [5]:

- High-performance
- RISC Architecture with 118 powerful instructions and 32 general purpose working registers
- Data and Non-volatile Program Memory
  - 2K bytes of Flash
  - 128 bytes EEPROM
  - 128 bytes SRAM
- Peripheral Features
  - Two 8-bit Timer/Counters, one with PWM outputs
  - Internal and external Oscillators
  - Internal and external Interrupts
  - Programmable Watchdog Timer
  - 11 single ended channels
  - 10-bit Analog to Digital Converter with two different voltage input gain stages
  - Four software selectable power saving modes, these being:
    - Idle mode – stops the CPU while allowing the Timer/Counters and interrupt system to continue functioning.
    - Sleep mode – only ADC is functioning.
    - Power-down mode – saves the register contents, but freezes the oscillators.
    - Standby-mode – same as Power-down mode, but external oscillators are enabled.
- 16 general purpose I/O lines
- Operating Voltages: 2.7V – 5.5V
- Speed Grades: 0-8MHz
- Power Consumption
  - Active 1Mhz, 3V and 25ºC: 0.70mA
  - Idle Mode 1MHz, 3V and 25ºC: 0.18mA

Block Diagram

As explained in the previous chapter, the ATtiny26L has several features. In order to get a visual image of how the microcontroller is constructed and where the different features are placed within the chip, see Figure 13. For further explanation of the features, the Atmel microcontrollers are delivered with an application note of about 180 pages which is provided for further insight for the especially interested [5].

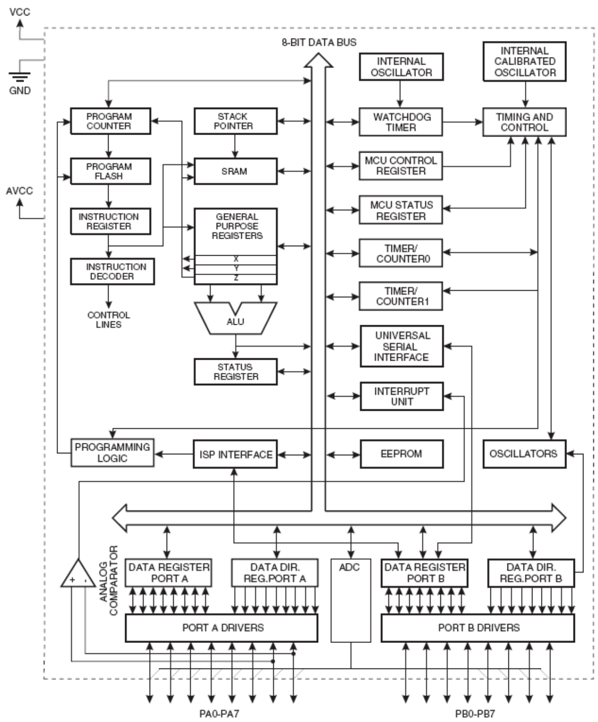

Figure 13: The ATtiny26L Block Diagram [5].

Pin Configuration and Description

A short explanation of the different pins and their functions is given below in Figure 14 and Table 1. The different purposes these pins were used for are explained later in Chapter 2.4.2.

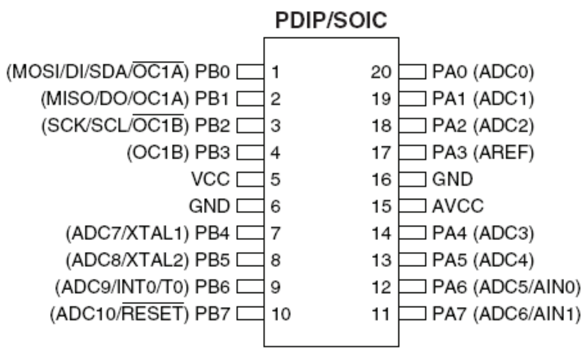

Figure 14: The ATtiny26L pin configuration [5].

Table 1: Gives an explanation to the different pins from the ATtiny26L microcontroller [5].

VCC	Digital supply voltage pin.
GND	Digital ground pin.
AVCC	Supply voltage pin for Port A and the A/D Converter. It should be externally connected to VCC.
Port A (PA7…PA0)	8-bit general purpose I/O port, functions for analog inputs for the ADC and analog comparator.
Port B (PB7…PB0)	8-bit general purpose I/O port, functions for the ADC, clocking, timer counters, USI, PSI programming.
XTAL1	Input to the inverting oscillator amplifier and internal clock operating circuit.
XTAL2	Output from the inverting oscillator amplifier.
MOSI, MISO, SCK, RESET	These four, VCC and GND are used for programming of the Atmel microcontroller.

2.3.2. TEN 40-2411 Traco Power DC/DC Converter

The Traco Power 40-2411 converter, see Figure 15 is a high efficiency converter built to operate in temperature areas between -40ºC to 85ºC. It is constructed in a compact low profile case, making it a low weight component. The converter is delivered with built-in filters at the input and output to minimize external filtering. Further standard features include remote On/Off, output voltage trimming, over voltage protection, under voltage lockout and short circuit protection [3].

Figure 15: TEN 40-2411 Traco Power DC/DC Converter [3].

The TEN 40-2411 converter has an input voltage range of 18–36 VDC and delivers, without any additional trimming, a steady 5 VDC voltage output. It has a maximum output current capacity of 8 Amps and a typical efficiency of about 90%.
The main application for the converter on the controller card will be to step down the 12 – 16.4 VDC from the Li-ion battery pack, see Chapter 4.2.3, to the desired 5 VDC of the Atmel microcontroller and the mosfet`s delivering power to the LED lights.
Main reasons for choosing the Traco Power DC/DC converter for this application is because of the light weight it introduces to the final product, at the same time as the efficiency is one of the best efficiencies available if one has to buy a commercially available product. The stated efficiency for the converter can be read from the application note and is shortly presented in Figure 16 and Figure 17 below [3].

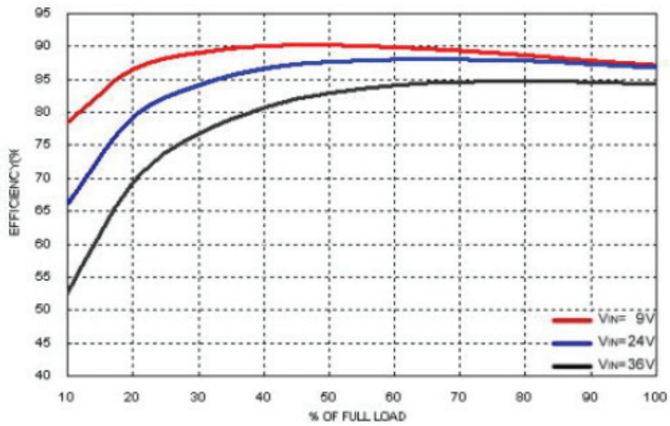

Figure 16: Efficiency versus output current [3].

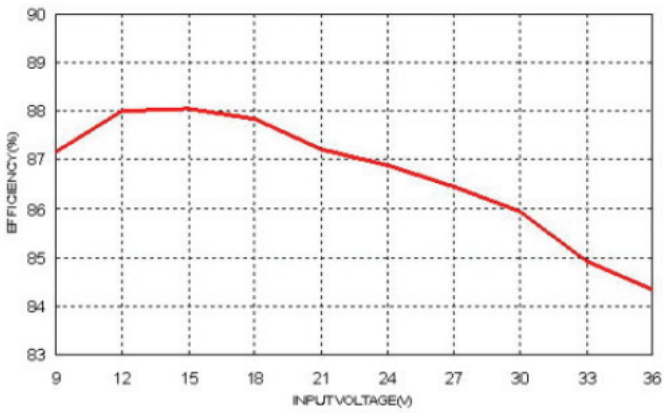

Figure 17: Efficiency versus input voltage. Full load [3].

From both figures it can easily be seen that the efficiency is about 90%. The battery pack is delivering an input voltage of about 12 – 16.4 VDC at the same time as we are drawing about 4 Amperes of the total 8 Amperes available, making it 50% of the full load.
With more time available, the smartest thing one could to was to buy extremely efficient and expensive components and construct the DC/DC converter by oneself. In this way extremely efficient converters can be a reality.

2.3.3. STT3PF30L Mosfet

The STT3PF30L mosfet is a p-channel 30 V, 3 A power mosfet developed by ST Microelectronics. It has a low on resistance less than 0.165 Ω and has an extremely high packaging density. Its main applications stretch from DC motor drive, DC/DC converters, battery management and power management in portable/desktop PCs [6]. For easier integration, the mosfet is delivered with 4 interconnected drain pins, see Figure 18. These pins are extremely convenient, because they give the user more designing options when placing them on the PCB card. The physical size of these mosfet components is 2.8 mm x 2.6 mm and it easy to understand that it requires a steady hand to solder them onto the PCB card.
The main application for these mosfets was to deliver the necessary current to the LED lights, after receiving a positive input to their gate pins from the microcontroller.

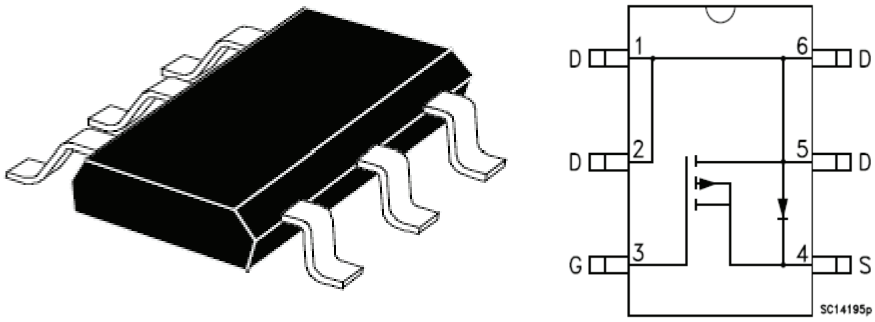

Figure 18: Power mosfet used on the controller card [4].

2.3.4. Other Components

Additional components used on the controller card are the Tyco Electronics reset switch, Kemet ceramic chip capacitors, KOA flat chip resistors and the SPI series wire wound chip inductors, see Figure 12 above [4].
Main application for the reset switch is as stated in the name, to reset. To reset the controller card if it gets stuck in a loop and does not manage to restart on its own.
In order to supply the card with the desired voltage and current, the use of filter capacitors and inductors has been used, see Figure 4 above. By using these components, one makes sure that the microcontroller is richly supplied with a desired voltage and current, hopefully avoiding any unwanted spikes. Using resistors is in most cases not desired, but a few resistors have been used in order to lower the 5 VDC from the output of the Traco DC/DC converter to about 3.5 VDC, which is the voltage needed to provide energy to the LED lights.

2.4. Constructing the Controller Card

Now that the components and procedure for how one designs a controller card in Cadsoft Eagle have been presented, the main focus now will be on explaining the controller card that has been manufactured for controlling the lights. This procedure will be presented in the steps it was performed, and figures will be used to illustrate the process in a presentable way. The process will be split in three parts, these being:

- Design process using Cadsoft Eagle 4.16
- Testing the interconnections by the use of a breadboard and programming a code in C
- Manufacturing the controller card

2.4.1. Design Process

The Figure 4 above showed only a part of the total design constructed for the lightning in the vehicle. Total design is presented below in Figure 19 and is showing all the components presented above and their interconnection. The Atmel microcontroller is powered up by the Traco DC/DC converter, which again gets its power from the Li-ion battery pack presented later in Chapter 4.2.3. The inputs to the microcontroller are given by switches placed at the steering wheel and instrument panel in the vehicle, easy accessible for the driver. The inputs trigger the gate terminals on the power mosfets, which again deliver the necessary energy to the LED lights used for left blinking lights, right blinking lights, front/back lights and brake lights.

A function provided by the Cadsoft Eagle is the Electrical Rule Check which performs an interactive check of the total card. It checks if there are traces crossing each other, lines not properly connected or voltages and ground signals not provided. This function is not bulletproof, but it has been used as a guideline throughout the designing process to minimize any unwanted mistakes.

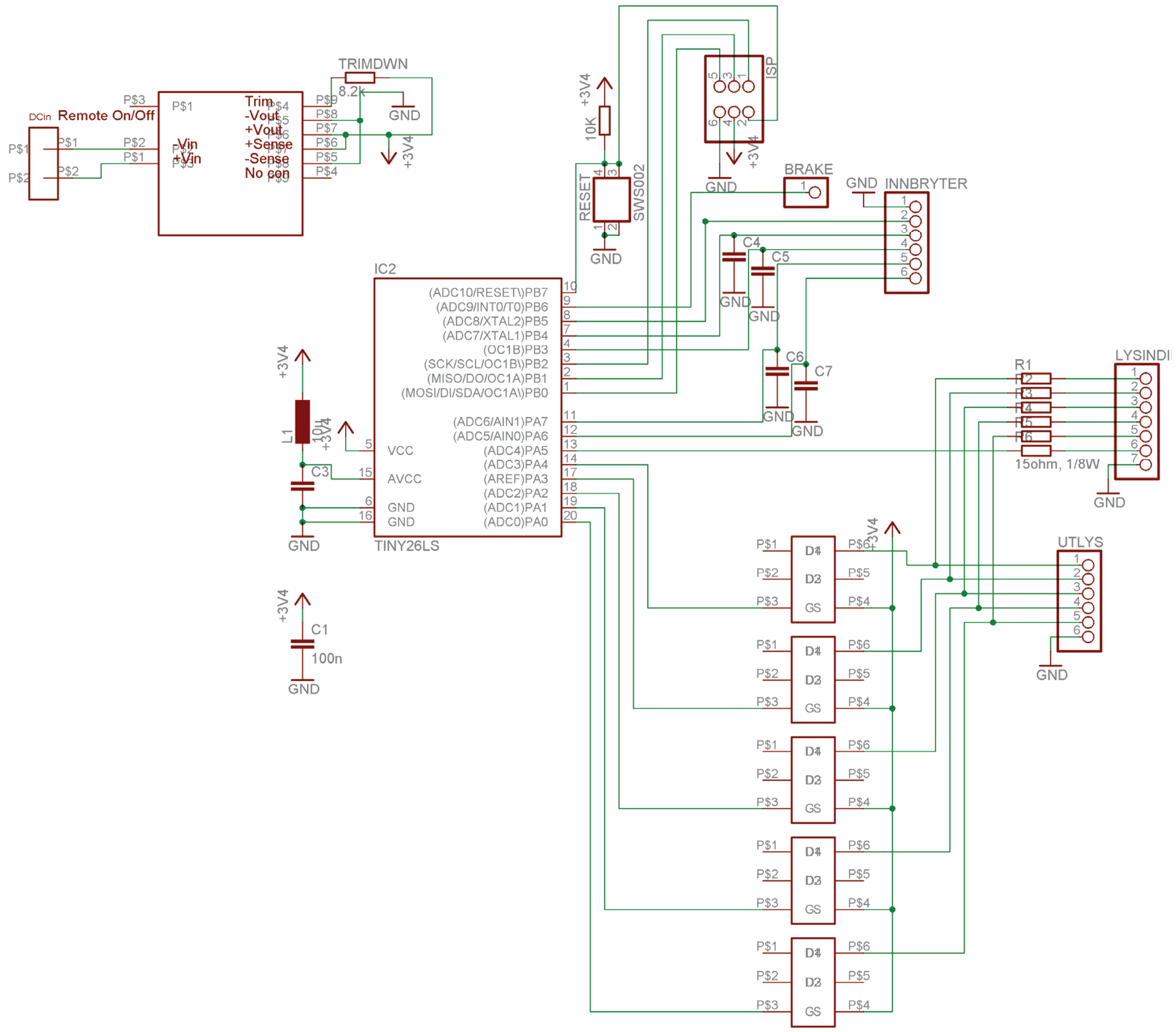

Figure 19: Total schematic of the controller card for lights.

The next step is to use the total schematic and design a layout for the controller card which has all the requirements presented earlier in Chapter 2.2. After transferring the schematic to the layout editor in Cadsoft Eagle the designer is met with a rather confusing image, see Figure 20. What Cadsoft Eagle does is to place all the components outside the working area and provides the designer with the possibility to choose where he or she wishes to place the components. This is convenient because the individual designers know, based on the implementation, where it would be desirable for them to have the different components, as well as the inputs and outputs.

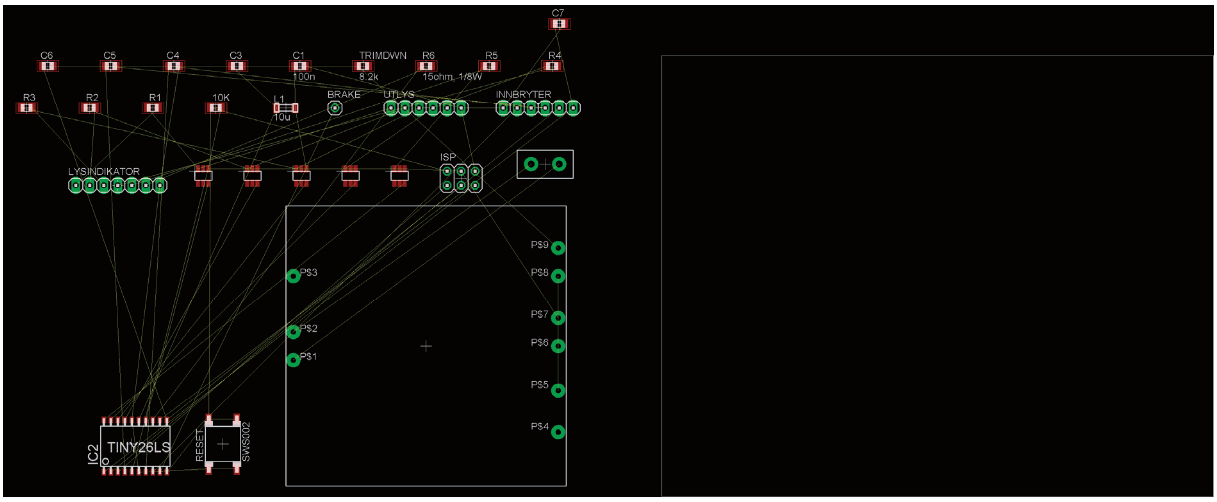

Figure 20: First view in layout editor after completed schematic interconnections.

The next step is to move and place all the components within the working area. The working area indicates the physical size of the final card. Since a free version of the Cadsoft Eagle program is being used, the working area can not be extended beyond the borders presented in Figure 21.

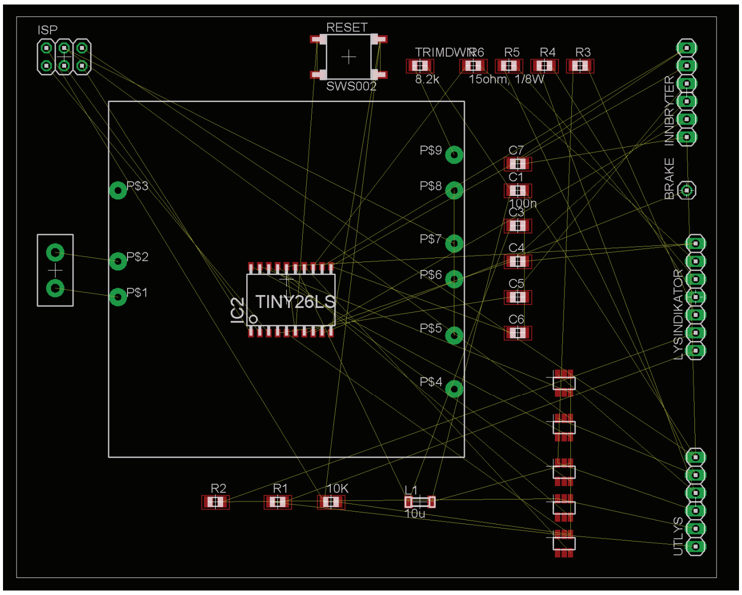

Figure 21: All components placed within the final controller card.

After placing the components inside the working area, one has to make a decision regarding which of the components that should be on the top and which components that should be at the bottom of the controller card. This is done in order to simplify the routing process. The ATtiny26L microcontroller has 20 pins and it is very difficult to connect these pins to their designated positions without crossing a line or two in the process. Figure 22 below shows which components that have been placed on top and under the controller card.

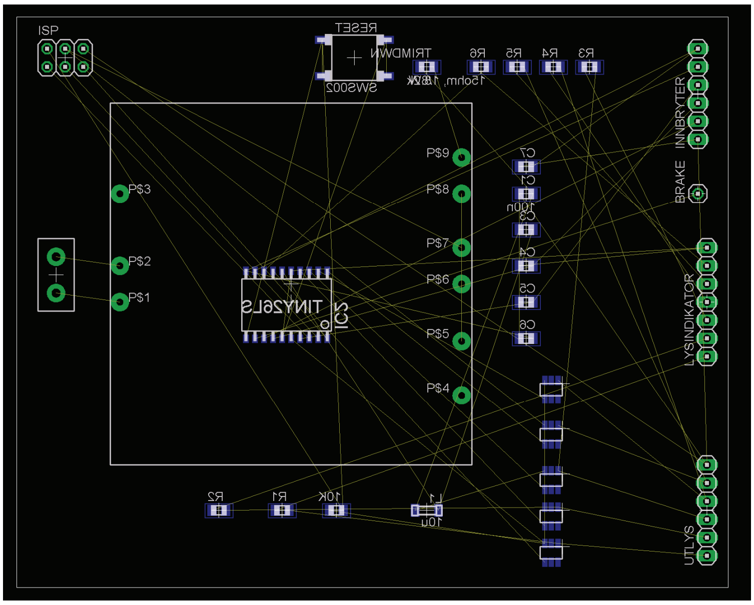

Figure 22: The total controller card. Blue components are placed under the card and the rest is above.

The next step is, as explained earlier in Chapter 2.2 and shown by Figure 5 and Figure 6, to interconnect the components while keeping in mind that different traces carry different amounts of current and that the via holes should be as wide as they possibly can. This is done in order to reduce any complications when manufacturing the physical card.

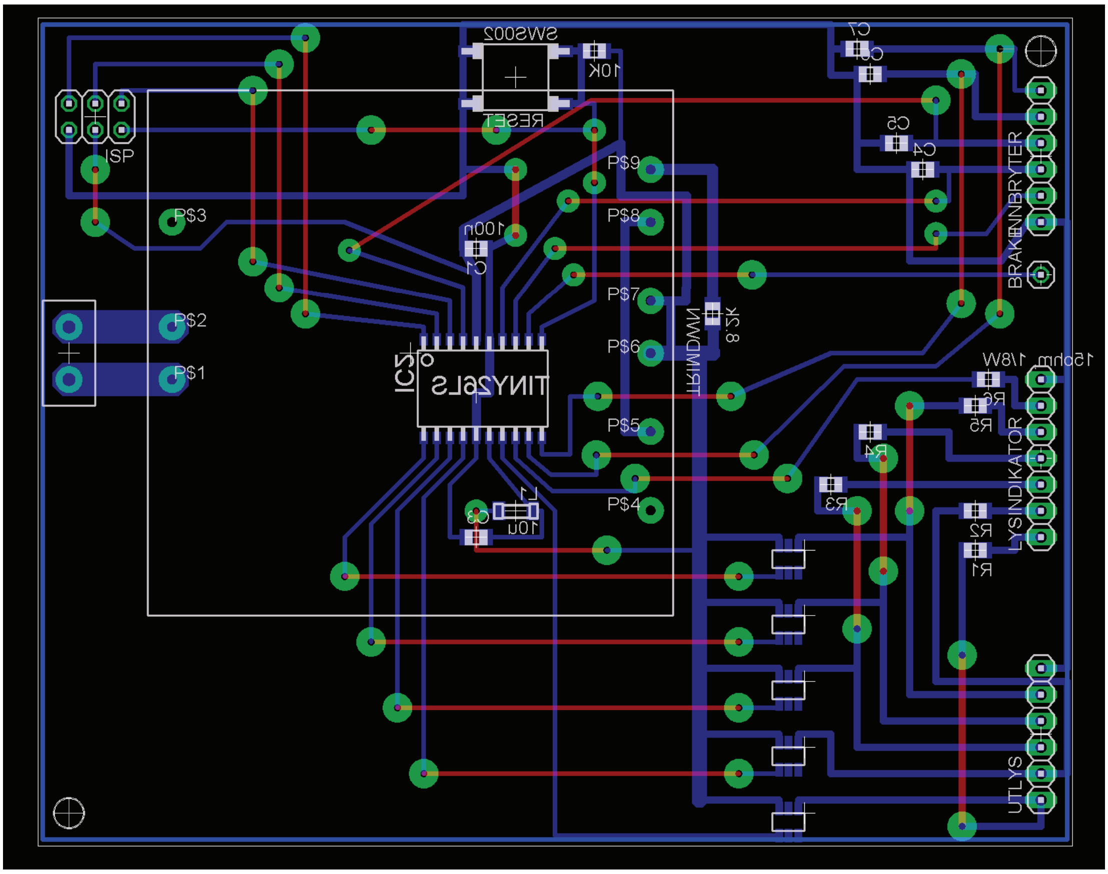

Figure 23: Final card designed for controlling the lights.

Final interconnection in the layout editor is presented above in Figure 23. It is easy to see that there are different thicknesses to the various traces. Red traces are on the top, blue on the bottom and via holes indicate where it is necessary to drill in order to connect the two sides.

Last task is to apply ground (GND) to as much of the card as possible. Every component on the controller card requires an earth potential. Making this ground a common ground to all of the components will reduce the need for many connecting trace and stabilize the final product. Figure 24 shows the controller card with a common ground potential.

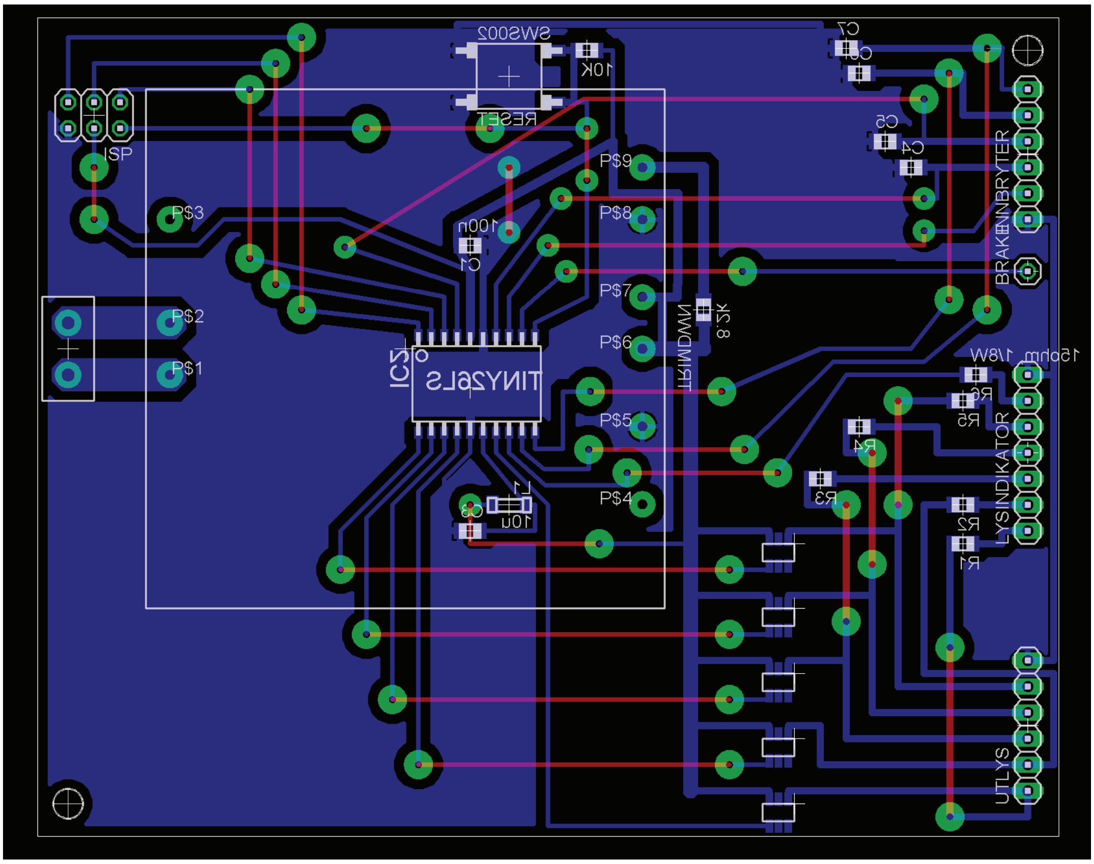

Figure 24: Final card with common ground potential.

2.4.2. Testing Interconnections and Programming in C

Before manufacturing the final controller card, if is always smart to check if ones reasoning is correct. Based on the design and previous experience one often has a feeling that things should be working perfectly, but there is often a huge difference between something on the paper and something that is constructed. Due to this, the interconnection shown in Figure 24 has been realized by the use of a breadboard. The same connections were connected between the components and a code has been written in order to test if the different inputs would in fact light up the designated lights at the output. Figure 25 below shows the test performed using a breadboard.

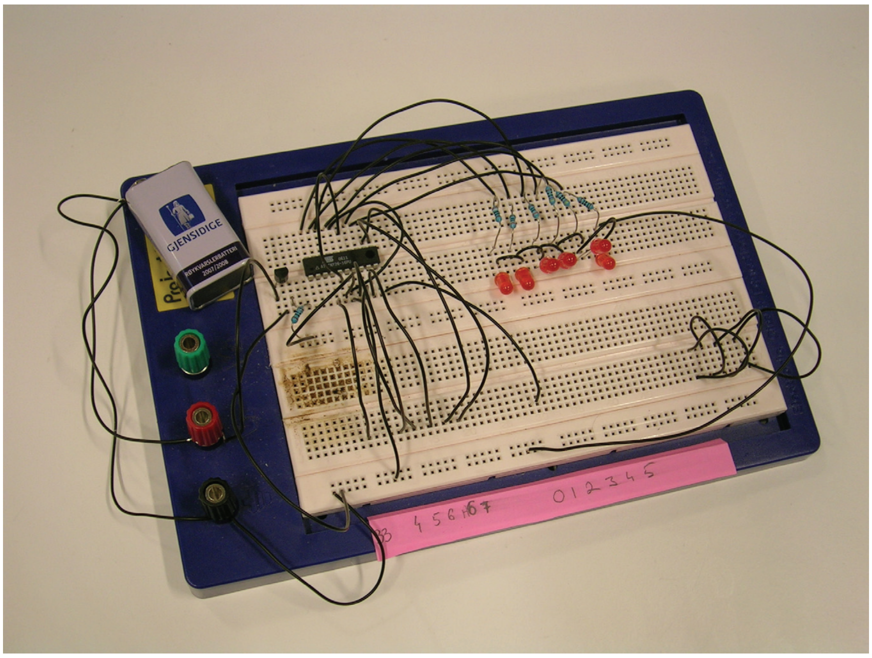

Figure 25: Breadboard used to test the interconnections.

In order to have a successful test, the microcontroller needs to be programmed. One has to indicate which ports that should be designated as the input ports, and which ports that are the output ports. Further on one has to program what applying a positive signal on one of the inputs should lead to, and of course where this response should happen. If the brake is pressed down, then brake lights should light up, and not the left blinking lights.
The different pins on the microcontroller have been given the responses presented in Table 2 and Table 3 below. In addition to these responses, the different inputs and outputs have been indicated with a colour. This colour is the colour of the cables that have been used in the vehicle, and will help distinguish the different signals.

Table 2: Designated input and output signals on the microcontroller.

Input pins				
9	(ADC9/INT0/T0)	PB6	Brake Lights	Red
8	(ADC9/INT0/T0)	PB5	Left Blink	Green
7	(ADC7/XTAL1)	PB4	Right Blink	Blue
4	(OC1B)	PB3	Front Lights	White
11	(ADC6/AIN1)	PA7	Back Lights	Orange
12	(ADC6/AIN1)	PA6	Warning	Yellow
Output ports				
13	(ADC4)	PA5	Indicator	Yellow
14	(ADC3)	PA4	Left Blink	Green
17	(AREF)	PA3	Right Blink	Blue
18	(ADC2)	PA2	Front Lights	White
19	(ADC1)	PA1	Back/Brake Lights	Red
20	(ADC0)	PA0	Brake Lights	Orange

Table 3: Designated control sequence when activating the different input pins.

Control Sequence		
Brake Lights	PB6 on	PA1 on
		PA0 on
	PB6 off	PA1 off
		PA0 off
Left Blink	PB5 on	PA4 on/off blinking
	PB5 off	PA4 off
Right Blink	PB4 on	PA3 on/off blinking
	PB4 off	PA3 off
Front Lights	PB3 on	PA2 on
	PB3 off	PA2 off
Back Lights	PA7 on	PA1 on
	PA7 off	PA1 off
Warning Lights	PA6 on	PA4 on/off blinking
		PA3 on/off blinking
	PA6 off	PA4 off
		PA3 off

Due to lacking experience in programming, a lot of effort has been placed on searching after similar problems by other people on the Internet. The site AVRfreaks was used and experience has been gathered by reading about how to control the ATtiny26L microcontroller. In addition friends with more experience have been asked for guidelines in the programming process.
Eventually the code for controlling the lights has been written and is presented in Appendix B. The same code has been tested on the breadboard and the result was a success. The different inputs triggered the correct outputs and it was now possible to move on to the manufacturing process.

2.4.3. Manufacturing the Controller Card

The manufacturing process requires different equipment and several steps have to be followed in order to have a successful product. Due to this, the process will be presented stepwise and a short explanation with a figure will be given at each step.

1. The designed layout of the card is printed on transparent paper. The traces on the front of the card are kept the same when printing, but the traces on the back have to be mirrored. When now put together, these two will be the first image of how the final card will look like and its size, see Figure 26.
2. The printed traces are placed on both sides of a PCB card which is then placed inside an illumination device, see Figure 27. Here the traces will be imprinted onto the PCB.

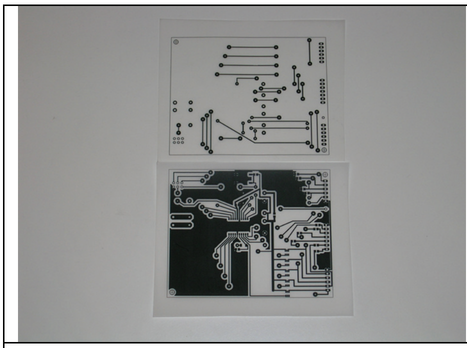

Figure 26: Designed layout printed on transparent paper.

Figure 27: 3M illumination device.

3. The imprinted card is then placed inside a corroding aggregate at around 50ºC for about 15 min, see Figure 28. This process will only leave behind the desired traces.
4. Figure 29 below shows the final card, before any components have been soldered onto it. It can also be seen that the via holes have been drilled out.

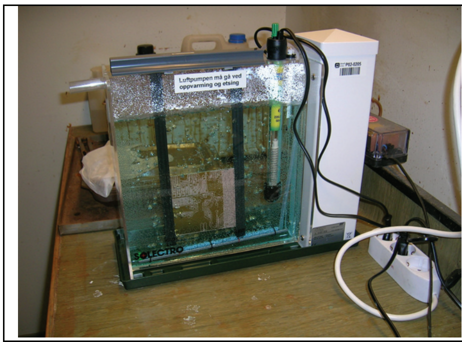

Figure 28: Selectro AB corroding aggregate.

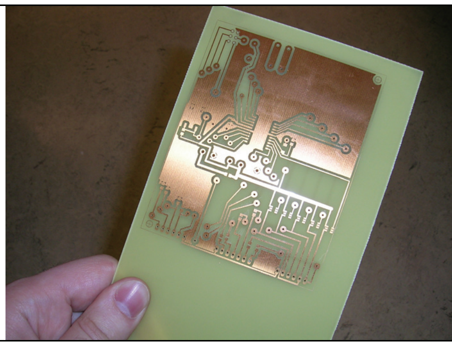

Figure 29: Final card without the soldered components

5. Finally the components presented previously are soldered onto the surface of the card, both at the front and at the back, see Figure 30 and Figure 31. The controller card is at this stage ready to be programmed and tested.

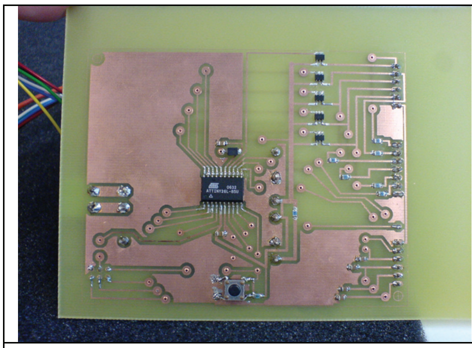	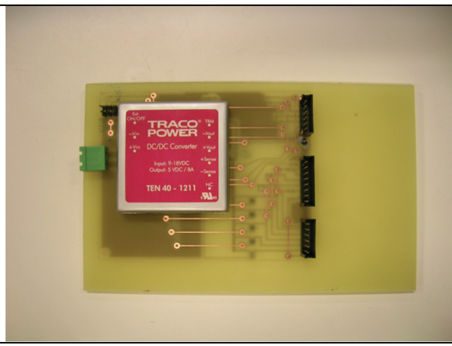
Figure 30: The final controller card, back.	**Figure 31: The final controller card, front.**

3. Plan B

Due to some fluctuations at the output voltages of the mosfet`s placed at the bottom of the controller card, the plan B, as mentioned earlier in Chapter 2, was utilized. Plan B involves utilizing a commercially available product and programming it to do the same tasks as the initial controller card was supposed to do. In order to avoid surprises like lights suddenly not functioning when participating in the Shell Eco-marathon competition, this second possibility of controlling the lights would only bring more assurance that a working solution is available, should a bigger fault occur with time.

3.1. LOGO! Micro Automation Module

For simple automation tasks the Siemens LOGO! Micro Automation module is the number one logic module to utilize. It has maximum user friendliness and high functionality. The modules are flexible and can be used in areas raging from transport facilities, house and building services management, heating/ventilation/air conditioning, monitoring systems and other special solutions. Thanks to the high memory capacity and efficient utilization, the LOGO! modules can be used to control complex installations [7]. Should a need for additional signals emerge, one can simply add expansion modules to the system and in this way easily meet the demands. See Figure 32 beneath for illustrative explanation.

Figure 32: The LOGO! Micro Automation Modules [7].

The LOGO! modules offer a selection of 38 integrated functions and up to 200 blocks with which the user can construct just the system he or she requires. Operator control and monitoring are made extremely user-friendly by means of a backlit display, in addition to the LOGO! Soft Comfort software with which one can program the device, see Figure 33 [7]. The Soft Comfort program offers simple construction of ladder and function block diagrams by simply selecting, dragging and dropping the relevant functions and their connections.
One can create simple switching programs quickly either at the device or on the PC by utilizing the eight basic functions, see Figure 34. One can additionally create complex switching programs quickly by utilizing the remaining 30 special functions [7].

Figure 33: Illustrates the LOGO! Soft Comfort software [7].

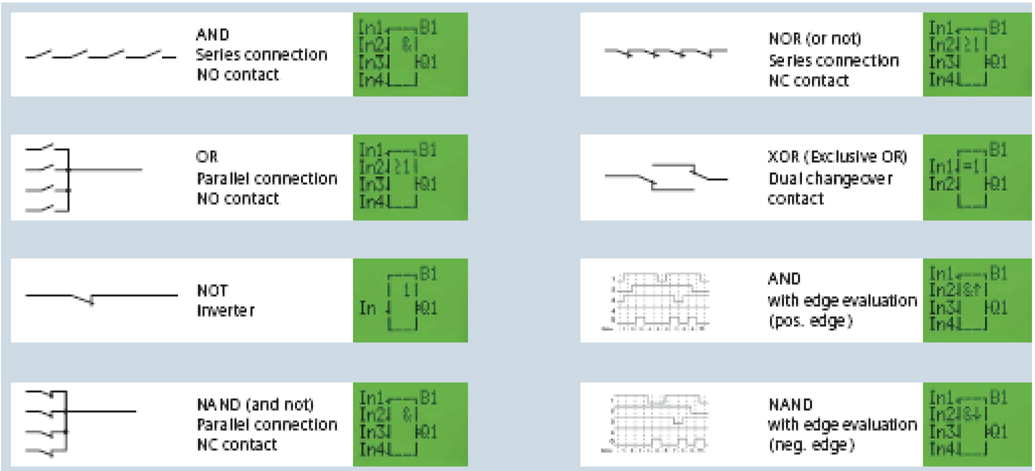

Figure 34: The eight basic functions [7].

Although the LOGO! modules accept a wide range of input voltages raging from 12 V DC, 24V AC/DC and 115/240 V AC, the module chosen for our vehicle is the 12/24 V DC, see Figure 35 above. The main reason for this is the wide range of acceptable input voltage, which is perfect for the rest of the system in the vehicle. The theoretical input voltage has a range from 10.8 V DC to 28.8 V DC. Since the Li-ion battery pack used to power up the module will range between 12 V DC and 16.4 V DC, it is easy to understand that these two components will fit perfectly together. This module has 8 inputs and 4 relays at the output. The inputs will be used to the different switches placed on the steering wheel and the instrument panel in the vehicle, and the four outputs will respectively be used for left blinking lights, right blinking lights, front/back lights and brake lights, see Figure 36 for an illustrative design describing the interconnection of the LED lights and their placement in the PureChoice vehicle.

Figure 35: The 12/24 VDC RC LOGO! module [7].

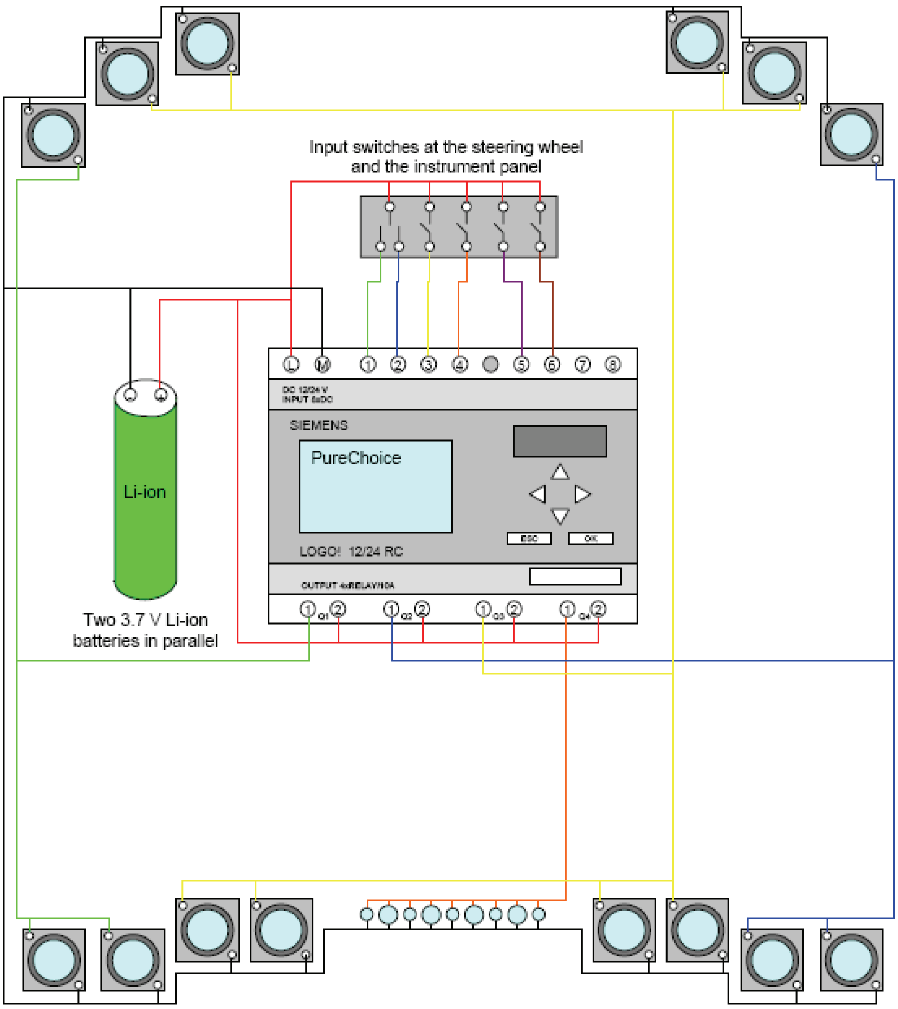

Figure 36: Siemens LOGO! Micro Automation module and the LED Lights.

Figure 36 above illustrates the interconnection of the different LED lights in the vehicle. The placement of the LED lights and the colour of the cables connecting them are coherent with the real connections inside the PureChoice vehicle. This has been done to simplify any changes or maintenance jobs that have to be performed on the vehicle in the future. For more information about the different placements and how they look, see Chapter 3.3.

3.1.1. Programming the LOGO! Micro Automation Module

Since it was clear what kind of responsibility the LOGO! module was going to have, it was fairly simple to get started on the programming of the inputs and outputs. As mentioned above this device has only four outputs. Although an additional device could be attached in order to widen the output capacity, this was not necessary, because this device was sufficient for the task it was going to perform. Only difference compared with the manufactured controller card, was that now both the front and back lights had to be placed at the same output. What this implies is that both of these lights would be activated at the same input. This has no effect what so ever to the proper operation of the lights in the vehicle.
The inputs could be used as before, namely to put on left blinking lights, right blinking lights, main lights and brake lights. In addition to these, warning lights and show-off lights were programmed. Doing this only required a small switch at the instrumentation panel, see Figure 40, because the same LED lights and cables would be used to control them, introducing almost no additional weight in the vehicle. The warning lights would rather supply the driver with more safety. While the show off lights, on the other hand, were there in case we had something to celebrate.
The final program for controlling the LED lights is presented in Figure 37 below. Note that the brake lights input signal has been inverted. This is because the push button placed on the brake pedal in normally leading. Inverting this signal would give the desired function, namely the brake lights lighting up just when the brake pedal is pressed down.

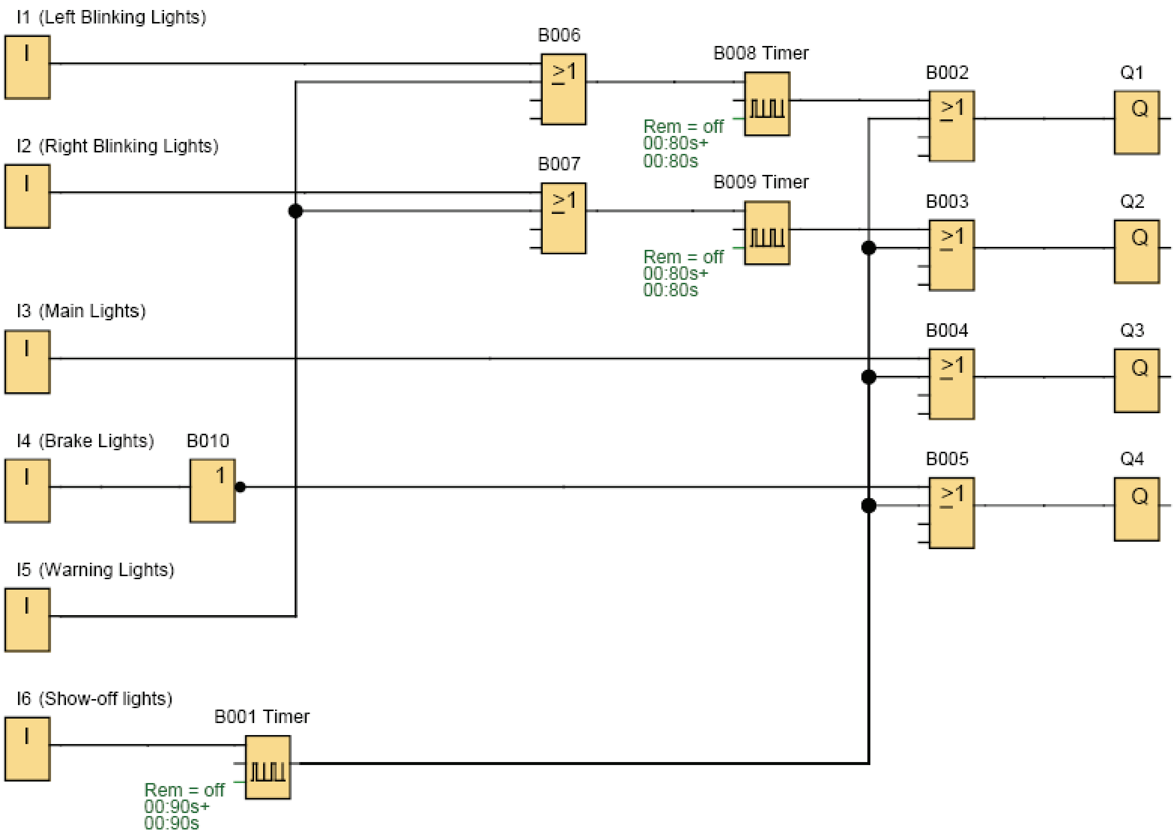

Figure 37: The constructed controlling program for the LOGO! Micro Automation module.

3.1.2. Testing the LOGO! Micro Automation Module

A small test was performed with the setup mentioned in Figure 36 and programmed controlling program in Figure 37. Since two different voltages were utilized in controlling the lights, one for the LOGO! module and the other to energize the lights, a test was performed in order to see just how much energy they consumed at different controlling sequences. Table 4 below shows the results of the performed test.

Table 4: Energy consumption test.

Energy Consumed		
	LOGO!	Li-ion batteries
Only module, idle mode	0.014 A	0
Blinking, one LED light	0.033 A	0.149 A
Constant on, three LED lights	0.034 A	0.230 A
Constant on, four LED lights	0.034 A	0.375 A
Three LEDs on, one LED	0.054 A	0.357 A
Blinking, two LED lights	0.051 A	0.294 A
Constant on, nine LED lights	0.086 A	0.751 A

Table 4 shows that the LOGO! Micro Automation module is working in a smart and logical way. The module is only drawing the necessary power needed in order to control the different input signals, and give the necessary signals to the outputs. In addition to a small energy consumption powering up the module. All the necessary energy needed to light up the different lights comes from the two VARTA Li-ion batteries, which is exactly what was desired from this construction.

3.2. Self-manufactured Controller card vs. LOGO! Micro Automation Module

Now that two different solutions were available, it was important to make a decision on which one of these that would be better for implementation in the PureChoice vehicle. Factors considered when comparing the two solutions were weight, stability, implementation and utilization. Table 5 below summarizes the main results.

Table 5: Comparison between the manufactured card and the LOGO! module.

<table>
<tr><td></td><td>Self manufactured controller card</td><td>LOGO! Micro Automation module</td></tr>
<tr><td>Weight</td><td>65g ++</td><td>190g</td></tr>
<tr><td>Stability</td><td>Device shows some instability, registered at the output voltage from the mosfets.</td><td>LOGO! is a commercially available device, hence no instability was registered.</td></tr>
<tr><td rowspan="2">Implementation</td><td>Due to lack of a dashboard in the vehicle, the implementation proved to be difficult. The entire vehicle is constructed using carbon fiber, and it is a known fact that carbon conducts current.</td><td>Due to lack of a dashboard in the vehicle, the implementation proved to be difficult for this device as well. The benefit with this device is that it is constructed with an outer shell made of thick plastic.</td></tr>
<tr><td>If the card is used in the vehicle, it has to be properly shielded from the rest of the vehicle.</td><td>It is robust at the same time as it is easy to implement inside the vehicle.</td></tr>
<tr><td rowspan="3">Utilization</td><td colspan="2">Both devices deliver the desired functions. Only difference is that the self manufactured controller card needs more attention when connecting or disconnecting to it. This is unfortunate, because often time can be of the essence.</td></tr>
<tr><td colspan="2">The Li-ion batteries powering both of these solutions needs to be connected and disconnected quiet frequent due to the charging process. This process will most likely lead to more damage to the manufactured card than the LOGO! Module.</td></tr>
<tr><td colspan="2">The utilization of the LOGO! Module is also easier to understand by those not used to work with electrical components.</td></tr>
</table>

The results of this test are all leading to one logical outcome, this being that it is more convenient to use the commercially available LOGO! module to manage the lights in the vehicle. Although a lot of time has been spent making the self made controller card, this has not been in vain. A lot of experience was acquired in the process and it would be wishful thinking to believe that the first controller card constructed would operate perfectly.

3.3. Implementation of the Lights in the PureChoice Vehicle

Figure 38 and Figure 39 show the solutions for the lights in the PureChoice vehicle. Both back lights and front light have been interconnected keeping in mind that it should be easy to replace them in case a fault should occur. LED lenses were used at the front lights in order to spread the light as much as possible. All the application notes explaining the different LED lights used and their holders are provided and can be read by the especially interested [8].

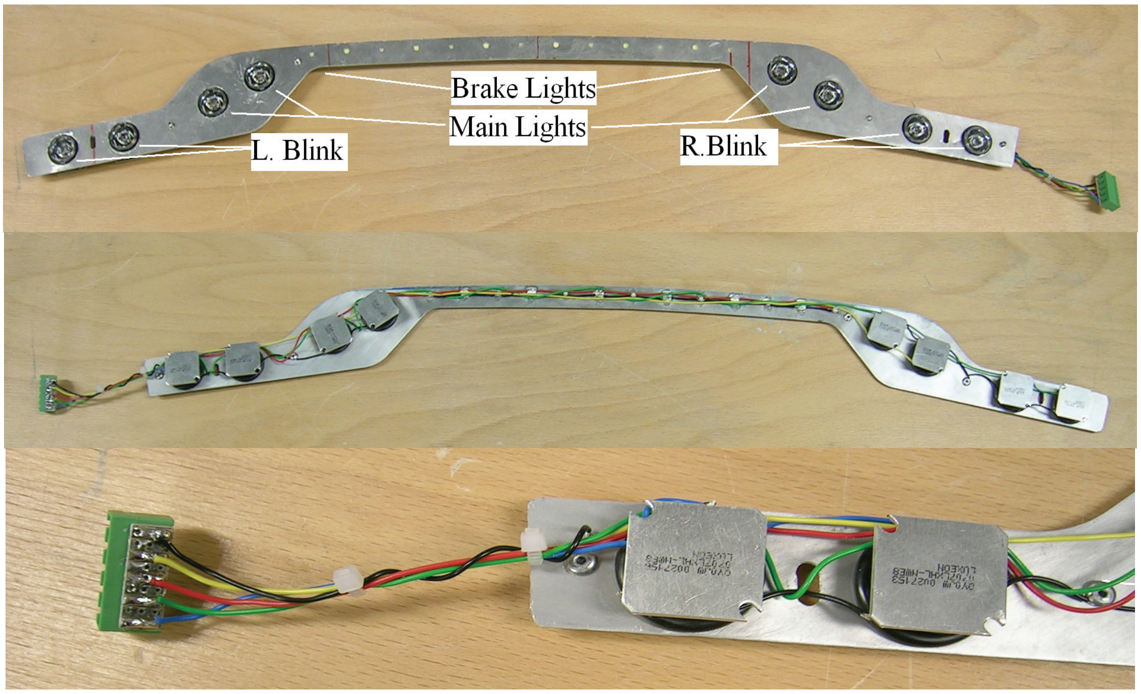

Figure 38: Interconnection and design of the back lights.

Figure 39: Holders with the lenses for the front lights.

Main focus when connecting the different input switches to their respective output lights was to keep the design as easy as possible, at the same time as one manages to hide as much of the cabling as possible. The solution in the PureChoice vehicle is presented below in Figure 40. The unconnected red cables are for the Li-ion battery pack, which at this point was being charged up.

Figure 40: The driver consol with the steering wheel.

Figure 41 and Figure 42 below show the LED lights in the working condition. Although the interconnecting and soldering process took a lot of time, it was all worth the effort when one saw just how beautifully the lights lighted up. Although all the lights are lighting up in the figure below, the individual LED lights have different responsibilities in the vehicle.

Figure 41: Front lights in the PureChoice vehicle.

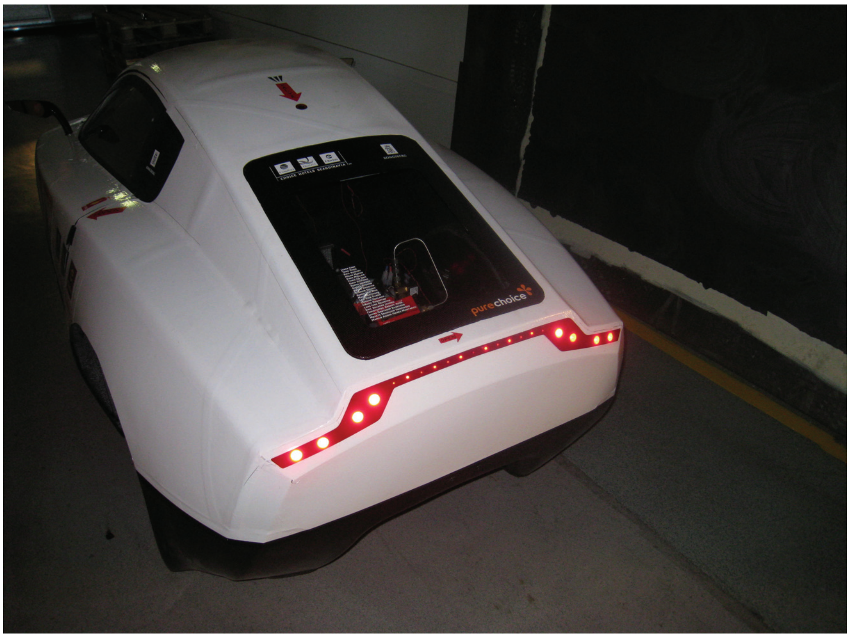

Figure 42: Back lights in the PureChoice vehicle.

4. Introduction of the Batteries

A battery is a device consisting of two or more electric cells joined together converting chemical energy into electrical energy. The DC electricity is generated due to the chemical reaction between the positive and negative electrodes, and the electrolyte joining them. By reversing the direction of current through the device, the chemical reaction can also be reversed, and the battery is said to be in a charged state, hence secondary or rechargeable batteries [1]. The voltage of a cell is determined/limited by the chemical specifics of the reacting material. To gain the desirable output voltage cells are stacked in series. To gain higher ampere hour [Ah] capacity, cells are placed in parallel. The purpose of the battery is to store energy. The energy is measured in Watthour, where one Wh is equivalent to 3600 Joules. The energy [Wh] is determined by the amount and nature of each chemical involved.
At present there are many different types of batteries available. Commercial rechargeable batteries suitable for use in vehicles span from the well known lead acid battery to batteries such as nickel iron, nickel cadmium, nickel metal hydride, lithium polymer and lithium ion, sodium sulphur and sodium metal chloride. Independent of which of these one chooses to utilize, there are often similar performance criteria demanded from them. Some of these criteria include specific energy, energy density, specific power, commercial availability, cost, operating temperatures, self-discharge rates, number of life cycles and recharge rates [1]. It is therefore important that their different performances and behaviour is understood before one chooses a specific battery module for his of hers design. For instance, some batteries have a very good specific energy, but a rather low specific power. If these batteries are used in vehicles, it means that they can drive the vehicle very slowly over a long distance. Some basic knowledge about batteries is also important in regard to likely hazards in an accident and the overall impact of the use of battery chemicals on the environment [1].

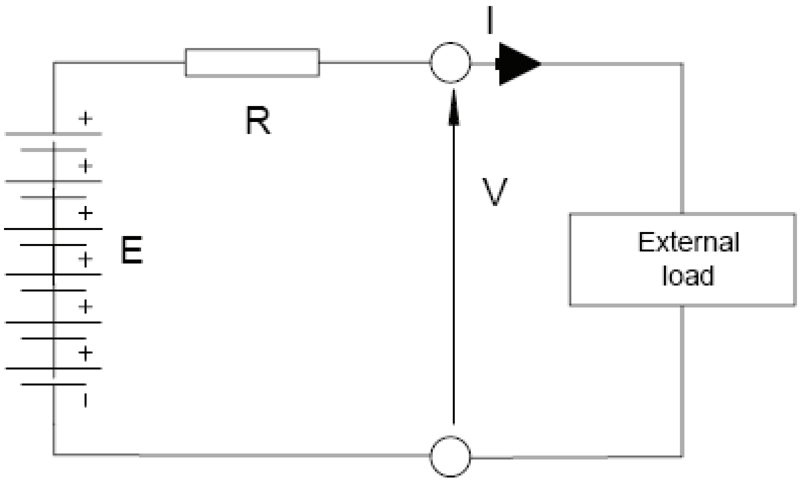

Figure 43: Equivalent model of a battery [1].

The equivalent circuit of a battery is shown in Figure 43. It is composed of six cells is series representing the fixed voltage E and the terminal voltage V, due to the internal resistance loss IR. From basic circuit theory we can extract the formula shown in Eq. (4-1).

$$V = E - IR \tag{4-1}$$

If the battery is being charged the voltage will rise by IR, and if it is being emptied it will fall by IR. Although, if the current I is zero, then the fixed voltage E and the terminal voltage V are equal and this voltage is referred to as the open circuit voltage.

If the capacity of a battery is 7.2 Amphours, this means that it can provide 1 Amp for 7.2 hours, 2 Amps for 3.6 hours, or in theory 7.2 Amps for 1 hour. It is important to understand that while a battery may be able to provide 1 Amp for 7.2 hours, it will never be able to deliver the theoretical 7.2 Amps for an entire hour. This change in behaviour occurs because of unwanted side reactions inside the cell [1].

4.1. Battery Types

Since there are so many different battery types available today, a research involving the most relevant and available types has been performed. Based on this research the correct batteries for the vehicle were determined and acquired from suppliers. For further information about the chosen batteries, see Chapter 4.2.

4.1.1. Nickel Cadmium (NiCad)

The Nickel cadmium battery was invented by the Swedish scientist Waldmar Jungner in 1899. At that time it was expensive and therefore limited to special applications. It was first in 1947 that they started the research on sealed NiCad batteries, making them more commercially available. When you seal the battery you are able to recombine the gases created in the battery while it is charged. This has two major advantages, first that hazardous gasses are not spilt in the environment. And second, the chemicals are not lost from the battery making it possible to use the battery several times.

NiCad batteries biggest strength is the fact that it performs well under hard conditions. It poses no problems with deep discharges and high discharging currents. Unfortunately the battery relies on full recharge/discharge cycles. If the battery is used incorrectly, crystals will form on the cell plates, and lead to lower maximum-capacity and fewer charge/discharge cycles. This is commonly known as the memory effect. Incorrect use is often overcharging and charging when the battery is not properly discharged. The battery has a high self discharge rate (40% in three months). NiCad is also the most environmentally unfriendly battery mentioned [9].

4.1.2. Charging NiCad

Even though battery charges are often given low priority, they are important in determining the reliability and longevity of the batteries. For the best results, batteries should remain as cool as possible while charging. The charging efficiency is about 90% at fast charge and about 70% at slow charge.

Nickel based chargers are divided into three categories:

- **Slow charge** – normal charging time 14-16 hours at 0.1 C. Often used in cord-less phones, portable CD-players and other consumer goods.
- **Quick charge** – charges the battery in approximately 3-6 hours at a current of about 0.3 C. The charging changes to trickle when ready. Used in laptop computers, camcorders and cell phones.
- **Fast charge** – Charges a battery in about 1 hour at 1.1 C. This is the preferred charge because of low/non production of crystals on the cell plates, preventing the memory effect.

C-rate refers to the percent factor of the battery's Ampere hour [Ah] capacity. Assuming that the battery has 7.2 Ah it means that 0.1 C = 0.72 A, 1.0 C = 7.2 A and 1.1 C = 7.92 A. Trickle charging is a charge at very small currents at about 0.05 C [9].

Because of the importance of proper charging, NiCad batteries need an overcharge protection. This is commonly solved with a detection of voltage drop, rate-of-temperature-increase and absolute temperature detection. This often combined with a timer. The charger shuts down on the first detection. As seen in Figure 44 it can be very difficult to define when the battery is completely charged. The voltage drop occurs first at about 120% (20% overcharge), the calibration of the dV/dT must be exact to detect the temperature detection at 100% battery charge. The time control and absolute temperature are often used as back-up because they are less reliable [10].

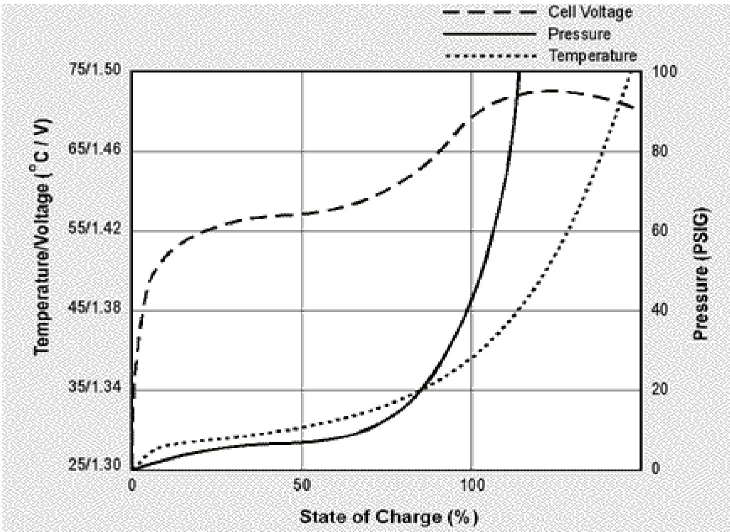

Figure 44: The charging characteristics of a NiCad and NiMH battery [10]

4.1.3. Nickel Metal Hydride (NiMH)

The Nickel metal hydrate batteries are an evolution from the nickel hydrate batteries used in aerospace technology in the late 1960s and 1970s. Research began in the 1970s as a way to store hydrogen to the far more expensive and bigger NiH batteries. After seeing the potential of NiMH in the 1970s the commercialization started first in the 1980s, after they learned how to stabilize the battery cells.

NiMH batteries have many similarities with the NiCad, though they have some different advantages and disadvantages. The NiMH is light in weight giving far more energy pr. kg. than the NiCad, and has minimal problems with memory effect. It is also the only battery mentioned in this report that is environmentally friendly. Disadvantages are the high rate of self-discharge and limited cycle life. Where NiCad may have up to 1000 cycles (if stored properly) NiMH will notice a capacity drop already after 200-300 cycles. It has also problems under hard working conditions like high currents and fast discharges. This and storage in high temperatures lowers the cycle life [9].

4.1.4. Charging NiMH

The charging of NiMH has many similarities with the NiCad, only more complex and more difficult to perform. The battery charging curve is similar to the one shown in Figure 44. The difference is that the voltage drop after the fully charged point is very small, and almost none existing at charged rates below 0.5 C. This, combined with the extremely low temperature emission at low charging currents, makes it almost impossible to slow charge these batteries. Apart from this, the charging system is based on the same principles as the one mentioned in Chapter 4.1.2. The only difference is that the equipment used to monitor the charging has to be even more exact [10].

4.1.5. Lithium-ion (Li-ion)

The research of the lithium-ion batteries began already in 1912 under G. N. Lewis, but it was first in the 1970 the first non-rechargeable lithium batteries became available. Due to safety concerns because of the instability of the lithium under charging, the attempt to make rechargeable lithium batteries failed. Li is the lightest of all metals and has the greatest electrochemical potential, therefore also giving the best gravimetric and volumetric energy densities.

To avoid much of the instability, the research changed towards non-metallic lithium ions. Even though the lithium-ion batteries have a slightly lower energy density than the original lithium batteries, they are safe and have twice the energy density of a typical NiCad battery. The cell voltage is about 3.6 V, making it possible for many applications including cell phones, to run on a single cell. Li-ion works well under discharge, behaving similar to the NiCad battery. It has no memory effect, low self discharge and causes little harm when disposed.

The disadvantage with the lithium-ion batteries are their fragility. It needs a protection circuit to maintain safe operation. The protection circuit has to limit the peak charging voltage and prevent the voltage of falling too low during discharge. In addition the temperature is monitored and charging/discharging currents are limited [11]. Additional disadvantage with the lithium-ion batteries is the price. Compared to the other battery types, lithium-ion batteries are often four times more expensive.

4.1.6. Charging Li-ion

The charging of lithium-ion batteries has to follow strict guidelines. Most cells are charged to 4.20 V ± 0.05 V. If charging to 4.10 V the capacity drops by 10%, but cycle life is extended (Newer cells show similarly good cycle life at 4.20 V). The charging of lithium-ion batteries occurs in three stages, see Figure 45. Simplified we can say that stage one charges the voltage, and stage two charges the capacity. Stage three is used as a topping, and compensates for the already very small self discharge. It is very important not to overcharge the battery because the lithium ions will convert to solid lithium and make the battery a safety risk [11].

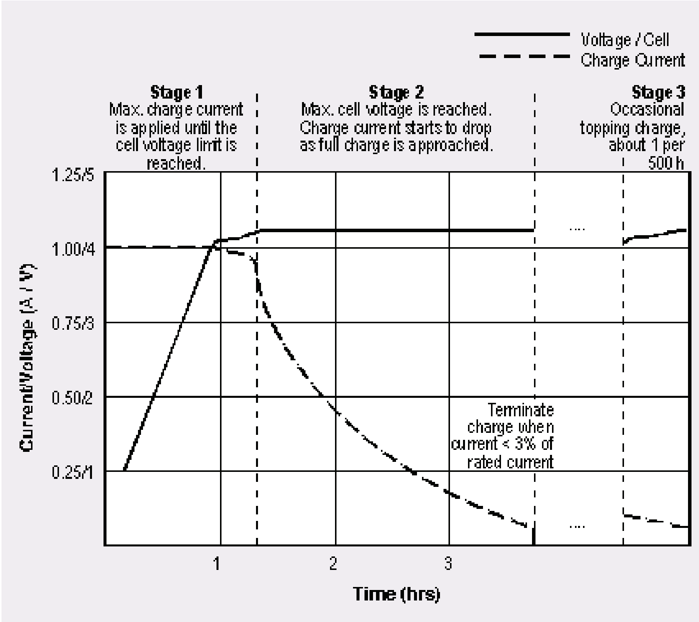

Figure 45: The three stages of lithium-ion battery charging [11].

The normal charging time is about three hours where stage one is roughly one hour and stage two is two hours. Some manufacturers claim that they have a fast charger, but what they have is a charger which stops when stage one is finished (desirable voltage acquired). This utilizes just about 70% of the battery's capacity. Some applications use chargers with currents of 1 C+, as for example cell phones. This is because cycle life is not as important when the product is often disposed before the capacity drops significantly [11].

4.1.7. Lithium-polymer (Li-Poly)

Compared to the lithium-ion battery the lithium-polymer battery provides many of the same characteristics. The difference is that the lithium-polymer battery does not use a volatile electrolyte and can therefore sustain significant abuse without explosion or fire. In order to replace the traditional porous separator the lithium-polymer uses a polymer soaked with gelled electrolyte. Compared to the rest of the batteries the lithium-polymer battery has the highest gravimetric energy density, as well as the highest volumetric energy density, see Figure 47 below. Unfortunately the lithium-polymer technology is not a mature technology and there are no standard sizes available. The technology finds its market in wafer-thin geometries such as batteries for credit cards, making this technology the most expensive one available. Although it is worth mentioning this technology, the lithium-polymer battery is not relevant in our case and the explanations of it will be limited [14].

4.1.8. Lead acid (Pb-acid)

The lead acid was first invented by the French physician Gaston Plantè in 1859 and became the first rechargeable battery ever for commercial use. By the mid 1970s researchers developed the maintenance free battery which could operate in any position (unlike the well known car batteries which needed water refilling and which were not recommended to be used in the upside down position). These batteries were called sealed-lead-acid (SLA) and valve-regulated-lead-acid (VRLA). This can be confusing because technically both batteries are the same.

The lead-acid batteries are very heavy batteries because of the use of lead (Pb) as electrodes. They have the lowest energy density of the batteries mentioned, in addition to poor performance at low temperatures. At higher temperatures, on the other hand, they have problems with decreased cycle life. A guideline that can be followed is that for every 8 °C increasing above 25 °C, the cycle life is cut in half. Lead acid batteries do not like deep cycling. Each full discharge causes damage and slightly lowers the batteries capacity. It is important to store the batteries at a fully charged state. If not, the battery's capacity may decline dramatically over time. If all precautions are held, the cycle life of a lead-acid battery is about 200-300 cycles. The use of lead always causes environmental concerns [12].

On the other hand, lead acid batteries are cheap. They perform relatively well under high load currents. They have no problems with memory effect, and have a self discharge rate at 40%, which is remarkably better than the NiCad [12].

4.1.9. Charging Pb-acid

Lead-acid batteries have no possibility of fast charging. The normal charging time is about 6 – 12 hours. It takes five times as long to charge a lead-acid battery to the same level as it does to discharge. For nickel based batteries the ratio is 1:1 and for lithium-ion based it is roughly 1:2. The charging characteristics have some similarities with the Li-ion batteries, but clearly differ itself from NiCad and NiMH batteries. The charging characteristic is shown in Figure 46. This is how the batteries would behave if they were charged by a special designed charger. One can also charge lead-acid batteries with a common power supply [13].

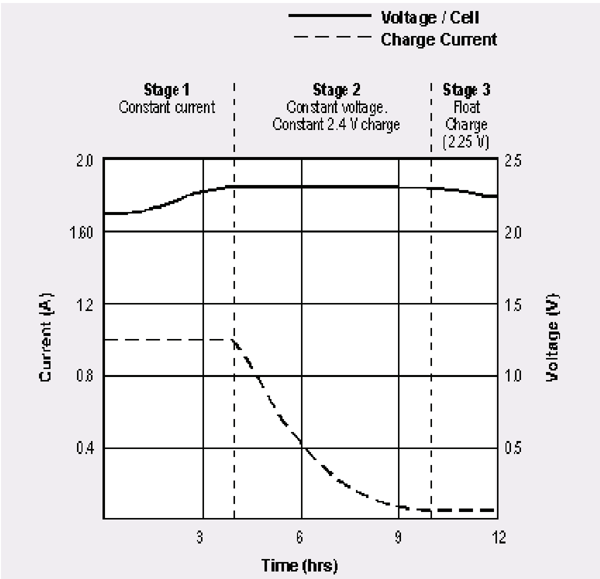

Figure 46: The battery charging characteristic [13].

If you use a power supply make sure you have a safe charging voltage and current (given in the battery data sheet). This voltage is typically 10-15% higher than the total battery voltage. The charging current is between 10–30% of the rated Ah capacity. It is important not to overcharge under these conditions, since the constant power supply will not shift to trickle or float charge [13].

4.1.10. Summary

Now that the different batteries have been discussed, it is natural to summarize the most important aspects about them, see Table 6, Table 7 and Figure 47. As mentioned earlier in Chapter 1.1 there is a need for two battery packs in order to have a proper operation of the vehicle and its safety concerns. One of the batteries will only be used to provide external power in the start-up sequence of the fuel cell system. The other will be responsible for the safety system, providing energy for the lights and their control, hydrogen sensor for the safety of the driver if a leak occurs in the vehicle, two solenoid valves for controlling hydrogen supply to the fuel cell and the horn.
It is easy to understand that these two applications for the battery packs differ a lot from each other. Chapter 4.2 presents the different needs for the batteries and based on this comparison the correct battery types are chosen.

Table 6: The approximation of: relative cost, weight, operating temperature, number of cycles, shelf life (if properly stored) and the electrochemical voltage-potential difference [14].

Chemistry	Relative Cost	Weight	Temp (ºC)	Cycle Life	Shelf Life (Months)	Volts Per cell
Lead Acid	X	Very Heavy	-15 to 50	180+	6	2.0
Nickel Cadmium	2X	Heavy	-20 to 65	500+	6	1.2
Nickel Metal Hydride	2.5X	Moderate	-10 to 60	500+	12	1.2
Lithium Ion	4X	Light	-10 to 60	500+	12	3.7
Lithium Polymer	5X	Light	-10 to 60	500+	12	3.7

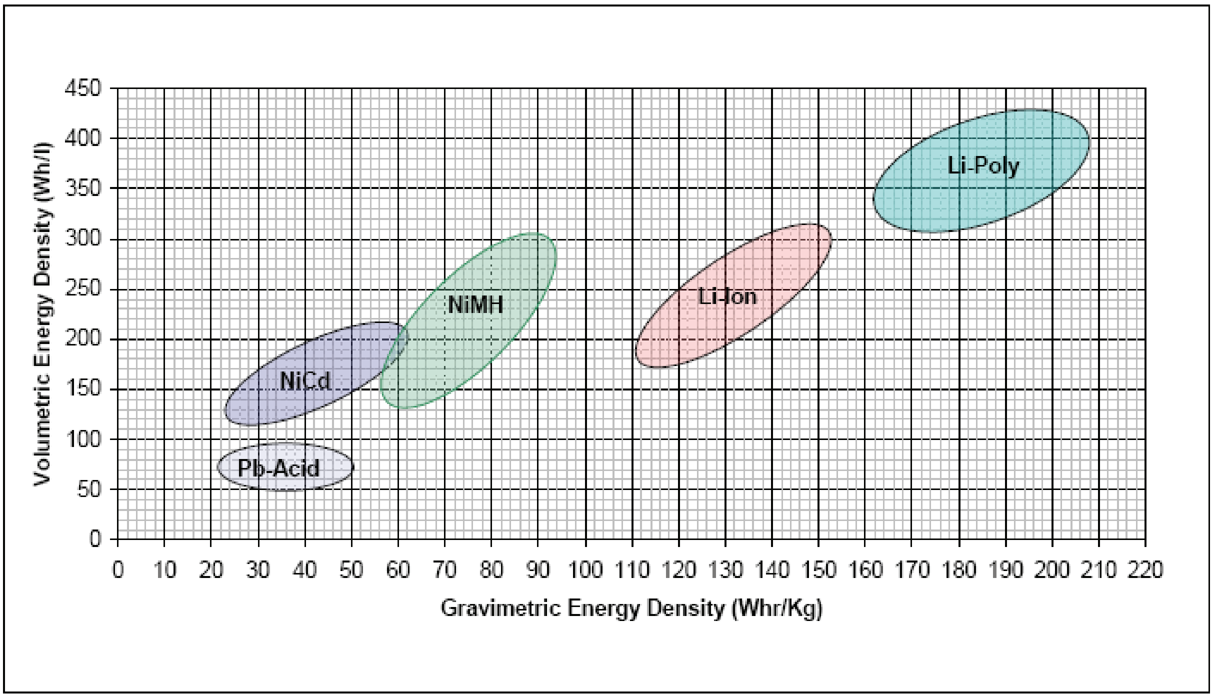

Figure 47: Gravimetric and volumetric energy density [14].

Table 7: Summary of advantages, disadvantages and common application of the NiMH, NiCad, Li-ion and Lead acid batteries [14].

Type	Advantages	Disadvantages	Applications
NIMH	High volumetric and gravimetric energy density Long cycle life Good storage characteristics No memory effect/voltage depression Environmentally friendly Slow and rapid charge compatible	Overcharge/overdischarge Protection needed	Cellular phones, camcorders, emergency backup lighting, power tools, laptops, electric vehicles
NiCad	Long cycle life Good storage characteristics Rapid charge compatible	Low volumetric and gravimetric energy density Memory effect/voltage depression Environmental and health concerns (e.g. kidney damage, itai-itai (ouch-ouch) disease in Japan, and Mutagenic)	Calculators, power tools, tape recorders, flashlights, medical devices (e.g., defibrillators), electric vehicles, space applications
Li-ion	Very high volumetric and gravimetric energy density Good storage characteristics	High cost Costly charge and discharge control required Lower rate capability Low high temperature performance Potential health risks/catastrophic failures	Laptops, cellular phones, electric vehicles, digital cameras, camcorders, DVD players
Li-poly	Very thin profile Flexible form factor Lightweight Improved safety	Expensive No standard sizes High cost-to-energy	Calculators, digital cameras, pagers, lap tops, phones, PDAs
Lead acid	Low cost High rate capabilities	Low volumetric and gravimetric energy density Fair cycle life Must be charged to be stored Environmental and health concerns (e.g. mental retardation, interference with kidney and neurological function, hearing loss, blood disorders, hypertension)	Wheelchairs scooters, golf carts, vehicles and UPS

4.2. Determining the Right Battery Type

As mentioned above the applications for the two different battery packs differ a lot compared to one another. Table 8 summarizes the desired characteristics and based on these characteristics the different battery types will be determined.

Table 8: Comparison between the two different applications for the batteries.

	Responsibility	Placement	Weight	Cost
Battery type 1	Provide energy for the start-up sequence of the fuel cell system	Outside the vehicle. Batteries used for this purpose are according to the Shell Eco-marathon rules not allowed to be carried inside the vehicle.	Since the battery is not situated inside the vehicle when driving, the weight is not a big concern.	The PureChoice project has acquired sufficient funds and the price is therefore not a big concern.
Battery type 2	Provide energy for the lights and their control, hydrogen sensor, two solenoid valves and the horn.	Inside the vehicle.	Since the battery will be situated inside the vehicle it is desirable to minimize the weight of it as much as possible.	

Based on the comparison performed in Table 8 and what has been learned so far in Chapter 4, it is fairly simple to draw the conclusion that the two different battery types needed in the PureChoice vehicle are the lead-acid and lithium-ion batteries.
The reason for this decision is because the lead-acid battery is cheap and will provide the necessary power to power up the fuel cell system, while the lithium-ion battery is light and has the highest gravimetric and volumetric energy densities.
Further information about the batteries acquired and their suppliers is given below in Chapter 4.2.1 and 4.2.3.

4.2.1. Biltema Battery

The lead-acid batteries acquired are the Biltema 80-410 batteries, see Figure 48. These batteries are 12 V, 7.2 Ah, valve regulated, lead-acid batteries. Since the fuel cell needs a voltage in the range between 22 V – 30 V to power-up the surrounding controlling system, two of these batteries have been acquired and connected in series.

Figure 48: Biltema battery [15, 16].

Some of the specifications worth noticing are [16]:

Nominal discharge time at 4.32 A:	1 hour
Maximum charging current:	2.16
Maximum discharge current for 5 seconds:	288 A
Weight:	2.7 kg

The full capacity description is shown in Figure 49 [15]. The figure is illustrating how much current that theoretically can be drawn over a given amount of time. It is very important to remember what was mentioned earlier in Chapter 4, namely that it is not possible to draw 7.2 A during one hour from a 7.2 Ah battery. In order to define just how the batteries will behave when used and in order to be sure that they contain enough energy, a battery test was performed, see Chapter 4.2.2.

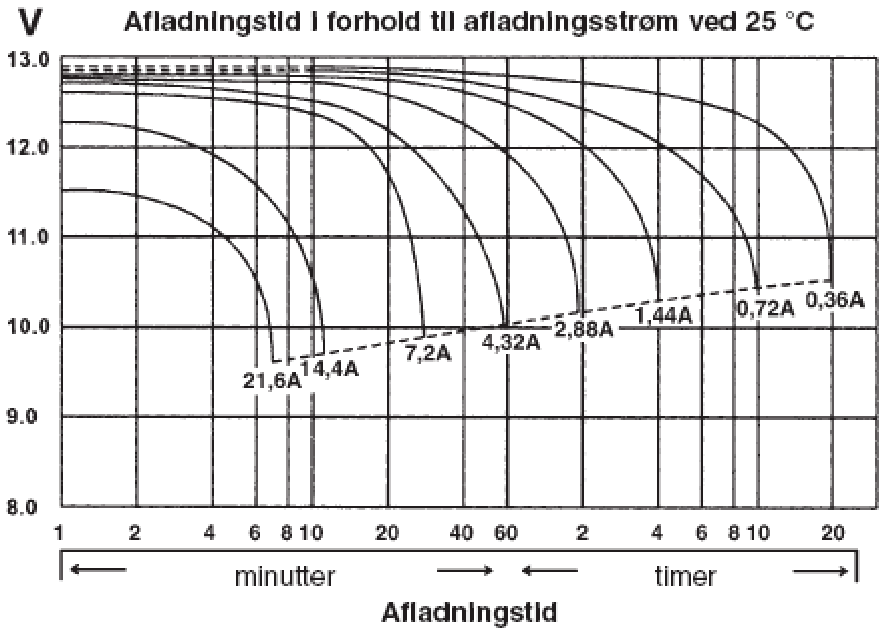

Figure 49: The figure is showing how the battery will behave at different constant currents. Cut of voltage is marked with the dotted line. Y-Axis is showing voltage and x-axis is showing the time [16].

4.2.2. Testing the Biltema Lead-acid Battery

With a battery test you will find the capacity of a battery at a given current. The test is performed by keeping a constant current over time, see Figure 50. When the voltage drops below the “cut off voltage” (the cut off voltage is given by the manufacturer) you stop the test. The time in hours multiplied with the constant current gives you the capacity of the battery in Ah (Ampere hours). It is important to notice that the capacity given by the manufacturer is always at very low currents, seeing that these tests always give the best results. The higher constant current you draw the lower will the capacity of the battery be.

The batteries were tested at a constant current of 3.5 A and the “cut off voltage” given in the application note was at around 19.2 V [16].

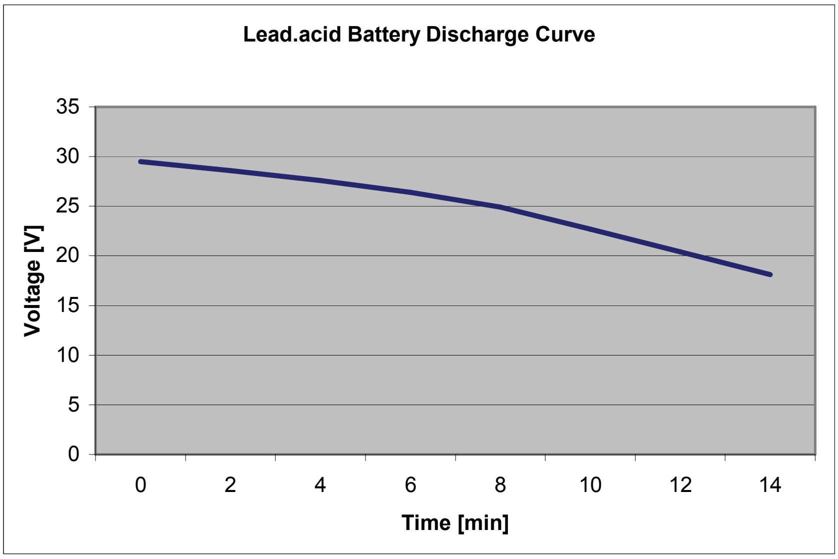

Figure 50: Discharge curve for the two Biltema lead acid batteries.

After about 14 min the battery pack consisting of two 12 V, 7.2 Ah batteries was depleted. The time in hours is 0.233 and the current drawn is 3.5 A. Multiplying these two will give us 0.82 Ah which is the total capacity one can utilize. This capacity is way lower than the theoretical capacity of 14.4 Ah. For additional information about the test performed, see Appendix C.
Now that the total capacity has been determined, the necessary energy considerations can be determined, see Eq. (4-2). The highest available capacity will then be:

$$0.82Ah \cdot 24V = 19.6Wh \approx 70.6kJ \tag{4-2}$$

Energy needed to power-up the fuel cell system, see Eq. (4-3):

Fuel cell demands:
- 2.7 Amp average
- 25 Volts
- 8.5 sec

$$Energy = 25V \times 2.7A \times 8.5\sec = 573.75J \tag{4-3}$$

It is easy to see that that the energy the lead-acid batteries are able to provide is more than enough for providing the necessary start-up power.

4.2.3. Lithium-ion Battery

The lithium-ion batteries acquired to provide energy for the safety system in the vehicle are the VARTA 3.7 V, 2.2Ah batteries, see Figure 51 and Table 9. The main reason for choosing this battery type is because of their extremely light weight, easy application and availability. Since the batteries are sold separately, one has the opportunity to calculate just how many batteries that are needed in series and parallel construction in order to meet the energy demands of the safety system, see Chapter 4.2.5. This way of constructing the battery pack will ultimately save any unwanted weight in the vehicle.

Along with the batteries, the appropriate lithium-ion charger was also purchased, both supplied from Farnell, see Figure 51. In order to avoid charging the batteries one at the time, a small connection board was constructed to speed up the charging process and make it a simpler task. At a later stage an additional lithium-ion charger was bought to further speed up this process. As mentioned earlier in Chapter 4.1.6, the Lithium-ion batteries have often a charging time of about 2.5 – 3 hours and it was necessary to minimize this time as much as possible. In order to define just how the batteries will behave when used and in order to be sure that they contain enough energy, a battery test was performed.

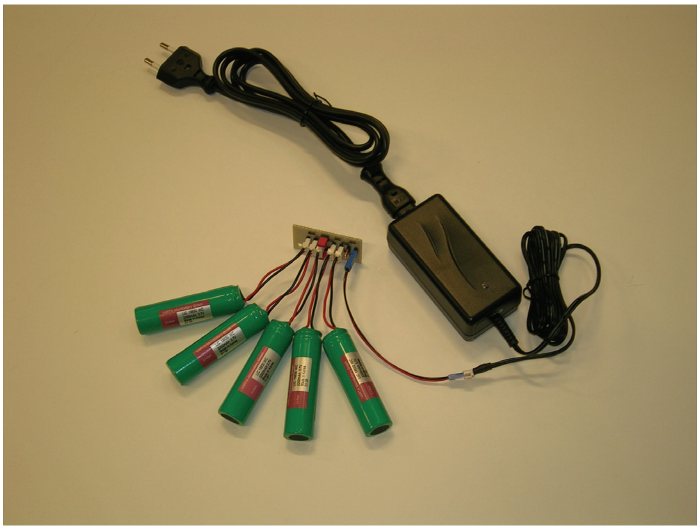

Figure 51: 3.7 V, 2.2Ah VARTA Li-ion batteries.

Table 9: Key figures for the VARTA Li-ion battery [17].

Key figures:	
Type	Li-ion
Nominal Voltage	3.7 V
Operating Range	2.75 V to 4.2 V
Typical Capacity	2200 mAh
Max Charge Voltage	4.2 V
Max Charge Current	1600 mA
Max Discharge Current	2200 mA
Standard Charge	1100 mA 3h
Fast Charge	2200 mA 2.5h
Specific Energy	177 Wh/kg
Weight	46 g apiece

4.2.4. Testing the VARTA Li-ion Battery

When testing the VARTA Li-ion battery, same procedure was performed as when testing the lead-acid Biltema battery. A constant current was kept over time and after the voltage had dropped below the “cut off voltage”, the test was stopped and the energy was calculated.

The battery was tested at a constant current of 1 Amp and the “cut off voltage” given in the application note was at around 2.75 V [17]. Note from Figure 52 that the voltage is stable for a longer time compared to the discharge curve of the lead-acid battery. This is typical for Li-ion batteries, and is often why they are preferred over other types of batteries.

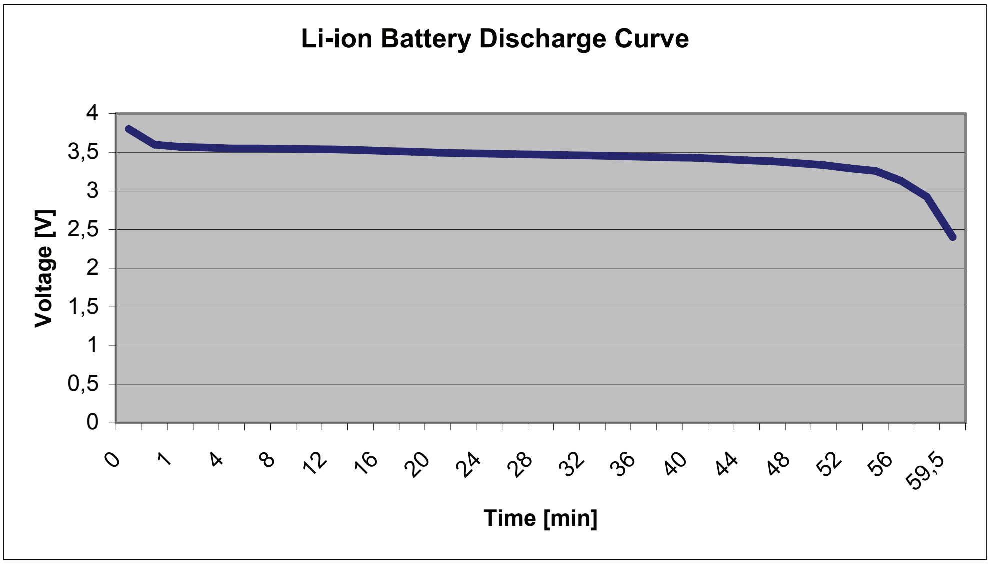

Figure 52: Discharge curve for the VARTA Li-ion battery.

After about 60 min the 3.7, 2.2Ah VARTA Li-ion battery was depleted. The time in hours is 1 and the current drawn is 1 A. Multiplying these two will give us 1Ah which is the total capacity one can utilize. This capacity is lower than the theoretical capacity of 2.2Ah. For additional information about the test performed, see Appendix D.

Battery’s highest available capacity:

$$1Ah \cdot 3.7V = 3.7Wh = 13.32kJ \qquad (4\text{-}4)$$

Now that one knows just how much energy it is possible to utilize from a single battery, see Eq. (4-4), it is possible to calculate just how many batteries that are needed in order to provide the necessary energy for the safety system in the PureChoice vehicle.

4.2.5. Determining the Amount of Li-ion Batteries Needed

Before determining how many batteries that are needed in the final battery pack, it is important to calculate just how much energy the safety system in the vehicle will consume. The safety system includes, as mentioned earlier in Chapter 1.2, components such as the LOGO! Micro Automation module controlling the lights, hydrogen sensor for the safety of the driver, two solenoid valves for controlling hydrogen supply to the fuel cell and the horn. In addition to these, an energy measurement device called Watt's up was also supplied by the same battery pack. Their individual characteristics and calculated energy demands are presented below in Table 10. Since the energy from the batteries is needed for 54 minutes and 25 seconds (3265 sec), which is the time available to finish the race at the Shell Eco-marathon competition before being disqualified, this time has been used as the minimum requirement for the final battery pack.

Table 10: Energy needed from the Li-ion battery pack.

LOGO!	14 V	0.034 A	3265 sec	$E = 14 \times 0.034 \times 3265 = 1554.14J$
Nexa Solenoid Valve	14 V	0.5 A		$E = 14 \times 0.5 \times 3265 = 22855J$
ASCO Solenoid Valve	14 V	0.80 A		$E = 14 \times 0.8 \times 3265 = 36568J$
HydroKnowz Hydrogen Sensor	14 V	0.08 A		$E = 14 \times 0.08 \times 3265 = 3656.8J$
Watt's up	14 V	0.007 A		$E = 14 \times 0.007 \times 3265 = 319.97J$
Horn*	14 V	2.0 A	280 sec	$E = 14 \times 2 \times 280 = 7840J$
*using the horn for 20 sec of the 4 min needed per driving lap, for 14 laps				
** 14 V has been used because that is the voltage the battery pack was holding for most of the time, although the voltage varied between 12 V and 16.5 V.				

Total energy consumption of the devices in the vehicle is 72 794 Joules. Since this energy is right on the limit of what is necessary, additional 30% of energy is added as a buffer. The new energy required is therefore 94.6 kJ. It is important to note that the horn is demanding about 2 amperes when it is activated and enough batteries have to be placed in parallel to meet this requirement.

4.2.6. Constructing the Li-ion Battery Pack

Now that the total energy has been calculated and the individual capacity of the batteries is determined, it is possible to construct the necessary Li-ion battery pack, see Figure 53.
The total pack needs to be able to deliver the operating voltage of 12 – 16.5 V, a maximum ampere value of 2 amperes and contain enough energy to meet the 94.6 kJ demand.

Four 3.7, 2.2 A VARTA batteries in series provide the needed voltage range 12 – 16.5 V and contain 53.28 kJ. Placing additional 4 batteries in parallel gives the needed voltage range 12 – 16.5 V, the 2 A peak current and 106.56 kJ of available energy. In case larger spikes than two amperes should occur, one additional row of Li-ion batteries was placed in parallel. These batteries not being the same at the ones mentioned above. The additional four batteries placed are the prismatic 3.7 V, 1.1 Ah VARTA Li-ion batteries. This has been done to bring some additional safety. Additional weight introduced by these four batteries is only 80 grams, and is a small price to pay in weight in order to be safe. Due to time issues the last batteries were not tested as thoroughly as the other, but same reasoning can be applied for them as for the 2.2Ah Li-ion batteries.

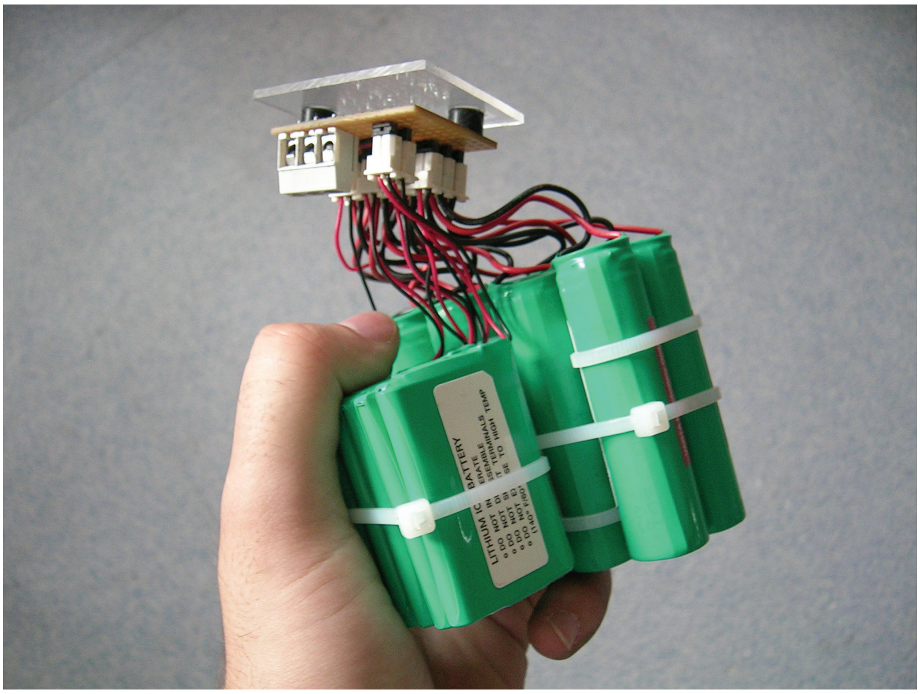

Figure 53: The constructed Li-ion battery pack and the discharging circuit.

The total energy of the combined battery pack is therefore 106.56 kJ + ($0.5Ah \cdot 3.7V \times 4 = 7.4Wh = 26.64kJ$) = 133.2kJ. Total energy available was now about 40 % more than what was necessary. Combined weight of the battery pack and the constructed discharging board is 512 grams, which is a considerable reduction in weight compared to the Li-ion battery packs available from different distributors in the US.
Two different voltages are drained from the battery pack because two of the 14 batteries are only used for delivering energy to the lights. This has been done in order to avoid using resistances to reduce the total battery voltage to the desired voltage required by the LED lights. Avoiding the use of resistances also minimizes unwanted losses in the system.

5. Introduction of the Supercapacitors

The capacitors in vehicles are often characterised as devices that allow the recovery of kinetic energy when the vehicle slows down, and to increase the available peak power during times of rapid acceleration, thus allowing a smaller engine or fuel cell to power a vehicle [1]. Supercapacitors, also known as ultracapacitors, are devices that have high specific powers, which means that they can take in and give out energy very quickly. Unfortunately, the amount of energy they can store is currently rather small. They are therefore characterizes as devices that have a good power density, but a poor energy density. Additionally, supercapacitors have a long cycle life, they are relatively inexpensive, require almost no maintenance and do not deteriorate with use [18]. In recent years the supercapacitor technology has advanced tremendously, but additional advances are needed before they alone can serve as the sole energy source of a vehicle. If, on the other hand, the supercapacitors are used in conjunction with batteries or fuel cells, they would be excellent portable energy sources with sufficient specific energy and specific power for the next generation of vehicles [19]. For multi-stop vehicle operations tests have shown that a 25-30% fuel saving was obtained in a compact hybrid vehicle fitted with regenerative braking [20]. A further explanation of these devices is presented below.

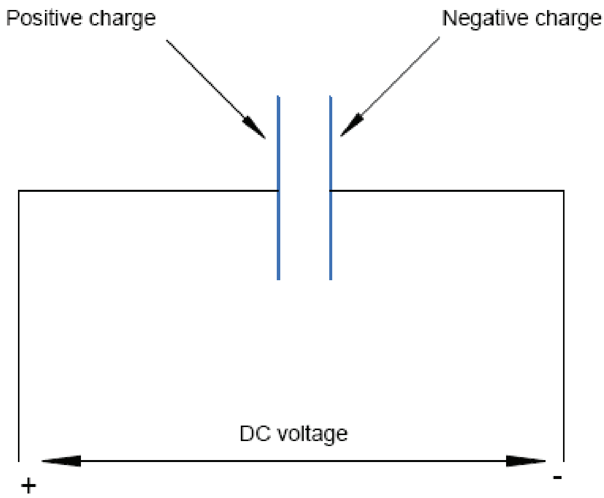

Figure 54: Principle of the capacitor [1].

As shown in Figure 54, a capacitor is a device in which two conducting plates are separated by an insulator, with a voltage connected across. One plate on the capacitor is positive whereas the other one in negative. Opposite charges on the plates attract each other, thus storing energy. The charge Q stored in a capacitor is shown in equation (5-1), where the capacitance C is given in Farads and the voltage V in Volts.

$$Q = C \times V \qquad (5\text{-}1)$$

The equation (5-2), on the other hand, illustrates the energy that can be stored in a capacitor, where E is the energy stored in Joules.

$$E = \frac{1}{2} C V^2 \qquad (5\text{-}2)$$

The capacitance C of a capacitor in Farads is given by the equation (5-3), where ε is the permittivity of the material between the plates, A is the plate area and d is the separation of the plates.

$$C = \varepsilon \frac{A}{d} \tag{5-3}$$

It is fairly easy to understand that if the value d can be reduced, than the capacitance C in Farads will increase. This is the case for modern supercapacitors. Large plate areas combined with very small separation of the plates are giving us incredibly large values in Farads, where a 4000 F capacitor can be fitted into a container the size of a beer can.

The main problem with today's supercapacitors utilizing this technology is that the voltage across the capacitor can only be between 1 to 3 V. Considering the previously mentioned equation (5-2), it is easy to see that the energy that can be stored in a capacitor will be considerably reduced. Immediately one would try to solve this problem by placing several supercapacitors in series in order to increase the voltage, which manufacturers of course need to do. By doing this one unfortunately creates additional issues, where the main being that if two capacitors C1 and C2 are connected in series, then it is well known that the combined capacitance is given by the Eq. (5-4).

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \tag{5-4}$$

At the same as one adds cost by introducing more capacitors, one also reduces the total capacitance in the system. Since the energy increases as the voltage squared, this solution does result in more energy stored, but not as much as one could expect by only considering the equation (5-2), without knowing all the additional outcomes.

If all these factors were not enough, there is the additional problem of *charge equalisation*. What this implies is that if one considers a string of capacitors in series, where the same current flows through the individual capacitors; one would ultimately expect that the charging and discharging of these capacitors would happen simultaneously. In real life this is not the case, mainly due to the different self-discharges of the individual capacitors. The insulation between the plates of the capacitors is not perfect, and obviously the self-discharge can not be equal. When charging a capacitor module with several modules in series there would be a difference in the charge build-up across the individual capacitors. This charge-up can in some cases lead to that one of the capacitors is charged beyond the maximum of 3 V and hence destroyed. In systems consistent of more than six capacitors, the only solution to this is to have *charge equalisation circuits* [1]. These circuits are connected between two and two neighbouring capacitors, continuously monitoring the voltages between them and moving charge from one to the other. This way the charge from one pair would be moved to the next and the voltages on the individual cells would at all times be the same, or at least close to the same value. An illustrative figure of the *charge equalisation circuits* is presented in Chapter 5.2, where the BCAP1500 E270 supercapacitor module for the PureChoice vehicle is explained. Although these circuits make it possible to add several capacitors in series, the drawback is that they increase the cost and size to a capacitor storage system. They also consume some energy, although very efficient designs are available today.

5.1. The BCAP1500 E270 Supercapacitors

The supercapacitors chosen for the PureChoice vehicle are the 1500 Farad 2.7 Volt modules by the name BCAP1500 E270, see Figure 55. They are constructed in the sense that they have high energy density at the same time as they have low internal resistance. Their application spreads from renewable energy, industrial, UPS, telecommunications and consumer electronics [21].

Figure 55: The BCAP1500 E270 supercapacitor.

Further information and some relevant calculations are given in the Table 11 below.

Table 11: BCAP1500 E270 per module specification [21].

BCAP1500 E270		
C	1500 Farads	Capacitance
V	2.70 V DC	Operating Voltage
V	1.5 – 2.75 V DC	Normal Voltage Range
Vol	0.264 l	Volume
m	0.32 kg	Mass
ESR, DC	0.63 mΩ	Equivalent Series Resistance
ESR, 1kHz	0.43 mΩ	Equivalent Series Resistance, 1kHz
Ic	3.0 mA	Leakage Current after 72 h, 25ºC
Rth	4.5 C/W	Thermal Resistance
Isc	3900 A	Short Circuit Current
Emax	4.75 Wh/kg, (5-5)	Maximum Specific Energy
Pmax	13245 W/kg, (5-6)	Maximum Theoretical Specific Power
Pd	4339 W/kg, (5-7)	Maximum Accessible Specific Power

$$E\max = \frac{\frac{1}{2}CV^2}{3600xmass} = \frac{\frac{1}{2}\cdot 1500\cdot 2.7^2}{3600\cdot 0.32} = \underline{4,75Wh/kg} \tag{5-5}$$

$$P\max = \frac{\dfrac{V^2}{4R(1kHz)}}{mass} = \frac{\dfrac{2.7^2}{4\cdot 0.43\cdot 10^{-3}}}{0.32} = \underline{13245W/kg} \tag{5-6}$$

$$Pd = \frac{\frac{0.12V^2}{R(DC)}}{mass} = \frac{\frac{0.12 \cdot 2.7^2}{0.63 \cdot 10^{-3}}}{0.32} = \underline{4339 W / kg} \qquad (5\text{-}7)$$

These values confirm that the supercapacitors contain high specific powers per kilo of weight. Compared to a single 3.7 V Li-ion battery, see Table 9, it is easy to see that a BCAP1500 E270 supercapacitor can store less specific energy per kilo of weight. At the same time it is worth noting that the supercapacitor module is able to deliver its stored energy almost instantaneously, while the Li-ion battery experiences inertia when drained.

5.2. Constructing the Supercapacitor Module

Main reason for ordering the 1500 Farad Supercapacitors, which can seem over dimensioned, is because of the changing application for them. Areas where they would be used have been changed several times and due to this one ended up having bigger supercapacitors then needed. The supercapacitor module constructed was assembled for the propulsion system presented in Figure 2. At this point in the project we needed a power source that would be able to deliver energy to the lights, their control and any additional measurement devices. They could also be used to provide power to the fuel cell system in case it turned off during the race. Since the supercapacitors were larger than what was necessary for this task, the amount of supercapacitors in series would be reduced by the use of a DC/DC converter, see Figure 64. The V28A24C200BL converter used for this purpose has a voltage range between 9.5 – 30 V and can deliver a desired fixed voltage at the output. The DC/DC converter allows the user to use just the right amount to supercapacitors in order to meet the energy demands. Reducing the need for many supercapacitors in series will ultimately reduce any unnecessary weight in the vehicle.
When determining just how many supercapacitors that should be placed in series, it was important to remember that all voltage below 9.5 V would not be possible to utilize. The normal voltage range for an individual BCAP1500 E270 supercapacitor is between 1.5 and 2.75 V DC, see Table 11, this range being the range in which one can store and use energy from.

Figure 56 below illustrates the voltage profile of a supercapacitor. The voltage profile has two components; a resistive- and a capacitive component. As the supercapacitor module is charged and discharged, the capacitive component will change due to the internal stored charge in the individual supercapacitor modules. This charge is directly reflecting the change in voltage, because the voltage of the module will have a minimum and maximum operating voltage [22].

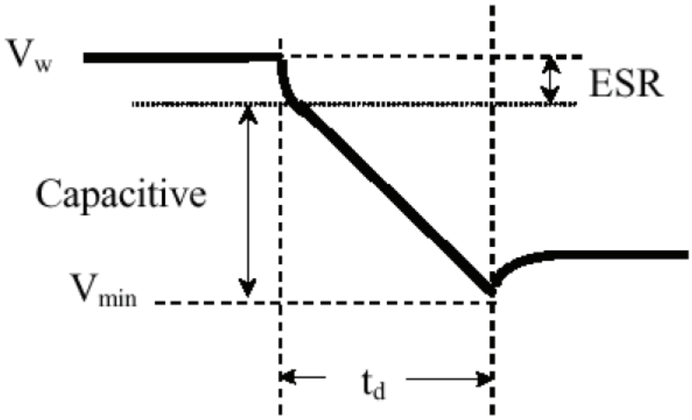

Figure 56: Constant current discharge profile [22].

where:

V_w	= working voltage
ESR	= voltage drop due to equivalent series resistance
Cap	= voltage drop due to discharge of the capacitor
V_{min}	= minimum voltage allowed by system
t_d	= discharge time

As the supercapacitor module is charged or discharged, the internal energy of the module is changing and can directly be see as a drop or rise in the total voltage [22].

Combining five supercapacitors in series would result in a voltage range between 7.5 V DC and 13.75 V DC, which is not desired because it would not be possible to utilize all the energy stored below 9.5 V. If on the other hand six supercapacitors are combined in series, they would give a voltage range between 9 V DC and 16.5 V DC, and therefore be able to deliver more energy and adapt better with the V28A24C200BL converter. The energy difference between using five and six supercapacitors in series is shown in Eq. (5-8) and Eq. (5-9). Note that placing 5 supercapacitors in series will increase the voltage five times, but it will also reduce the total capacitance five times, as explained earlier in Chapter 5.

$$E = (\frac{1}{2}CV^2) = (\frac{1}{2}\times(1500\div 5)\times(13.75-7.5)^2) = 5859.4J \qquad (5\text{-}8)$$

$$E = (\frac{1}{2}CV^2) = (\frac{1}{2}\times(1500\div 6)\times(16.5-9)^2) = 7031.3J \qquad (5\text{-}9)$$

Placing one additional supercapacitor in series would give 1171.9 Joules more and only introduce an additional weight of 320 grams.

The components used when constructing the supercapacitor module are shown in Figure 57 and Figure 58 and the final module is shown in Figure 59.

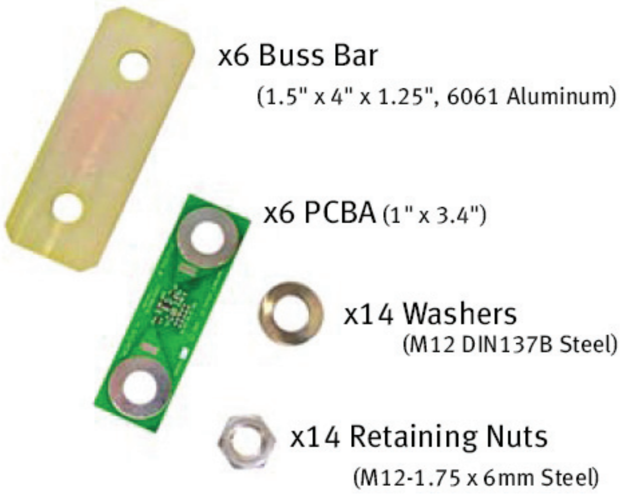

Figure 57: The interconnection parts and the equalisation circuits used to construct the supercapacitor module [23].

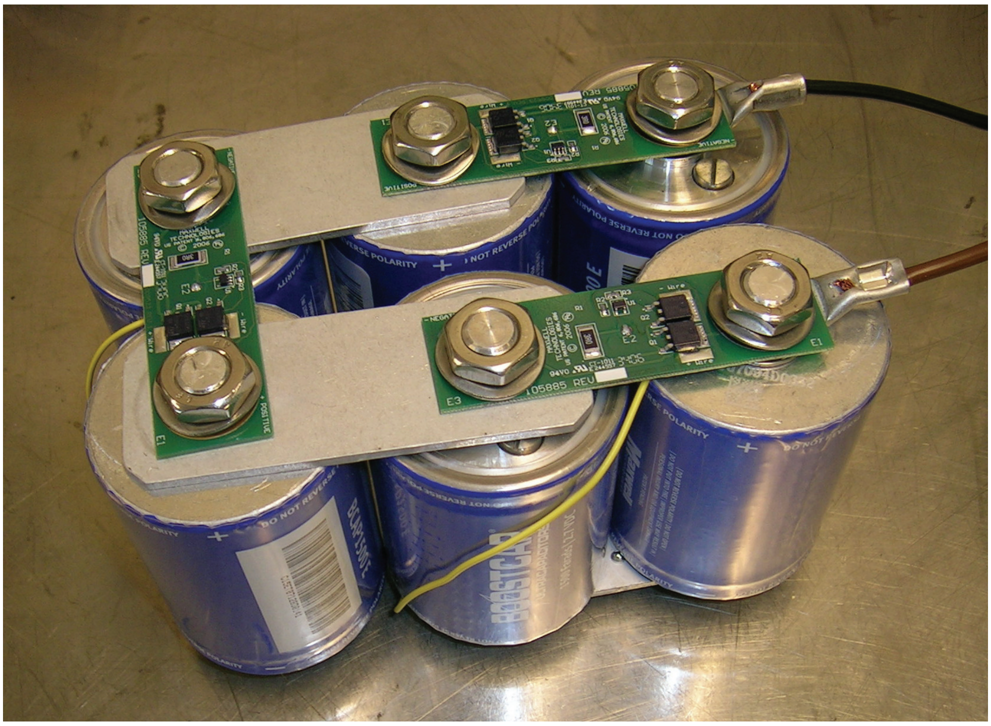

Figure 58: The constructed supercapacitor module.

Final supercapacitor module constructed has a combined weight of about two kilos. It has a voltage range between 9 and 16.5 V DC and when charged it contains energy equivalent to 7031.3 Joules. The module shown in Figure 58 is not charged. One has to show great concern when utilizing supercapacitors. They have to be properly shielded from the rest of the system and from each other. If not a short circuit can occur. Since these supercapacitors contain a lot of charge, the explosion can lead to severe damage or personal injuries.

5.3. Testing the BCAP1500 E270 Supercapacitors

The constructed supercapacitor module was tested with a lab setup shown in Figure 59. It was tested how much time it would take for an empty module to be charged to full capacity, charging it at a constant current rate of ten amperes, see Figure 60. The charged module was then depleted with the same current it was charged by, see Figure 61. The two tests were compared and an appropriate efficiency for the module was determined. For additional information about the performed test, see Appendix E.

Figure 59: Shows the setup used when testing the supercapacitor module. A "Watt`s up" energy measurement device is used to register necessary Wh and Ah ratings.

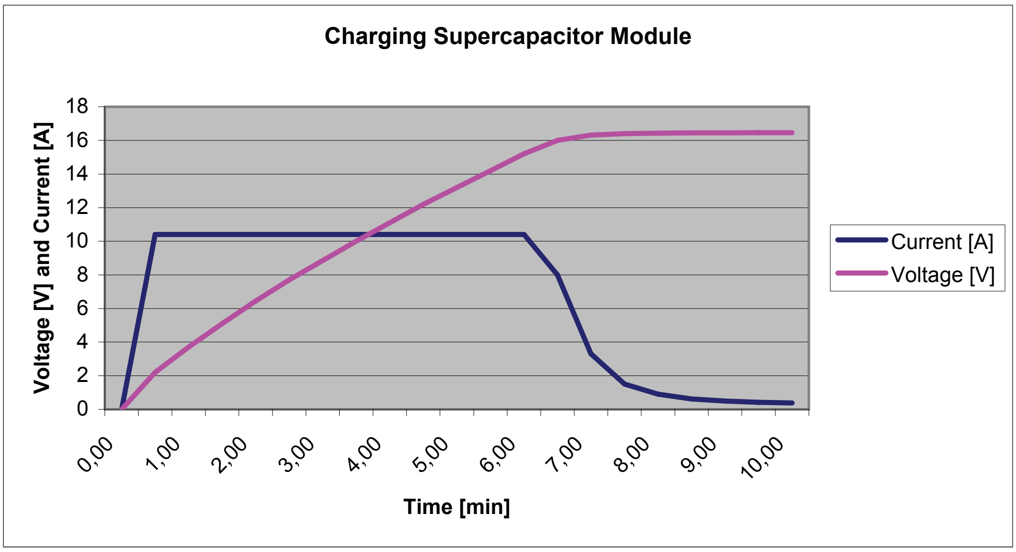

Figure 60: Registered voltage and current values when charging the supercapacitor module.

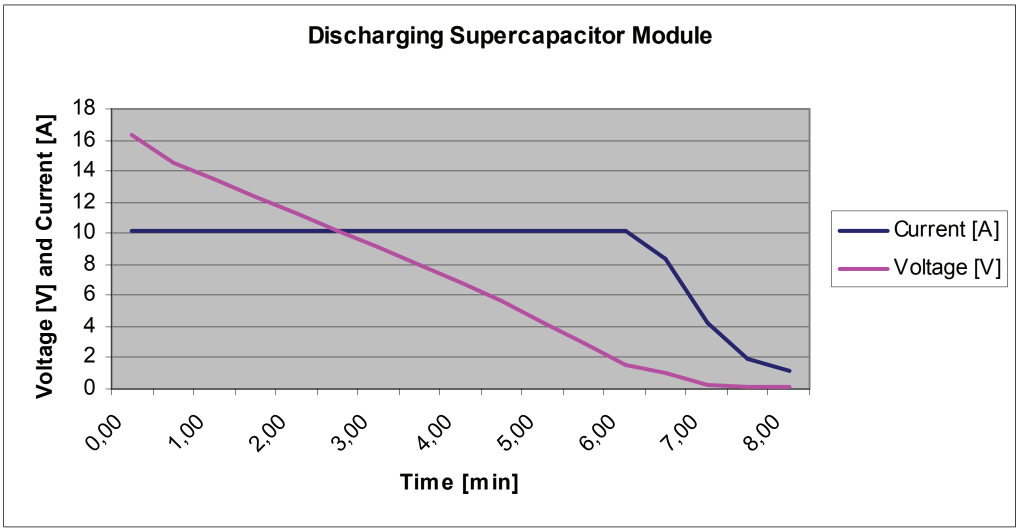

Figure 61: Registered voltage and current values when discharging the supercapacitor module.

Figure 60 shows that the supercapacitor module is almost fully charged after about 6.5 minutes because this is the point where the current starts decreasing rapidly and the voltage is slowly being built up. Same time can be registered when discharging the module. The module is almost depleted after about 6.5 minutes.

Total charged energy was 11.4 Wh and average charging current was 1.209 Ah.
Total discharged energy was 10.4 Wh and average charging current was 1.143 Ah.

Calculated efficiency is therefore 10.4 / 11.4 Wh = 0.912 % which is a disappointment when compared with the theoretical efficiency of about 99 %. The reason for this difference is most likely due to the simple testing setup or due to uncertainty in the registered values.

Simple calculations can be performed in order to determine how big the efficiency should have been, see Eq. (5-10) - Eq. (5-12). The equivalent series resistance is as mentioned in Table 11, 0.63 mΩ.

$$P_{LOSS} = I^2 \times ESR \times N_{SERIES} = 10^2 \times (0.63 \times 10^{-3}) \times 6 = 0.378W \quad (5\text{-}10)$$

$$P_d = U \times I = 16.5 \times 10 = 165W \quad (5\text{-}11)$$

$$\eta = 1 - \left(\frac{P_{LOSS}}{P_d} \right) = 0.998\% \quad (5\text{-}12)$$

6. Introduction of the DC/DC Converters

DC–DC converters have a DC voltage on the input and output side, these two voltages usually being different from each other. The most common used converters are Buck (step down), Boost (step up) and Buck–Boost (step up, step down) converters. In this chapter the concentration will be about the step up converter, because if a DC/DC converter is needed in the PureChoice vehicle, it will be used to step up a low voltage.

In order to understand how the converter works, focus will be oriented on explaining a simple Boost converter. Figure 62 shows the basic Boost converter circuit, consisting of an inductor, a diode, a transistor and a capacitor.

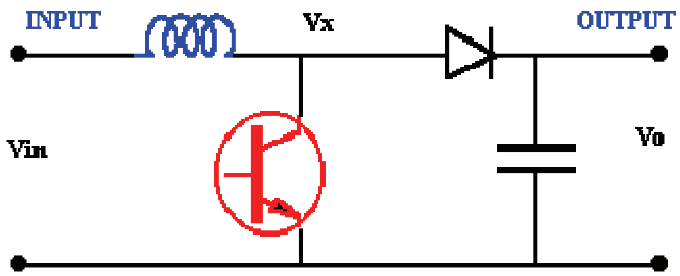

Figure 62: A basic boost converter. V_{inn} is the input voltage, V_x is the voltage across the inductor and V_o is the output voltage [24].

To get an easy understanding of how this circuit works one can think about the transistor as a door. When the transistor is ON, the door is open and electrons may flow unobstructed through. When the “door” is shut (transistor OFF), electrons will not pass through the transistor giving a difference in electrical voltage potential on the different sides. t_{on} will then be the time the door is open, and t_{off} the time the door is shut. T is the sum $t_{off} + t_{on}$. D is the duty ratio and is the mathematical term of t_{on} divided by T, see Figure 63.

The diode has the ability to lead a current only in one direction. The opening of passage is determined by which of the sides on the diode that have the highest voltage potential. If the anode (left side) has the highest potential, the diode will be in a conducting mode. And opposite, if the cathode (right side) has the highest potential, the diode will block and no current will pass through.

When the transistor is ON (conducting current) the input voltage equals the voltage across the inductor $V_x=V_o$. When the transistor is OFF the diode starts conducting a current, and the voltage across the inductor equals the output voltage (24).

Giving the equations:

$$V_{in}t_{on} + (V_{in} - V_o)t_{off} = 0 \qquad (6\text{-}1)$$

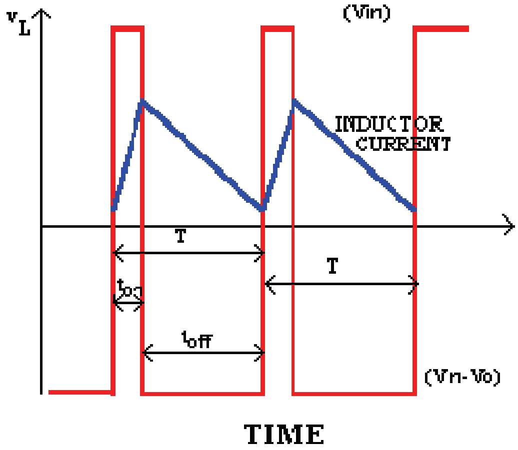

Figure 63: Voltage over the conductor as well as the current through it, with regards to t_{on} and t_{off}[24].

If considering only power and disregarding the losses, one ends up with the equation (6-2). It is important to notice that even though the voltage rises and the current drops, the power is constant (this is a modified truth since there are always losses, but in good converters these losses are relatively small).

$$V_o I_o = V_d I_d \tag{6-2}$$

$$\frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{(1-D)} \tag{6-3}$$

As shown by previous definitions T divided by t_{off} will always give a value higher than 1, giving a higher V_o than V_{inn}, see Eq. (6-3). It can also be noticed that the current falls by the same factor the voltage rises [24].

6.1. 28 V Input Maxi Family DC/DC Converter Module

As shown in the second considered propulsion system, see Figure 2, there are several DC-DC converters present. These converters are mainly there in order to transfer energy to and from the supercapacitor module. Due to the fact that it takes time to order and get the necessary components in time, it was found necessary to order some DC/DC converters before knowing if they would be needed in the final propulsion strategy or not. They were ordered in order to be prepared for any changes along the way.

The converters acquired provide several advantages. They have the ability to be placed between the fuel cell and the motor, accepting a wide range in the input voltage, and deliver a stable output voltage to the motor. In addition, the DC-DC converters can be used to lower the size of the battery or the supercapacitor module in the sense that they also here can accept a lower voltage and boost it up to the desired voltage for the system. This will lower the quantity of individual batteries or supercapacitor modules connected in series, hence lowering the weight. Should the propulsion system on a later stage require more energy, one would only need to add more modules in series, which would not require a change in the bigger and more expensive components.
Unfortunately, a DC-DC converter in a propulsion system does not only lead to benefits, it also has drawbacks. Main drawback being the efficiency. Typically normal commercially available DC-DC converters have efficiencies between 80 and 90%, meaning that the total system efficiency would decrease and one would directly dispose the energy as heat. This is unfortunate when for instance competing in a race where the main focus is to keep as high of a system efficiency as possible and neglect all equipment not needed. This is also why one refers from placing any DC-DC converters in the main power chain as long as it is possible. When this has been said, it is not said that one should not be prepared for the unforeseen.

The RoHS V28A24C200BL and V24A36C400BL converters have been acquired from the Norwegian Craftec company, which is delivering the Vicor products produced in the UK. It is a well designed DC–DC converter with high theoretical efficiency, low noise, light weight and small outer dimensions, see Figure 64. Additionally it includes high frequency ZCS/ZVS switching, providing high power with low noise. The V28A24C200BL converter weights only 230 grams and is able to deliver up to 200 watts of power [25].

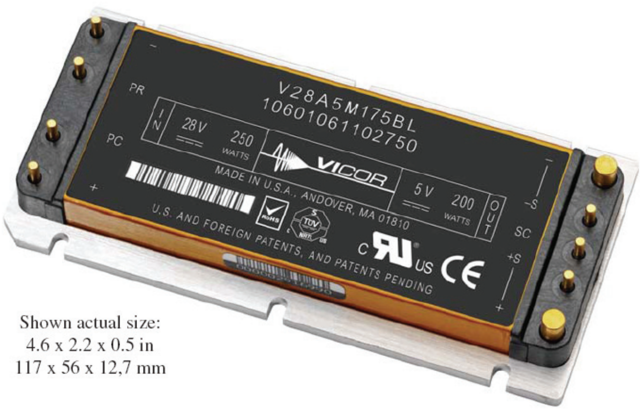

Figure 64: The V28A24200BL converter. The left side is the primary (low voltage) side and the right side is the secondary (high voltage) side [25].

As mentioned earlier in the basics of step up DC–DC converters, the main application for a step up converter is to raise the input voltage to a desirable higher output voltage. This converter is designed to boost all input voltages in the range 9 V to 28 V and up to 24 V. In order to choose input and output voltages you need a regulation opportunity. This problem is solved with the possibility to regulate the output voltage with resistors between pin SC and S+ or S-, where S+ is used to trim up and S- is to trim down the output voltage, see Figure 65. If one has a 12 V input which one wants to convert to a 24 V output, a resistor has to be placed between SC and S+. To find the exact size of the resistance, the formula given by equation (6-5) can be used. In addition to managing the output voltage by fixed resistors, there is also the ability to adjust or program the voltage by potentiometers or voltage DACs.

$$R_U = \frac{1.000(V_{out} - 1.23)V_{nom}}{1.23(V_{out} - V_{nom})} - 1.000 \qquad (6\text{-}5)$$

$$R_D = -\frac{1000 \cdot V_{out}}{V_{nom} - V_{out}} \qquad (6\text{-}6)$$

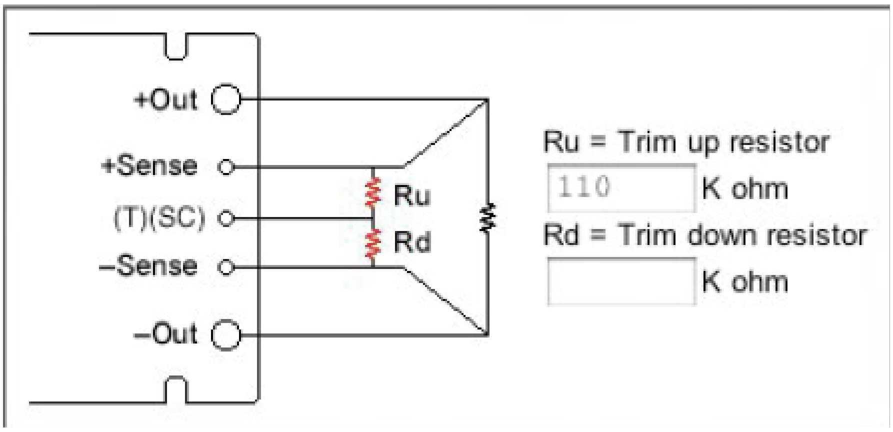

Figure 65: Resistor values for fixed output voltage trimming [App].

Another important quality is the “watchdog” circuit implemented in the converter. This circuit can help to secure the system to a certain extent. The circuit monitors input voltage, operating temperature, and internal operating parameters. This system will shut down the converter if any error occurs. The PC will then periodically go high to check if the fault has cleared, and once it has, it will turn the converter back on again (25).

6.2. Testing the V24A36C400BL DC/DC Converter

Due to late delivery of the V28A24C200BL DC/DC converter, there was not enough time to test it. Instead the already delivered V24A36C400BL DC/DC converter was tested [26]. These two have almost all the same similarities. The main difference is the power they can deliver because the V24A36C400BL converter can deliver up to 400 watts of power.

Main focus for the test was to determine the efficiency of the converter, see Figure 66. To check how close or far off the theoretical efficiency of 88% the converter really is [26]. This is important because lower efficiencies produce more heat due to the lost energy in the conversion.

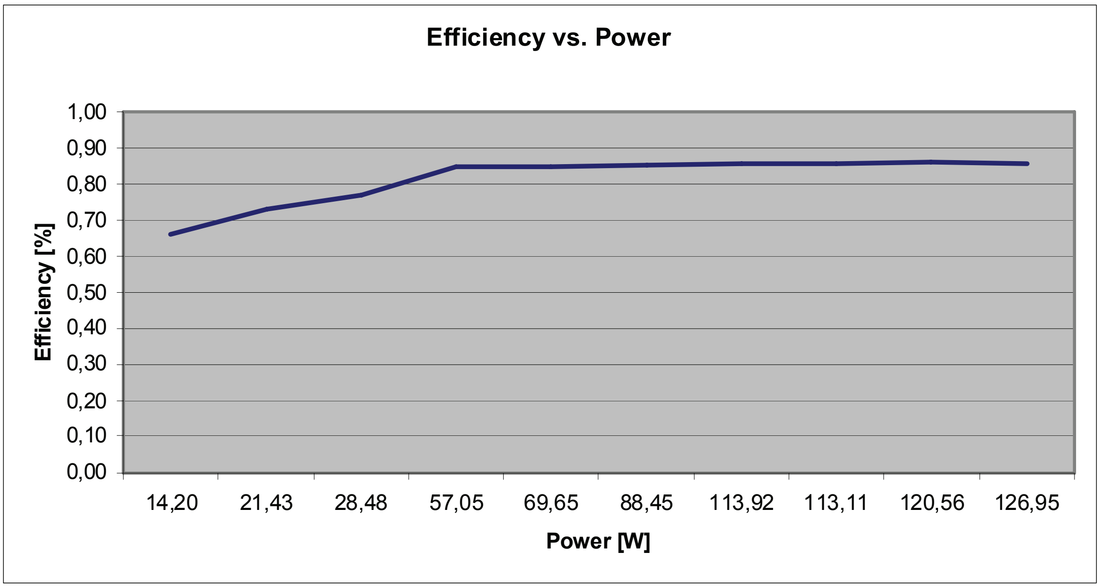

Figure 66: Efficiency vs. Power curve for the V24A36C400BL DC/DC converter.

The results from the test were positive. Determined efficiency was estimated to 86% which is almost the same as the theoretical efficiency given in the application note for the converter [26]. It is important to remember that this DC/DC converter is a commercially available converter which does not cost too much either. If one considers all the additional features it includes and how easy it is when it comes to implementation in an existing system, then this converter is a very good converter. As mentioned earlier in Chapter 6.1 this converter can even be controlled using voltage digital to analogue controllers.
If, on the other hand, the converter is supposed to be used in a system where the main focus in to save energy, it is just not good enough. This converter has unfortunately a lower efficiency than what is actually possible to construct, as long as price and time are not a big concern. For additional information about the performed test, see Appendix F.

7. Discussion

In this chapter the different solutions and components chosen for the vehicle will be compared with their purposes. Further on, the components, their results and possible improvements will be commented. Finally, the placement of the components and a suggestion for possible improvements in this area will be given for the next year's team to consider.

7.1. Propulsion System

The propulsion system presented earlier in Figure 3 turned out to be very successful. With this system the PureChoice vehicle managed to drive as far as 729 km with the energy in one litre of petrol. A large part of the success is due to the designed system being extremely easy and containing a minimum of the required components.
When the technical innovation group was visiting our paddock at the Shell Eco-marathon competition to see if we deserved to get the price in this category, one of their positive comments was regarding our simple propulsion system. Their comment was that "it is not a big benefit to have a very complicated system if it does not manage to drive the vehicle forward". They had seen a lot of impressive and technologically demanding systems, but when put together, they were not functioning.
The advice for the next year's team is therefore to keep things simple, if not to minimize the weight, then to make it easier to detect faults if the system is not working properly. A lot of improvements can be made to the propulsion system by simply replacing the already existing components with new and hopefully self-manufactured ones.

7.2. Self-manufactured Controller Card

Although the manufactured controller card for lights did not work as well as initially hoped, it is a card that can be improved by the next team. The interconnections in the schematic, the designed layout and the programmed C-code are all working properly. The main error experienced was with fluctuating voltages at the drain pins on the different mosfet`s. This might be due to poor soldering or perhaps they got too heated up while soldering. The physical size of the mosfet`s is only 2.8 x 2.6 mm, making the soldering process very demanding.
All the necessary files from the Cadsoft Eagle and the C-code written are provided to make it easier for additional improvements [27]. Additional components have also been acquired from Farnell and Elfa, minimizing the time needed to construct a new and better controller card.

7.3. LOGO! Micro automation Module

The LOGO! Micro Automation module is a wonderful device to utilize when different areas of the application need to be controlled. It is a very light module using minimum energy to operate. The benefit of using this device is that there are endless opportunities in the control functions. Several different voltages can be applied directly to the different output signals. In this way the different energies needed by the components in the vehicle can all be supplied by the right voltages and current levels whenever necessary. The LOGO! module is also very robust and easy to implement in an already existing system.
One of the main problems with both the LOGO! module and the self-manufactured controller card was that it was difficult to find the appropriate placement in the PureChoice vehicle. The

entire vehicle is constructed in carbon fibre, with very little arrangement opportunities due to no internal dashboard. Carbon fibre is a leading material; it is not possible to place electrical components directly on top of it without properly shielding them. Advantage with the LOGO! module is that it is entirely enclosed inside plastic, simplifying the placement to a certain extent. Since the best arrangement for all the input signals would be at the driver position, the module was placed on the air duct right behind the main steering console, see Figure 40. The benefit of placing the module here was that it was possible to minimize the wiring needed in the vehicle. Unfortunately it can be rather difficult to make the necessary interconnections due to the restricted space. Hopefully the next team can construct a lightweight dashboard and place the LOGO! module higher and more user friendly.

7.4. Batteries

Shortly summarizes, the research performed on different battery types really paid off. The research performed saved both money and unnecessary weight in the vehicle. As mentioned earlier, the total weight of the Li-ion battery pack was only 512 grams, which is remarkably lower than what is commercially available. Although more time could have been used on searching for a light and suitable battery pack online, it was more beneficial for us to construct our own. The disadvantage of the Li-ion pack is that it always needs to be taken in and out of the vehicle due to the charging procedure. Using only one of the acquired battery chargers, and charging the batteries inside the vehicle would lead to very slow charging due to the low current the charger can supply [28].
When placing the battery pack inside the vehicle, the same problems were experienced as with the LOGO! module. It would be highly beneficial for the next team to design a dashboard in the vehicle where components such as batteries, control modules, measurement devices and input switches could be placed. This would minimize the wiring needed, consequently reducing weight and giving a stronger feeling of being inside a normal car.

7.5. Supercapacitors

Although not used in the vehicle, the supercapacitor module constructed was kept as a back-up in case it would be required. If problems were experiences with the Nexa fuel cell module turning off during the race, the supercapacitor module would have been implemented in the next race to provide the necessary energy to again power up the fuel cell system. The benefit of using external batteries to power up the system is that one does not add additional weight in the vehicle during driving. The disadvantage of using batteries for this purpose is that it is not possible to start up the fuel cell system again should an error occur while driving. This problem would then be solved by placing the supercapacitor module inside the vehicle, and using it to supply the fuel cell system with necessary energy whenever needed.

When using supercapacitors it is extremely important to shield them from any conductive material, in our case being the carbon fibre. That is also why the entire module consisting of six supercapacitor modules in series has been placed inside a plastic box, shielding them from each other and the rest of the system. Only the positive and negative cables are accessible through two small openings in the box, also these being shielded from one another. These two cables can not come in contact with each other if the supercapacitor module has been charged up!

7.6. DC/DC Converters

The acquired DC/DC converters were not used during the race in Nogaro, France. This is because there was no need for the supercapacitor module. As mentioned earlier, the purpose of a DC/DC converter would be to lower the quantity of individual supercapacitor modules needed. Therefore, if there is no need for the supercapacitor, then there is also no need for the converter. Although the use of a converter would lead to some losses, the converters acquired were functioning well and would perform as intended.
If DC/DC converters are needed by the next team, it is strongly recommended to acquire the necessary equipment and construct the converters on one's own. This will give higher efficiencies than almost any commercially available DC/DC converters.

8. Conclusion

During the last two semesters the group consisting of 13 master students from five different institutions at the Norwegian University of Science and Technology, NTNU, has been putting all their energy and expertise in designing and constructing a vehicle with the goal of driving 850 km with the energy in one litre of petrol. After a successful participation in the Shell Eco-marathon, the PureChoice vehicle, weighing only 69 kg, managed to drive 729 km with the energy in one litre of petrol. The team won second price in the hydrogen driven Urban Concept vehicles and two special awards; the communication award and the safety award.

This was a very demanding project, but because it was so interesting to work with, not even the long working days managed to lower the commitment in the group. In addition to the practical and theoretical work done on the vehicle, a lot of experience was gathered on how it is to work in larger groups. We have relied on and helped each other throughout the different tasks. All of us having the same goal; winning the competition in Nogaro.

This project has also brought us closer to the industry because we needed to stay in contact with commercial suppliers to obtain the necessary equipment. Finally, we needed to advertise our project, mainly to satisfy our sponsors, but also to make the project more familiar to the general public. The idea is to run the same project for many years to come, so getting good advertising for it now will make it easier for the next group to secure the necessary funding, and further improve the vehicle.

This project has been very informative and I am very pleased with the product and the experiences gained.

9. Experience and Recommendations

Since this was the first participating team from the Norwegian university of science and technology, there was a lot of confusion regarding which propulsion strategies were allowed. After visiting and participating in the competition, this impression has completely changed. The experience gathered in the areas of control of lights, batteries and supercapacitors will therefore be presented in the different points below. This will save the next team a lot of time, which can rather be used on more important tasks. Some recommendations will also be given regarding the components; both the components utilized and the components that could be acquired by the next team. Finally, a short summary of the experience with the suppliers will be given.

Propulsion System:

- As different propulsion strategies are being considered, remember to draw all the necessary interconnections in, for instance AutoCAD or Microsoft Visio. The technical team from the Shell Eco-marathon will ask for these drawings.
- Remember also to print out some copies of the final propulsion system and bring them to the competition. You will be asked to provide them in paper form. Since it can be time consuming to find a printer there, this can easily be solved at home.

Light system:

- The teams are only asked to demonstrate the lights in proper working condition. The technical inspection team is not strict regarding what type of lights the individual teams have chosen. Since energy can be taken from the internal battery pack and this power is not calculated upon when the total distance is determined, a lot of design opportunities are available to the lighting of the vehicle.

Batteries:

- Be careful when placing the batteries in the vehicle because their position is close to the steering consol. Also make sure that you shield them from the carbon fibre by for instance putting them in a plastic box. Instability was registered when placing them directly onto the carbon fibre air duct.
- Try to get hold of a Li-ion charger that can deliver up to 5 amperes. If such charger can be obtained, then the Li-ion batteries can be permanently places inside the vehicle with for instance two external connectors for charging. Much like when a normal electrical car is charged up. By doing this, a lot of time will be saved.
- If such charger can not be obtained, then try to find a commercially available Li-ion battery pack with accompanying charger. Remember to consider the weight of the battery pack and that it has enough specific energy.
- The rules on batteries can seem rather strict and confusing. This is only on the paper. At the competition one is only asked to explain what the battery does if the technical inspection team feels that the battery you are using is extremely large. The Polish team was asked about this, because they had a 25 kg lead-acid battery pack in their vehicle.

- If enough funding is available consider replacing the Biltema battery with e. g. a NiMH battery. Main reason for this is to lower the weight and make it easier to transport.

Supercapacitors:

- As mentioned earlier, be very careful when placing supercapacitors inside the vehicle.
- Do not remove the plastic around the individual supercapacitors. It works as a good insulator between the individual modules.
- Make sure you keep the plus and minus terminals close to each other when constructing your own module, see Figure 58. Placing them far away from each other will increase the electromagnetic field between them.
- Some teams used a supercapacitor module as a voltage buffer between the fuel cell and the inverter. If a new and smaller fuel cell is acquired by the next team, then this propulsion strategy might save substantial amounts of energy. Try to get hold of some 350 or 650 farad supercapacitors and perform a test to check if this strategy will be beneficial.

Suppliers:

- When ordering the necessary components for the PureChoice vehicle a lot of time was spent on finding local suppliers. Main reason was of course to minimize the time needed in transportation. Appendix G below summarizes the different companies contacted, what they can help with and who one can contact. These people are already familiar with our project and will be more than happy to assist you in any way they can.

10. References

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[2] Shell Eco-marathon General Rules and Regulations 2008*

[3] TEN 40-2411 Traco Power DC/DC Converter Application Note*

[4] Components Used on the Controller Card*

[5] ATTiny26L 8-bit AVR Microcontroller Application Note*

[6] STT3PF30L Mosfet Application Note*

[7] Siemens LOGO! Micro Automation Module Application Note*

[8] LED Lights & Holder Application Notes*

[9] http://www.batteryuniversity.com/partone-4.htm (5. June 2008)

[10] http://www.batteryuniversity.com/partone-11.htm (5. June 2008)

[11] http://www.batteryuniversity.com/partone-12.htm (5. June 2008)

[12] http://www.batteryuniversity.com/partone-6.htm (5. June 2008)

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[17] 3.7 V, 2.2Ah VARTA Li-ion Battery Application Note*

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[21] BCAP1500 E270 Supercapacitor Application Note*

[22] How to Determine the Appropriate Size Ultracapacitor for Your Application, Application Note*

[23] Integration Kit for BOOSTCAP® Ultracapacitor Application Note*

[24] http://www.powerdesigners.com/InfoWeb/design_center/articles/DC-DC/converter.shtm (5. June 2008)

[25] V28A24C200BL DC/DC Converter Application Note*

[26] V24A36C400BL DC-DC Converter Application Note*

[27] Cadsoft Eagle files and the C-code written*

[28] Mascot charger for Li-ion batteries*

*All application notes and additional information is provided on the accompanying CD.

11. Appendices

11.1. Appendix A: Calculation of Trace Width

These formulas calculate the minimum width of traces on and inside the PCB.

$$I = 0.0150 \times dT^{0.5453} \times A^{0.7349} \quad \text{for internal traces} \quad \text{(A-1)}$$
$$I = 0.0647 \times dT^{0.4281} \times A^{0.6732} \quad \text{for external traces} \quad \text{(A-2)}$$

where:

dT = temperature rise above ambient in ºC
A = cross-section area in $mils^2$

A standard PCB is 35 µm (1 ounce/sqrfoot (oz)) copper.
A normal temperature rise is 10 ºC.

Conversion between mils and mm is given by the following formula, see equation (D-3).

$$mm = \frac{mils}{1000} \times 25.4 \quad \text{(A-3)}$$

Example, external trace
I = 3A
dT = 10 ºC

$$I = 0.0647 \times dT^{0.4281} \times A^{0.6732}$$
$$3 = 0.0647 \times 10^{0.4281} \times A^{0.6732}$$
$$A = 69 mils^2$$

$$A = Height \times Width$$
$$Height = 35 \mu m = (mils / 1000) \times 25.4$$
$$Height = 1.378 mils$$
$$Height = A / Height = 69 / 1.378$$
$$Height = 50 mils = 1.27 mm$$

From this example it is easy to see that an external trace carrying 3 A should at the minimum be 1.27 mm wide. This way of calculating the trace width has been made use of throughout the entire design process of the controller card for lights. In addition to calculating the track width, Table A1 below was utilizes as a quick reference.

Table A1: Track Width Reference Table (for 10 ºC temp rise). Track Width is in Thous (mils)

Current (Amps)	Width for 1 oz	Width for 2 oz	mill
1	10	5	52,0
2	30	15	17,2
3	50	25	10,3
4	80	40	6,4
5	110	55	4,7
6	150	75	3,4
7	180	90	2,9
8	220	110	2,3
9	260	130	2.0
10	300	150	1,7

1oz = copper thickness of 35 µm
2oz = copper thickness of 70 µm
1mil = 1/1000 inch

11.2. Appendix B: C code for the ATTiny26L Microcontroller

```
//DESCRIPTION:
//VCC-
//GND-
//IN-
//OUT-
//
//


#include <iot26v.h>
#pragma interrupt_handler timer1_compa_interrupt:5

unsigned char ant_ms;
unsigned int sek;


void main (void)
{
////////////////////////////////////////////////////////////////////////////////////////////////////DEF
 DDRB=0x00;                    // PORTB IN
 PORTB=0xFF;                   // ENABLE PULL UP
 DDRA=0x3F;                    // PORTA=OUT,  PORTA7=IN, PORTA6=IN
 PORTA=0xC0;                   // ENABLE PULL UP ON PORTA7 AND PORTA6
                               // LOW ON PORTA0-5
 ant_ms=0;
 sek=0;
 SREG=SREG|0x80;
 while (1)
 {


  TCCR1B=0x00;
  TCNT1=0;
  sek=0;
  PORTA=PORTA & 0xEF;
  PORTA=PORTA & 0xE7;
  PORTA=PORTA & 0xF7;

  if (PINB & 0x08)
   {
    PORTA=PORTA | 0x04;
   } else {
    PORTA=PORTA & 0xFB;
   }


  if(PINA & 0x80)
```

```
 {
  PORTA=PORTA | 0x02;
 }

if(PINB & 0x40)
 {
        PORTA=PORTA | 0x03;
 }

if(!(PINB & 0x40)& !(PINA & 0x80) )
 {
  PORTA=PORTA & 0xFC;
 }

if((PINA & 0x80)&&(!(PINB & 0x40)))
 {
  PORTA=PORTA & 0xFE;
 }


while (PINB & 0x20)
{
// delay 50ms
 TCCR1B=0x81;
 OCR1C=1000;
 TIMSK=0x40;

        if(sek==1)
        {
        PORTA=PORTA^0x10;
        sek=0;

        }

if (PINB & 0x08)
 {
  PORTA=PORTA | 0x04;
 } else {
  PORTA=PORTA & 0xFB;
 }

if(PINA & 0x80)
 {
  PORTA=PORTA | 0x02;
 }



if(PINB & 0x40)
```

```
  {
        PORTA=PORTA | 0x03;
  }

 if(!(PINB & 0x40)& !(PINA & 0x80) )
  {
  PORTA=PORTA & 0xFC;
  }

 if((PINA & 0x80)&&(!(PINB & 0x40)))
  {
  PORTA=PORTA & 0xFE;
  }
 }


while (PINB & 0x10)
 {
// delay 50ms
  TCCR1B=0x81;
  OCR1C=1000;
  TIMSK=0x40;

        if(sek==1)
        {
        PORTA=PORTA^0x08;
        sek=0;

        }

 if (PINB & 0x08)
  {
  PORTA=PORTA | 0x04;
  } else {
  PORTA=PORTA & 0xFB;
  }

 if(PINA & 0x80)
  {
  PORTA=PORTA | 0x02;
  }

 if(PINB & 0x40)
  {
        PORTA=PORTA | 0x03;
  }



 if(!(PINB & 0x40)& !(PINA & 0x80) )
```

```
  {
   PORTA=PORTA & 0xFC;
  }

 if((PINA & 0x80)&&(!(PINB & 0x40)))
  {
   PORTA=PORTA & 0xFE;
  }
 }


while (PINA & 0x40)
 {
// delay 50ms
 TCCR1B=0x81;
 OCR1C=1000;
 TIMSK=0x40;

        if(sek==1)
        {
        PORTA=PORTA^0x18;
        sek=0;

        }

 if (PINB & 0x08)
  {
   PORTA=PORTA | 0x04;
  } else {
   PORTA=PORTA & 0xFB;
  }

 if(PINA & 0x80)
  {
   PORTA=PORTA | 0x02;
  }

 if(PINB & 0x40)
  {
        PORTA=PORTA | 0x03;
  }

 if(!(PINB & 0x40)& !(PINA & 0x80) )
  {
   PORTA=PORTA & 0xFC;
  }



 if((PINA & 0x80)&&(!(PINB & 0x40)))
```

```
   {
    PORTA=PORTA & 0xFE;
   }
  }


}
}


 void timer1_compa_interrupt (void)
 {
  ant_ms++;

  if(ant_ms==1000)
  {
   sek++;
   ant_ms=0;

  }
 }
```

11.3. Appendix C: Discharging two 7.2 Ah, 12 V Lead-acid Batteries

Constant current discharge, A = 3.5 Amp.
Values registered and their respective graphs are presented below in Table C1 and Figure C1.

Table C1: Registered values when discharging one Lead-acid battery.

U [V]	A [I]	P [W]	T [min]
29,5	3,5	103,25	0
28,6	3,5	100,1	2
27,6	3,5	96,6	4
26,4	3,5	92,4	6
24,9	3,5	87,15	8
22,7	3,5	79,45	10
20,4	3,5	71,4	12
18,1	3,5	63,35	14

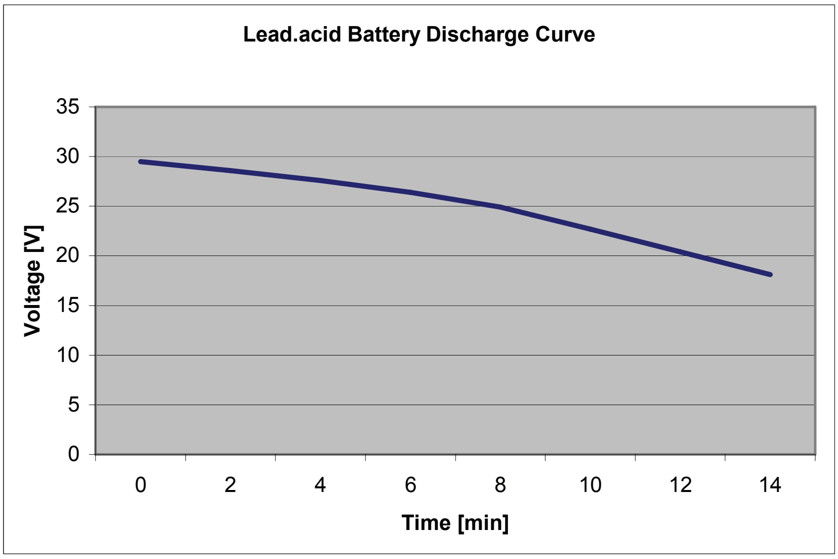

Figure C1: Lead-acid battery discharge graph.

11.4. Appendix D: Discharging and Charging one 3.7V, 2.2 Ah VARTA Li-ion Battery

Constant current discharge, A = 1 Amp.
A 4 Amp, 16 Ohm, potentiometer was used and the resistance was continuously adjusted in order to keep the load equal to one ampere. Since this potentiometer is not digital the load fluctuated slightly, but was kept within the 0.985 A and 1.025 A values. Values registered and their respective graphs are presented below in Table D1, Figure D1 and Figure D2.

Table D1: Registered values when discharging one Li-ion battery.

U [V]	A [I]	R [kΩ]	P [W]	T [min]
3,8	0	4,5	0	0
3,6	1	3,6	3,6	0
3,57	1	3,57	3,57	1
3,56	1	3,56	3,56	2
3,55	1	3,55	3,55	4
3,549	1	3,549	3,549	6
3,545	1	3,545	3,545	8
3,54	1	3,54	3,54	10
3,535	1	3,535	3,535	12
3,526	1	3,526	3,526	14
3,515	1	3,515	3,515	16
3,508	1	3,508	3,508	18
3,495	1	3,495	3,495	20
3,488	1	3,488	3,488	22
3,482	1	3,482	3,482	24
3,475	1	3,475	3,475	26
3,47	1	3,47	3,47	28
3,462	1	3,462	3,462	30
3,456	1	3,456	3,456	32
3,449	1	3,449	3,449	34
3,443	1	3,443	3,443	36
3,434	1	3,434	3,434	38
3,428	1	3,428	3,428	40
3,41	1	3,41	3,41	42
3,396	1	3,396	3,396	44
3,382	1	3,382	3,382	46
3,357	1	3,357	3,357	48
3,333	1	3,333	3,333	50
3,291	1	3,291	3,291	52
3,26	1	3,26	3,26	54
3,132	1	3,132	3,132	56
2,923	1	2,923	2,923	58
2,4	1	2,4	2,4	59,5

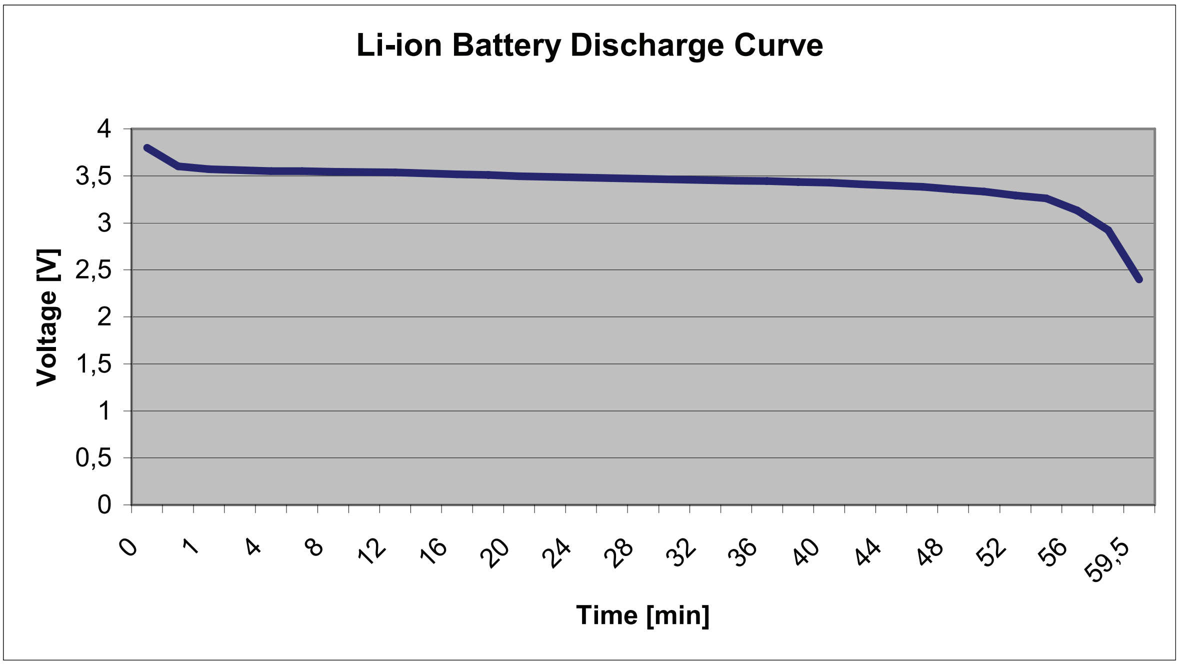

Figure D1: Li-ion battery discharge graph.

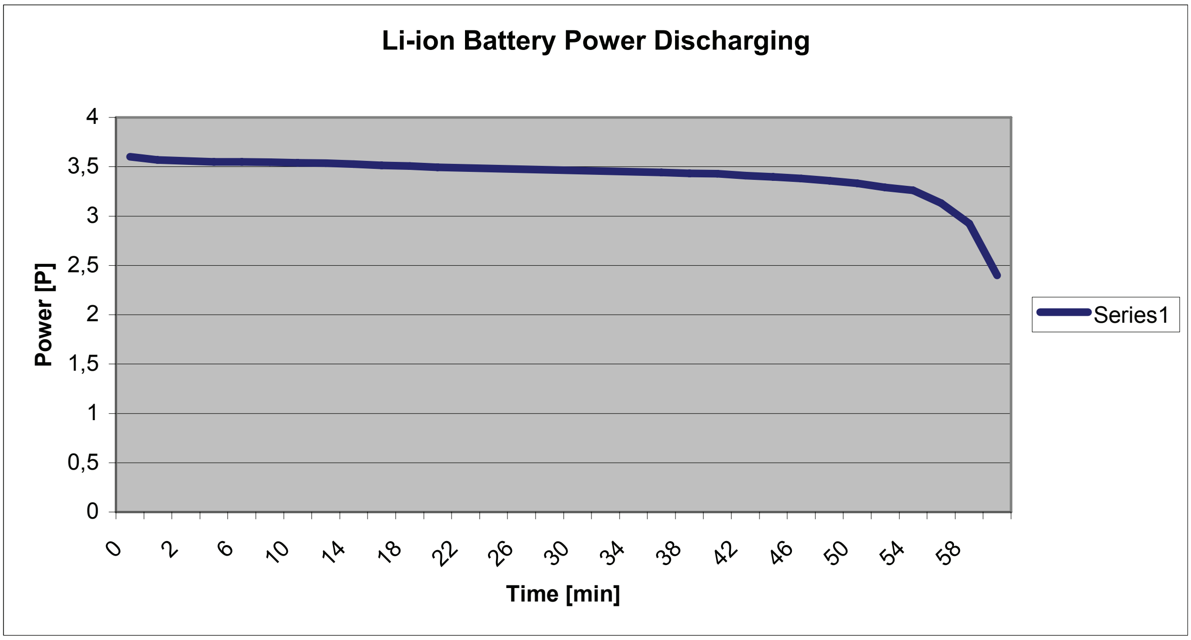

Figure D2: Li-ion battery power discharging graph.

Constant current discharge, A = 0.76 Amp
Battery voltage before charging: 3.231 V
Stated charging time: at 1.1 A = 3 hours
at 2.2 A = 2.5 hours

Values registered and their respective graph is presented below in Table D2 and Figure D3.

Table D2: Registered values when charging one Li-ion battery.

U[V]	A [I]	P [W]	T [min]
3,231	0	0	0
3,427	0,765	2,62166	0
3,56	0,764	2,71984	1
3,623	0,764	2,76797	2
3,713	0,763	2,83302	4
3,779	0,762	2,8796	6
3,831	0,761	2,91539	8
3,854	0,761	2,93289	10
3,863	0,761	2,93974	12
3,872	0,761	2,94659	14
3,878	0,761	2,95116	16
3,886	0,761	2,95725	18
3,891	0,761	2,96105	20
3,898	0,76	2,96248	22
3,9	0,76	2,964	24
3,907	0,76	2,96932	25
3,938	0,76	2,99288	30
3,963	0,759	3,00792	45
3,986	0,759	3,02537	60
4,01	0,759	3,04359	75
4,034	0,758	3,05777	90
4,065	0,685	2,78453	105
4,085	0,621	2,53679	120
4,108	0,506	2,07865	135
4,124	0,423	1,74445	150
4,146	0,345	1,43037	165
4,16	0,287	1,19392	180
4,17	0,238	0,99246	195
4,184	0,205	0,85772	210
4,196	0,173	0,72591	225
4,209	0,152	0,63977	240
4,19	0,124	0,51956	255
4,225	0,106	0,44785	270
4,232	0,091	0,38511	285
4,236	0,082	0,34735	300

After about three hours the battery can be said to be fully charged. Leaving it on for additional two further hours will only increase the voltage by 0.076 V.

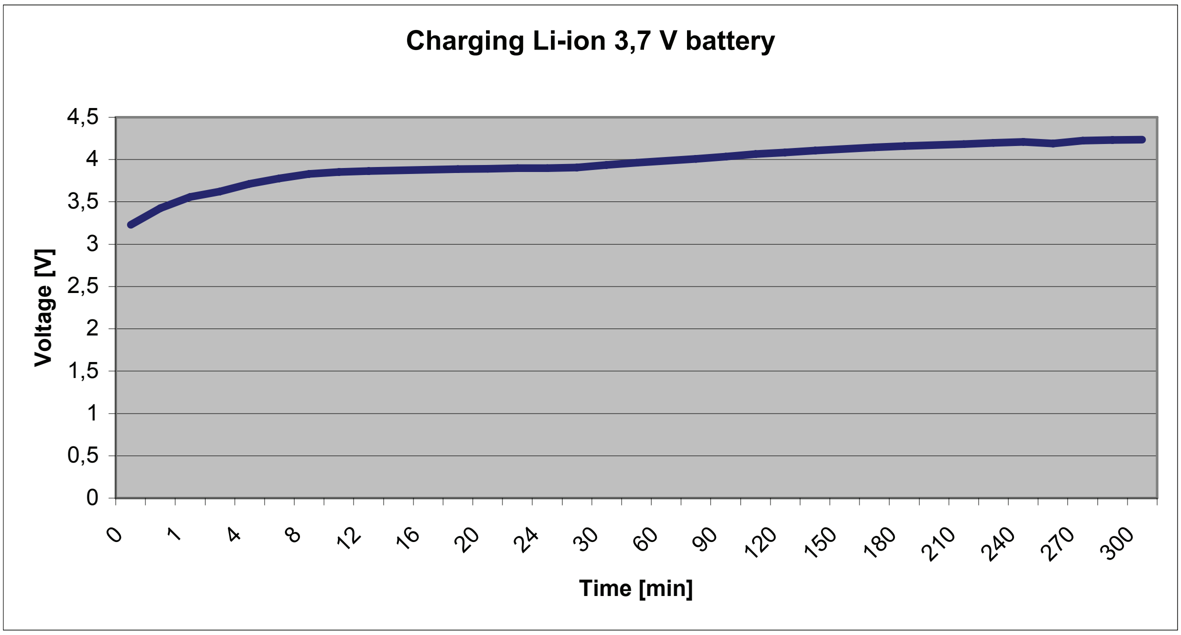

Figure D3: Li-ion battery charging graph.

11.5. Appendix E: Charging and Discharging the Supercapacitor Module

Constant Charge Current, A = 10.4 Amp.
Total Charged Energy = 11.4 Wh
Average Charging Current = 1.209 Ah
Highest Peak Power Registered = 164 W

Table E1: Registered values when charging the supercapacitor module.

T [min]	U [V]	A [I]	P [W]
0	0	0	0
0,5	2,2	10,4	22,88
1	3,7	10,4	38,48
1,5	5,1	10,4	53,04
2	6,45	10,4	67,08
2,5	7,7	10,4	80,08
3	8,85	10,4	92,04
3,5	10	10,4	104
4	11,1	10,4	115,44
4,5	12,2	10,4	126,88
5	13,2	10,4	137,28
5,5	14,2	10,4	147,68
6	15,2	10,4	158,08
6,5	16	8	128
7	16,32	3,3	53,856
7,5	16,4	1,5	24,6
8	16,43	0,9	14,787
8,5	16,45	0,62	10,199
9	16,45	0,49	8,0605
9,5	16,46	0,42	6,9132
10	16,46	0,38	6,2548

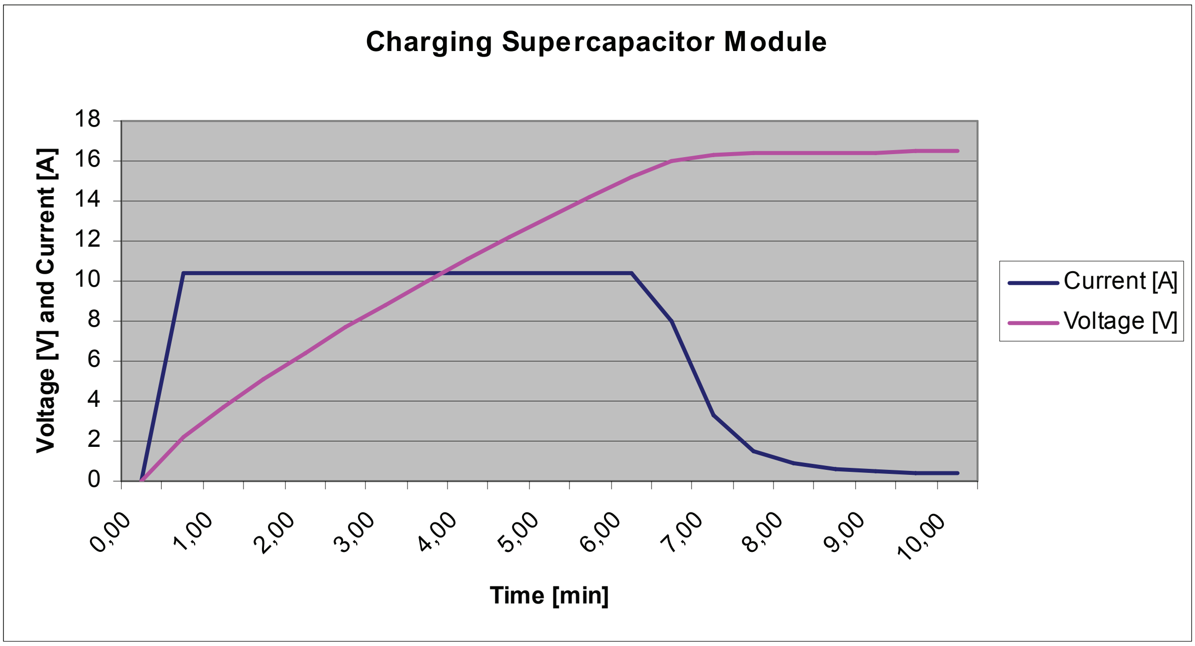

Figure E1: Registered voltage and current values when charging the supercapacitor module.

Constant Discharge Current, A = 10.2 Amp.
Total Discharged Energy = 10.4 Wh
Average Discharging Current = 1.143 Ah
Highest Peak Power Registered = 161.5 W

Table E2: Registered values when discharging the supercapacitor module.

T [min]	U [V]	A [I]	P [W]
0	16,3	10,2	166,26
0,5	14,5	10,2	147,9
1	13,5	10,2	137,7
1,5	12,4	10,2	126,48
2	11,3	10,2	115,26
2,5	10,2	10,2	104,04
3	9,1	10,2	92,82
3,5	8	10,2	81,6
4	6,8	10,2	69,36
4,5	5,6	10,2	57,12
5	4,3	10,2	43,86
5,5	3	10,2	30,6
6	1,6	10,2	16,32
6,5	1	8,3	8,3
7	0,3	4,2	1,26
7,5	0,11	1,9	0,209
8	0,1	1,1	0,11

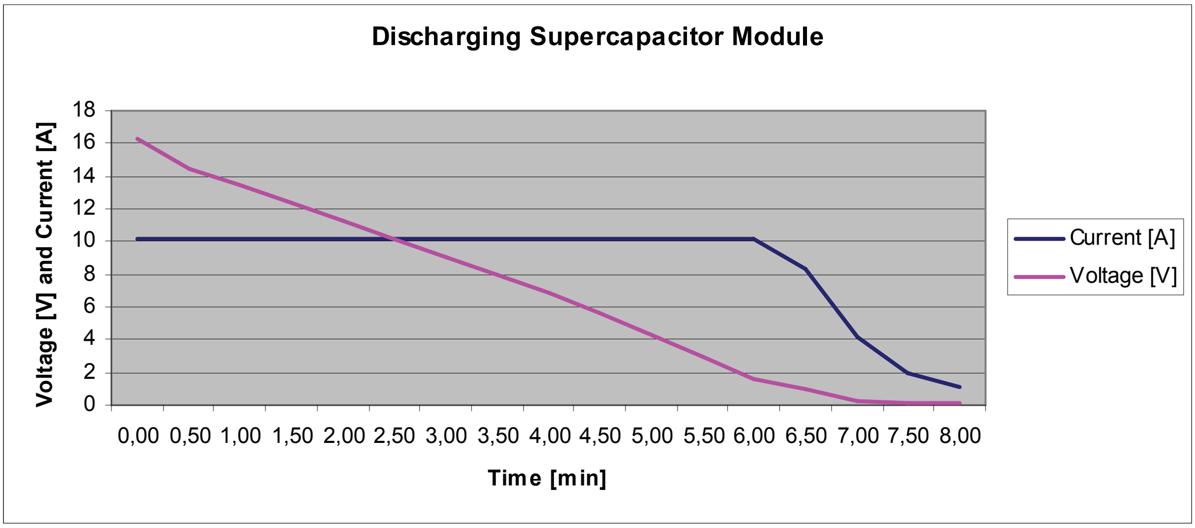

Figure E2: Registered voltage and current values when discharging the supercapacitor module.

11.6. Appendix F: Testing the V24A36C400 DC/DC Converter

The Vicor DC/DC converters are constructed with the possibility to adjust or program the output voltage via fixed resistors, potentiometers or voltage DACS. Table F1 shows which resistance values that have to be placed between the SC and S- pins in order to lower the output voltage.

Table F1: Voltage regulation via the SC and S- pins.

Vin constant = 24 V	
Rd kohm	Vout
none	35,8
500	35,93
300	35,85
35,85	34,83
17	33,92
8	31,86
5	29,88
3,5	27,9
2	23,9
1,25	19,86
0,71	14,9
0,38	12,68
0,16	12,67

Table F2 shows the registered values when testing the efficiency of the converter and Figure F1 shows the efficiency vs. power graph.

Table F2: Registered values when testing the DC/DC converter.

Vin	Iin	Pin	Vout	Iout	Pout	Eff.
24	0,9	21,53	35,86	0,4	14,2	0,66
24	1,23	29,4	35,84	0,6	21,43	0,73
24	1,55	37,18	35,83	0,8	28,48	0,77
24	2,81	67,54	35,77	1,6	57,05	0,84
24	3,42	82,1	35,74	1,95	69,65	0,85
24	4,33	103,8	35,71	2,48	88,45	0,85
24	5,55	133,15	35,69	3,19	113,92	0,86
24	5,5	132	35,57	3,18	113,11	0,86
24	5,85	140,3	35,68	3,38	120,56	0,86
24	6,18	148,32	35,56	3,57	126,95	0,86

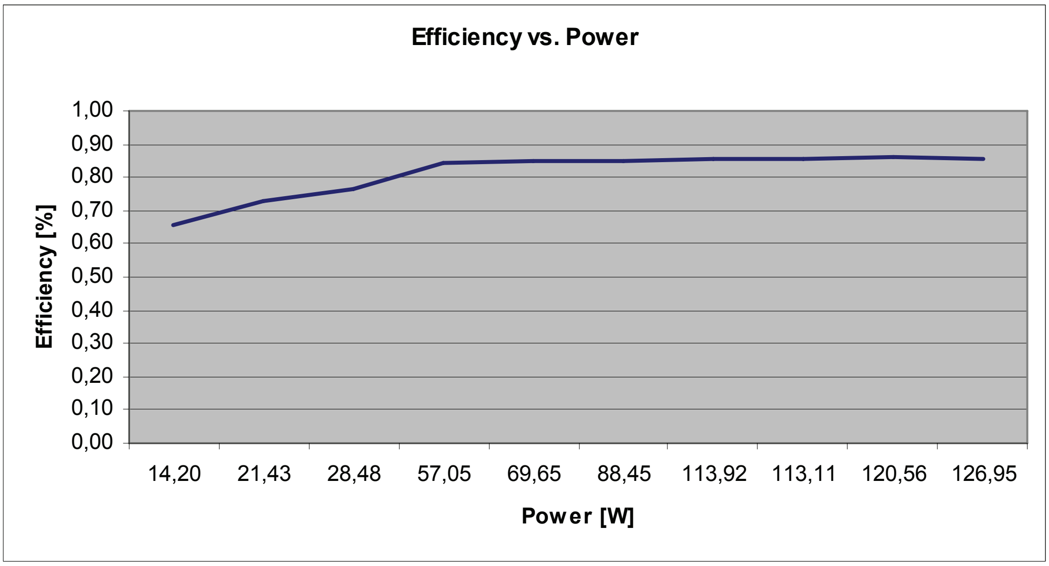

Figure F1: Efficiency vs. Power curve for the V24A36C400BL DC/DC converter.

11.7. Appendix G: Contacts

This is a summary of the contacts that helped during the construction of the PureChoice vehicle. They can be contacted in case there is a need for their services.

Farnell and Elfa
When ordering contact:

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For help with manufacturing PCB cards:

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Supercapacitors

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DC/DC Converters

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Norwegian deliverers: Farnell and Elfa

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