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Master of Science Thesis

Design of a Sustainable Electric Vehicle Charging Station

Bill V. E. Bakolas

Abstract

Electric vehicles only become useful in reducing greenhouse gas emissions, if the electricity used to charge their batteries comes from renewable energy sources. This thesis was conducted within the electric mobility framework of the Green Village, the project put forward to test the Green Campus Concept. The objective was to design a Station that charges electric vehicles, using sustainable energy technologies. To achieve an optimal performance of the selected components, a particular layout architecture was suggested. Additionally, a computer model was developed to simulate the Station operation under variant energy generation and consumption inputs, as established by fitted meteorological data and predicted usage patterns. Simulations were run using the Station model and the corresponding results were analyzed. Finally the economic aspects of the project implementation were examined and conclusions were drawn regarding the commercialization of its conceptual attributes.

Keywords: sustainable energy, electric vehicles, charging station, direct current, renewables, simulation, power flow control

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Challenge the future

Design of a Sustainable Electric Vehicle Charging Station

MASTER THESIS PROJECT

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Οὐδέποτε ὠρέχθην τοῖς πολλοῖς ἀρέσκειν. Ἅ μὲν γὰρ ἐκείνοις ἤρεσκεν, οὐκ ἔμαθον· ἃ δ' ᾔδειν ἐγώ, μακρὰν ἦν τῆς ἐκείνων αἰσθήσεως

Επίκουρος (341 π.Χ. - 270 π.Χ.)

I never desired to please the rabble. What pleased them, I did not learn; what I could discern, far were from their perception.

Epicurus (341 B.C. - 270 B.C.)

"...to all the times you have to dangle a carrot in front of you,
willingly holding the stick yourself"

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Abbreviations

1φ	1-phase
3φ	3-phase
AC	Alternating Current
a.k.a.	Also Known As
BB	Battery Bank
BMS	Battery Management System
BSc	Bachelor of Science
BTW	Belasting Toegevoegde Waarde (= Value Added Tax)
BV	Besloten Vennootschap (= Ltd)
CAN	Car Area Network
CO_2	Carbon dioxide
DC	Direct Current
DKK	Danish Krone (1 DansK Krone ≃ 0.1344 €)
DoD	Depth of Discharge
EU	European Union
EV	Electric Vehicle
EVSE	EV Supply Equipment
EVCS	Electric Vehicle Charging Station
GC	Green Campus
GV	Green Village
i.e.	'id est' (= latin for 'that is')
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
IR	Investment Return
IRR	Internal Rate of Return
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LED	Light Emission Diode
MCP	Measure Correlate Predict
MOSFET	Metal–Oxide–Semiconductor Field Effect Transistor
MPPT	Maximum Power Point Tracker
MSc	Master of Science
NMHC	Non-Methane HydroCarbons
NO_x	Nitrogen Oxides
NV	Naamloze Vennootschap (= SA or PLC)
OBC	On-Board Charger
PM	Particulate Matter
PV	PhotoVoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
SAE	Society of Automotive Engineers
SEI	Solid Electrolyte Interface
SET	Sustainable Energy Technology

SoC	State of Charge
SPCS	Solar Powered Charging Station
STC	Standard Test Conditions
TF	Thin Film
TUD	Technische Universiteit Delft – Delft University of Technology
VAWT	Vertical Axis Wind Turbine
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
Wp	Watt peak
WT	Wind Turbine

Preface

This report concludes my thesis at the Green Campus Company, on sustainable charging of electric vehicles. The corresponding research was conducted as the conclusive part of my studies in the Sustainable Energy Technology Master of Science programme of the Delft University of Technology. My work lasted nine months, from February to October, during which I designed a Charging Station based on renewable energy sources.

The Green Campus Company is an initiative of TU Delft, founded to realize an inspiring vision. That is to "create a sustainable, lively and entrepreneurial campus where we discover, learn and show how to solve society's urgent challenges'". A vision that all those who have worked, work and will work on the project, want to see realized at the TU Delft, in the economic heart of the Netherlands.

The Green Campus development requires several years, during which innovative ideas will pass from design to implementation and become established as commercial projects. The first step in this long process however is what is known as the Green Village. This is a temporary test and try-out laboratory site within the TU Delft campus, which shall provide the environment and possibility to assess the Green Campus concepts. These have been organized into 12 dynamic missions, one of which is electric and clean transport. The quest for such a system is what I embarked on when I joined the Green Campus for this project, which evolved into research and development of the infrastructure necessary to charge electric cars with direct current generated by renewables.

The work approach I followed encompasses four main practices; study of electric vehicles, design and dimensioning of charging system, development of simulation model and meetings with suppliers to assess components availability, costs and feasibility on the whole. It is important to mention that different types of electrical vehicles support different types of chargers. As a result it was imperative to decide whether we would be charging cars, scooters or bicycles. This is where the lack of information concerning the users to whom Green Village services would be targeted, proved aggravating. Nevertheless, finding compatible solutions is what in hindsight made the overall endeavor more challenging.

The report itself is structured in such a way that would allow a reader who lacks technical background to be introduced to the basics of sustainable energy technology and understand the reasons which necessitate the development of electric vehicle charging points inside the Green Village. Building on that knowledge, enables one to touch upon the complexity that is the technical setup and modeling of the Station. A solid comprehension however, requires a background in electrical engineering, simulation techniques and programming. Some more demanding data processing practices are addressed to the experts in meteorology who grasp the importance of data mining. Furthermore, a good knowledge on electrochemistry is required to understand the phenomena taking place inside the batteries of electric vehicles.

ACKNOWLEDGEMENTS

Being fascinated by the advances in automotive technology, I consider the knowledge I gathered from working at the Green Campus as highly valuable. It gave me the opportunity to explore the world of electric transportation, which I personally consider will play an increasingly important role in the years to come. The research I conducted, substantiated to my mind the importance, building a network of chargers has, in giving electric vehicles a fair chance to outrival internal combustion vehicles.

I am therefore particularly grateful to Ad van Wijk, professor of Future Energy Systems at TU Delft and the visionary behind the Green Campus and Green Village Concepts. He trusted me to work on a subject that I proposed, thus giving me the opportunity to investigate what appealed to me personally. Without his critical thinking none of this would have happened.

Heartfelt thanks go out to Chris Hellinga, scientific consultant in the Delft Energy Initiative of TU Delft. Not only did he provide sophisticated guidance but was also cordially supportive on a more personal level, throughout this thesis.

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Last, but definitely not least, I am grateful to my sister Dimitra Bakola, for reviewing the very first draft of my report with her unparalleled cultivation, which more than makes up for her lack of technical expertise. Let me conclude with a warm ‘thank you’ to my family and friends for always being there for me.

1 Introduction

In a world of growing energy consumption and depleting fossil fuel reserves, renewable energy sources become the means to fulfill the need for a sustainable power production regime. This poses an unprecedented challenge for engineers who struggle to create concepts that not only are technically sound, but also have the potential to sail through the Symplegades of capital investment, towards a successful implementation amidst a competitive market. In the sections that follow, attention is focused on the Green Campus project as the reader is introduced to the main issues regarding electric transportation.

1.1 Background

For too long universities have been the epicenters of innovative concepts; loci where ideas are born, thoughts are exchanged and knowledge is actively transferred. Now though, more than ever, universities have an additional, more challenging role to play. That is to lay a fertile ground, on which new ideas will be given a fair chance to materialize, grow and diffuse into society.

Hitherto, most concept projects were treated as "hot potatoes" with academic institutions handing them over to the industry, eager to avoid the admittedly expensive development and testing phases. The problem is that even companies cannot guarantee their realization in today's stringent economy. This very notion was the basis on which Green Campus (GC) was envisioned.

1.1.1 Green Campus

The Green Campus vision is to create a sustainable, lively and entrepreneurial campus where people discover, learn and show how to solve society's urgent challenges (van Wijk A. , 2011). A vision to be realized at the TU Delft Technopolis; an entrepreneurial environment where students, researchers and companies will be brought together to develop concept solutions, by engineering commercially viable products and services.

Accelerating the transition to a fully sustainable future is perhaps the best way to describe the core purpose of the Green Campus, analyzed further into more specific objectives that include, among others, renewable power generation, waste water treatment and green transportation. Various concepts will be developed and ultimately put to practice onto a vigorous, testing ground, constantly improving and reinventing itself. The main actors in this scene being of course students, faculty members, research groups, partner educational institutes etc.

An ongoing, step by step approach is the only way to ensure the feasibility of each individual project, as well as the bankability of the endeavor on the whole. This is of course no easy task and definitely not one that the academia alone could handle. For this reason private companies shall contribute to the cause with their own expert personnel, equipment and funding. What do they gain out of it? New collaborations, innovative services and products, publicity and, last but not least, a profit on their investment.

The Green Campus development is planned in three phases on a time horizon set in no less than 10 years. First, the basic installations will be built comprising landmark projects like the harp, buildings that incorporate accommodation and dining facilities together with exhibition and meeting venues, accompanied by the necessary transportation infrastructure (Figure 1.1). During phase two, the so called “future labs” will be developed, i.e. a cluster of new and existing buildings, bringing together scientists and companies for the research and development of innovative solutions and products. The third and last phase shall bring about the long term development era, when the Green Campus is scaled up and becomes geographically interconnected in order to realize the Science Port Holland scheme (Science Port Holland NV, 2010).

Figure 1.1: Green Campus projects.

1.1.2 Green Village

To prove that all the plans presented above can indeed work, a testing ground is required. The Green Village (GV) will do just that. It will provide the environment and possibility to assess the Green Campus concepts on a smaller scale. Investigating anything from technology and implementation issues to business models and services, the Green Village will become a temporary test and try out laboratory site for topics such as the DC grid, LED lighting, water recirculation and of course EV charging. Starting in 2013, a modular core of refurbished shipping containers will be developed on a green, 16,000 m² location, next to TU Delft's Sport Center.

To begin with, a small community of 30 containers will house the offices of the Green Campus Company and its partners, as well as meeting rooms, labs, and student dormitories. The ultimate challenge is to make all these sustainable to the point of autarky. This is to say that the Village should be autonomous in terms of energy and materials. In other words, all the clean water should be produced on site by rain and wastewater purification. Next to that, environmentally benign or recyclable materials will be utilized but more importantly, all the consumed energy should be generated using renewable energy sources. The Village will provide all necessary functionality over a period of 4-6 years until the first Green Campus buildings are complete. After this, the Green Village will be dismantled, sold and the area will be restored to its original state (Green Campus Company, 2012).

Figure 1.2: Green Village artistic impression.

1.2 Electric Mobility in the Green Village

Having outlined the main features of the Green Campus and Green Village projects, it is now time to shed light on how this MSc thesis concept came about.

1.2.1 Motivation

The very principles that formed the basis for the GV, idem to those of the GC, i.e. sustainability and commercial viability, made it imperative to explore the subject of mobility within the TU Delft. This concerns the transportation of mainly people but also goods. Up to now, the latter has been handled by heavy utility trucks, usually running on diesel engines. Vehicles like these carry food, office or other kinds of supplies inside the campus, on a daily basis. As for personal transportation, it can indeed be argued that using a bicycle is as sustainable as it gets. Nevertheless, it is mostly students living in Delft who use their bicycle every day. The commuters living farther away usually prefer their cars or at best public transport.

To make matters worse, related studies show that 87% of commuters travel to work every day with no other passengers occupying the car, but the drivers themselves (Scottish Government, 2009-2010). This means that most of the time a 1.5 - 2 ton car has to move to transport the net weight of just one person, i.e. less than 100 kg. Then, considering the total energy efficiency in terms of consumption per unit distance per passenger, the current status quo in transportation seems profoundly wasteful. Especially when the maximum of 35% for the thermal efficiency of internal combustion engines (Zhao, Harrington, & Lai, 2002) is already quite low to begin with.

With all these in mind, it quickly became clear that, were the promise for a carbon-free Green Campus to be kept, it would be imperative to promote green transportation today. After all, the GV constitutes the best formula to develop solutions which can be tested and proven to work, in time for their deployment at the GC.

1.2.2 Genesis

To be able to move towards more sustainable mobility patterns, today, one has to utilize existing solutions, i.e. off the shelf products. On that note, electric vehicles, or EVs, are already driving around, even though public charging points are limited, compared to petrol stations.

More importantly, EVs have three times higher 'tank-to-wheels' efficiency than internal combustion engine vehicles. In addition, EVs emit no tailpipe CO_2 and other pollutants such as NO_x, NMHC and PM at the point of use (European Commission, 2011). Overall, they are clean and quiet, providing smooth operation with considerably less noise and vibration on the road.

Of course, the development of the necessary charging infrastructure is key to accelerating the transition to fully electric mobility in the near future. In fact, the increasing number of electric car owners makes it imperative to generate the electricity required for charging, from renewable energy sources.

It is that very notion which sparked the idea to design a sustainable Charging Station (CS) for Electric Vehicles. Such a station would be placed inside the GV and would offer charging services to visitors, TU Delft employees, students or any EV owner coming to charge their vehicle. It goes without saying, that the energy the station consumes should be generated from RES.

1.2.3 Research Questions

The idea introduced above formulated into this Thesis, for which research questions were defined around three main aspects, namely the design, the modeling and the feasibility.

Above all, the Station had to be designed, both as a physical layout but also in terms of the technical setup. This is where it became important to answer "what technology is required exactly and how should it be configured?" and "is that technology compatible with the plans for the rest of the village?" Also "can such a unit indeed be autarkic with current technology?" and "what level of power output should be expected?" Answers to these questions are given in sections 2.1, 3.3 and 5.1 respectively.

Essential to all projects being developed for the Green Village is the ability to create models which can simulate the behavior of a system, prior to its actual implementation. That way, possible design mistakes can be diagnosed and corrected without ever leaving the drawing board. As such, the ability to build a model for the Charging Station had to be explored, which begs the question, “what would be the most suited environment for such a model?” Also, “how can it be adjustable to design changes along the way?” Last, “what data should be inputted to provide accurate simulation results?” These questions are answered in sections 2.2 and 2.3.

Finally, “what conclusions can be drawn regarding the feasibility of the real project?” In other words, “could a cost analysis be performed for the suggested Station design?” To answer these questions, a series of meetings with suppliers and industry experts took place at the last stages of this Thesis, during which critical information were collected regarding the cost and availability of the required components. A cost assessment analysis is presented in section 4.2.

1.2.4 Commercialization

The decision to proceed with this project went hand in hand with the commitment to make it economically feasible. As soon as the primary technical characteristics of the Station were established, weight was given to discovering possible patterns that could substantiate a business case. As a result, the idea was born to not only create added value by charging electric vehicles, but also make a profit from renting EVs. In both cases however, cars would be the most costly type of vehicles to either charge or purchase respectively. This meant that lower-end vehicles, like scooters or bikes, would be a more affordable solution, given the scale of the GV.

Commercial options for related EVs along with corresponding costs and suggested services are presented in chapter 4, where the Station logistics is discussed.

1.3 Similar Projects

Every day, new ventures are initiated around the globe, which try to associate EVs with renewables. A nearby example is the ongoing EDISON program in Denmark, which is short for “Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks”. With a budget of 49 million DKK (≅ 6.6 million Euro), EDISON is a research consortium between DTU, DONG Energy, Risø, IBM, Siemens and other partners, attempting to create a platform which would allow EV users to prioritize renewable energy when recharging their vehicles (EDISON, 2009). In other words, users can select between for example a wind farm and a coal fired plant, as the source where the energy required to charge their cars is generated. Similar to that is the REV Project, set up at the University of Western Australia, which builds or converts EVs since 2008 and which in 2012 installed a first solar CS in West Perth (UWA, 2012).

As for additional projects, the University of Iowa constructed a Solar EVCS in the summer of 2011 (Facilities Management UIOWA, 2011). On July 2011, Mitsubishi Motors also installed a solar-powered charging station at its headquarters in California (Mitsubishi Electric & Electronics USA, Inc., 2011). Furthermore, modular versions have also been deployed like the Solar Canopies installed in Seattle since August 2011 (Williams, 2011). Perhaps the most interesting project however, simply due to the resemblance it bears to the Green Village Concept, is the Mini E solar charging station installed in New York City by Beautiful Earth Group. The station was constructed back in December 2009, with recycled, decommissioned steel shipping containers stacked atop each other and a series of 24 roof mounted PV modules of 235 W each, manufactured by Sharp (BE Group, 2009).

Currently, wind energy is slowly finding its way to EVCSs as well. An example of that is 'Sanya Skypump' i.e. the world's first wind powered EVCS, developed under joint collaboration between General Electric and Urban Green Energy, a vertical axis wind turbine manufacturer (UGE, 2012). On August 2012, the first Skypump system was installed at the Cespa waste management site in Barcelona, Spain with a cost of $30,000 (Gordon-Bloomfield, 2012).

Table I summarizes the technical specifications of the aforementioned projects and photos of the stations are demonstrated in Appendix A.

Table I: Existing Electric Vehicle Charging Stations

Station	SET	Charging Spaces	Installed Power	Cost
UIowa EVCS	224 PV panels[1]	20[2]	57 kW[2]	$950,000[2]
Mitsubishi SPCS[3]	96 PV panels	4	16.8 kW	$130.000[4]
Solar Canopy[5]	15 PV panels	1	3.75 kW	$60,000
Mini E SPCS[6]	24 PV panels	1	5.63 kW	$25,000[7]
Sanya Skypump[8]	1 VAWT	1	4 kW	$30,000

1.4 Conclusions

If the projects presented above show something, that is the diversity of the deployed systems. Beside the fact that solar cells are used to generate electricity in almost all EVCSs, the remaining components have to be customized to fit the requirements of each project. Moreover, the offered charging services vary from station to station, targeting different user groups. Therefore, in order to be compatible with the Green Village design philosophy, a high level of flexibility was

1 (Facilities Management UIOWA, 2011)
2 (The University of Iowa, 2011)
3 (Mitsubishi Electric & Electronics USA, Inc., 2011)
4 (Durand, 2011)
5 (EV4 Oregon LLC, 2011)
6 (BE Group, 2009)
7 (Brown, 2009). *The project was financed by BMW*
8 (Gordon-Bloomfield, 2012)

required, straight from the beginning of this thesis project. Luckily, that quickly became apparent, leading to a strong commitment to keep in line with the frequently changing solutions developed for the Green Village. This very notion is reflected on the models presented in Chapter 2.

2 Station

This chapter deals with the technical implementation of the charging Station. In the sections that follow, the physical design is presented and modeled. The model is then used to simulate the operation of the Station under various weather conditions. The simulation results are illustrated and analyzed at the end.

2.1 Design

The request to make Green Village fully autarkic meant that the Station should be able to generate virtually all the energy it consumes. Sustainability is therefore the essence on which the design was based. A desk study was therefore performed to find out what the commercially available options are, regarding renewable energy technologies. The result was a number of possible solutions including solar cell modules, wind turbines and fuel cells.

To discover the optimal integration of these renewables, it was necessary to experiment with variant architectural layouts. For that reason, a three dimensional model of a standard 20 feet container was built to scale, using the computer design suite 'SketchUp Pro' (Trimble ltd., 2012). In addition, accurate 3D models of the most prominent RES components were developed. Various topology combinations were then tested, before arriving at the end-design depicted in Figure 2.1.

The suggested design is able to house PV panels on the container rooftop and small windturbines on the sides. Moreover, the space inside is enough to accommodate charging infrastructure for at least two cars or about eight scooters. The only limiting factor of course, is the power the renewable energy components would actually generate.

Before the energy yield is addressed though, it is important to note how the Station operation was originally envisaged. Electric vehicles such as cars, scooters, segways or even trucks should be able to charge their batteries in no more than eight hours. The maximum 8-hour charging time was selected to relate to a normal work day. In that sense for example, a TU Delft employee using an electric car would drive to the University in the morning and park the car at the GV EVCS to recharge while they are working. At the end of an 8-hour shift, their vehicle should be fully charged, ready to travel back home.

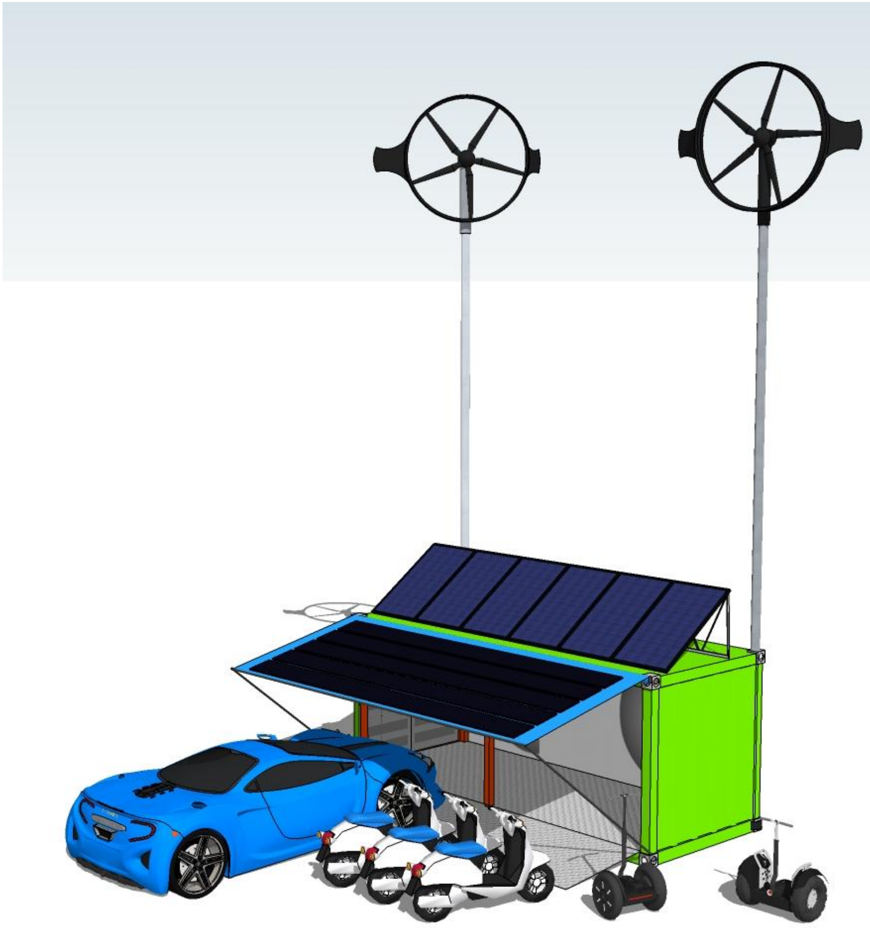


Figure 2.1: 3D view of the Green Village EV Charging Station

2.1.1 Features

Having explained the basic design criterion, it is now time to present the key features of the proposed layout.

2.1.1.1 *Mobility*

The Station will be housed in a standard shipping container measuring 20 feet long by 8 feet wide, i.e. L:6.1 x W:2.44 in meters (Figure 2.2). As a result it can be loaded on a truck and transferred to areas where it can be positioned in order to cover permanent or temporary charging needs.

Autonomy combined with mobility make it easy to deploy multiple units initially throughout the Green Village, and at a later stage, on specific spots inside the Green Campus (e.g. parking lots, Delft Zuid Station, electric bus or taxi stops etc.). After the Station has served its purpose on a particular location, it can be dismantled, transferred and put back together elsewhere.

Figure 2.2: Photo of 20ft container with both front and full side door.

2.1.1.2 *Innovative thinking*
The Station encompasses an innovative design methodology combining state of the art technology with common tools. This contributes greatly to the simplicity of use, making every day charging a user friendly experience. An example of lean design, that serves a double cause, is the tent covering the Station entrance. This provides shade or protects the equipment and occupants from the rain, but also creates an ideal surface for the use of flexible solar cells.

2.1.1.3 *Autonomy*
Energy is generated sustainably, utilizing a combination of green energy solutions, namely small wind turbines and PV modules, discussed in detail in paragraph 2.1.2. However, it takes a considerable amount of energy to charge the batteries of EVs. This is why the Station cannot be fully autonomous, but needs to be connected to the local power network of the Green Village (see paragraph 2.1.3).

It should be stressed that battery storage is not included in the Station design. This decision stemmed from the fact that a high capacity battery bank (GVBB) will be included in the Green Village. That is sized to both handle the fluctuating power demand of the village and also provide backup power to the Station. A centralized storage system is after all faster to install, easier to control and cheaper to maintain.

Whenever the Station's own electricity production is not enough to charge the connected vehicles, stored energy will be utilized instead. This will of course be replenished at times of surplus of generated power or when no vehicles are using the Station.

2.1.2 Components
The term 'components' refers to the renewable energy technologies responsible for generating power, as well as the necessary balance of plant devices. Selecting those devices was no easy task. The most challenging part of the process, aside

from having to meet the Station's technical requirements, was that certain parts should be compatible with the rest of the village.

To give GV a fair chance to even get off the ground, acquisition cost has to be kept as low as possible. The only way to accomplish that marketwise, is by procuring equipment via turnkey contracts. Put more simply, buying in bulk would ensure low prices. As a result, the designers of each individual project within the Green Village had to select components which could fit other projects as well.

To complicate matters more, priority had to be given to certain partner companies involved with the Green Campus Concept, who either as project integrators, consultants or dealers, supply specific solar cell and wind turbine brands themselves. Keeping in mind the above, the following components were selected:

2.1.2.1 *wind turbine*

The Windtronics BTPS6500 (Figure 2.3) is the wind turbine model to be deployed in the Green Village, selected for its small size, easy installation and low cost. Two of these turbines will be installed on the back left and right corners of the charging Station container. The rotor, 1.82 m in diameter, is based on a bicycle wheel design. Each module has a rated power output of 1500 W at 13.9 m/s wind speed. This is generated as permanent magnets, located on the blade tips, pass by stator windings, located inside the outer shroud, while the rotor rotates. At hub height each wind turbine will stand 12 m from the ground on top of an 8.7 m pole. Analytical technical specifications are given in Appendix B.

Figure 2.3: Windtronics BTPS6500 wind turbine installed on a container office in Netherlands (GE4ALL, 2012)

2.1.2.2 *solar panel*

Two types of solar panels will be installed on the Station, i.e. crystalline silicon PV panels on the rooftop and amorphous silicon thin film modules onto the tent.

The PV panel shown in Figure 2.4 contains 60 polycrystalline silicon cells that generate 245 Wp maximum power under STC[1]. Manufactured by Suntech, these modules are designed to offer the best price/performance ratio (Suntech Power Holdings Co. Ltd., 2012).

Figure 2.4: Suntech STP245S - 20/Wd+ solar panel (Suntech, 2011)

A total of six PV panels will be installed in a row on the container roof, at a 36° tilt angle, which is the optimal year-round inclination for the latitude of Netherlands (de Keizer, Alsema, & Groeneveld, 2007). It goes without saying that the Station will be facing south. However, for ideal orientation an azimuth offset of 6° to the west has to be kept as well (Geskus, 2012). This can easily be satisfied either by pivoting the PV row alone (Figure 2.5), or by positioning the entire container to face 6 degrees to the west.

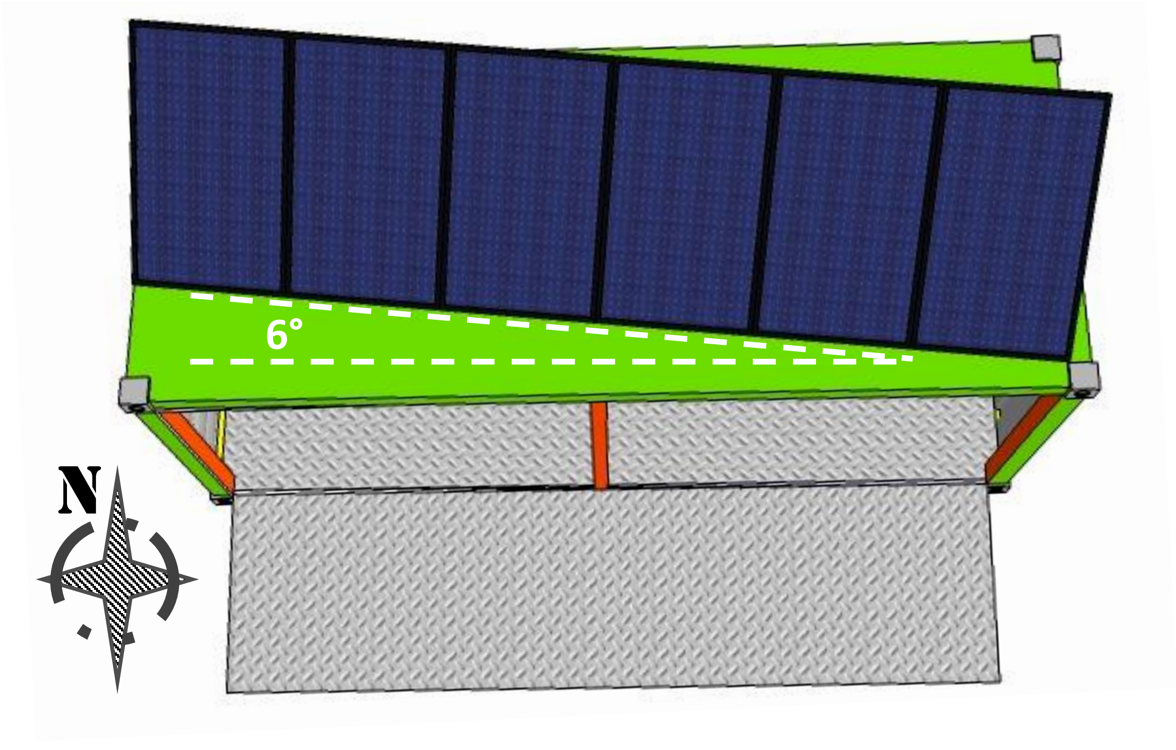


Figure 2.5: PV orientation

[1] Standard Test Conditions: irradiance 1000 W/m^2, AM=1.5, Cell temperature = 25 °C.

As for the decision to position all six panels in a row and in portrait configuration, this was done to avoid shading as explained in Appendix D.

Figure 2.6 displays Uni-Solar's PowerBond ePVL flexible solar module. 22 multi-junction amorphous silicon solar cells generate 144Wp maximum power under STC. Measuring 5.4 m in length and 37 cm in width, five of these thin film modules will adhere directly onto the Station tent.

Figure 2.6: Uni-Solar PowerBond ePVL-144 thin film PV module (United Solar Ovonic, 2011)

As seen in Figure 2.7 however, to allow a 2m ground clearance for the tent, their tilt angle had to be limited to 16°, which according to actual measurements, only causes a 3% drop in the incident sunlight (Siderea, 2010)!

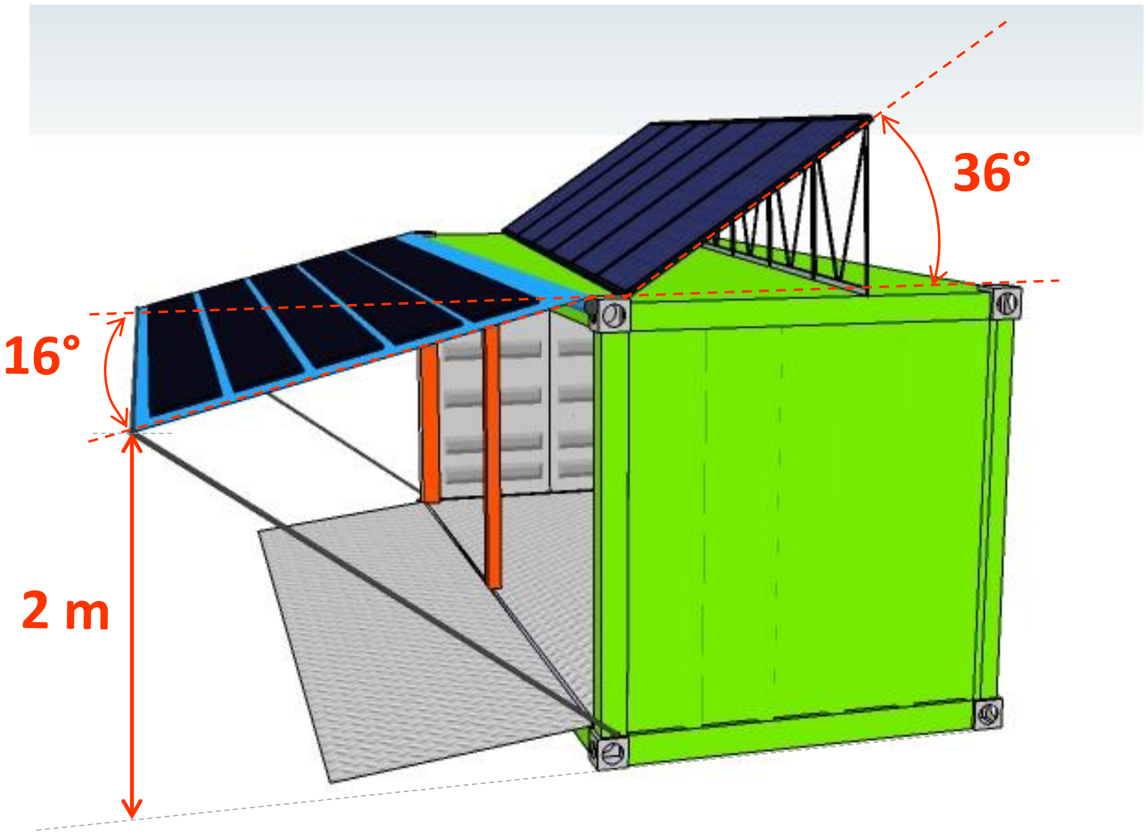


Figure 2.7: PV configuration

2.1.2.3 *solar power optimizer*

According to electrical circuits theory, when connected to a load, the internal resistance of a solar cell and the resistance of the load have to match in order to achieve maximum power transfer to the load. Solar cells however, have highly nonlinear current – voltage characteristic curves. This means that the internal (a.k.a. characteristic) resistance of the cell is not constant, depending on the illuminance, the temperature, etc. (Zeman, 2009). As a result, to draw the maximum power out of a photovoltaic module, under variant load and/or variant illuminance, one has to use a maximum power point tracker (MPPT). This essentially adjusts the module voltage, measuring the output current, until the resulting power reaches the nominal value. Of course, several different algorithms have been proposed and are currently used to control this process (de Brito, Sampaio, Luigi, e Melo, & Canesin, 2011).

Normally, solar panels are connected into strings, with each string connected to an inverter. MPPT is usually performed by the inverter for the whole array. The problem with this topology is that not all panels in a string generate the same power, mainly because of partial shading and manufacturing tolerance. In other words, at each moment, each panel generates different maximum power, thus can output different current level. Nevertheless, since each panel is connected to the next in series, the same current has to flow through all panels in the line. Clearly, this current is limited by the one panel producing less at the moment. In this case then, maximum power transfer can never actually be achieved. Even if an MPPT unit is indeed used, maximum power will be drawn out of the least producing panel but certainly not out of all the other panels in the string.

The solution to this problem is to use an individual MPPT unit for every solar module. Such a unit is called a ‘power optimizer’. Figure 2.8 shows the model to be used in the charging Station, manufactured by Femtogrid, one of the main Green Campus partners. Installed in all modules, both crystalline and thin film, it will increase the system performance offering up to 30% higher energy yield (Femtogrid Energy Solutions BV, 2012). It should be noted that installation is quite easy as the power optimizers stick on the back of the modules and connect directly to the PV junction box. Furthermore, they offer the ability to monitor the individual power production of each panel by sending information to a central node, over ZigBee communication protocol. More on the electrical characteristics of this solar power optimizer can be found in Appendix F.

Figure 2.8: Femtogrid PV300 Power Optimizer (Femtogrid Energy Solutions BV, 2012)

2.1.2.4 *wind power optimizer*

Maximum Power Point Tracking is also performed on wind turbines with similar methods (Örs, 2009). Figure 2.9 illustrates the wind power optimizer designed specifically for the wind turbines to be used in the Green Village (Femtogrid Energy Solutions BV, 2012). For more detailed technical specifications see also Appendix G. Two of these devices will be deployed in the EVCS, each controlling one wind turbine.

Figure 2.9: Femtogrid Wind Power Optimizer (Femtogrid Energy Solutions BV, 2012)

2.1.2.5 *inverter*

The ultimate goal of the Station is to charge EV batteries. Given that batteries operate in DC and direct current is indeed what all solar panels and the selected wind turbines generate, an inverter arguably seems useless. That however, counterintuitive though it might be, is unfortunately not the case. All throughout Europe electricity reaches home users running on 50Hz alternating current at 230V. It only makes sense that EV manufacturers would design the vehicle's onboard charger so that users can primarily charge at home. As a result, all existing EV models plug into the standard AC mains wall outlet to charge. That said however, the latest electric car models offer additional connectivity options, such as the popular DC fast charging, which are discussed analytically in section 3.1.

Clearly then, the Station would not be able to work without converting the DC power coming from RES to single phase AC power available at any domestic socket. For that an inverter is required. The model selected for the Station appears in Figure 2.10. It can deliver up to 2.55 kW of DC power and was designed to work together with the wind and solar optimizers presented above (Femtogrid Energy Solutions BV, 2012). The complete list of specifications is given in Appendix H, yet it is important to emphasize that the particular inverter contains a transformer. This provides galvanic isolation between input and output, which prevents possible DC faults from being transmitted to the AC side and damaging the connected EVs.

Figure 2.10: Femtogrid Inverter 2400 (Femtogrid Energy Solutions BV, 2012)

2.1.3 Interconnection

The Station shall connect to the village central storage system via a bidirectional DC link. Supplementary power will usually be flowing from that storage system to the Station, yet at times when the Station itself generates excessive power, it is also possible to feed the surplus back to the village, thus recharging the battery bank.

Figure 2.11 summarizes the Station technical design, drawing an outline of the connected components. Two wind turbines, six solar panels and five thin film modules, all connect to the two Station inverters through their individual power optimizers. In total, the Station has a 5.19 kW installed power capacity, all coming from renewable energy. Electric vehicles will be able to plug into the Station outlets to recharge on clean, green electricity.

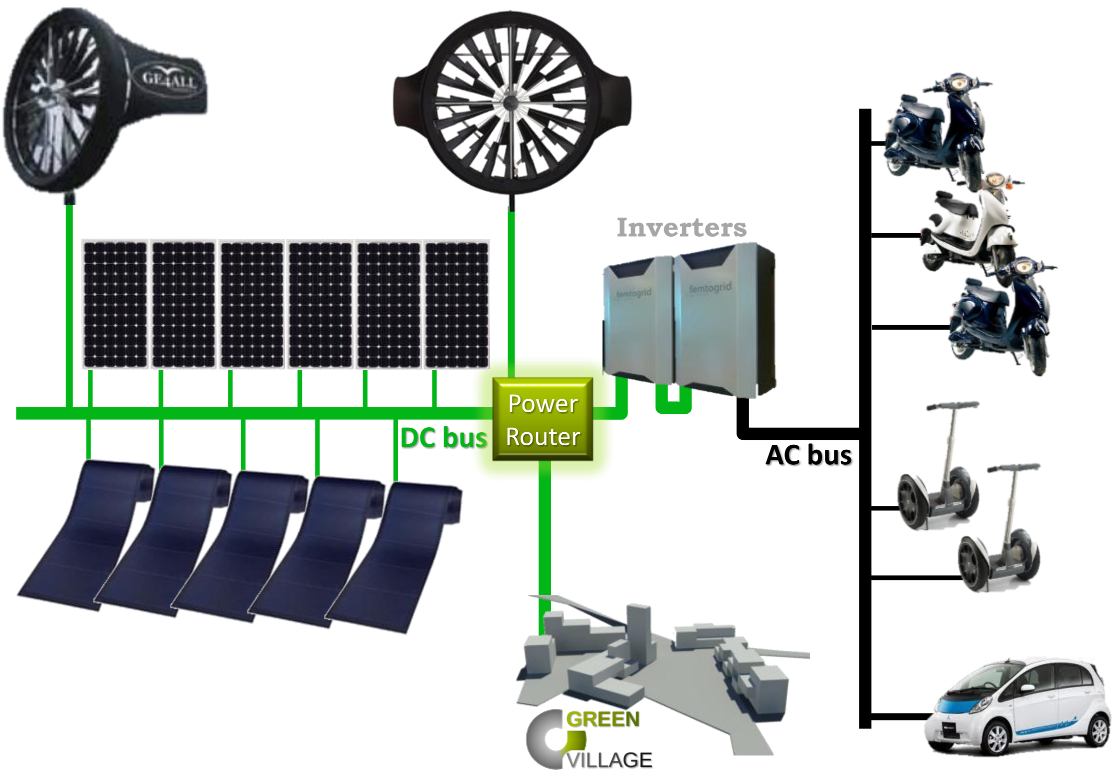


Figure 2.11: Layout of basic components.

2.2 Modeling

Developing models which can simulate the operation of various subsystems deployable in the green Village is of the utmost importance. The developed computer models shall become valuable tools in the hands of the plethora of involved researchers, all coming from different disciplines and focusing on different segments of the Green Village. After all, only such practical tools can guarantee the continuity and coherence of the overall engineering, throughout the long development period of the Green Village.

Nevertheless, it should be stressed that during the preliminary design of the village, few decisions were set in stone. This is to say, that there was a significant degree of uncertainty with regards to many of the technical requirements of the infrastructure to be developed, the available budget and ultimately the end-users themselves. Many of the related variables were, and at that stage had to remain, just that; variables. This called for a great level of flexibility in the developed models; such that would allow them to be fully customizable in order to easily adapt to design changes that inevitably took and will continue to take place along the way.

With the above in mind, a widely used simulation program was selected to model the Station components and operation. This is Simulink®, a block diagram environment for multi-domain simulation and model-based design, which builds upon MATLAB (Mathworks, R2012a). In the paragraphs that follow the developed models are introduced.

2.2.1 Challenges

Prior to building any actual model, the fundamental electrical and electronic subsystems were identified. These were then individually modeled in detail, using the Simscape - SimPowerSystems™ library in Simulink. This library provides blocks that simulate the operation of real power electronic elements such as thyristors or MOSFETs. Initially, the idea was to combine all these subsystems into one overall model. It soon became clear however, that this would not be practical in terms of compilation time. This is because obtaining accurate simulation results, while using the detailed power conversion models, requires considerably high time resolution, or put simply, excessively small time steps. Said time steps are in the order of 10^{-6} seconds or lower, which would mean that it would essentially take days to run a simulation scenario of just some hours. Combined with the fact that the immense intermediate data volume, created by the simulation itself, would easily exceed the memory normally allocated to MATLAB in most computers, this often caused the simulation to crash.

To avoid these pitfalls, it was decided to develop two types of models; dynamic and static. The first, simulate the response of the power conversion electronics for each subsystem and the second tests the operation of the total system, without modeling each hardware component in detail.

2.2.2 Dynamic

The term 'dynamic' relates to the fact that the SimPowerSystems library provides automated tools that evaluate the dynamic response of the subsystems, by means of harmonic distortion, load flow, and other key electrical power system analyses. Such diagnostics did not fit the scope of this thesis and were thus not performed. However, the corresponding dynamic modeling is included here because it will serve as a valuable stepping stone to anyone who shall handle the design and configuration of the hardware required for DC charging in the Green Village (see chapter 3).

The advantage of the dynamic models is that they provide measurements of the voltage and current flowing through the electronic elements of each subsystem. In particular, the dynamic models developed during this thesis concern the three main Station subsystems; the boost converter, the inverter and the rectifier (Figure 2.12).

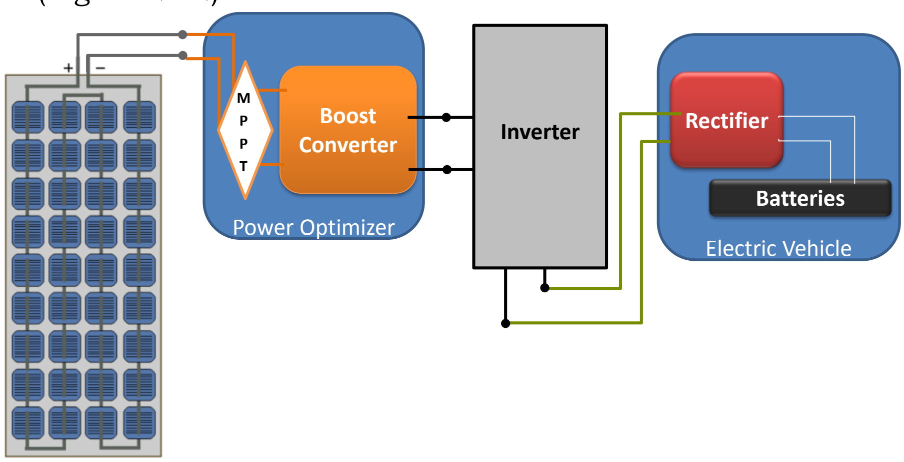


Figure 2.12: Power Conversion Subsystems.

2.2.2.1 *Boost converter*

A boost or step-up converter is a DC-DC power electronics unit which increases the fixed voltage supplied to it. In other words, it receives a DC input of a certain voltage and converts it to a DC output of higher voltage. This is achieved by making use of a power switch, such as a MOSFET or IGBT, together with the energy storage properties of an inductor. Figure 2.13 shows the circuit of a MOSFET boost converter (Rizzoni, 2005). Notice that a capacitor is also included to filter out the voltage ripple at the output.

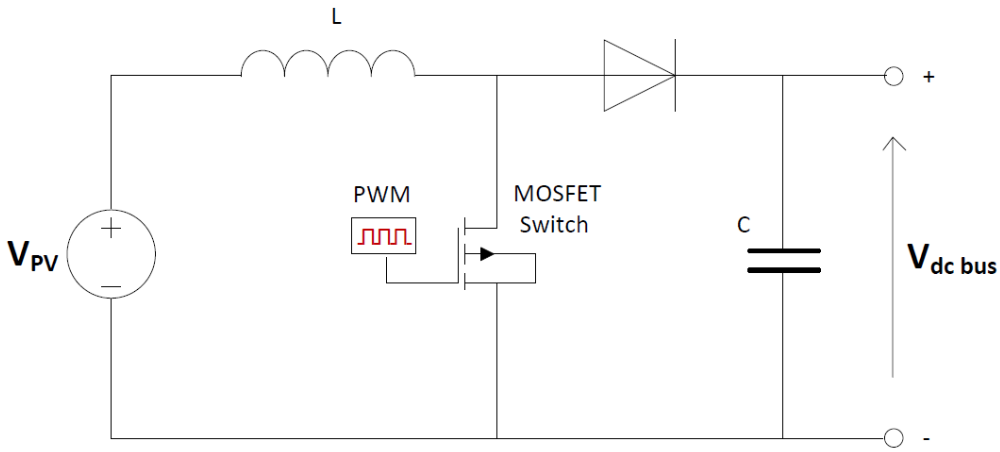
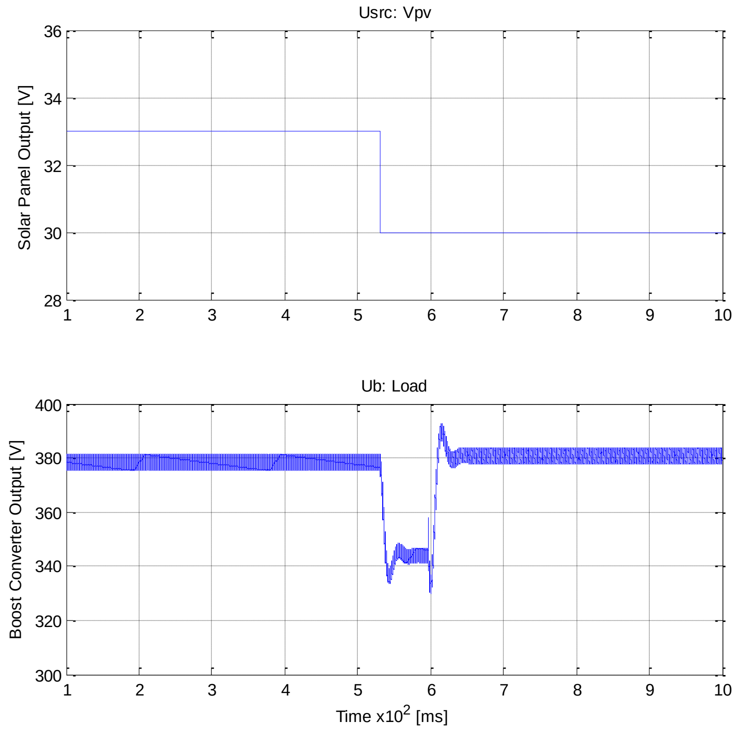


Figure 2.13: Basic schematic of a MOSFET step-up converter.

In the case of the GV charging Station, boost converters are implemented inside the power optimizers. There, they raise the voltage output of each PV module (typically around 30 V) to 380V, which is the voltage level of the array dc bus feeding the inverter. The boost converter is also fitted with a regulator, whose responsibility is to maintain the output voltage at a constant level, unaffected of fluctuations in the input voltage. The regulator achieves that by controlling the width and period, i.e. the duty cycle, of the MOSFET pulses.

Figure 2.14 gives the response of the dynamic boost converter model when a drop occurs in the input voltage. This drop simulates a cloud passing over the Station, which would cast shade on the solar panels lowering their voltage output. Notice that the regulator compensates for that and regains rated output voltage rather quick.



At t = 100 ms the solar panel generates 33 V which is stepped up to 380 V. At t = 530 ms the PV output drops to 30 V. As a result the boost converter output drops to 340 V The voltage regulator detects the drop and adjusts the duty cycle accordingly to counteract it. At t = 630 ms the output regains its 380 V rated value.

Figure 2.14: Response of the dynamic boost converter model.

2.2.2.2 *Inverter*

A power inverter is a DC-AC conversion unit, used to supply AC voltage of certain frequency from DC sources. This is achieved by making use of a so called H-bridge, like the one drawn in Figure 2.15. Depending on the type of output, single or three phase, the bridge consists of 4 or 6 switches (MOSFETs, IGBTs etc.) respectively. Figure 2.15 shows the circuit of an IGBT single phase inverter (Rizzoni, 2005). Notice that a transformer is often used to match the output voltage to the grid. This has the added benefit of isolating the DC from the AC side, as mentioned in subparagraph 2.1.2.5.

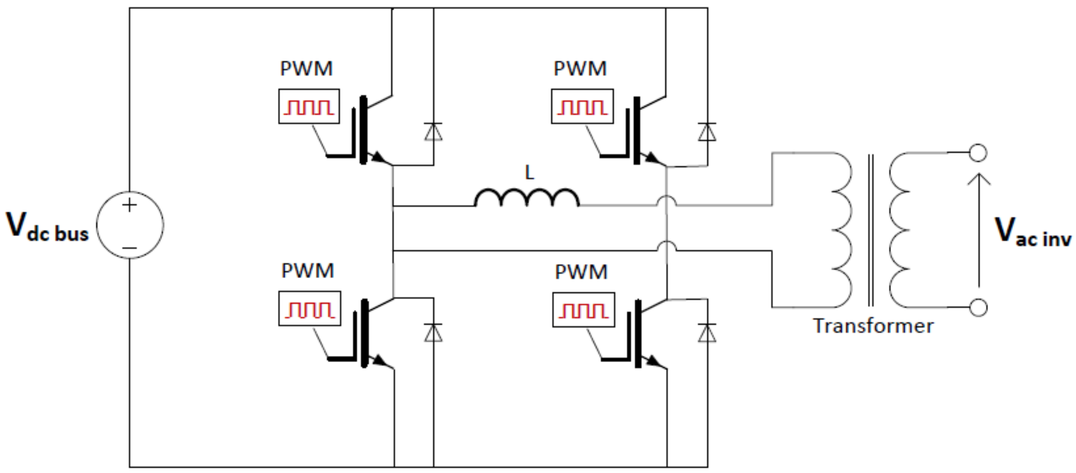
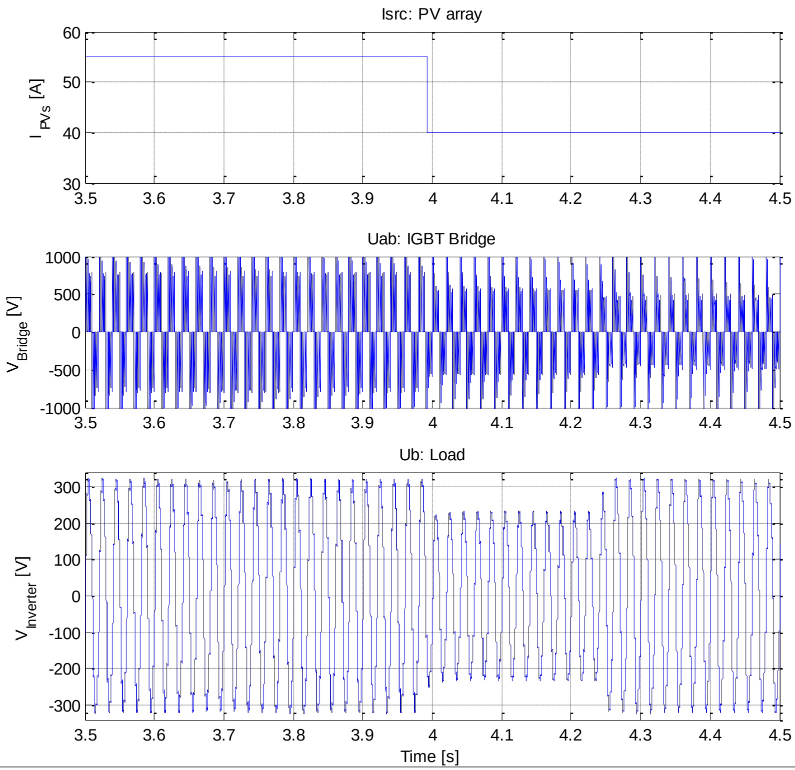


Figure 2.15: Circuit schematic of a single phase IGBT inverter.

Figure 2.16 gives the response of the dynamic inverter model under fluctuating power produced by the PV panels. When a drop occurs in the dc current output of the PV array, the PWM controller takes proper action to counteract it.



At t = 3.5 s the solar panel array generates 55 A_{dc} which are fed into the inverter to convert to sinusoidal AC with 325 V peak voltage (=230 V_{rms}). At t = 4 s the PV output drops to 40 A_{dc}. As a result the inverter output drops to 233 V peak voltage (=164 V_{rms}). The PWM controller detects the drop and increases the modulation index accordingly to counteract it. At t = 4.25 s the inverter output regains its 230 V_{rms} rated value.

Figure 2.16: Response of the dynamic inverter model.

2.2.2.3 *Rectifier*

A rectifier is an AC-DC power conversion unit, present in any ordinary battery charger that connects to the grid. As such, it is also a crucial component of EV battery chargers. Its operation is again based on the H-bridge - only reversed, compared to the inverter. Figure 2.17 draws the schematic of a single phase PWM rectifier.

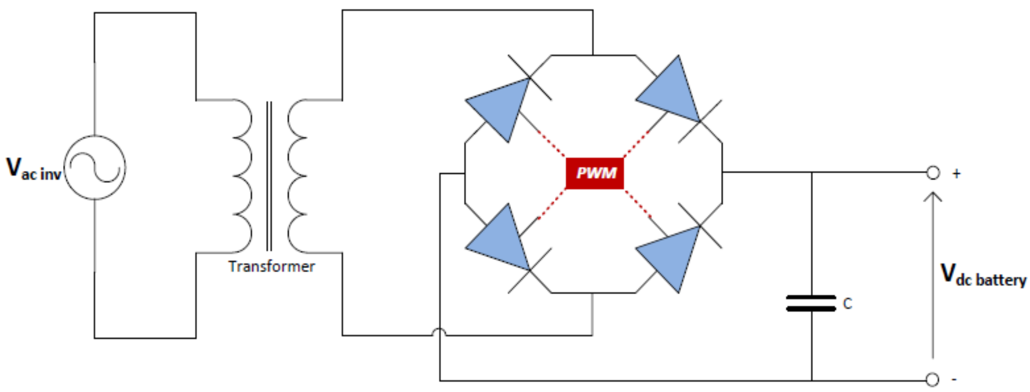
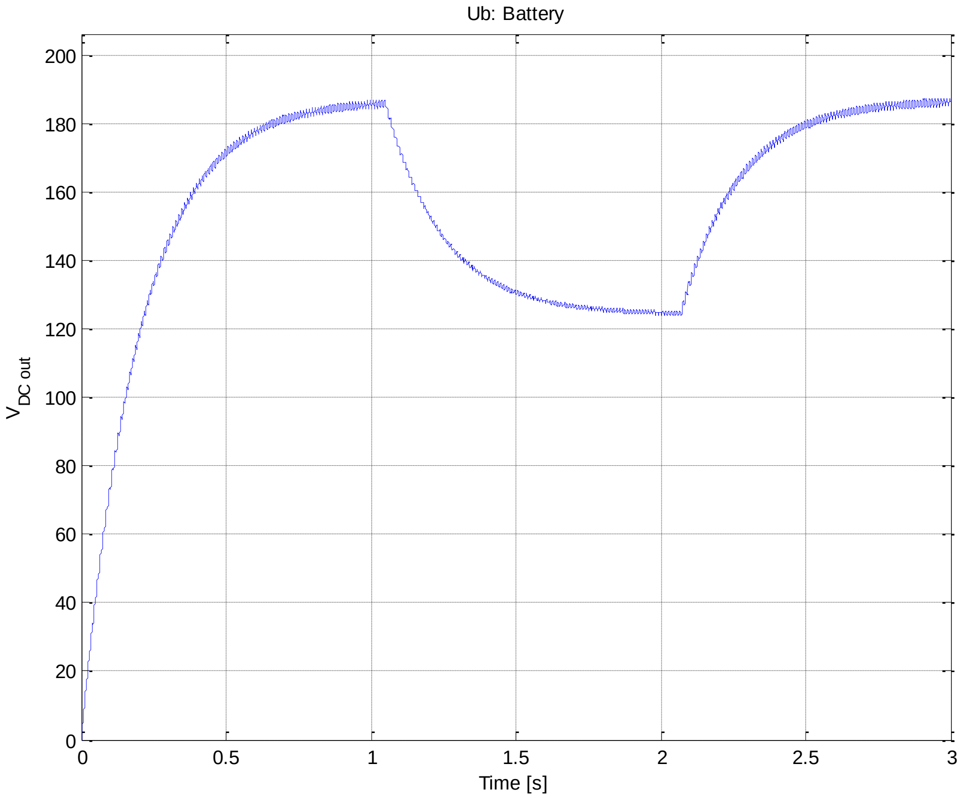


Figure 2.17: PWM controlled rectifier schematic.

Figure 2.18 gives the response of the dynamic rectifier model developed for this thesis, to changes in the modulation index.



At t = 1 s the modulation index drops from m = 0.99 to m = 0.2. The rectifier Voltage drops from 185 V to 125 V as a result of that. At t = 2.1 s the modulation index is increased to m = 0.99 again, The rectifier reaches nominal output by t = 3 s.

Figure 2.18: Response of the dynamic rectifier model.

The decision to model all electronic subsystems as single phase on their AC side was based on two reasons. First, the inverter supplied by Femtogrid was indeed single phase. More importantly though, not all EVs support 3phase charging. In fact, except for some of the recent electric car models, all lower-end EVs like scooters or bikes, can only charge in 1φ-AC. Of course, 3φ cars also offer single phase charging connectivity, yet the same does not hold for single phase scooters. Even if a 3φ inverter was somehow obtained, say by another supplier, charging a scooter on only one phase would cause unbalanced loading of the 3φ inverter rendering it unable to operate correctly.

2.2.3 Static

The term 'static' was introduced here to differentiate the two models. It does by no means suggest that the simulation accuracy of this model is sacrificed. Perhaps it would be better described as 'power model', since it does not use the voltage and current driven blocks of the SimPowerSystems library, to perform power conversion from AC to DC and vice versa. Instead, it models the system directly in terms of power flow. This makes it considerably less complex to model the Station controller and simulate variant strategies for its operation, as explained further in subparagraph 2.2.3.2 below.

The architecture of the Static Model is delineated in Appendix I. Each of the Station components presented in paragraphs 2.1.2 and 2.1.3 were modeled with fully customizable Matlab functions which contain the manufacturers' specification data. Notice that special attention was given to the design of the graphic user interface (GUI). The model contains some 1684 blocks forming a rather complex structure. To make it user friendly, groups of blocks were organized in subsystems and icon images were added. A total of eight EVs are represented in the Station model (further discussed in paragraph 2.3.5), which the user can easily connect or disconnect via simple on/off switches.

2.2.3.1 *Conditional power flow*

Two were the main aspects considered when configuring the Static Model with regard to power flow. Both have to do with power abundance and utilization. The first and most obvious consideration was that renewable energy is not always available when needed. Of course, electronics do help to mitigate moderate fluctuations in power, yet the subsystems described earlier can only do so much to safeguard the system stability at times when the energy yield is minimal or worse, nonexistent.

This led to the realization that a backup connection to the local GV grid is a sine qua non, which in turn begs the question: "what happens when the village itself cannot handle the extra burden?" In other words, imagine a situation where numerous vehicles need to charge but the Station's own production does not suffice. And on top of that, the GVBB is running dangerously low. How should the system respond then? Especially when storage capacity is sized to provide peak shaving and not manage the full load. Mind you, given the lifetime and cost of batteries, oversizing quickly creates more problems than it solves, hence can only be performed sparingly.

The following subparagraph answers these questions by suggesting a power flow control strategy.

2.2.3.2 *Controller strategy*

The fundamental objective of any distribution network operator is to constantly match power supply and demand. In fact the same, albeit on a smaller scale, holds for any autonomous system. As such, an autarkic EV charging Station would need a unit that controls the power flow between its energy generating and energy consuming components. That is not the complete story in the Green Village charging Station though. The difference lies in that it is interconnected to the rest of the village. This poses an additional challenge, which is no other than balancing power supply and demand first within the Green Village itself.

Unlike the national electricity transmission network, the village DC grid will be local in nature, with limited installed power capacity. Therefore it will not always be the case that there is enough renewable power available for the village's own needs, let alone for charging EVs. The battery bank will of course be there to act as a buffer, yet no one can rule out the possibility of the storage system itself running low on power whilst cars are charging. Should this occur, priority had to be given to covering the village power needs, even at the expense of an uninterrupted Station operation. After all, predicting all outcomes, however rare, and taking proper measures to mitigate the consequences is what makes a system well designed.

The control strategy suggested for the Station power flow was implemented algorithmically and embedded as a C/C++ compiled Matlab executable (Matlab Coder, R2012a). The source code is given in Appendix J. The algorithm runs at every simulation step, thus constantly balancing supply with demand, at each moment in time. Figure 2.19 depicts the programming logic in the form of a flowchart.

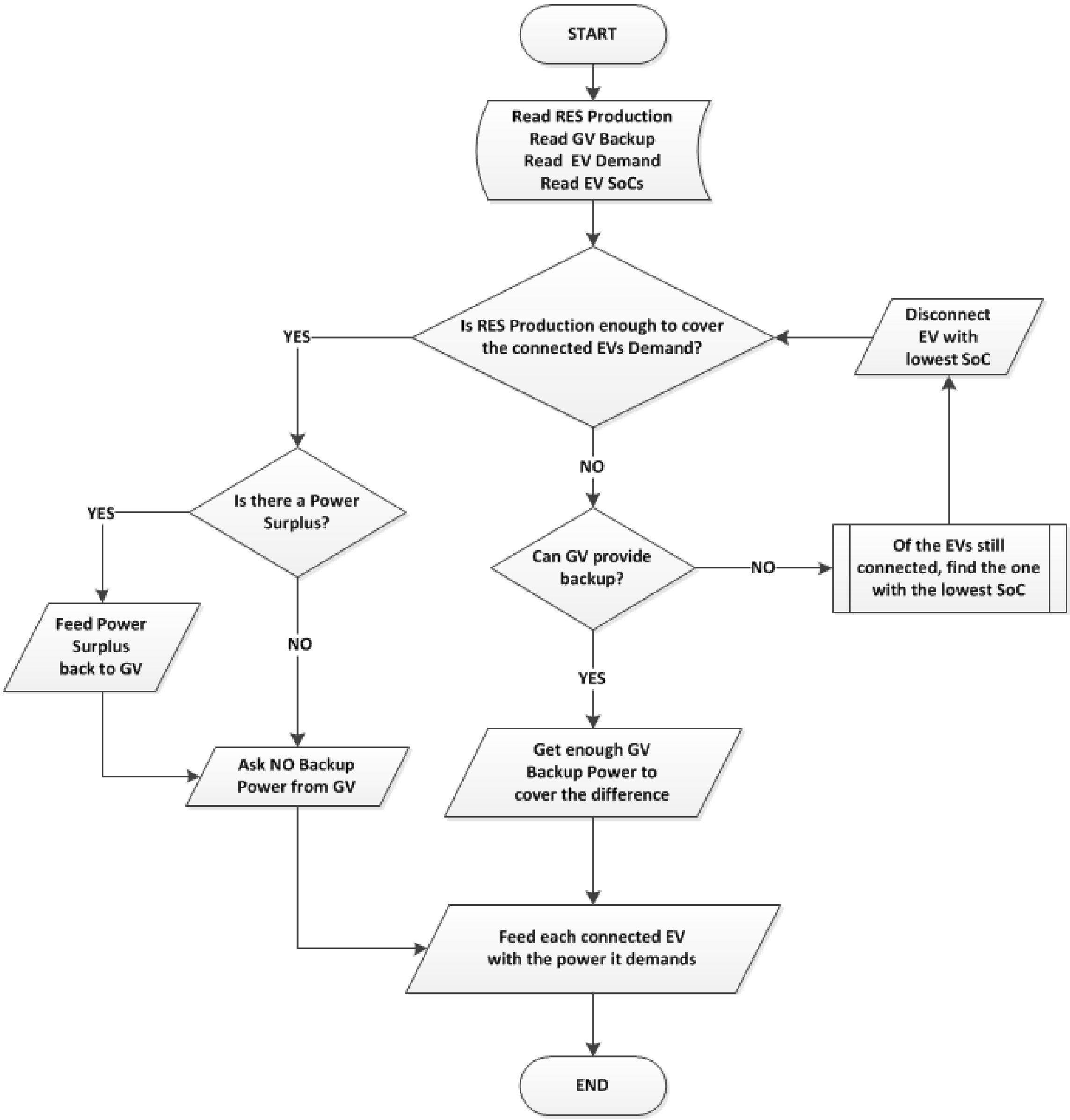


Figure 2.19: Block diagram of the Station controller strategy.

Perhaps the simplest way to describe the decision process would be the following.

If the power generated by the renewables deployed on the Station is enough, the controller feeds all EVs with the energy they require. The surplus, if any, is sent to the village to be stored in the GVBB. This also holds at times when there are simply no EVs using the Station.

Whenever there is not enough RES power, the controller requests supplementary backup power from the village.

If the village cannot provide backup, the Station controller is designed to counteract that by denying charge to the EVs that are almost empty[1], with the hope of leaving enough renewable power to bring the rest to a usable SoC, faster.
It should be noted, that according to the Static Model setup, the Green Village would not provide backup only at the extreme case where the GVBB storage system is running very low (e.g. at a SoC < 20%). Then interconnection is designed to shut off power flow from the GV towards the Station. Not vice versa though. Should a surplus occur at that point, the Station would still be able to feed the GVBB with it.

2.3 Simulation

This section explains how the simulation input data were obtained. It also describes the process followed to setup the initialization parameters which are necessary to run the Static Model.

2.3.1 KNMI meteorological data

The starting point for accurate meteorological data throughout the Netherlands is undoubtedly the data center of the Royal Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut or KNMI). The institute collects data from numerous meteorological stations positioned all over the country. The station closest to the Green Village site is located in Zestienhoven airport outside Rotterdam, at about 6 km away from the TU Delft campus. Wind speed and solar irradiance are among the many measurements conducted there ever since 1956 (KNMI, 2007).

To run simulations, a time-series dataset was downloaded from the official KNMI website. It contains hourly values of both wind speed and solar irradiance measured at Zestienhoven over 2011. Graphs illustrating these data are included in Appendix K.

2.3.2 Data Processing

The obtained time-series dataset required some processing before it could be used as input in Simulink.

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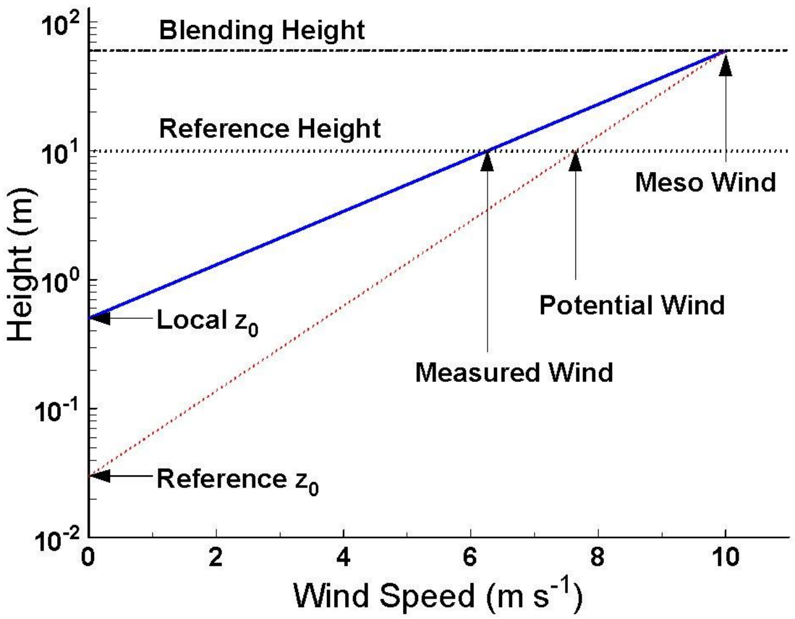
[1] The decision to deny charge to the EVs with the lowest SoC was based on a possible rental service idea (see paragraph 4.1). If for example scooters were rented out to users, priority would be given to the scooters with the higher SoC. Those could then charge faster and be ready to rent. Nevertheless the controller algorithm is fully customizable and can easily be adapted to do the opposite, i.e. prioritize the EVs charged less.

In the event that the station is not used for such a service, it is wise to reconfigure the algorithm so that it does not deny charge to EVs based on which has the lowest SoC, but on which requires the most energy to reach full charge.

2.3.2.1 *Wind velocity*

The year-round potential wind speeds in Rotterdam had to be extrapolated to fit the wind regime of Delft and the GV location in specific. Although very near each other, the two locations are different regarding the surface profiles of the atmospheric boundary layer. The airport is surrounded by flat grass fields which classify as 'open landscape' according to Davenport and Wieringa (Stull, 1999). In fact, KNMI gives a roughness length $z_0 = 0.03$ for the Zestienhoven meteo-station. On the other hand, the south side of the Technopolis in Delft is classified as 'roughly open landscape' with trees and low vegetation around it. Using the 'roughness map of the Netherlands' program (HYDRA, 2000), the roughness length on site the Green Village location was calculated to be $z_0 = 0.07$ (see Appendix L).

Clearly then, it would be wrong to assume the same friction velocity at both locations. Hence the logarithmic law that describes wind shear is not enough to provide a reasonable correlation. A simple method to do that is the two layer blending height model (Wieringa, 1986). This suggests that the mesoscale wind, blowing at a so called 'blending height' of 60 m, is representative for a 5 km by 5 km area below it (see Figure 2.20). In other words the wind speed at that height is unaffected by the surface roughness sublayer; a very sound approximation given the geographic adjacency and close point to point representativity between the outskirts of Delft and Rotterdam.



The graph depicts the concept of blending height. Local wind measurements are extrapolated to blending height. A wind speed approximation for a site with the same mesoscale wind climate but different local roughness or height can be determined from the wind speed value at blending height, by extrapolating downward using the new roughness (van Wijk B. , 2011).

Figure 2.20: Data fitting based on the Blending Height Model (Wener & Groen, 2009).

The wind shear logarithmic equations for each location are:

$$U_{GV}(z) = \frac{u_{GV}^{*}}{k} ln\left(\frac{z}{z_{0\,GV}}\right)$$

and

$$U_{16Hoven}(z) = \frac{u_{16Hoven}^{*}}{k} ln\left(\frac{z}{z_{0\,16Hoven}}\right)$$

Where, $U(z)$ is the wind speed at height z, z_0 is the roughness length, u^* is the friction velocity and k the von Kármán constant. Dividing the two above equations and solving for U_{GV} yields:

$$U_{GV}(z) = U_{16Hoven}(z) \cdot \xi \cdot \frac{ln\left(\frac{z}{z_{0GV}}\right)}{ln\left(\frac{z}{z_{016Hoven}}\right)}$$

Where ξ is the ratio of the two friction velocities calculated with the two layer blending height model. Equating the mesoscale winds 60 m above the Green Village and the Zestienhoven meteo-station yields ξ as:

$$\xi = \frac{u_{GV}^{*}}{u_{16Hoven}^{*}} = \frac{ln\left(\frac{60}{z_{0GV}}\right)}{ln\left(\frac{60}{z_{016Hoven}}\right)}$$

The timeseries measurement data from Zestienhoven are given at a 10 m reference height. Substituting this, gives the final expression for the extrapolated wind speed at the GV site:

$$U_{GV}(z) = 0.7835 \cdot U_{16Hoven}(10)$$

This means that the wind speeds to be used as input to the Static Model simulation are approximately 78.35% of the values reported in the timeseries data file downloaded from KNMI.

2.3.2.2 *Solar Irradiance*

The solar irradiance data did not require any fitting, since it is safe to assume that the sun in Delft shines the same as in Rotterdam. Local variations caused by clouds or precipitation are considered to average out over the year. The only data processing required was a change in the measurement units. The KNMI values were given in J/cm^2 per hour, thus were translated to W/m^2.

2.3.3 Daily scenarios

To avoid having simulations run for too long, it was decided to develop daily scenarios which would be indicative for the whole year dataset. As a result, three scenarios were formulated using the wind data and three more using the solar data. These represent a day with low wind speeds, an average windy day and a day with strong wind. Idem, a day with limited solar irradiance, a day with average sunlight and a very sunny day were also compiled.

To represent the low wind (sun) scenario, the day in 2011 with the least amount of wind (sun) was selected. Similar to that, the day in 2011 with the most wind (sun) was selected to represent a very windy (sunny) day. As for the average scenarios, these were developed by compiling the separate mean hourly values of all the days in 2011. For the record, most windy was the 36th day of 2011 (February 5), least windy was the 274th (October 1), most sunny was the 165th (June 14) and least sunny the 14th (January 14).

2.3.4 Turbulence and pyranometers

To make the simulations more interesting, or put otherwise, to enable more vigorous testing of the model stability under transient phenomena, the hourly averaged measurements were too brief. The system input variables would only change once every hour, living little to be explored in terms of fluctuations in power production. To solve this issue a virtual turbulence was superimposed to the hourly averaged wind data, which provided wind velocity fluctuations on a minute basis. As for solar irradiance, pyranometer measurements on a minute scale were obtained from an existing PV installation at TU Delft.

2.3.4.1 *Turbulent wind field*

The turbulence sequence was created using a turbulent 3D wind field simulation model, developed by the Wind Energy Laboratory of the Aerospace Faculty at TU Delft (Bierbooms, 2006). This runs as a Matlab function which simulates turbulence using the Kaimal Power Spectral Density (Veers, 1988). The generated sequence contains turbulent wind velocity values which are random yet have an absolutely zero mean value, so as to avoid inducing a false result in the power output of wind turbines. The tool was used to generate 3 different turbulence timeseries, one for each of the daily scenarios described above, with the parameters given in Table II.

Table II: Simulated turbulence parameters

Input Parameter	**Value**
Number of generated turbulence values	1 per minute
Mean wind speed	Hourly average of each scenario
Standard deviation	5-10% of mean of hourly average values (depending on scenario)
Hub height	12.186 m (*Windtronics*)
Maximum frequency of the spectrum	5 Hz

These parameters were fine tuned to produce a turbulence sequence befitting each scenario. As such, not only the hourly wind speed data of each scenario were inputted but more importantly, a different standard deviation was used for each dataset. This was 5% of the mean wind speed for the high wind scenario and 10% for the low and average wind speed scenarios. In particular, the standard deviations used were: 0.6140$^{m}/_{s}$ (High Wind), 0.3760$^{m}/_{s}$ (Average Wind) and 0.0955$^{m}/_{s}$ (Low Wind). As for the maximum spectral frequency, it was limited to 5 Hz below which, the distribution of energy content in its auto power spectral density is higher (Bierbooms, Site Conditions for Wind Turbine Design, 2012). Figure 2.21 is a graph showing the hourly wind speed values of the 3 daily scenarios along with the added turbulence.

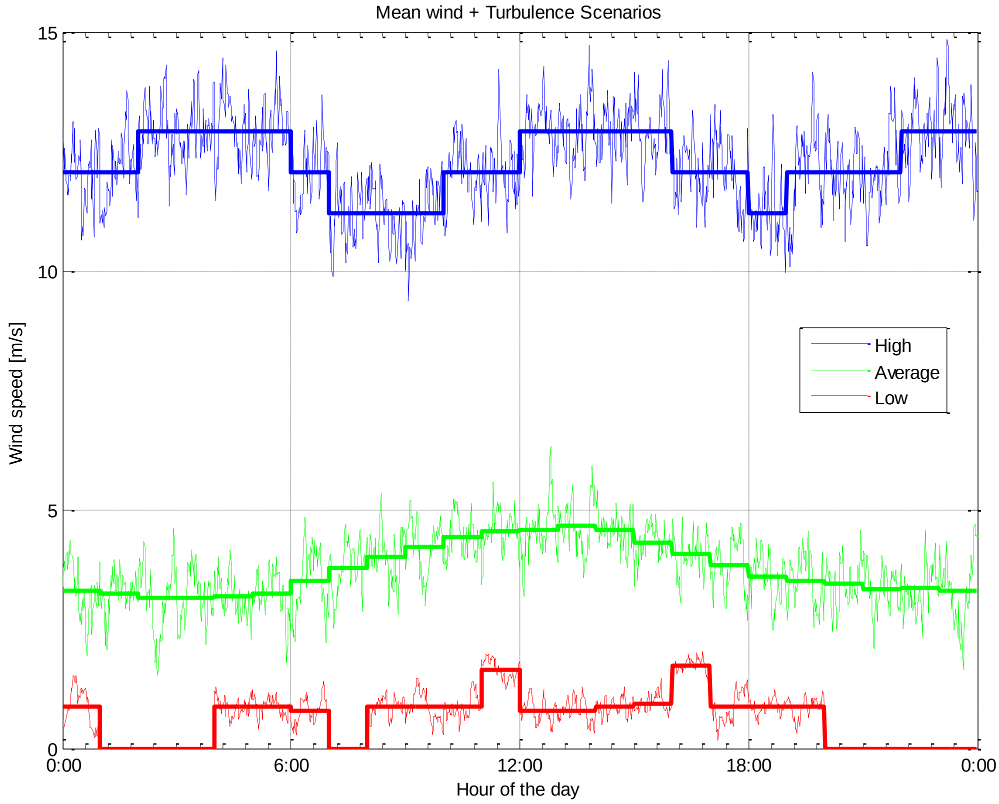


Figure 2.21: Typical wind day scenarios with superimposed turbulence.

2.3.4.2 *Pyranometer measurements*

Per minute solar irradiance measurements are being collected since June 2007, at the 9 kW DENlab PV system (3TU datacentrum, 2011), installed on the roof of the lower EWI building (Faculteit Elektrotechniek, Wiskunde en Informatica) in TU Delft (see Figure 2.22 below). The corresponding dataset is available online providing minute based readings of the solar irradiance in Delft.

Unfortunately, the DENlab data contain numerous false readings mainly because the particular PV modules stay in the shade of surrounding buildings, especially during the summer months. The data were therefore corrected, as shown in Appendix M, to provide unbiased simulation results. The graph in Figure 2.23 plots the typical sun day scenarios, which concludes the data processing performed for this thesis. Notice that the large drops in solar irradiance, which only last for a few minutes, were caused by cloud passing, thus were not corrected as false readings.

Figure 2.22: PV modules installed on the Faculty of Electrical Engineering, Mathematics and Informatics – TU Delft.

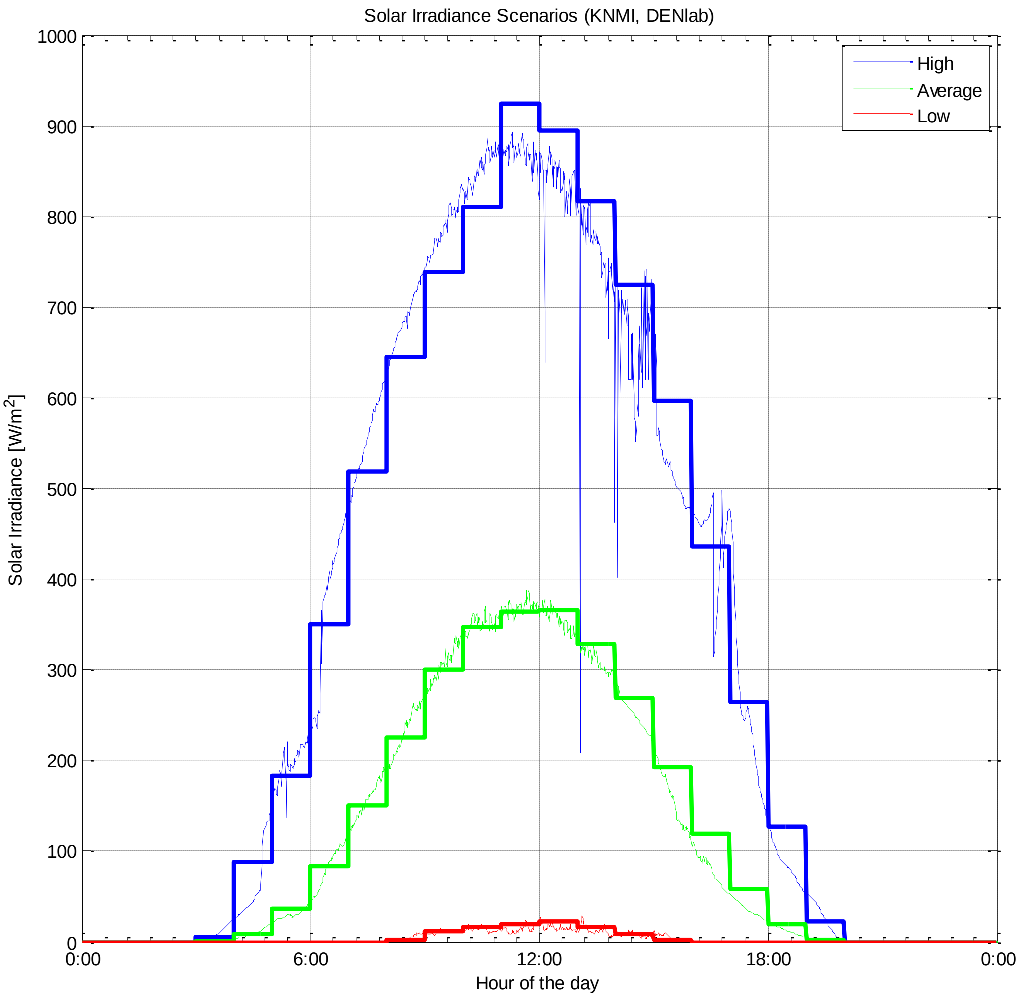


Figure 2.23: Typical sun day scenarios (KNMI data + DENlab measurements)

2.3.5 Electric vehicles

The last Station components that needed to be modeled, before being able to run simulations, were the electric vehicles themselves. EV charging characteristics as well as detailed battery specifications are considered highly proprietary information hence are almost never disclosed. Therefore, the modeling setup was based on data which were indeed available by the manufacturers, or could be deduced from those. The corresponding Simulink models however were designed to be easily customizable in order to simulate many other EVs. Elements of the dynamic rectifier model have also been utilized. Before presenting which specific EVs were eventually modeled, it is useful to discuss the different EV types available in the market, along with their corresponding battery capacities.

The main EV type, which is also the most popular, is the electric car. There are two types of electric cars; all-electric and plug-in hybrid. The first rely solely on electricity stored in batteries to move, whereas the second combine battery storage with internal combustion engines to provide range extension. As with regular internal combustion cars, several classes of electric cars exist according to their size and motor power. These range from single occupant cars, like the Volpe which can fit in an elevator (Thornhill, 2012), to large SUVs, like the Tesla Model X. Battery capacities of all-electric cars range from 12 kWh (Toyota FT-EV III) to 85 kWh (Tesla Model X) with typical values around 24 kWh (Nissan Leaf). Plug-in Hybrid car battery capacities are more in the range of 2,66 kWh (Suzuki Swift) to 22 kWh (Fisker Karma).

Lower end vehicles include motorbikes, scooters and bicycles or personal transporters. Few electric motorbikes exist, with battery capacities ranging from 3.1 kWh (Brammo Enertia) to 6 kWh (Zero S). The situation is totally diferent in the scooter class where the commercially available options are numerous, ranging from 0.96 kWh (Tomos e-lite) to 3.7 kWh (Vectrix) in battery capacity. Rather extended is the list of electric bicycles as well. On board batteries here have capacities in the range of 234 Wh (Giant Twist) to 558 Wh (Wisper 905SE), yet these only offer electric assistance and not electric propulsion. Last but not least Segways are personal transporters with 780 Wh battery capacity.

As far as electric trucks are concerned, mostly conversion solutions are available in the market where normal diesel trucks are retrofitted with batteries and electric assistance motors to reduce fuel consumption. Such a system (Odyne) uses batteries with either 14.2 kWh or 28.4 kWh capacity. Having said that, there is also a company (Smith Electric Vehicles) which manufactures two all-electric utility truck models. As expected given their weight, these use very large battery banks indeed (Smith Edison: 51 kWh, Smith Newton: 120 kWh).

Consequently, three electric vehicles were considered for the Static Model, one from each class. Their technical specifications are given in Table III and photos in Figure 2.24.

Figure 2.24: Static Model Electric Vehicles

Table III: EV Technical Specifications

Model	Battery		Charging time	Range
	Capacity	Voltage		
Mitsubishi iMiEV[1]	16 kWh	330 V	7 hrs	104 km @ 80 km/h
Peugeot e-Vivacity[2]	2x 1080 kWh	24 V	3 hrs	65 km @ 45 km/h
Segway i2[3]	2x 390 Wh	73.6 V	8-10 hrs	26 km @ 20 km/h

2.4 Results

This section presents the results obtained by running the Static Model simulation on days with different wind and sun potentials. The paragraphs that follow reveal the Station's response, at times when the electric vehicle states and prevailing weather conditions, test the power flow requirements the system was designed to meet. To display in a clear way the power exchanged through the GV-EVCS interconnection, the Green Village's own supply and demand were set to zero

[1] (Mitsubishi Canada, 2011)
[2] (Peugeot Scooters, 2011)
[3] (Segway, 2007)

before running the following simulations. This is to say that the Green Village is considered to neither consume nor generate any power at that time.

2.4.1 Charging with RES

The graph in Figure 2.25 is a simulation of the station operation on a particularly sunny day with strong wind. In this case, four scooters and two segways can charge only on the power produced by the RES capacity onboard the Station.

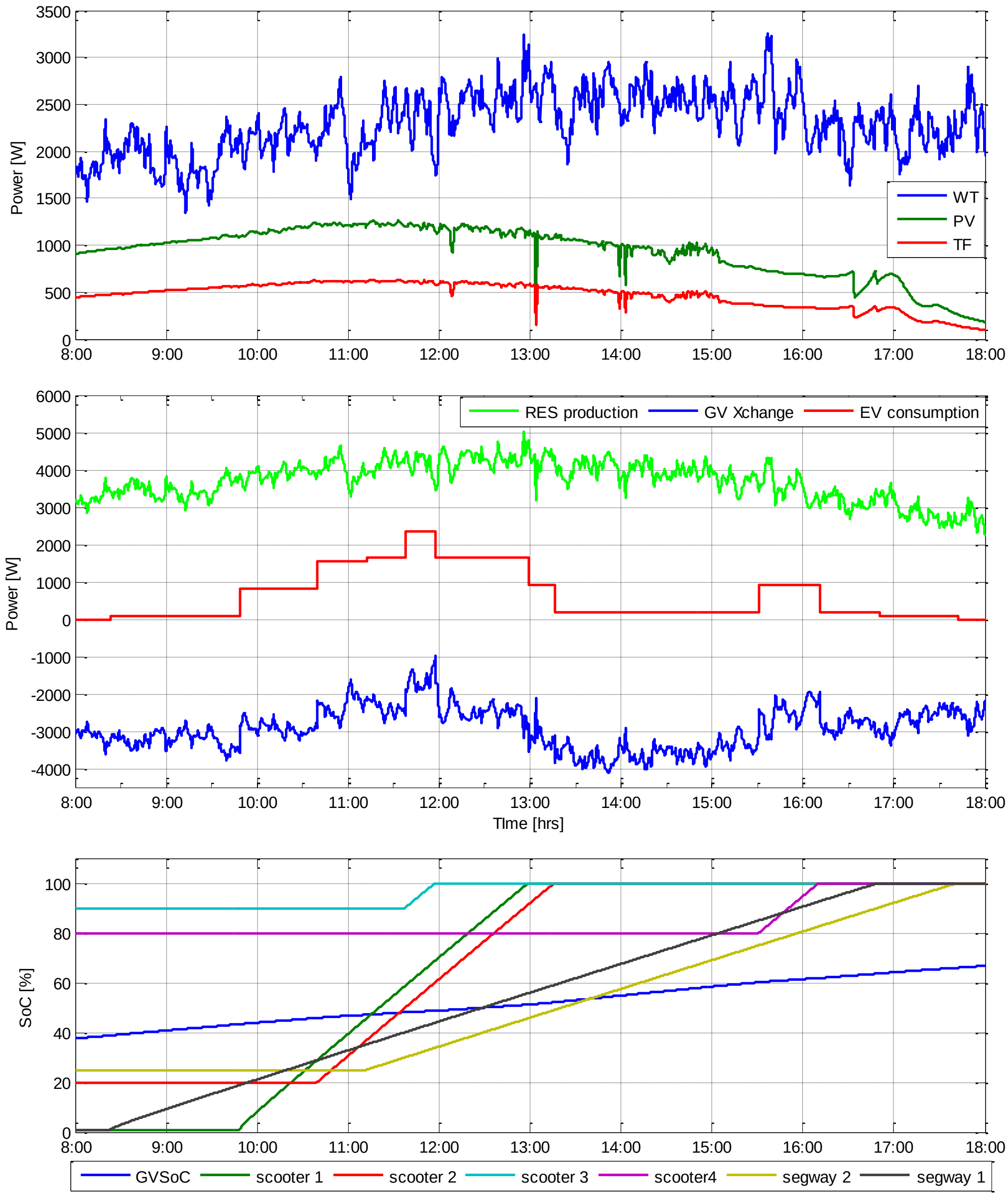


Figure 2.25: Simulation results on high wind, high sun scenarios.

In particular, at 08:23 a totally discharged segway 1 (1% SoC) starts to charge, consuming about 100W for about nine and a half hours until 17:43. At 09:48 scooter 1 connects to the Station barely having any charge (1% SoC) and starts consuming 700W. Roughly three hours later, at 13:00, it reaches full charge yet before that, at 10:40, at 11:13 and at 11:38, scooter 2 (20%), segway 2 (25%) and scooter 3 (90%) respectively also connect to the Station. Consequently, three scooters and 2 segways happen to charge simultaneously for 20 minutes (11:38 - 11:58), with nothing else but sustainable power. Actually, the power output is high enough to not only charge the batteries of these EVs, but also of the storage system in the Green Village, whose SoC increases from 37.58% to 66.69% inside the 10 hour window. Notice that for a moment at 12:56, the sun and wind are so strong that the output almost reaches the Station's maximum capacity.

2.4.2 Charging with RES + GV backup

Desirable though the above scenario might be, it is also an ideal case where both solar and wind potential are very high. Perhaps a more 'down to earth' simulation would be the one shown in Figure 2.26, where the Station operates on a day with average wind and sun. In total, five EVs start to charge at different moments throughout the 24 hour simulation time.

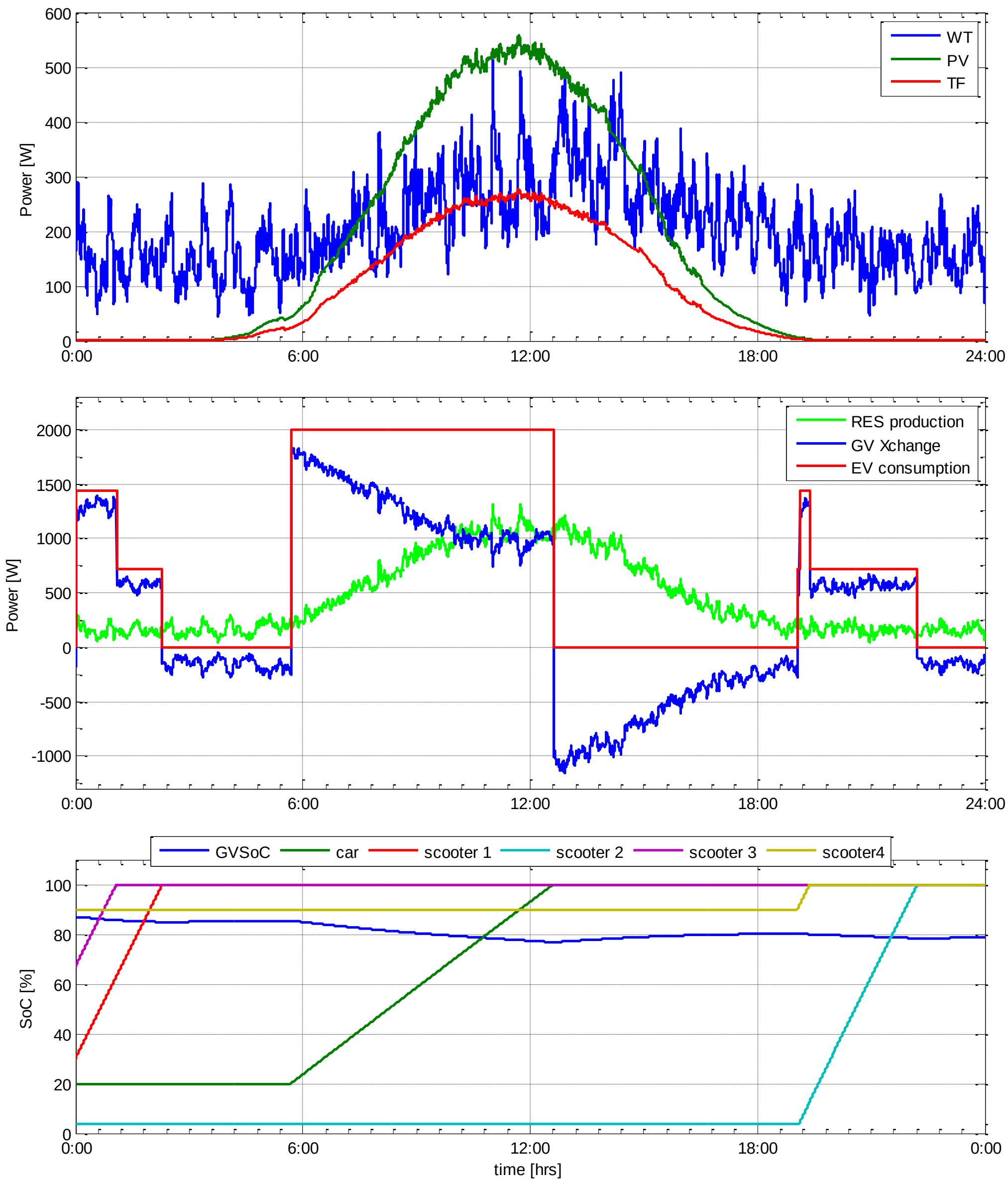


Figure 2.26: Simulation results on average wind, average sun scenarios.

At time 0:00, scooters 1 and 3 are charging. The generated solar power is zero, expectedly so, since it is midnight. Wind power is not enough for the two vehicles hence the GV provides enough backup power to bring scooter 3 to a full charge, after about one hour and scooter 1 after two hours and 17 minutes. From 02:17 to 05:42 no EVs are charging, thus all renewable energy is stored back in the green village. Renewable energy is generated mainly by the windturbines at that point, with the solar modules contributing some 60 W as well. At 05:42 the car is plugged in with a 20% initial SoC and gets charged to 100% by 12:38, consuming 2kW. Notice that the power supplemented by the GV decreases significantly by noon, when solar power is maximum.

After that, the GVBB gets charged from a 76.75% SoC to 80.34% while no EVs are connected to the station. At 19:03 and 19:07 scooters 4 and 1 begin to charge respectively. The power flow controller increases the backup supplemented by the green village to bring the scooters to a 100% SoC by 19:23 and 22:13 respectively. For the remaining 107 minutes the Station is again sending power back to the Green Village.

2.4.3 Charging without GV backup and insufficient RES

This simulation encompasses what can potentially be the Achilles' heel of any sustainable system based on renewable energy technologies. That is of course a day with exceptionally weak wind speeds and limited sunlight, diffused through heavy clouds. Being the opposite of the conditions described in paragraph 2.4.1, apart from rather pessimistic, this is also a quite rare scenario. Even for a high latitude country as the Netherlands. Most often, the winter days with the least solar irradiance are the ones with strong winds. And also, sunny summer days are usually calm. That being said, the system response to extreme conditions had to be tested as well.

Figure 2.27 depicts the simulation of the station operation on a day with average wind but awfully limited solar irradiance. To make matters worse, the GVBB is initiated at an extremely low SoC of just 7%. Then the village cannot provide any backup power to the station unless the GVBB is restored to a 20% charge. Consequently, the Station needs to rely on its own RES power production, limited though that might be. For this reason, the power flow controller allows charge to only the EVs whose consumption can be covered by the Station itself.

At the start of the simulation the Station can only charge segway 2, feeding the small surplus to the GV. After 2 minutes the wind picks up, resulting in a temporary power increase, which is enough for the controller to also allow segway 1 to charge. At minute six, the power drops again and only one EV can charge. In that case the controller is designed to prioritize the EVs with the highest charge. As a result, it discontinues charging segway 1, since its SoC (88.84%) is lower than that of segway 2 (96.26%). The procedure continues in the same manner until segway 2 reaches full charge after 28 minutes, leaving segway 1 to charge as well.

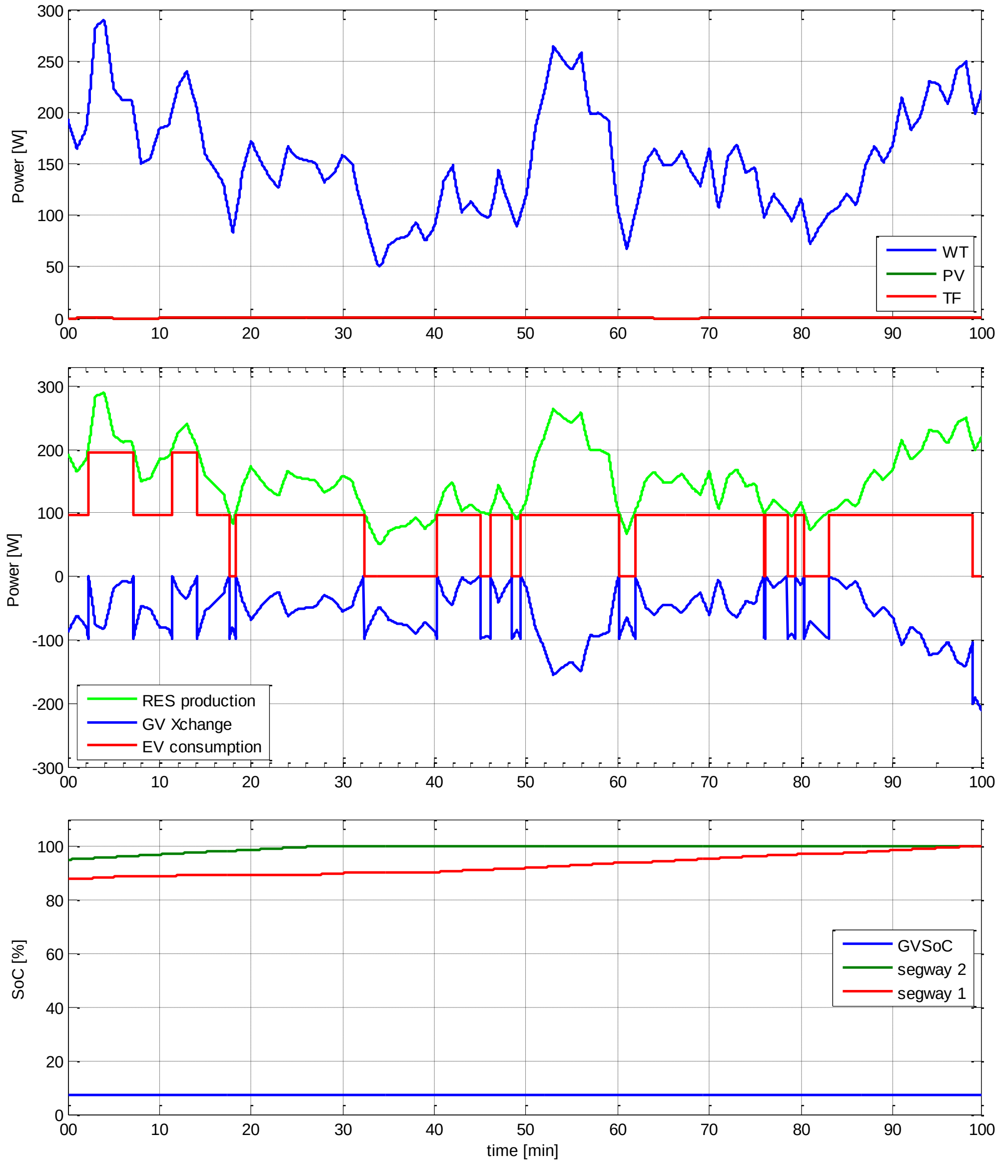


Figure 2.27: Simulation results on average wind, low sun scenarios.

2.5 Summary

To conclude this rather long chapter, a brief summary is in order. After an introductory chapter 1, in which the link between the Green Campus / Green Village projects and electric mobility was established, the reader was introduced to the concept of the Sustainable Electric Vehicle Charging Station.

To begin with, the proposed physical design was presented, based on a number of prerequisite features the Station should encompass. The components of that design, mainly renewable energy technologies and accompanying electrical equipment, were then analyzed. What is basically the main part of this MSc thesis came right after. This refers to the models developed to simulate the Station's operation.

Attention was focused on the Static Model, i.e. an extensive Simulink model which incorporates all the Station components and subsystems. This controls hundreds of variables (power availability, EV battery voltages and currents, SoCs, optimal charging durations etc.) every single moment in time, to decide what is the best way to feed power into the vehicles.

A meticulous discussion on how input data were obtained and processed followed and the chapter ends with an analysis of the simulation results. The latter, prove that the Station operates according to the intended design parameters, even under extreme circumstances.

3 DC CHARGING

Having presented the technical design as well as the modeling and simulation of the EV charging Station, it is now time to focus on what is considered a cornerstone of the Green Village development, the DC grid. It is a fact, that most of the electric and electronic devices people use every day work or can work with direct current. It is also a fact that more and more installed RES power capacity connects to the grid every day. It only stands to reason, that if the future power generation and transmission regime is based on direct current, so should the distribution networks reaching users. If that were to happen, there would be no need for power conversion, which would save the power losses involved in the process of creating DC from AC.

The obvious place to test this notion is the Green Village and as such the EVCS itself. The sections that follow, analyze the advantages, the challenges and the technical solutions, required for charging EV batteries on a direct current grid. First however, the currently available industry standards are presented.

3.1 Infrastructure

Differentiations exist in the available types of EV charging infrastructure. This stems mainly from differences in grid regulations and voltage levels between countries, but also patented industrial practices, unique to each manufacturer. Although thousands of electric cars are being used around the globe daily, there is still a long way before automotive companies and policy makers agree on a single, international charging standard, commonly acceptable to all.

3.1.1 EV charging modes

The International Electrotechnical Commission defines four types of charging in its ‘61851-1’ standard (IEC, 2010). These are given in Table IV with further details included in Appendix N.

Mode 1 refers to charging from a usual 230 V (or 120V for USA) socket outlet, available at any household. This is the slowest type of charging and is nowadays only used by lower end EVs like segways or certain scooters. The charger unit is located inside the vehicle itself, hence the name ‘on-board charger’ or OBC.

In Mode 2 the vehicle’s OBC connects to a standard single phase – 230V or three phase 400V outlet, yet an in-cable protection device is included as well.

Table IV: EV charging modes (EMSD EV, 2011).

Mode	Description	Voltage type	Voltage level	Max Current	Max Power
Mode I	standard socket outlet on-board charger	AC	1φ: 220V	16 A	3.5 kW
Mode II	standard socket outlet in-cable control box with control pilot cable on-board charger	AC	1φ: 220V 3φ: 400V	32 A	22 kW
Mode III	dedicated socket outlet with pilot control cable, permanently connected to AC mains on-board charger	AC	1φ: 220V 3φ: 400V	80 A	55 kW
Mode IV	external fast charger	DC	50 - 600V	400 A	240 kW

With ampacities reaching as high as 80 A, Mode 3 allows both slow and fast charging. The basic difference with the first two modes is that it requires a separate, special socket-outlet which is permanently connected to the main single or three phase line of the building. This unit is much safer to use and provides the user with additional control functions such as selecting when to start and stop charging (AeroVironment, 2011).

Mode 4 is the only type of charging that uses DC power fed directly to the batteries. A special external charger is required for that. Being able to provide a power output well in excess of 100 kW (Tesla Motors, 2012), these units cannot connect to any domestic line. Instead they need to connect to the 20kV distribution network, making them very expensive and quite difficult to deploy.

3.1.2 Fast charging standards

External DC fast chargers are being deployed worldwide, with power outputs ranging from 25kW to 60kW. Almost all of them use the Japanese CHAdeMO[1] standard. This utilizes a special plug that connects to a separate socket on the car body, other than that used for mode I –III charging. The plug contains the two main pins (positive and negative) for the DC power supply and a total of 8 auxiliary control and communication pins using the CAN protocol (CHAdeMO Association, 2011).

A recent development that is of interest, is the alternative standard proposed by the International Society of Automotive Engineers. Although it has not been approved yet, this system has the advantage of combining all four charging modes into a single 'combo plug'. As seen in Figure 3.1, it uses a total of 7 pins[2] and powerline communication over the HomePlug GreenPHY protocol (VDI, 2012).

[1] "CHAdeMO" is short for "CHArge de MOve" and a clever pun for "O cha demo ikaga desuka" in Japanese, translating to "how about some tea" in English. The symbolism of course being that fast charging takes as long as a tea break.

[2] The connector consists of 3 pins for AC charging, 2 for DC charging, and 2 multi-signal pins that allow: charging control over communication with PLC, integration into smart grid over SAE J2931 and proximity and control pilot functions. The 3 AC pins are either on a three phase (R,S,T) or a single phase configuration (L) with neutral (N) and ground (PE) poles. Audi, BMW, Chrysler, Daimler, Ford, General Motors, Porsche and Volkswagen have agreed to introduce the system in 2013.

What is particularly important about this, is that it is compatible with smart grids that allow grid controlled charging and that it can also be configured for slow DC charging at home.

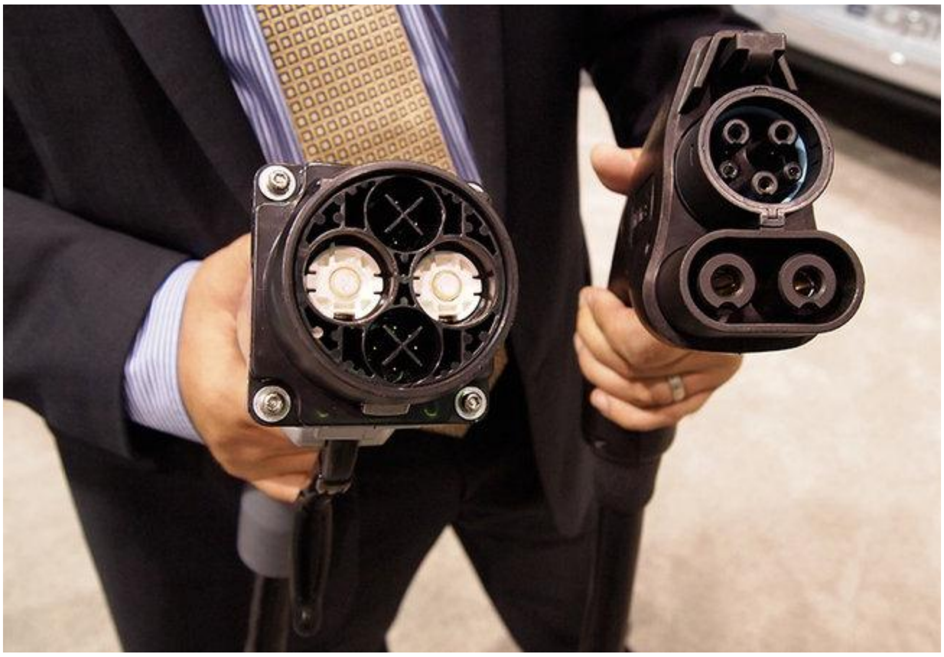


Figure 3.1: Two incompatible DC charging plugs: the CHAdeMO (left) and the SAE combined charger (right).

3.1.3 Battery management

The standards discussed so far concern the infrastructure outside the vehicle. It is useful to explain the charging technology used inside as well. When AC is fed to the OBC, it is first rectified and subsequently boosted to a voltage level that allows the 'desirable' direct current to flow into the batteries. In DC fast charging, no rectification is of course required. In both cases, the battery management system or BMS is the unit that decides what the desirable current flow is. The electronic components the BMS contains, measure a plethora of operating parameters and regulate accordingly the flow of current in (charging) and also out (discharging) of the batteries. The more the measured parameters, the more sophisticated the battery management system is. Usually, lower end EVs like scooters have simpler BMS units, which allow limited controllability. In electric cars with lithium ion batteries though, the BMS constantly monitors the parameters listed in Table V in order to decide on proper actions.

Table V: Electric car battery parameters monitored by BMS.

Measurement	Battery Management System	
	computation	**action**
Cell Voltage	Cell SoC	Cell balancing
Total Voltage	• Total SoC • Remaining charge • Remaining range	Initiate/stop charge, (dis)charging current, DoD warning
Temperature	Battery health	(dis)Charge current limit, required coolant flow, cell balancing
Coolant flow	Pump/fan speed	Feedback to BMS
Current	Energy delivery	Feedback to BMS

3.1.3.1 *Cell charge/discharge characteristic*

The voltage of a Li-Ion battery cell is about 3.6V. This is far from constant though. As seen in Figure 3.2, when fully charged[1] the cell voltage is close to 4.2V, which gradually drops to 2.7V at fully discharged state[2]. In between the two states, there is a steady voltage plateau which corresponds to the region between 20% and 80% SoC. There, a cell operates safely, without any sudden pressure and temperature rises (caused by splitting of water molecules) which prove harmful and cause aging. As a result, it is preferable to operate batteries within that charge region.

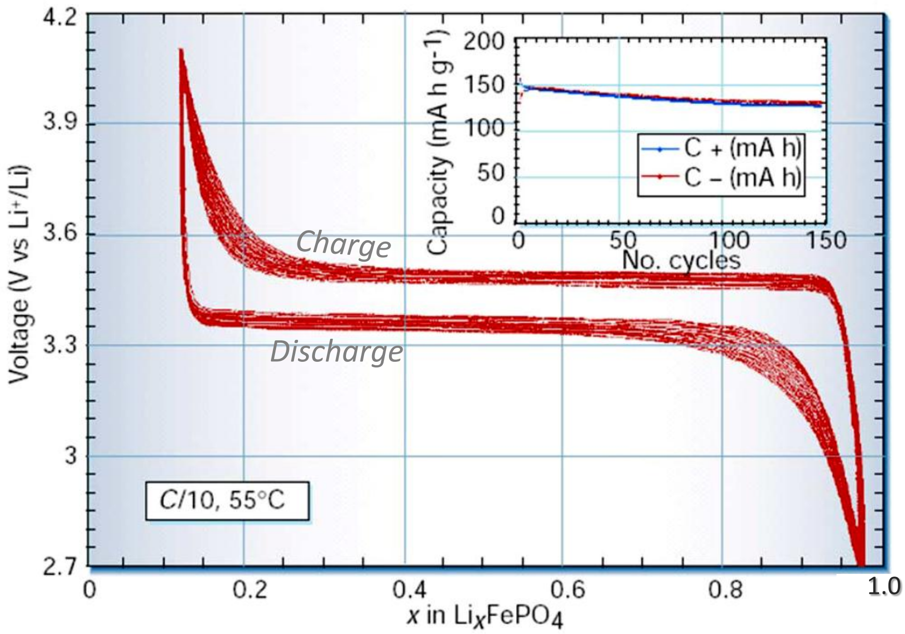


Figure 3.2: Charge and discharge curves of a $LiFePO_4$ battery cell (Wagemaker, 2011).

During discharge, the reduction/oxidation reactions inside the cell create a certain potential difference between the electrodes. Nevertheless, a voltage higher than that has to be applied to the cell to reverse the process and allow it to recharge. The skewness and kurtosis of the characteristic curves are affected greatly by the thermodynamics of host insertion. In other words, the rate with which chemical reactions occur inside the cell depends on the temperature. Optimal ionic transfer and electronic conductance are achieved at an optimal temperature.

Individual cells are connected in series to form a stack. One or more stacks combined together form the battery system of an electric vehicle (Figure 3.3). Periodic taps exist between cells or groups of cells to allow voltage measurements and cell balancing.

[1] The cell is fully charged when x = 0, which means the $FePO_4$ host compound of the anode (positive electrode while charging) is totally empty of lithium cations (Li^+).

[2] Respectively, when fully discharged the anode host compound (negative electrode while discharging) is full of Li^+, i.e. x = 1.0.

Figure 3.3: The battery pack of the Chevrolet Volt (General Motors, 2010).

3.1.3.2 *Monitoring*

Manufacturers examine the characteristics of their patented cell and map the voltage and temperature levels which correspond to different states of charge. With this knowledge, the BMS unit of an EV is able to calculate the state of charge by measuring the voltage and temperature of the whole battery pack. Typically, individual cells in a battery have somewhat different capacities hence reach different levels of SoC. The total state of charge is then the average of the SoCs of the individual cells.

While driving, the state of charge is computed and reported to the driver display. Based on the depth of discharge (DoD) and the driving speed, the vehicle's remaining range (km) is calculated. A warning system is implemented to alert the driver whenever the SoC falls below a certain limit. In principle, even when the 'empty' display is on, the batteries still have a remaining 3-10% SoC depending on the manufacturer. This is because the management system never allows the batteries to drain completely, to protect them from aging fast.

During charging, the BMS monitors the state of the battery and controls the charge uptake. More specifically, a controlled rectifier, like the one presented in subparagraph 2.2.2.3, regulates the current flow inside the battery, by means of the applied DC voltage. If a particularly high charging voltage is applied, the current intake is also high, enabling faster charging. This is the case in DC fast charging. Of course, the BMS controls the process to ensure that the 'charge current limit' is not exceeded.

EV manufacturers use different types of batteries, with patented cell stack topologies tuned to match the vehicle's specific electric motor. Voltage and consequently current levels vary between different vehicle models. For example Mitsubishi uses a 330V, 88 cell battery pack to supply 16kWh to the 'iMiEV', whereas Nissan uses a different Li metal compound, stacking together 192 cells to form a 360V battery pack which supplies 24kWh to the 'Leaf'. As manufacturers compete against each other to improve battery performance, it goes without saying that analytic information concerning the exact electrochemical cell characteristics and stack configuration are highly proprietary and thus kept secret.

3.1.3.3 *Protection*

The management system safeguards the batteries during charging to prevent overvoltage and overcurrent. Temperature is also regulated within safe margins using air or liquid cooling. Once the cells are restored to an average 80% SoC, the BMS performs what is known as cell balancing. This redistributes charge between the cells to achieve a uniform SoC. Cell balancing is performed to protect the cells with lower capacities. As a result the cell with the largest capacity can be filled without overcharging any smaller cell. Idem, it can be emptied without over-discharging any other cell. Nowadays, the most advanced BMSs balance the battery by drawing current from the most charged cell and transferring it to the least charged cells. This is where intermediate taps come into play.

3.1.3.4 *Aging*

All rechargeable batteries have a finite lifetime expressed in number of cycles. One cycle denotes a discharge and consequent recharge of the battery. The deeper the discharge per cycle, the less cycles the battery will last on the whole (see Figure 3.4). This is because cycling deteriorates battery performance with time; a process known as aging. On an electrochemical level, deep discharging (DoD>80%) causes the anode potential to drop below 0.8V against the lithium-metal cathode. At that point, the inorganic electrolyte solvants become thermodynamically unstable instigating side reactions at the interface between electrolyte and anode. If repeated too often, this leads to the formation of a Solid Electrolyte Interface (SEI) layer containing Li_2CO_3, alkyl-carbonates, polymers etc.

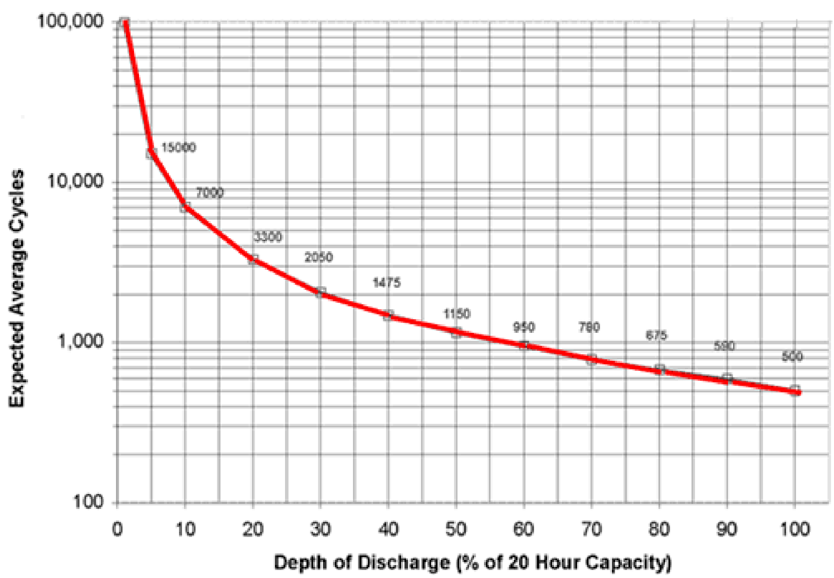


Figure 3.4: Battery lifetime indication; expected cycles reduce exponentially with DoD.

As the battery cycles, the SEI can either form a stable layer or grow extensively thicker (see Figure 3.5). In the first case, further side reactions are passivated, yet the formed layer insulates electronic conductance rendering the battery unusable. In the second case, the SEI grows thicker blocking lithium cation transfer and reducing active surface area. This results in an avalanche effect which can induce dissolution and recrystallization of the electrode material. In time, metallic needles form which can potentially protrude through the electrolyte into the other electrode and short circuit the battery. This has been the cause of isolated accidents where electric cars have caught fire (Wagemaker, 2011).

a. Li^+ insertion to host.	c. Stable SEI formation
b. Charge transport	d. Recrystallization and needle formation

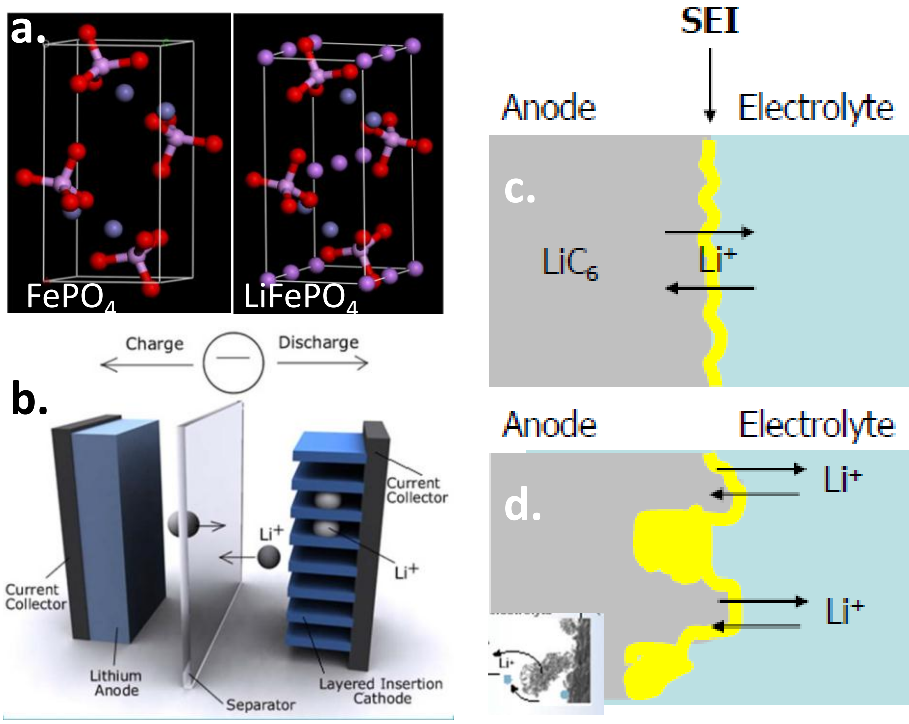


Figure 3.5: Cell electrochemical reactions

3.2 Transition to RES

There are undoubtedly numerous existing solutions, yet one thing is for sure; slow DC charging has not been implemented to date. The reason for that of course, is that domestic electricity is only available in AC. Hence, offering slow DC charging, as an extra function of the EV's OBC, would indeed render the option moot, since no or very few people could actually use it. Up until now at least! The increasing number of residential RES installations, mainly in the form of solar panels which do operate in DC, is bound to change all that. In fact, direct current advocates claim that now is the time for the long awaited grid transition, from AC to DC power, to take place. If that were to happen, it would urge manufacturers to add normal DC charging as an option, next to the fast DC charging they offer now.

Nevertheless, before, if ever, DC electricity becomes the norm for domestic use, several challenges should be addressed with respect to charging vehicles from a RES installation at home. These mainly concern the shortage of power.

As discussed in paragraph 2.3.5, new EV models have increasingly higher battery capacities, currently reaching 85 kWh in cars and 120 kWh in trucks. That being the case, residential RES installations would never be able to output enough power to keep the charging duration at a descent level.

To make this notion more explicit, assume an ordinary 5 kW PV system installed on the roof of a house not connected to the grid. Even if the power output was constantly at its maximum value, it would still take a new Tesla model S about 17 hours to fully charge its 85kWh batteries, relying solely on solar electricity. Imagine how many hours it would really take, if a more reasonable, average output is considered. Charging that lasts so long is clearly impractical, to say the least.

On the other hand, using a DC fast charger, the car owner would be able to charge in about 30 minutes. With the Tesla's 426 km range, an average person would not need to recharge for another 3 days, which is enough time for the PV system to generate the same amount of energy consumed during fast charging. And this assumes a capacity factor of 18.9%, which is the average for PV installations.[1]

Clearly then, connecting the installation to the grid seems to be the only practical way to avoid large and expensive battery storage but still travel green, as all the energy consumed by the car is gradually fed back to the grid. Grid connection does not come without problems though. Decentralized power production is always a challenge, as it puts additional stress to the grid. Thankfully, developments in smart grid technology can help significantly, by allowing the grid to control supply and demand on an end user level.

3.3 DC charging in the Green Village

A rather interesting solution, concerning charging EVs on DC, comes from one of the companies (Direct Current B.V.) affiliated to the Green Campus project. What they propose is an on-board DC charger with a 20 kW maximum power output. The reason for opting for an OBC, instead of an external charger, is to allow an independent development of the battery system. In essence, this answers to the standardization war that has been raging between manufacturers, ever since electric cars were made commercially available to the wide public.

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[1] DC fast charging usually restores a car to an 80% SoC. To generate that energy in 3 days a 5kW PV system would need to have a capacity factor of:

$$cf = \frac{80\% \times 85kWh}{3days \times 24\, {}^{h}/_{day} \times 5kW} = 18.88\%^{*}$$

**PV installation typical capacity factor < 25%.*

According to DC BV, all one needs is a 20kW OBC that connects to their patented 700Vdc network and whose output can be tuned to match the voltage and amperage specifications of different battery systems. The company's design philosophy is that users should be able to quick-charge their cars many times each day, where and whenever possible, but refuel only when absolutely necessary. For example, while stopped for a 15-minute coffee break, the proposed OBC could offer an extra 30km range to the car[1], or double that (i.e. 60km) if the stop lasted 30 minutes (e.g. lunch break). This way, people would need to refuel only before for example a direct 180 km trip, with no stops. Refueling could then be slower, lasting 1.5 hours (Stokman, 2012).

Apart from the charger itself, DC BV proposes an overall DC smart grid to surround it. The envisaged concept is to have a distribution network running at 7kV or 14kV (see Appendix P). A medium to low voltage (a.k.a. MV/LV) DC converter, would then convert the 7kV/14kV to 700Vdc. Such a unit is currently under development by DC B.V. When completed, it will contain a grounded middle node, essentially splitting the 700Vdc to 350Vdc in order to feed domestic devices (see Appendix Q). The proper flow of power from the distribution network to the in-building electrical installation will be monitored by a process manager called 'power router'.

Unlike AC grids, where frequency is a valuable means of regulating load fluctuations, stability is a much tougher nut to crack when it comes to DC grids. On that ground, the power router, combined with the on-board DC charger, constitutes a smart charging system which would react whenever it detects a voltage drop higher than 2%. Then, based on the prevailing grid conditions, it will be able to decide how much power can be fed to the vehicle without compromising stability. In particular, the unit monitors the availability of power in the grid and translates it to a price per kWh, with which the EV can charge. The price depends on the 'criticality level' the grid is in, while the EV is charging. DC B.V. proposes five levels, illustrated in Figure 3.6.

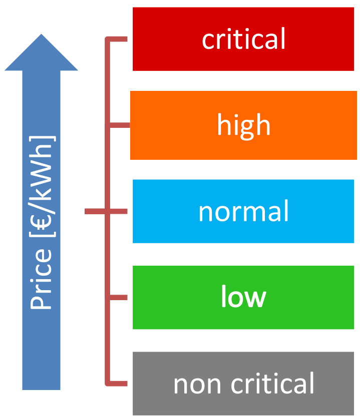

Figure 3.6: DC B.V. Criticality levels for EV charging

[1] DC BV's calculations are based on an electric Volkswagen Golf Variant with a 27kWh usable battery capacity (van Oorschot & Vos, 2010) and 180 km range, converted by Electric Cars Europe.

To incentivize users to charge during off-peak hours the price per kWh will be lower when criticality decreases. Next to that, the charger is C2G enabled, meaning that when in critical mode, it is able to discharge the vehicle batteries to assist the grid.

In principle, the model suggested by DC B.V. has many similarities to the controller strategy proposed for the Green Village EV Charging Station in subparagraph 2.2.3.2. Consequently, it is possible to combine forces to build a working prototype Station. This would make use of an MV/LV DC converter to establish a bidirectional interconnection between the Station container and the GV battery bank. This link could operate at either 700V or 1400V, depending on what voltage level will eventually be selected for the local DC distribution grid in the Green Village. A detailed schematic of the system connection is given in Appendix R.

4 Feasibility

This chapter deals with the most prominent economic aspects concerning the Station construction. The sections that follow introduce the Station capital and operational expenditure based on a business concept which could make the whole endeavor profitable.

4.1 Possible user services

A business concept that was envisaged since the beginning of this thesis, involves a rental service, whereby Green Village visitors would be able to rent electric scooters. The plan was to build an unmanned Station which would house both the renewables and the scooters. Rental would work on a self-service basis, where people could reserve a scooter online, pick it up at the Station and return it within 24 hours. A personalized smart card or the always convenient 'OV chipkaart[1]' would be billed, to pay the rental fee. This would be especially handy if it were combined with discounts when travelling by train.

For anyone to be able to drive the scooters on the bicycle lanes, without any special license or safety helmet, other perhaps than the usual car driving license, it is required to limit the maximum speed to 25km/h. An interesting scooter model fitting this description is the Emoto 80duo, with a 1.68kWh battery capacity, manufactured by the Dutch company Qwic.

To make the service easily accessible to visitors outside Delft, it would be wise to add a service point, at one of the city's train stations (Centraal or Zuid). Then, people could travel by train to Delft, rent an electric scooter, visit the Green Village and return it to the train station before leaving. This way, they would be able to combine a visit to the Green Village with a daytrip in Delft. It goes without saying, that such an arrangement requires careful planning in cooperation with the municipality of Delft, thus it is only mentioned here to signify the range of possibilities.

[1] Openbare Vervoer or OV chipkaart is a contactless smart card used for traveling with public transport in the Netherlands.

4.2 Cost of components

Table VI lists the current price of each individual component, including tax (BTW) and installation costs, as provided by Green Campus suppliers and partner companies.

Table VI: Capital expenditure (all prices include installation costs).

Station Component	Supplier	Price per item [€]	Number of items	Cost [€]
Container	BalkTrade B.V.[1]	3.000,00	1	3.000,00
Windturbine	GE4ALL B.V.[2]	5.212,24	2	10.424,47
Mast	Kaal Masten B.V.[3]	2.618,00	2	5.236,00
PV panel	GE4ALL B.V.	192,00	6	1.152,00
TF module	Ensupra L.L.C.[4]	250,00	5	1.250,15
PV power optimizer	GE4ALL BV	790,16	2	1.580,32
WT power optimizer	GE4ALL B.V.	101,15	11	1.112,65
Inverter	GE4ALL B.V.	1.493,45	2	2.986,90
Station Controller	Hellas Rectifiers B.V.[5]	5.000,00	1	5.000,00
EV Charger	Cohere B.V.[6]	3.000,00	3	9.000,00
Scooter	Qwic[7]	1.737,00	6	10.422,00
Monitoring Equipment & Software	Femtogrid B.V.[8]	1.000,00	1	1.000,00
Total Cost				**€ 52.164,34**

4.3 Investment evaluation

For those interested in the financial aspects of this idea, a key question would be: "under what conditions could this concept become a viable business case?' Admittedly, there are too many unknowns which need to be quantified before a solid business plan can be established. If nothing else, it is too early for anybody to have a clear picture of what the Green Village target group will look like. How this affects any definitive commercialization decisions is discussed in section 5.3.

[1] (den Boer, 2012)
[2] (Geskus, 2012).
[3] Procured by (GE4ALL, 2012).
[4] (Ensupra, 2012).
[5] Price estimated on basis of commercial off-grid (island) managers (SMA Solar Technology AG , 2012). The HVDC/LVDC converter is currently under development (Stokman, 2012).
[6] Such chargers have been procured and will soon be installed at TU Delft by Cohere B.V. (Coussement, 2012). Each of these chargers has 2 connections points and it costs €2500 with an expected additional €500 installation fee.
[7] Price suggested by (QWIC, 2012) assuming a 10% wholesale discount.
[8] Femtogrid Monitoring consists of two components: a Monitoring Box and a Monitoring Portal.

For the time being and in accordance with the technical scope of this thesis, suffice it to assume that the Green Village shall attract enough year-round visitors to support a rental service, as it was described above. What follows, is a simple economic analysis that evaluates the investment required to setup a basic business. It should be emphasized, that this analysis is included here merely as an indication. It does by no means relate to a complete strategic investment plan, which would require a higher level of expertise on economics.

Table VII calculates the investment return (I.R.) after 5 years, translated in net present value with the formula:

$$I.R. = \sum_{t=1}^{n} \frac{F_{in} - F_{out}}{(1+R)^t} - C$$

Where, t is the time of the cash flow, n is the payback time, F_{in} is the cash inflow at time t, F_{out} is the cash outflow at time t, R is the discount rate and C is the total cost of the Station.

The calculation was performed for a 5 year horizon, having selected a discount rate of 3%, which is still higher than the interest rate for savings below 100 thousand Euro in Netherlands, i.e. 1,9% currently (ABN Amro, 2012), (Rabobank, 2012). The RES capacity installed on the charging Station can accommodate 6 rental scooters, hence this was considered a reasonable number of fleet vehicles.

A variable quite difficult to predict is rentability, i.e. the number of days per year on which the scooters would actually be rented. This depends greatly on the overall publicity the Green Village will attract and relies on how well the rental service would be marketed. Even so, a cash flow forecast scenario was formulated. This assumes a gradual increase in rentability over the five year planning. For the first year, rentability was assumed to be as low as 100 days which roughly translates to only three full months. The Green Village is supposed to expand in the years to follow, which would make it more popular to visitors. By the fifth year rentability is assumed to be 300 days.

The rental fee itself plays an equally important role. Based on existing similar services (NS, 2012), it was estimated that a daily 15 Euro rental fee would attract competition.

Last, operational expenditure is expected to be proportional to rentability. For that reason, it was assumed to be 10% over the revenue. Additionally, a fixed 1500 Euro per year was assumed as maintenance costs, given that almost all of the Station components would be covered by manufacturers' warranties within the first 5 years of operation. In total, the projected amount is expected to cover scooter insurance and any potential maintenance costs not covered by warrantee. It should also cover the cost of the outsourced billing services.

Table VII: Rental Service net present value analysis[1].

Business Concept	**Variables**	**Comments**	
Payback time	5 years	Investment horizon	
Number of scooters	6		
Rental fee per day	€ 15,00	fixed for 5 years *(i.e. zero inflation)*	
Operational Expenditure is	fixed € 1500 + 10% of revenue *(annual projection)*		
Discount rate	3%	assumed rate, based on bank saving account interest	
Cash Flow Forecasting	**Rentability** [days/year]	**Revenue**	**Operational Expenditure**
1st year	100	€ 9.000,00	€ 2.400,00
2nd year	150	€ 13.500,00	€ 2.850,00
3rd year	230	€ 20.700,00	€ 3.570,00
4th year	250	€ 22.500,00	€ 3.750,00
5th year	300	€ 27.000,00	€ 4.200,00
Present value of net income	€ 68.449,40		
Capital expenditure	€ 52.164,34 total station cost *(see Table VI)*		
5 Year Investment Return (net present value)	**€ 16.285,06**		
Minimum rental fee	**€ 11,80**		
Minimum average rentability	**160 days**		
Minimum fixed OpEx	**€ 5.000,00**		
Internal Rate of Return (IRR)	**11,52%**		

The above parameterization yields an investment return of 16 thousand Euro after 5 years. This would render the investment profitable and thus a viable business proposal for the Green Village. It is perhaps valuable to note, that for the same variables, the absolute minimum rental fee for which there is a positive investment return, is calculated to be 11.80 Euro per day. Idem, to be able to make a profit, rentability should not be less than 160 days per year on average. As for the fixed operational costs, these should not exceed five thousand Euro per year. Last, the internal rate of return (IRR) is calculated to be 11.52%.

[1] Note: Unlike numbers elsewhere in this Thesis, currency values in Table VI and Table VII are denoted using a dot (.) for digit grouping. The decimal separation is delimited with a comma (,). For example 1000 Euro and 65 cents are written as € 1.000,65 which is the format used in most European countries.

5 Conclusions

Approaching the end of this Thesis, it is a good idea to synopsize that the end-design of this project regards a sustainable charging station for electric vehicles. The nominal power capacity is 5.19kW, coming from 2 windturbines and a total of 11 (6 crystalline and 5 amorphous silicon) PV modules installed on the Station. The renewables are connected to two inverters, each with a 2.55kW maximum DC input, which can provide a nominal 4.8kW output on the AC side.

Below, certain conclusions are drawn that answer the research questions related to the expected power output of the Station. Section 5.3 plans the road ahead for the implementation of green mobility in the Green Campus.

5.1 Power and Energy

The power production graph in Figure 5.1 reveals that maximum output would never be reached in 2011, which is to be expected since solar irradiance peaks are shifted in time, compared to peaks in wind velocity. Meteorological patterns suggest that strong winds normally occur during the winter months, whereas high solar irradiance is measured on summer days. In fact, the annual KNMI measurements given in Appendix K confirm these seasonal fluctuations.

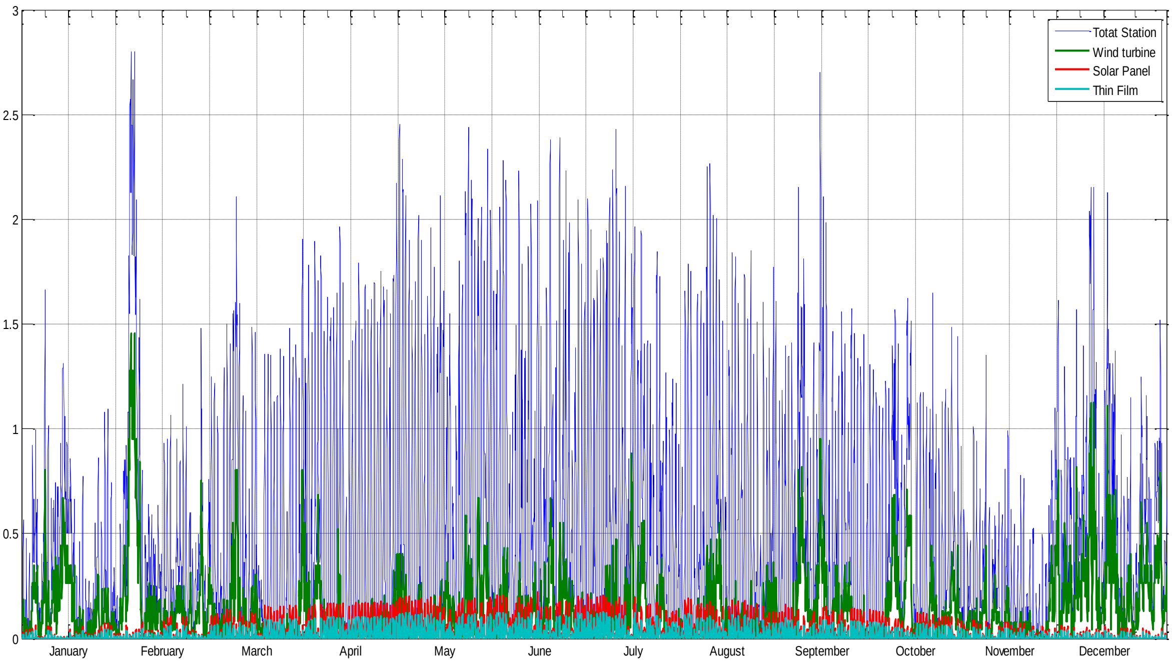

Figure 5.1: Power production over 2001 for the Station and per RES.

It is therefore safe to assume that the scenarios formulated in paragraph 2.3.3 do not usually coincide, i.e. the sunniest day of the year is not necessarily the windiest. For that reason, energy yield calculations are preferably performed using data measured on actual days. On that ground, Table VIII gives the results of such calculations, performed with the original KNMI hourly data, measured at the Zestienhoven weather station and fitted for the GV location in Delft.

Table VIII: Average generated Power and daily Energy yield

Green Village Charging Station		Day in 2011					Annual
		January 14 (least sunny)	February 5 (windiest)	Average (wind,sun) scenario	June 14 (sunniest)	October 1 (least windy)	2011
Mean Power	per WT	528 W	1152 W	99 W	35 W	6 W	140 W
	per PV	1 W	5 W	28 W	80 W	34 W	28 W
	per TF	0.6 W	3 W	17 W	48 W	20 W	17 W
	Station	**1022 W**	**2256 W**	**436 W**	**758 W**	**308 W**	**514 W**
Energy Yield [per day]	per WT	12161 Wh	26446 Wh	2298 Wh	819 Wh	148 Wh	1224 kWh/year
	per PV	23 Wh	121 Wh	679 Wh	1917 Wh	822 Wh	248 kWh/year
	per TF	15 Wh	78 Wh	418 Wh	1155 Wh	492 Wh	151 kWh/year
	Station	**24 kWh**	**52 kWh**	**10 kWh**	**18 kWh**	**7 kWh**	**4503 kWh/year**[1]

The mean daily power output of the formulated ‘average wind´ and ‘average sun’ scenarios (i.e. 436W), approximates very well the mean power of the real annual KNMI data (i.e. 514W). The same cannot be said for the energy yield. On a day described by the average scenarios, the Station generates 10kWh/day. The real annual yield is 4503kWh/year, which on average corresponds to 12.34kWh/day. It comes as no surprise, that this average is indeed much farther away than the amount of energy generated on any of the other four days.

If the above reasoning proves something, it is that there is a strong fluctuation in the amount of kWh generated from day to day. The deviations also suggest that the time shifted seasonal fluctuations in wind and solar power do not compensate for each other, such that would allow a steady energy generation profile throughout the year. At least not with the current mix of solar and wind energy installed on the Station.

Two conclusions can therefore be drawn. First, when running daily simulations using the developed Static model, one should be considerate of which daily scenarios to input. How these compare to the real annual yield, should be examined before interpreting the simulation results.

Second, the 4503kWh generated in a year’s time, show that charging six Emoto 80duo electric scooters every day, as proposed in section 4.3, is well within the capacity of the Station. In fact, it can handle nine of these scooters, charged daily from an 80% DOD. Idem, translated to 16kWh cars like the iMiEV, the annual yield is unfortunately enough to charge just one vehicle, 352 days of the year i.e. 96% of the time.

[1] Inverter efficiency = 96%

5.2 Capacity Factor

The capacity factor, not only for the whole installation but also per RES component, is calculated in Table I for the reader to compare to other projects.

Table IX: Capacity Factor.

Component	Capacity Factor
Wind turbine	9.31%
PV solar panels (c-Si)	11.57%
Thin film solar modules (a-Si)	11.94%
(Total) Charging Station	**9.9%**

5.3 Discussion

This section reflects on the lessons learned from the research on the Station and lays the ground for what can be recommended regarding the Green Campus.

At the very start of this Thesis, the Station was envisaged as a standalone, off-grid unit which would generate enough renewable power to charge EVs. In fact, the idea described in subparagraph 2.1.1.1 went as far as to describe a modular station which could easily be moved inside the Green Village. With an installed capacity of 5.19kW, the Station would generate enough energy to charge two 24kWh electric cars per day, if only it could accomplish a capacity factor of roughly 25%.

Although this seemed logical at the time, simulations based on measured data proved it was very optimistic indeed. Rather, the 9.9% capacity factor calculated above bears witness to the fact that the solar and wind potential at the GV site are quite limited. At least this is what MCP methods predict. Still, the research question remains; “can the Station indeed be autarkic with the current technology?” The answer is conditional. If a properly sized storage system is added to the Station, then it would be able to charge a small electric car once per day. Actually, there would not even be a need for an interconnection in that case.

Even so, the RES low power output soon became clear and led to the decision to interconnect the Station with the GV. This solution served two causes. It would provide backup power but still manage to avoid an additional large battery system.

The idea to combine charging with renting electric scooters was and remains an interesting option. Nevertheless, all the uncertainties surrounding the village implementation make it difficult to move from a conceptual basis to a more concrete business case. At least for the time being, that is. This realization begs the question “is it worth spending time and resources trying to find the right conditions that would make scooter rental profitable?” Put differently, “should one forget about scooters and only focus on car charging instead?”

Again the answers to these questions are conditional. It is hard to say what would be most profitable; cars or scooters. The answer is clearly cars if in the coming years, more and more TU Delft employees or green villagers own electric cars, which they would charge at the campus. On the other hand, in a future where the GV attracts many visitors, a well marketed scooter rental business could pay off. In any case, a market research seems like a good starting place to explore the potential of both options. After all, prior to building anything one needs to know who would use it and what they would be willing to pay for it. In other words a well-defined target group is a prerequisite to creating a business case out of a concept like the Green Village Charging Station.

To conclude, given the current status quo of GV developments, EV charging with renewables is definitely worthwhile in the Green Village, if the generated energy averages consumption over the year. For this to work, RES capacity has to be connected to the grid, either national or the local DC Grid of the village. An autarkic Station with battery storage seems pro tempore out of the question, since it is impossible to size a storage system with so many unknowns.

5.4 Green Campus Roadmap

Before planning the future, it is important to realize what can be built with existing equipment today. The fact is, almost all of the suggested components are available off the shelf, which is not surprising given that the Station was designed to be implementable. If proper funding is in place, a prototype Station can be put together in a matter of days. Of course, no GV interconnection would be established, simply because the village is not built yet. Instead, a connection to the normal grid could provide equal functionality.

If the current trends in EV sales continue, then by the time the Green Campus will be realized, there will be thousands of EVs in the Netherlands. It is important to plan in advance, in order to be in a position to satisfy the growing need for charging infrastructure in the Green Campus. This can only be achieved by developing a cluster of charging points. Sustainable power should not in that case be limited to autonomous units, like the Green Village Station. As the Green Campus grows in size, renewable energy should be produced both on site and elsewhere. For example, part of the energy required for charging could come from the Harp or the PV system installed on a university building. This clearly requires a strong local grid to support a decentralized energy generation and buffering scheme.

Research on Electric Vehicles themselves should also be in the scope of the Green Campus. Innovation, even as ambitious as designing an electric car from scratch, is the only way to explore the groundbreaking ideas a profit driven industry never would. A promising collaboration that sets the path in this direction is the one between Accenda and DC B.V., conceived under the umbrella of the Green Village Project. Combining expertise, the two companies will develop the technology required to charge the next generation of Ekolectric cars at the Green Village, using DC current (Accenda B.V., 2011), (Energy Club, 2011).

6 Recommendations and Future Work

Useful recommendations, which became apparent during this Thesis, are discussed in this final chapter. In addition, certain issues that regard the Station implementation on a practical level are presented as well.

6.1 Recommendations

Having read section 2.3, one must surely understand just how important accurate meteorological data are, when developing a project based on renewable energy sources. Measurements at locations near the Green Village do exist and indeed, endless time and effort can be spent practicing Measure-Correlate-Predict methods. Nevertheless, simulated data could never substitute actual performance measurements.

Especially parts like the Windtronics turbines, which have no or limited track record, must be tested in situ. It is therefore strongly recommended to install a network of meteomasts, positioned strategically at points of interest inside the Green Village and Green Campus. The sooner such devices start measuring wind and solar resources, the more data researchers will have to work with.

Funding is crucial to any GV development. What would attract investments is an operational station, for it would showcase the conceptual design and provide feedback with regards to user acceptance. If a demo Station were to be built tomorrow, it would be wise to connect it to the AC grid, at least for the beginning. Grid connection would of course be similar to the GV interconnection. At times when backup power is required, it would be purchased from the utilities and whenever the Station generates surplus, it would be sold back to them. Once enough data are gathered regarding user visit patterns, frequency of EVs coming to charge and actual on site RES power production potential, then it will be much easier to predict the system behavior and scale it up to the level of 'integrated autarky' envisaged for the Green Campus.

To wrap up, it is perhaps interesting to mention that while this Thesis was being written, the manufacturer who arguably put the electric car on the automotive map, i.e. Tesla Motors, unveiled a 'supercharger' (Figure 6.1). This is a grid connected DC fast charging station which feeds energy back to the grid, through the use of solar panels. It indicates that the Sustainable EV Charging Station designed for the Green Village, could well be what the future of electric mobility holds.

Figure 6.1: Tesla Supercharger (Tesla Motors, 2012).

6.2 Future Work

An interesting topic which should be investigated further is the effect wake would have between the two windturbines of the station. Given that wind in the area blows usually from the south, wake was not considered here. At times when the wind is coming from the East or West however, it would be valuable to know what power reduction to expect.

In fact, a study on wake effect in relation to the village layout is advisable for the entire Green Village, since the plan is to deploy multiple small wind turbines there. It could well be the case that the turbulence, created by the proposed containers' topology, limits the power output of roof mounted windturbines so much, that it is only useful to deploy one or two mid-range (50-80kW) turbines instead.

While on the matter of aerodynamics, a design characteristic that might create problems is the positioning of the PV panels on a vertical (portrait) orientation. This arrangement was selected to avoid shading between the modules, yet it could compromise the structural stability when strong wind blows on the back side of the array.

As far as the integration of thin film PVs on the Station tent is concerned, a mechanism which allows the tent to roll in and out lengthwise should be designed.

On the subject of wind turbine installation, there are two options; either to mount the pole on the container side or to fasten it onto the rooftop, using a concrete base. If side mounting is selected, rotor vibrations could be transferred to the container body creating noise. More importantly, a pole longer than 8.7m should be used to achieve the designed hub height of 12 meters. Then, a stronger monopile design might be required to prevent buckling. To check whether the second option is possible, the bearing capacity of the container structure should be calculated.

Last, vehicle to grid (V2G) was not a priority for this thesis simply because current vehicles do not allow it. Besides, V2G really becomes beneficial if implemented at large scales, where the number of connected EVs far exceeds the Green Village expectations. Not to mention that the V2GFull operating mode has some major user acceptance barriers to overcome, simply because discharging back to the grid inevitably reduces battery lifetime. That said, recent studies (Tuffner & Kintner-Meyer, 2011) show that V2GHalf[1] strategies work equally well in alleviating grid stress in times of need. Although there is no scientific study to either prove or disprove that a fluctuating charging current can harm EV batteries on the long run, users are more likely to accept this idea if it does not violate their desire to have the battery fully charged at a certain time.

Arguably then, it is interesting to investigate V2G deployment in the Green Campus as it could end up being the norm in the near future. Such a scenario however, would require a complex and admittedly very delicate configuration of the supply/demand system. Therefore, this research cannot be performed in simulation, without any real experimentation data. It is perhaps wise then, to incorporate it in the joint GV-Ekolectric project.

[1] In V2GHalf technology EV batteries do not discharge to feed power back to the grid. They only draw power from the grid, yet at a charging rate which is not constant. Put more simply, at peak consumption when the demand is high, the grid can choose to lower the charging current of EVs, within a reasonable range of course, in order to cut down on demand and channel elsewhere the power saved. In fact, in the near future when more and more SETs are introduced to the grid, the need to control power imbalances by managing load demand will be considerably higher. Studies claim that V2G will be a great help to grid operators, as they try to harness the fluctuations in the production of renewable energy technologies (Tuffner & Kintner-Meyer, 2011).

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Appendix A: Existing RES charging stations

Below photos of Sustainable Electric Vehicle Charging Stations are illustrated from projects implemented around the world.

The new charging station installed at EMC solar in West Perth (UWA, 2012).


The 57 kW Solar powered EVCS in the University of Iowa (Facilities Management UIOWA, 2011).

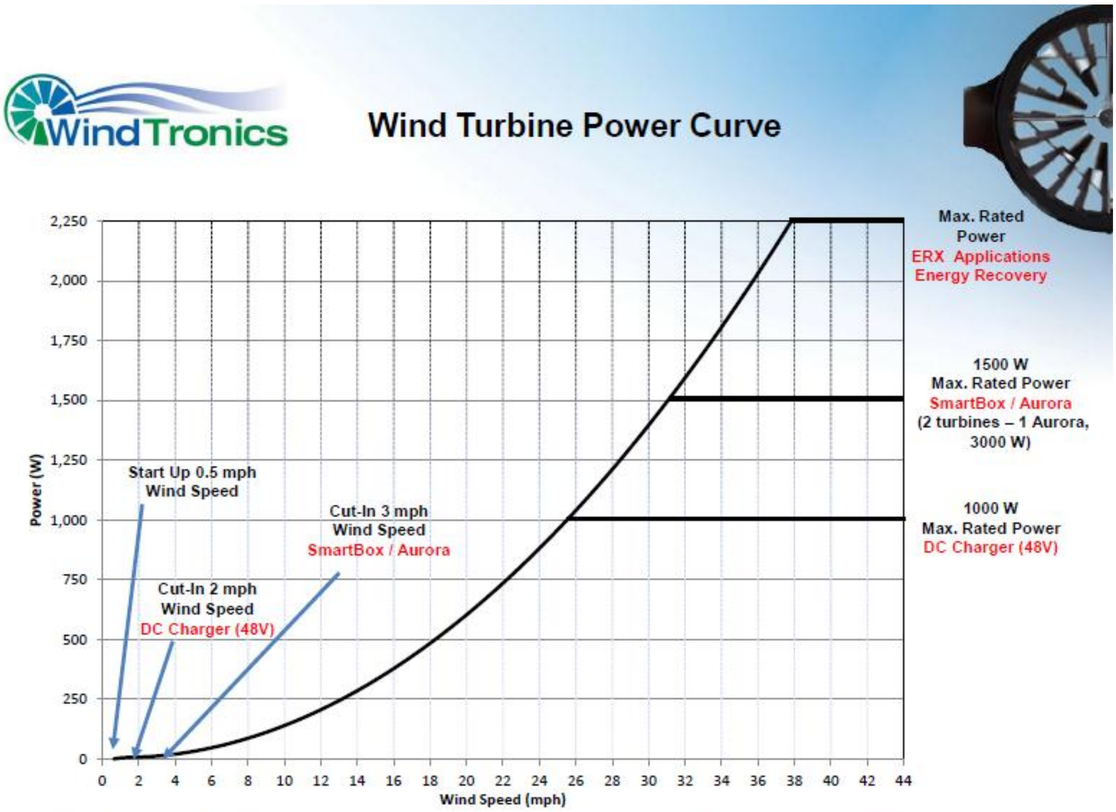
The 16.8 kW solar-powered charging station installed at the Mitsubishi Motors headquarters in Cypress, California (Mitsubishi Electric & Electronics USA, Inc., 2011).

The 3.75kW Single Solar Canopy charging station installed in Seattle by EV4Oregon (EV4 Oregon LLC, 2011).

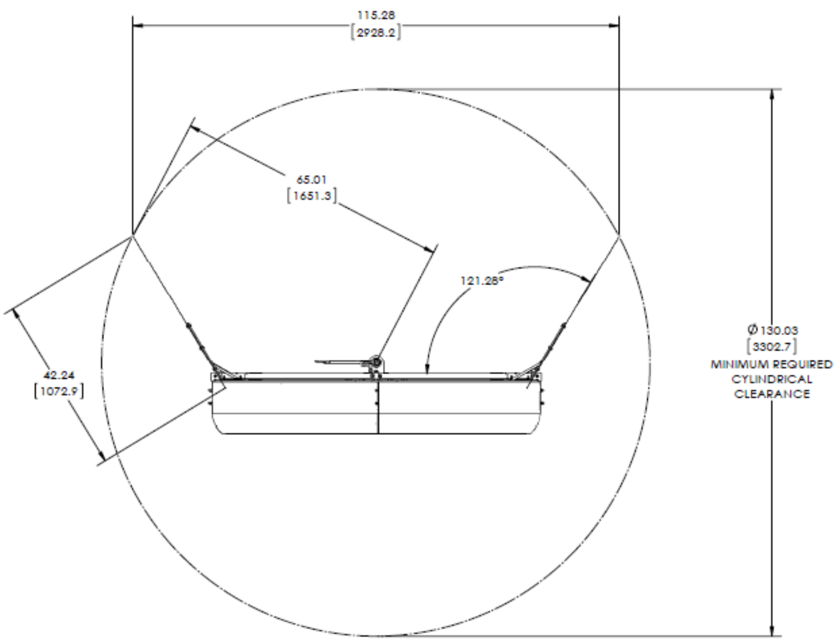
The BMW Mini E solar charging station installed in New York (BE Group, 2009)

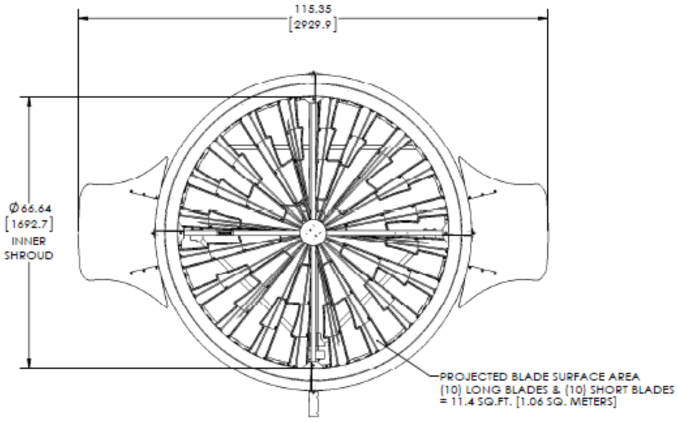
A Sanya Skypump EVCS installed in Barcelona, Spain. The system features General Electric's DuraStation charger and Urban Green Energy's UGE-4K VA wind turbine (UGE, 2012).

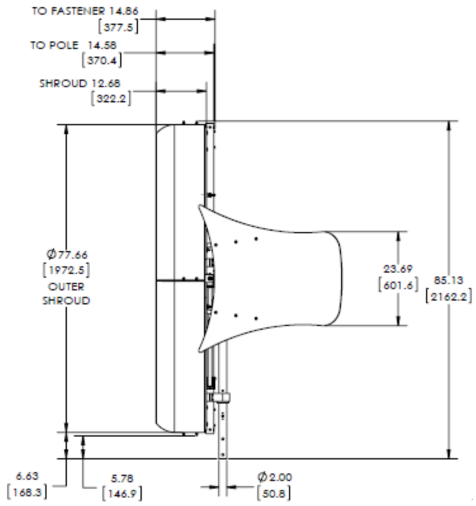
Appendix B : Windtronics BTPS6500 datasheet



Note: The wind turbine data for energy generation is measured against wind speeds at steady state (wind tunnel calculations). Actual production will vary depending on wind speed and site conditions.



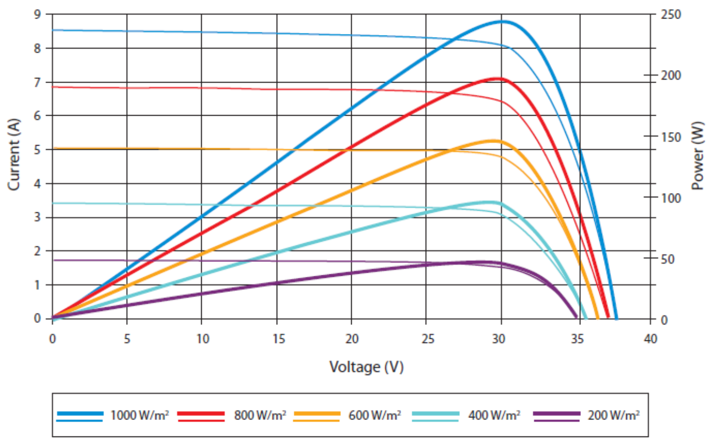


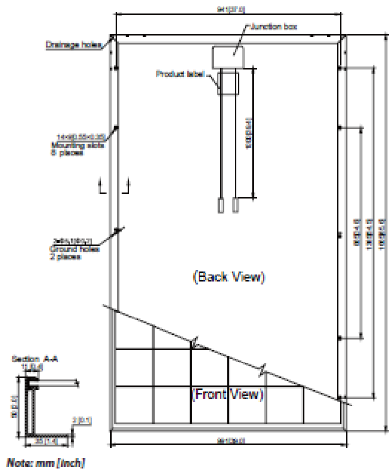


Model BTPS6500	Specification
Rated Power Output	1500 W at 13 9 m/s (31 mph)
Weight	Turbine 102 kg (225 lb.), Directional Fins 7.3 kg (16 lb.)
Rotor Diameter	1.82m(6ft)
Type	Blade Tip Power System'M
Blades	20 Glass Filled Nylon (10 short and 10 long)
Shut Down Speed	165 VDC or 17 9 m/s (40 mph)
Generator	Perimeter Tip Permanent Magnet/Stator System
Grid Feeding	Depends on Energy Management System chosen
Braking System	Electromagnetic
Duty Type	S1, Continuous Duty
Cut-In Wind Speed	0.9 m/s (2 mph)
Rated Wind Speed	13.9 m/s (31 mph)
Survival Wind Speed	62.6 m/s (140 mph)
Recommended Minimum Average Wind Speed	5.4 m/s (12 mph)
Sound Power Level	At 3 m (10ft.) away, less than 35 dB at 13.4 m/s (30 mph)
Temperature Operating, Storage andTransportation	-40 C to 60 C (-40 F to 140 F)

Appendix C: Suntech STP245S-20 datasheet

Current-Voltage & Power-Voltage Curve (245S-20)





Mechanical Characteristics		
Solar Cell	Crystalline silicon 156 × 156 mm (6 inches)	
No. of Cells	60 (6 × 10)	
Dimensions	1665 × 991 × 50 mm (65.6 × 39.0 × 2.0 inches)	
Weight	19.8 kgs (43.7 lbs.)	
Front Glass	3.2 mm (0.13 inches) tempered glass	
Frame	Anodized aluminium alloy	
Junction Box	IP67 rated	
Output Cables	TUV (2Pfg1169:2007), UL 4703, UL 44	
	4.0 mm² (0.006 inches²), symmetrical lengths (-) 1000 mm (39.4 inches) and (+) 1000 mm (39.4 inches)	
Connectors	RADOX® SOLAR integrated twist locking connectors	
Electrical Characteristics		
Measurement Conditions	STC*	NOCT**
Optimum Operating Voltage (Vmp)	30.5 V	27.8 V
Optimum Operating Current (Imp)	8.04 A	6.50 A
Open Circuit Voltage (Voc)	37.3 V	34.3 V
Short Circuit Current (Isc)	8.52 A	6.92 A
Maximum Power (Pmax)	245 W	181 W
Module Efficiency	14.8%	
Operating Module Temperature	-40 °C to +85 °C	
Maximum System Voltage	1000 V DC (IEC) / 600 V DC (UL)	
Maximum Series Fuse Rating	20 A	
Power Tolerance	0/+5%	

*STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5
Best in Class AAA solar simulator (IEC 60904-9) used, power measurement uncertainty is within +/- 3%

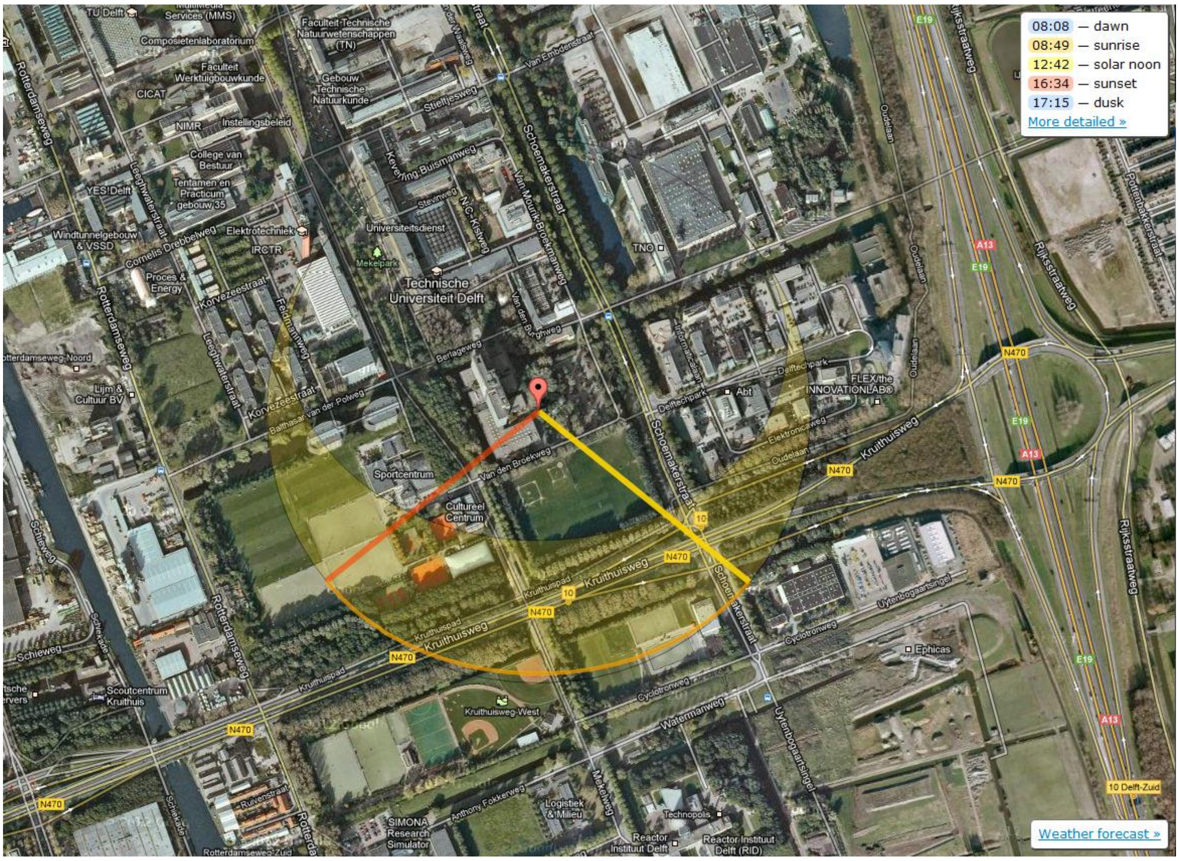
**NOCT: Irradiance 800 W/m², ambient temperature 20 °C, AM=1.5, wind speed 1 m/s
Best in Class AAA solar simulator (IEC 60904-9) used, power measurement uncertainty is within +/- 3%

Appendix D: Panel Configuration

Table X: Min and Max daylight calculations for GV site (SunEarthTools.com, 2012)

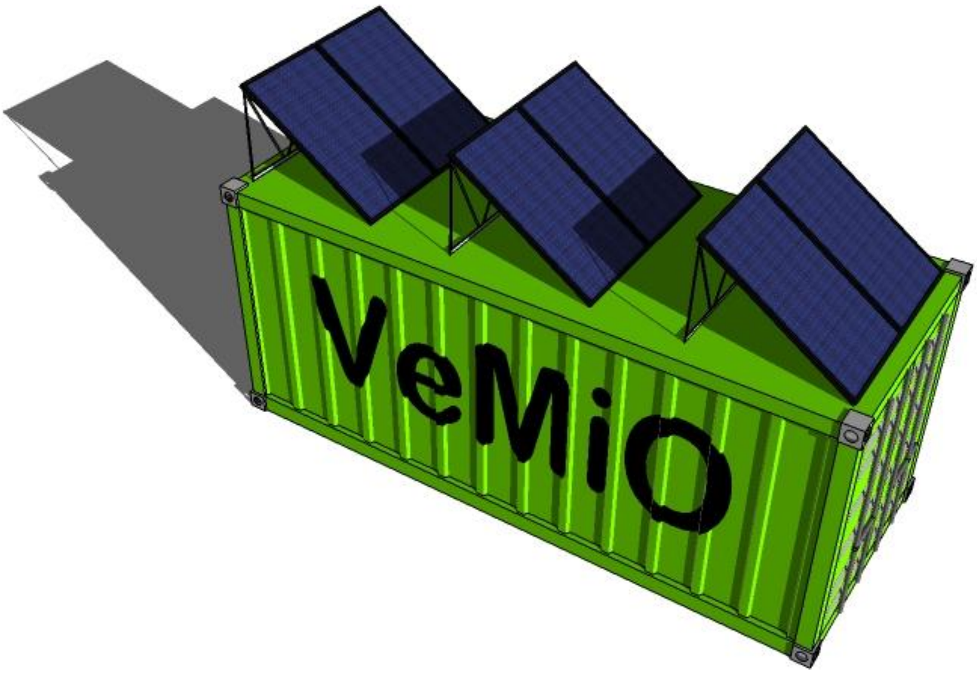
Date		21 June 2012	21 December 2012
Daylight		16hrs:44min:06sec	07hrs:44min:38sec
Sunrise	Time	04:22:19	07:48:28
	Sun azimuth	48.33°	128.86°
Solar noon	Time	12:40:00	12:40:00
	Sun elevation	61.43°	14.57°
	Sun azimuth	177.9°	179.81°
Sunset	Time	21:06:25	15:33:06
	Sun azimuth	311.66°	231.14°

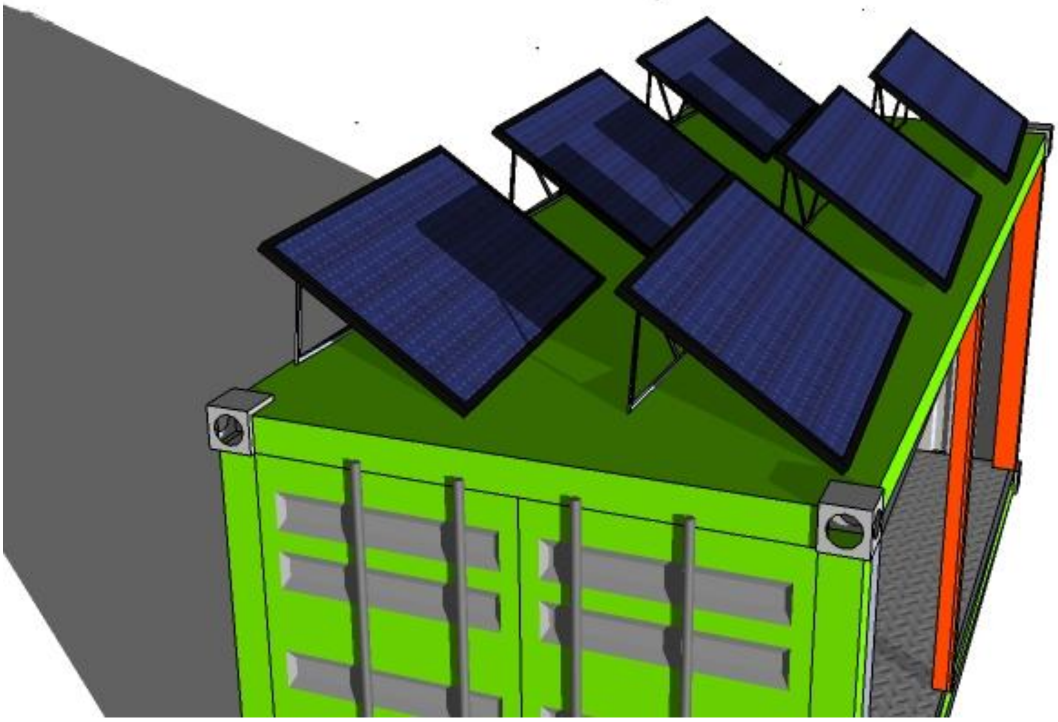
Sunpath on June 21st, 2012 (SunCalc, 2012)



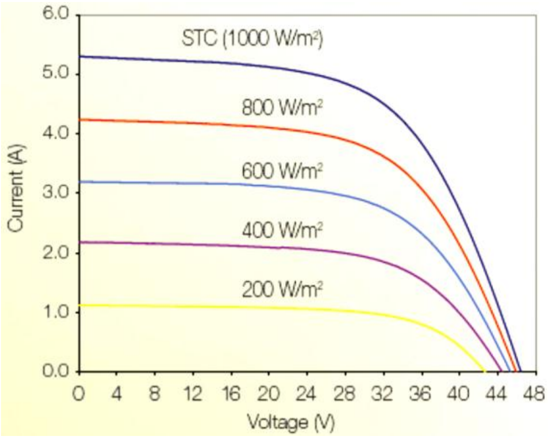
Sunpath on December 21st, 2012 (SunCalc, 2012)

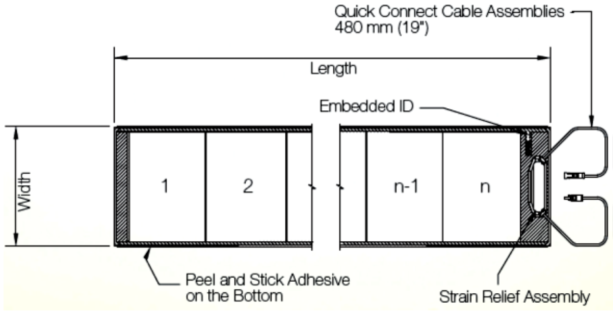
The Station should be positioned facing south. The optimal tilt angle for the PV modules is 36°. Based on the facts presented in Table X above and as observed in the pictures below, the only configuration that prevents panels from shadowing each other when the sun is low, is to place the modules on a single array. To fit the 6m container length, they have to be positioned on a portrait orientation as depicted in Figure 2.5.





Appendix E: PowerBond Unisolar ePVL 144 datasheet





Physical Characteristics		
Length	5412 mm	
Width	373 mm	
Laminate thickness	3 mm	
Overall Thickness: (including adhesive and terminal housing)	21 mm	
Weight	7.4 kgs	
Number of cells	22	
Cell type	Multi-junction amorphous silicon solar cells 356 mm x 239 mm	
Electrical Characteristics		
Measurement Conditions	STC*	NOCT**
Optimum Operating Voltage (Vmp)	33.0V	30.8 V
Optimum Operating Current (Imp)	4.4 A	3.6 A
Open Circuit Voltage (Voc)	46.2 V	42.2 V
Short Circuit Current (Isc)	5.3 A	4.3 A
Maximum Power (Pmax)	144 W	111 W
Limiting Reverse Current	10 A	
Maximum Series Fuse Rating	10 A	
Power Tolerance	+/- 5%	
*STC: 1000 W/m2, AM 1.5, 25°C Cell Temperature		
**NOCT: 800 W/m2, AM 1.5, 1 m/sec. wind		

Appendix F: Femtogrid solar power optimizer data

Solar Input (DC from PV modules)		
Maximum DC power	300	W
Nominal DC power	250	W
MPPT operating voltage range	8 - 42	Vdc
Maximum DC current	10	A
MPPT	decentralized per module	
Compatible with types of modules	mono- and polycristalline	
Power Optimizer Output (DC in operation)		
Nominal DC power	250	W
Nominal output voltage (Femtogrid voltage)	380	Vdc
Maximum output current	0.8	A
Maximum efficiency	97.4	%
MPPT efficiency	>99	%
Efficiency, European related (Euro ETA)	95.7	%
Standard Compliance		
EMC: Immunity	EN61000-4-2/3/4/5/6/11	
EMC: Emission	EN55022/EN60601-1-2	
	EN55022/EN61000-3-3	
Safety	EN60950	
CE/RoHS/WEEE/REACH	Yes	
Safety class	Class II	
Degree of protection	IP65	
General		
Relative humidity (non-condensing)	0 - 95	% RH
Dimensions with bracket (WxLxH)	288x342x51	mm
Ambient temperature	-40/+65	°C
Weight	1.45	kg
DC connections	MC4	Type
Output connections	Custom made by Wieland for Femtogrid	Type
Switch-on power	0.5	W
Safetyline voltage ('neutral')	48	V
Femtogrid feed through current in-out	20	A

Appendix G: Femtogrid wind power optimizer data

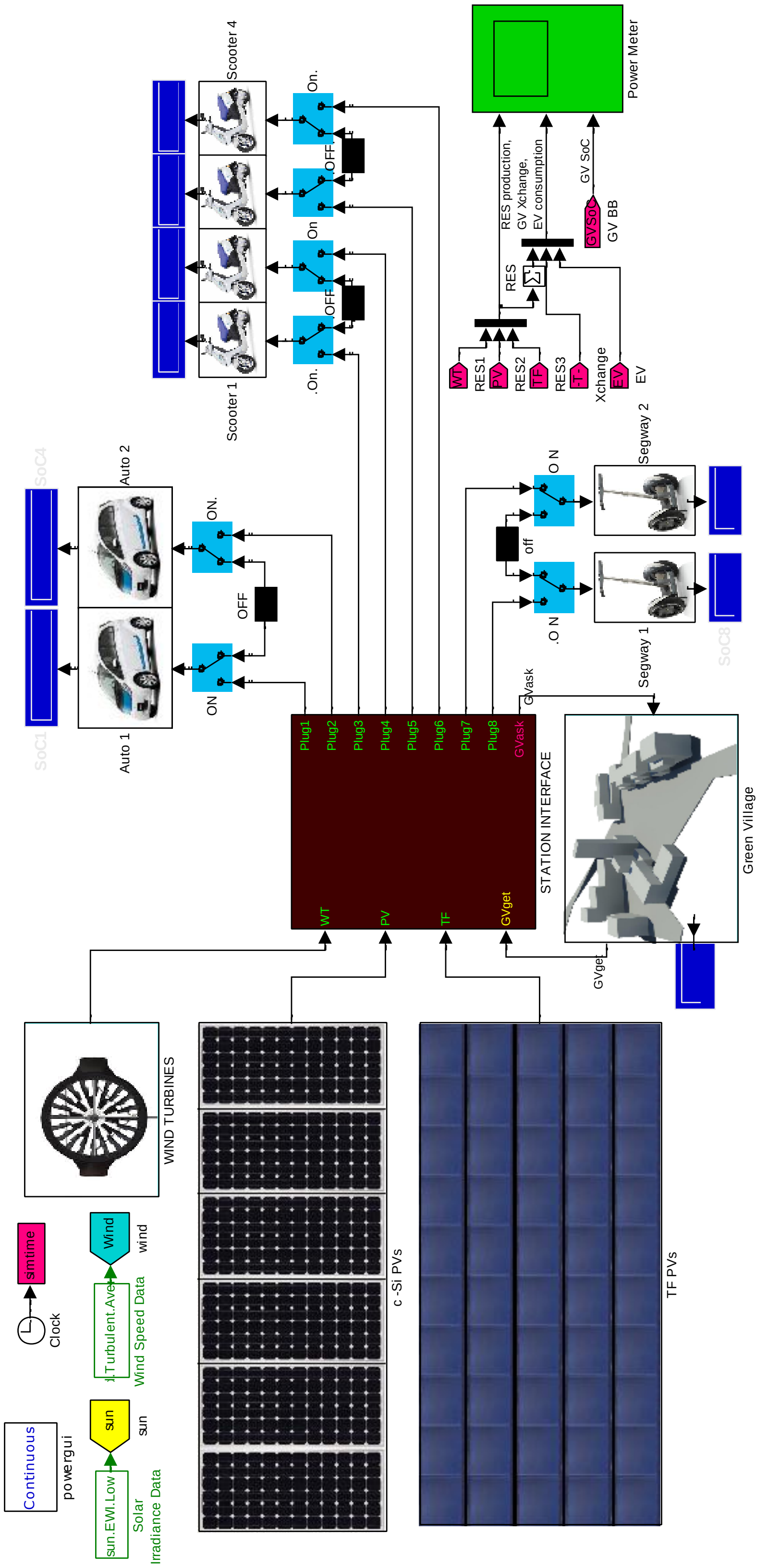
*Compatible only with **Windtronics BTPS6500** and **Honeywell WT6500***

Input characteristics Pmax 5 seconds	4500	W
Pmax constant	2600	W
Nominal DC power	2400	W
Voltage range	40/185	Vc
Break/safety voltage	180	Vdc
Maximum DC current	15	A
Dumpload	Built in, dynamic	
Power Optimizer Output		
Maximum DC power	2500	W
Nominal output voltage (Femtogrid voltage)	380	Vdc
Maximum output current	6.6	A
Cut in power (sustainable)	5	W
Standard Compliance		
EMC: Immunity	EN61000-4-2/3/4/5/6/11	
EMC: Emission	EN55022/EN60601-1-2 / EN61000-3-3	
Safety	EN60950	
CE	yes	
RoHS/WEEE/REACH	yes	
Safety class	Class I	
Protection rating	IP65	
General		
Parallel / Scalable	Yes, to a maximum of 7.5 kW	
Outdoor use	Yes	
Dimensions (WxLxH)	320x350x150	mm
Ambient temperature	-40/+65	°C
Weight	±5	kg
DC turbine connections	Wieland male RST25i3	Type
Output connections	Femtogrid/Wieland	Type
Operation power	5	W
Safety-line voltage ('neutral')	48	V
Femtogrid feed through current in-out	20	A

Appendix H: Femtogrid inverter datasheet

Solar Input (DC from PV modules)		
Maximum DC power	2550	Wdc
Recommended PV Power range	500 - 3000	Wdc
Nominal DC operating voltage	360 - 400	Vdc
Minimum input voltage for rated output	380	Vdc
Maximum DC current	6.7	Adc
MPPT	@ Femtogrid PV Power Optimizer	
Isolated transformer	Galvanic isolation	
Mains output (AC)		
Maximum AC Power (@tamb 25°C)	2400	Wac
Nominal AC Power	2200	Wac
Nominal output voltage range (country specific)	184 - 265	Vac
Maximum output current (continuous)@230 V	10.5	Aac
Maximum efficiency	96	%
Efficiency, European related (Euro ETA)	94.6	%
Power factor	1	
Frequency (country specific)	45 - 55	Hz
Standard Compliance		
EMC: Immunity	EN61000-4-2/3/4/5/6/11	
EMC: Emission	EN55022/EN60601-1-2	
	EN55022/EN61000-3-3	
Grid connection standards	NEN-EN 50438/VDE0126-1-1	
CE/RoHS/WEEE/REACH	Yes	
Safety class	Class I	
Degree of protection	IP31	
Temperature protection	>80	°C
General		
Wireless communication	ZigBee	
Dimensions (WxLxH)	323x202x646	mm
Ambient temperature	0 - 40	°C
Weight	38	kg
DC connections	Custom made by Wieland for Femtogrid	Type
Output connections	Wieland	Type

Appendix I : Static Model



Graphic User Interface of the Static Model in Simulink©

Appendix J : Power Flow Control Strategy

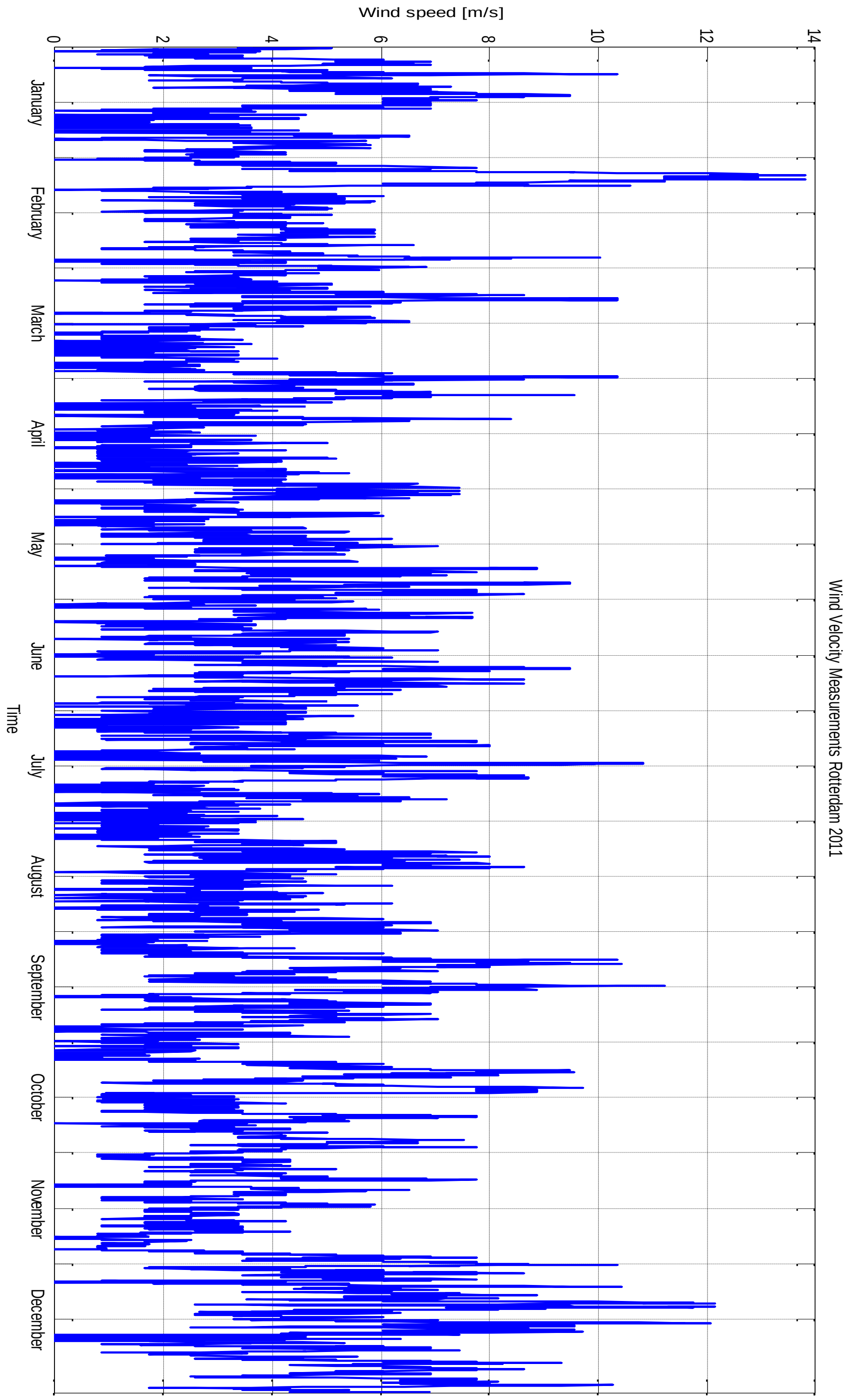
Below the embedded matlab code is given for the Static Model Controller algorithm.

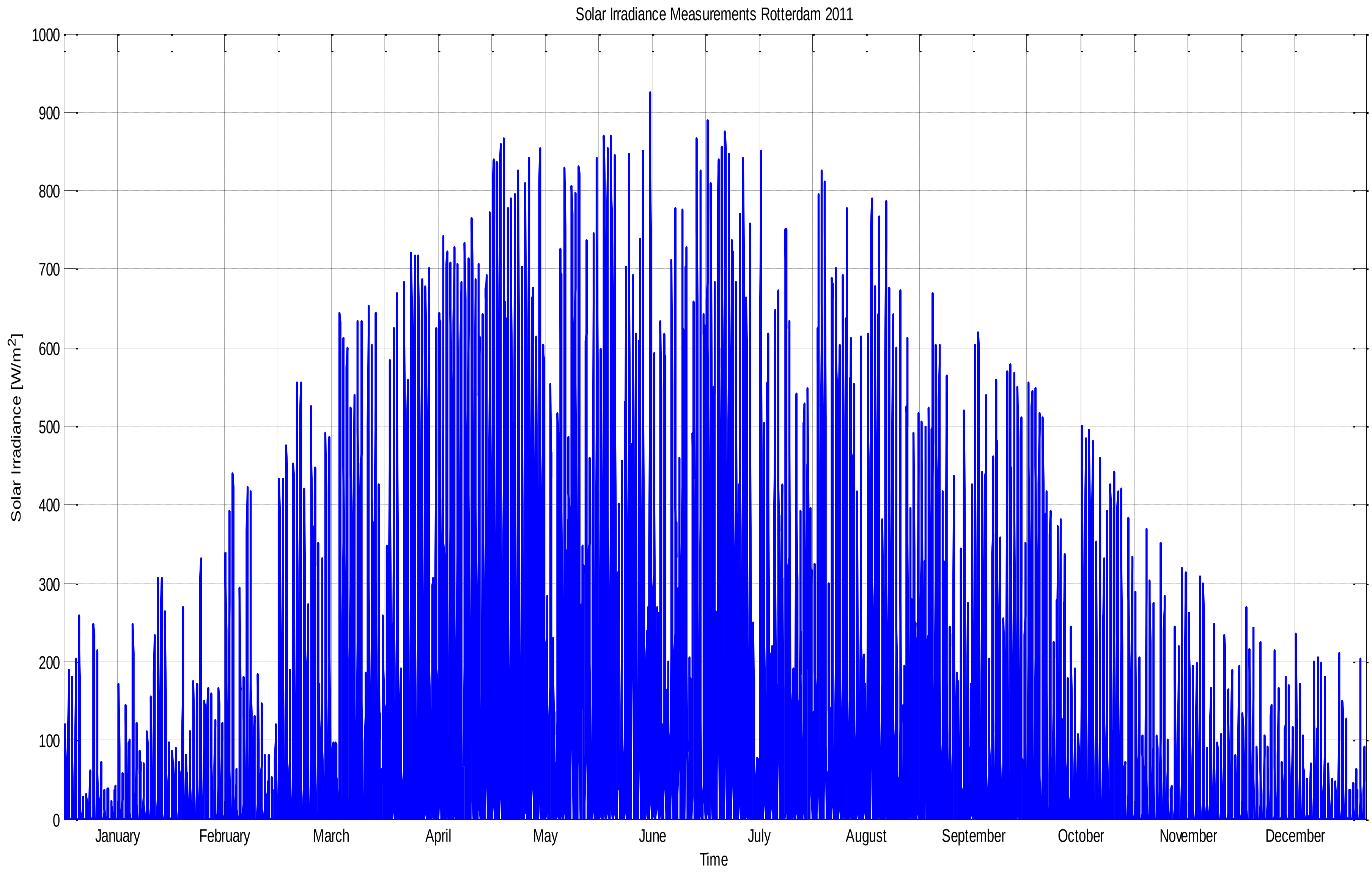
```
function [Plugs, askIGV]=Controller(IRES, getIGV, EVIcs, EVSoCs)
% syntax: [Plugs, askIGV]=Controller(IRES, getIGV, EVIcs, EVSoCs)
% Controller Strategy
%   If there is enough power, feed all EVs and send surplus to village.
%   If there is not enough power, ask backup power from village.
%   If the vilage cannot provide backup power, cut-off EVs that are
almost empty.
%   If supply is still not enough start praying for sun and wind! ;)

if sum(EVIcs) == 0   % NO EVs USING THE STATION, USE RES TO CHARGE GVBB
    Plugs=zeros(8,1);
    askIGV=-IRES;    % negative power flow i.e. VeMiO --> Green Village
elseif (IRES+getIGV) < 1.01*sum(EVIcs) % NOT ENOUGH POWER, ASK GV
    askIGV=sum(EVIcs)-IRES;    % positive power flow i.e. VeMiO <-- Green
Village
    if getIGV == 0              % GV can NOT give power, cut-down EVs
        [~, j]=sort(EVSoCs,'descend');
        Plugs=EVIcs;
        askIGV=-IRES;
       for i=8:-1:1;
           if sum(Plugs) > IRES          % search for the ones less
charged
              Plugs(j(i))=0;             % among the ones still charging
           else askIGV=sum(Plugs)-IRES; % negative flow VeMiO --> GV
                break                    % and unplug them, when RES power
           end                           % is enough for the rest.
       end
    else Plugs=EVIcs;        % GV can give power, use it
    end
else Plugs=EVIcs;            % ENOUGH RES POWER, GREAT!
     askIGV=sum(EVIcs)-IRES;     % negative power flow i.e. VeMiO -->
Green Village
end
end
```

Appendix K : KMNI Data

A timeseries data file was downloaded from the Royal Dutch Meteorological Institute website (KNMI Datacentrum, 2012). The windspeed values refer to potential wind speeds which are translated downwards to the potential wind speed at standard height and with standard roughness length; a correction method put forward by Wieringa and Rijkoort in 1983 (Wener & Groen, 2009).




Solar Irradiance Measurements Rotterdam 2011
Solar Irradiance [W/m2]
1000
900
800
700
600
500
400
300
200
100
0
January
February
March
April
May
June
July
August
September
October
November
December
Time

Appendix L: Roughness length at the GV location

The roughness lengths at the points appearing in the map below were calculated with the program ‘roughn_map.exe’, which was based on the derivations of Wieringa and Rijkoort from gustiness analysis in 1983. The executable program was developed by KNMI researchers in 2000 as part of the HYDRA project spanning from 1983 until 2005 (HYDRA, 2000).

Arranged clockwise, points A, B, C, D, E and F have the roughness length values written in Table XI below. Note that the Bouwkunde Faculteit burned down in 2008, which means that at the time the program was developed, the building was still standing. As a result, at the point located on the exact point of interest the program unfortunately returns an inaccurate value.

Table XI: Roughness lengths

Point on map	**Z_0**
A	1.0
B	0.47
C	1.6
D	0.11
E	0.033
F	1.1

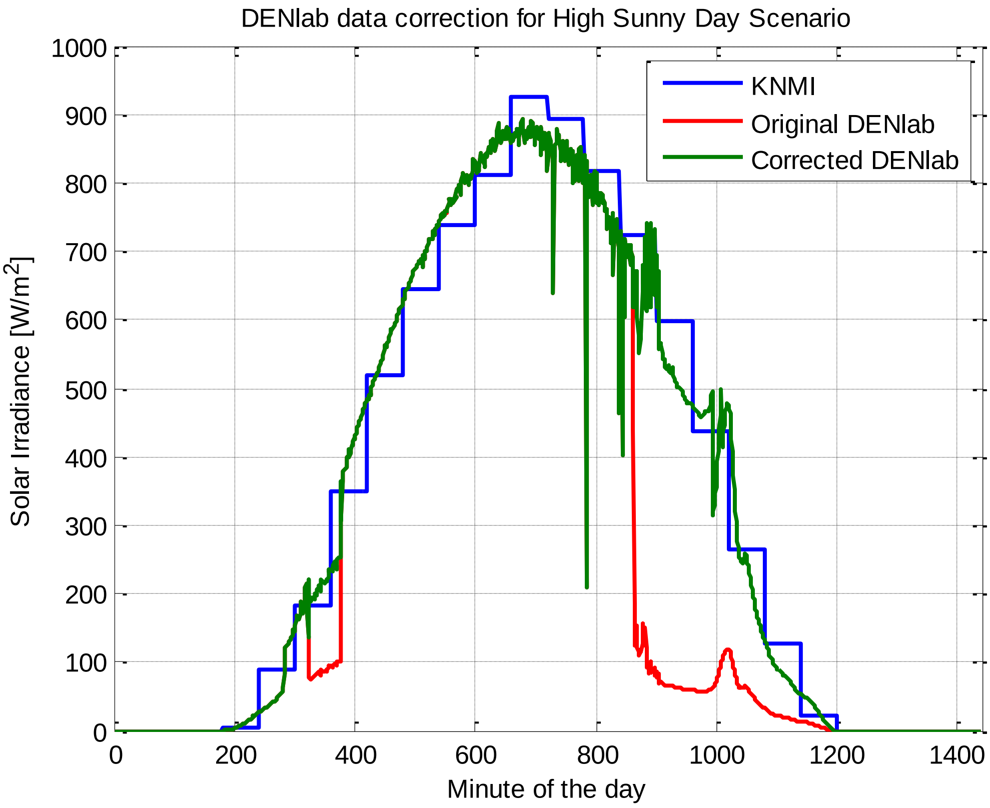
To correct for that error, other neighboring points had to be considered, bearing in mind that the wind on site usually blows from the south. The aerial photograph in the next page shows clearly that the points closer to 'B', both in terms of distance but also landscape similarity, are D and E. For this reason, the roughness length at the field where the Green Village will be built was calculated as the average of the values in points D and E, i.e.:

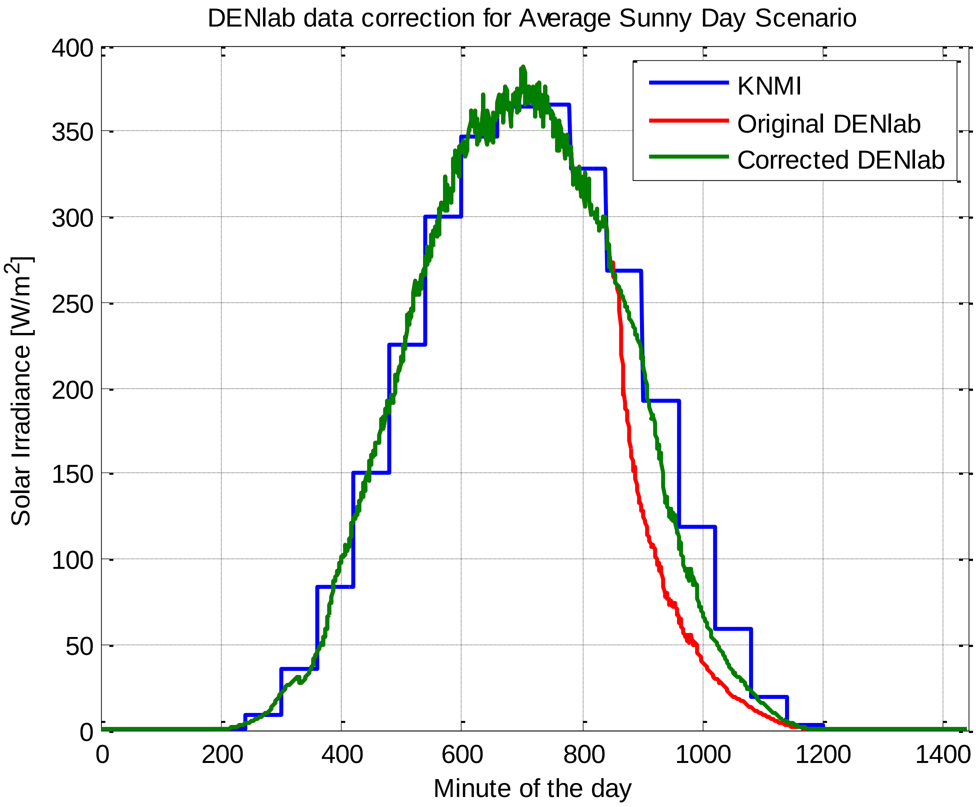
$$z_{0\,B} = z_{0\,E} + \frac{z_{0\,D} - z_{0\,E}}{2} = 0.0715$$

$z_{0a} = 1.0$
$z_{0f} = 1.1$
$z_{0b} = 0.47$
$z_{0c} = 1.6$
$z_{0e} = 0.033$
$z_{0d} = 0.11$
Kruithuisweg
N470
Mekelweg
Berlageweg
Van der Broekweg
Pieter Calandweg
Balthasar van der Polweg
Leeghwaterstraat
Kluyverweg
Anthony Fokkerweg
Watermanweg
Delftechpark
Schoemakerstraat
Molengraaffsingel
Cyclotronweg
Electronicaweg
Oudelaan
Sportpark TU Delft
Kruithuisweg-West (Sportpark)
Kruithuisweg-Oost (Sportpark)
Kruithuispad
Landzicht
Schiekade
Delftse Schie
© 2012 Microsoft Corporation

Appendix M: DENlab Data Correction

For about an hour, very early in the morning in June and for a large part of the evening, the PV modules installed at the low EWI building are shaded by the CiTG building on the east and the main EWI tower on the west, respectively. This causes false readings on the pyranometers measuring solar irradiance. As a result, the available data were corrected numerically by correlation to the hourly average values provided by the KNMI weather station in Rotterdam. The following graphs show plots of the original, the corrected and the mean values for the 'High Sunny Day' and 'Average Sunny Day' scenarios. The 'Low Sunny Day' scenario did not require corrections as it refers to winter months when the sun path does not reach that large an angle, to the east and west, for the buildings to cast shade on the modules.




DENlab data correction for Average Sunny Day Scenario
KNMI
Original DENlab
Corrected DENlab
Solar Irradiance [W/m2]
Minute of the day
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
1400

Appendix N : EV Charging modes

The following specifications are defined by the international standard IEC 61851-1 of 2010 titled 'Electric Vehicle Conductive Charging System- Part 1: General Requirements' (EMSD EV, 2011).

Terms and Definitions

An off-board charger is a charger connected to the premises wiring of the AC supply network (mains) and designed to operate entirely off the vehicle. In this case, direct current electrical power is delivered to the vehicle.

An on-board charger is a charger mounted on the vehicle and designed to operate only on the vehicle.

The charging cable assembly is a piece of equipment used to establish the connection between the EV and socket-outlet or the fixed charger.

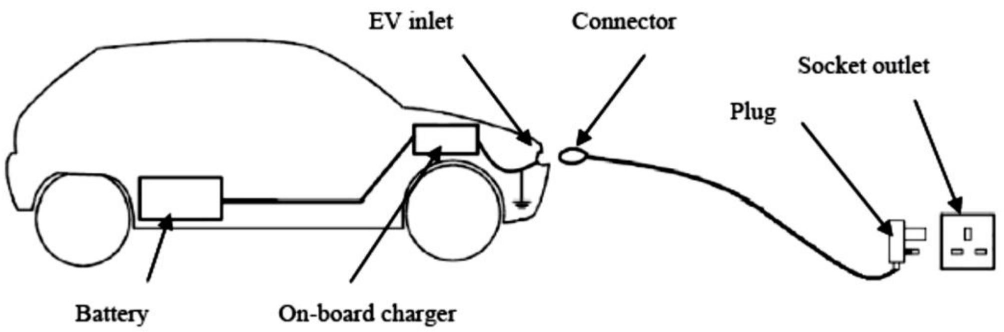
The control pilot is the conductor in the charging cable assembly connecting the in-cable control box or the fixed part of the charging facilities, and the EV earth through the control circuitry on the vehicle. It may be used to perform several functions.

The EV supply equipment (EVSE) refers to the conductors, including the phase, neutral and protective earth conductors, the EV couplers, attachment plugs, and all other accessories, devices, power outlets or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the EV and allowing communication between them if required.

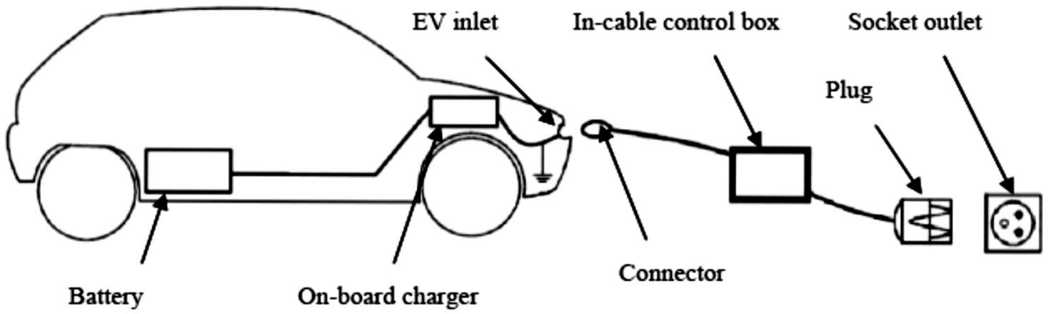
The in-cable control box is a device incorporated in the charging cable assembly, which performs control functions and safety functions. Think of it as the external power supply of your laptop, only larger and more powerfull.

Charging Modes

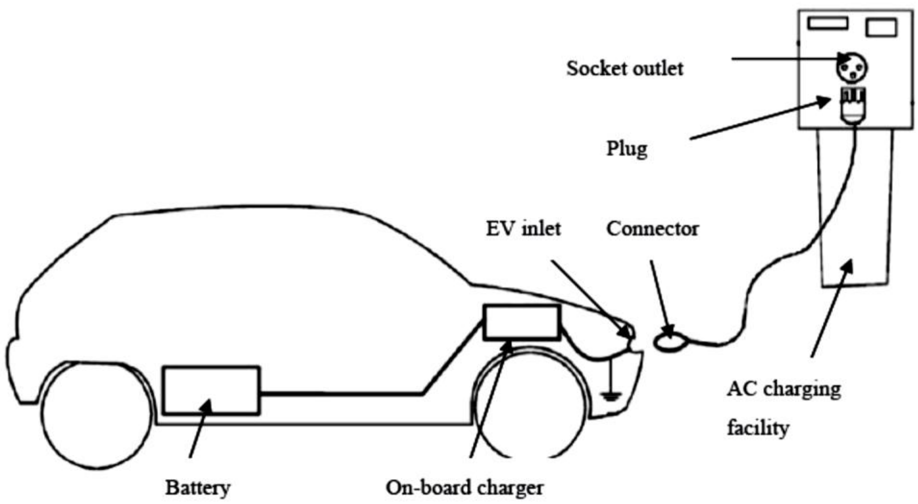
- **Mode1:** Use of a standard socket outlet without communication and the presence of a residual current device (RCD) is a must on the supply side, rated up to 16A.



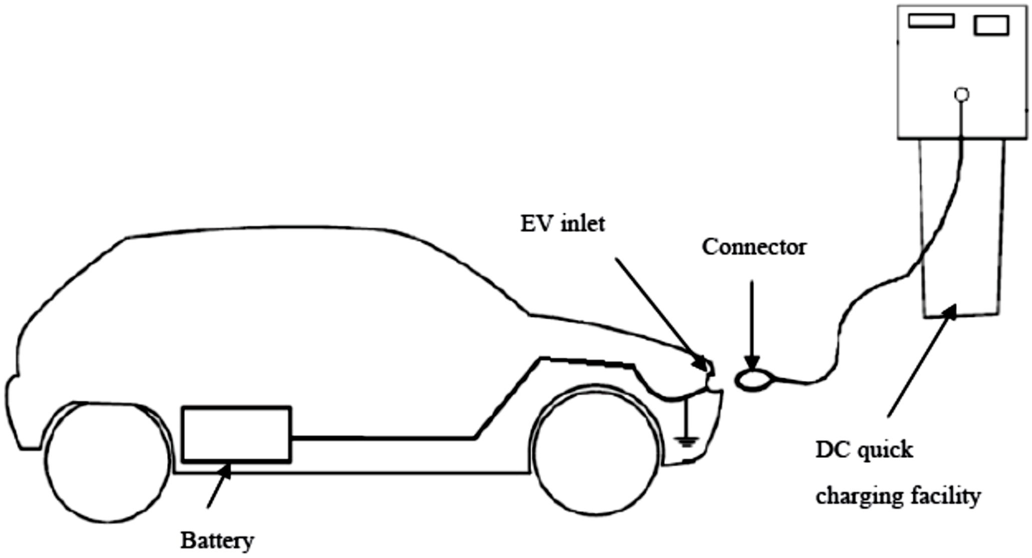
- **Mode 2:** Use of a standard socket not exceeding 32A outlet with in-cable or in-plug control pilot cable.



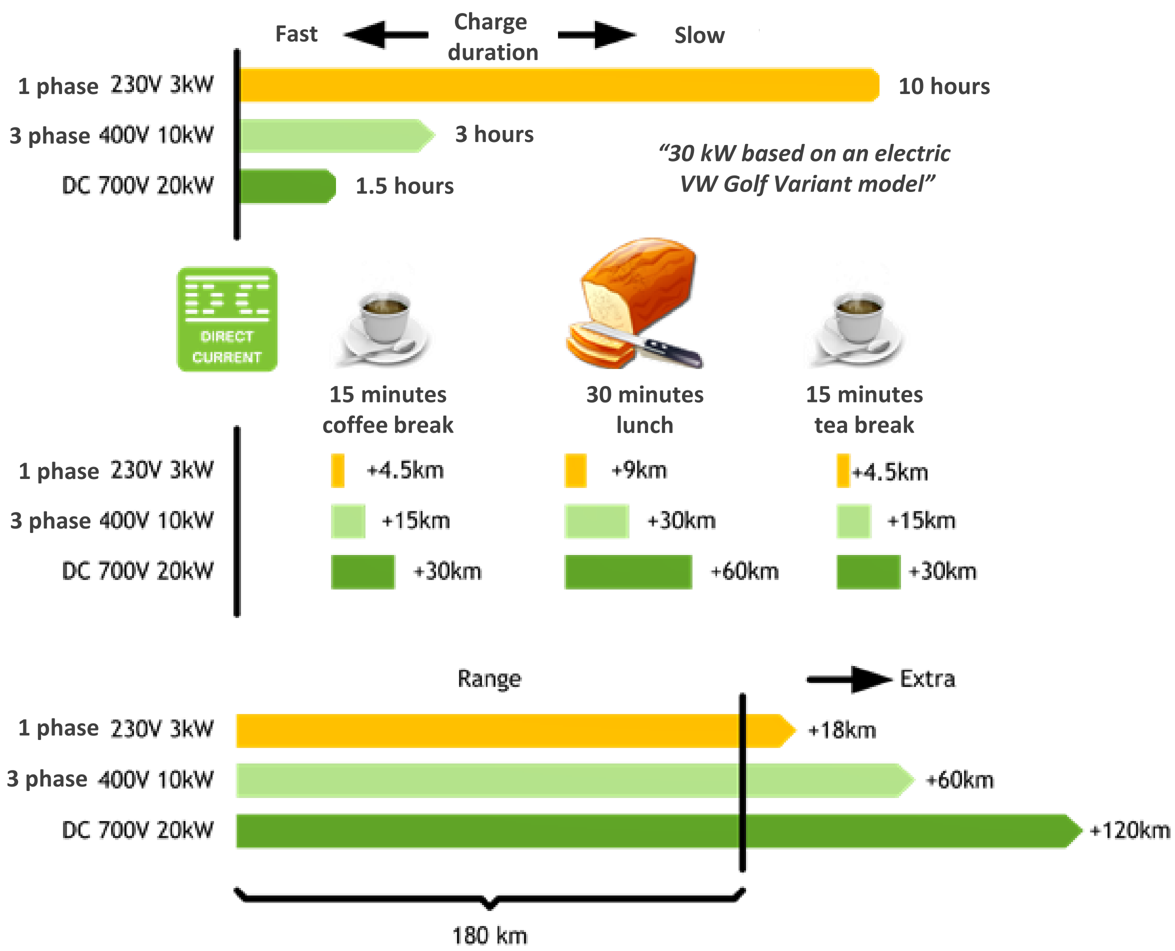
Mode 3: Use of a dedicated socket outlet where control pilot cable permanently connected to AC source.

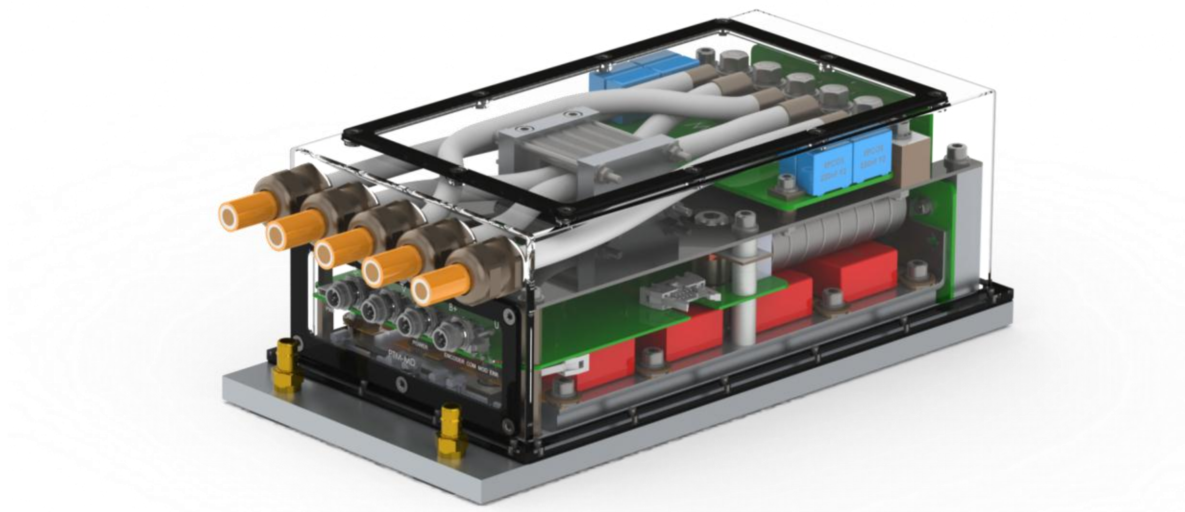


- **Mode 4:** Use of an off-board charger i.e. DC quick charger

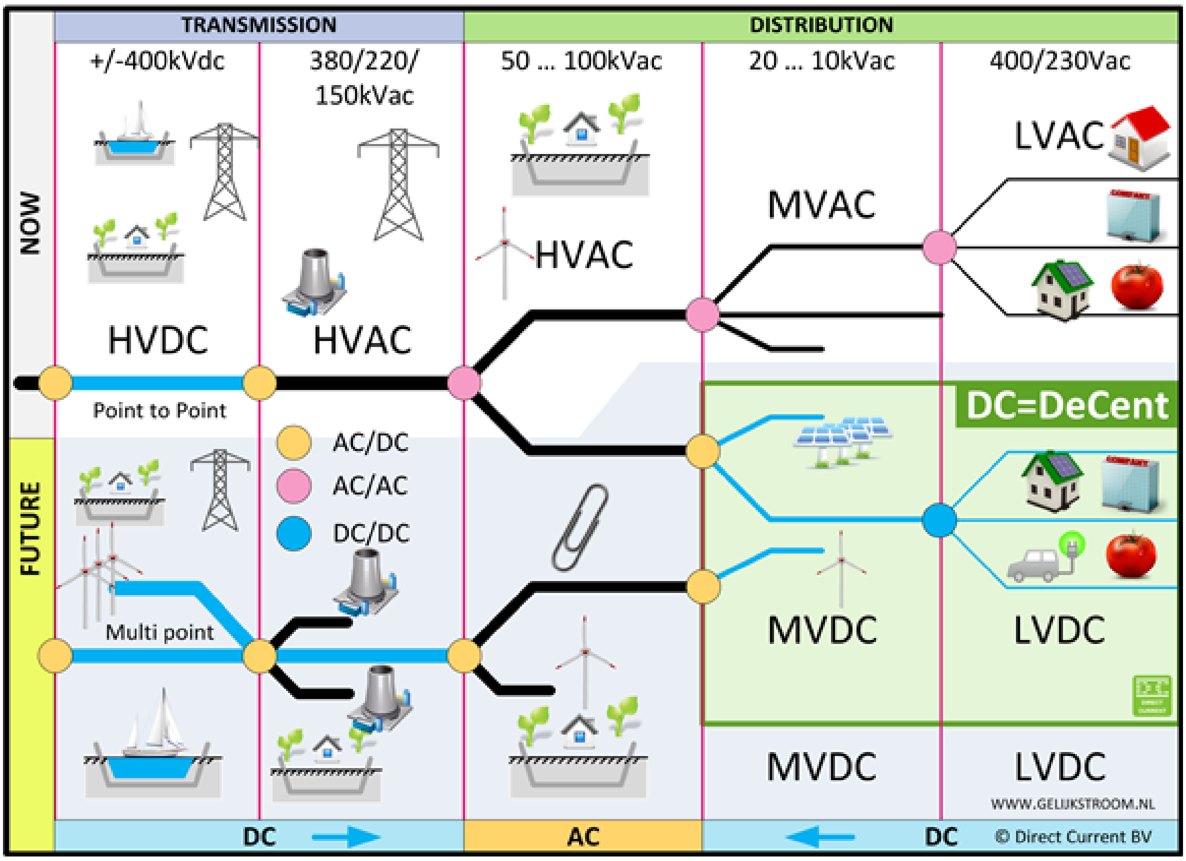


Appendix O : DC B.V. OBC design



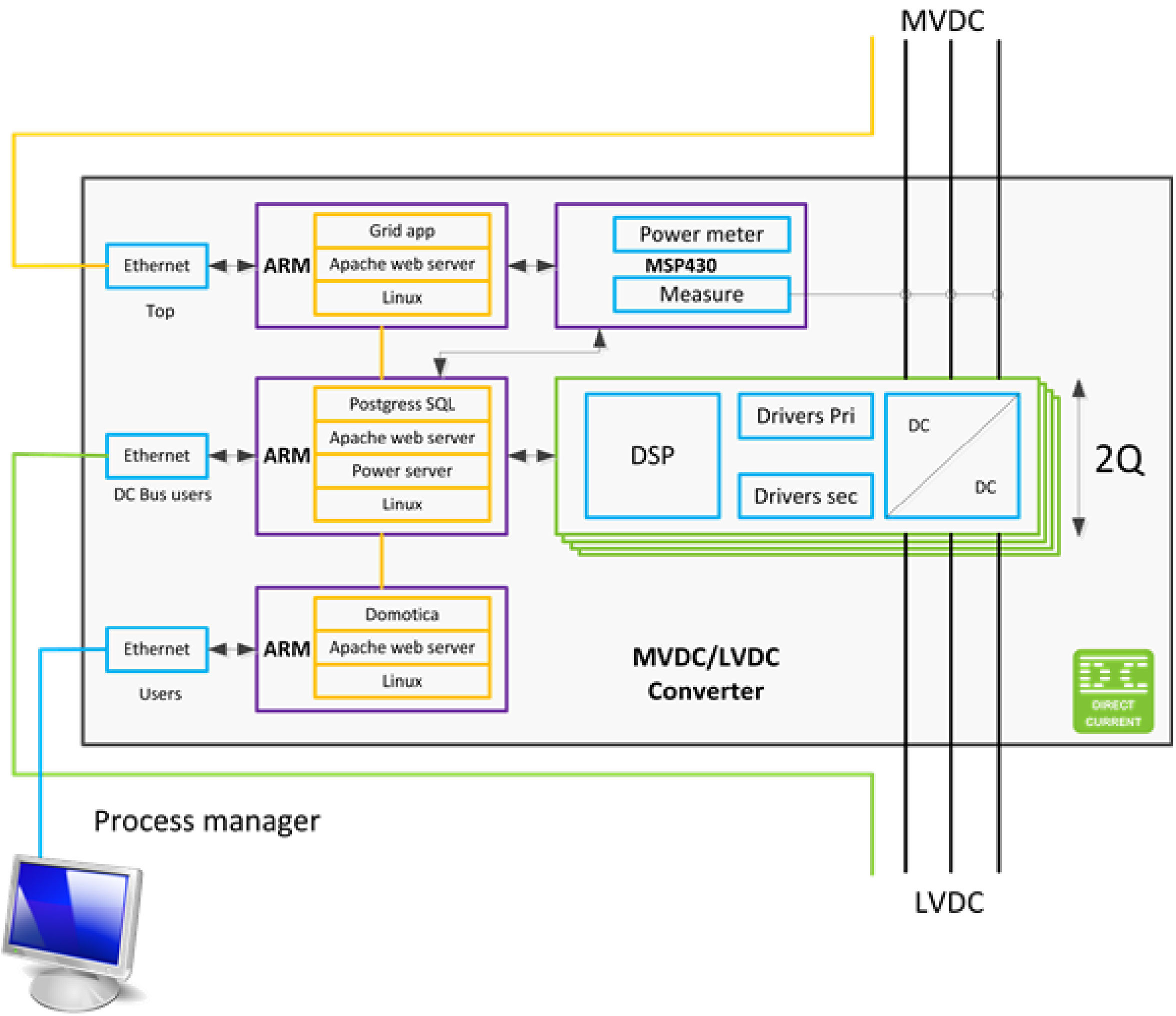


Appendix P: DC B.V.
Direct Current Transition Vision



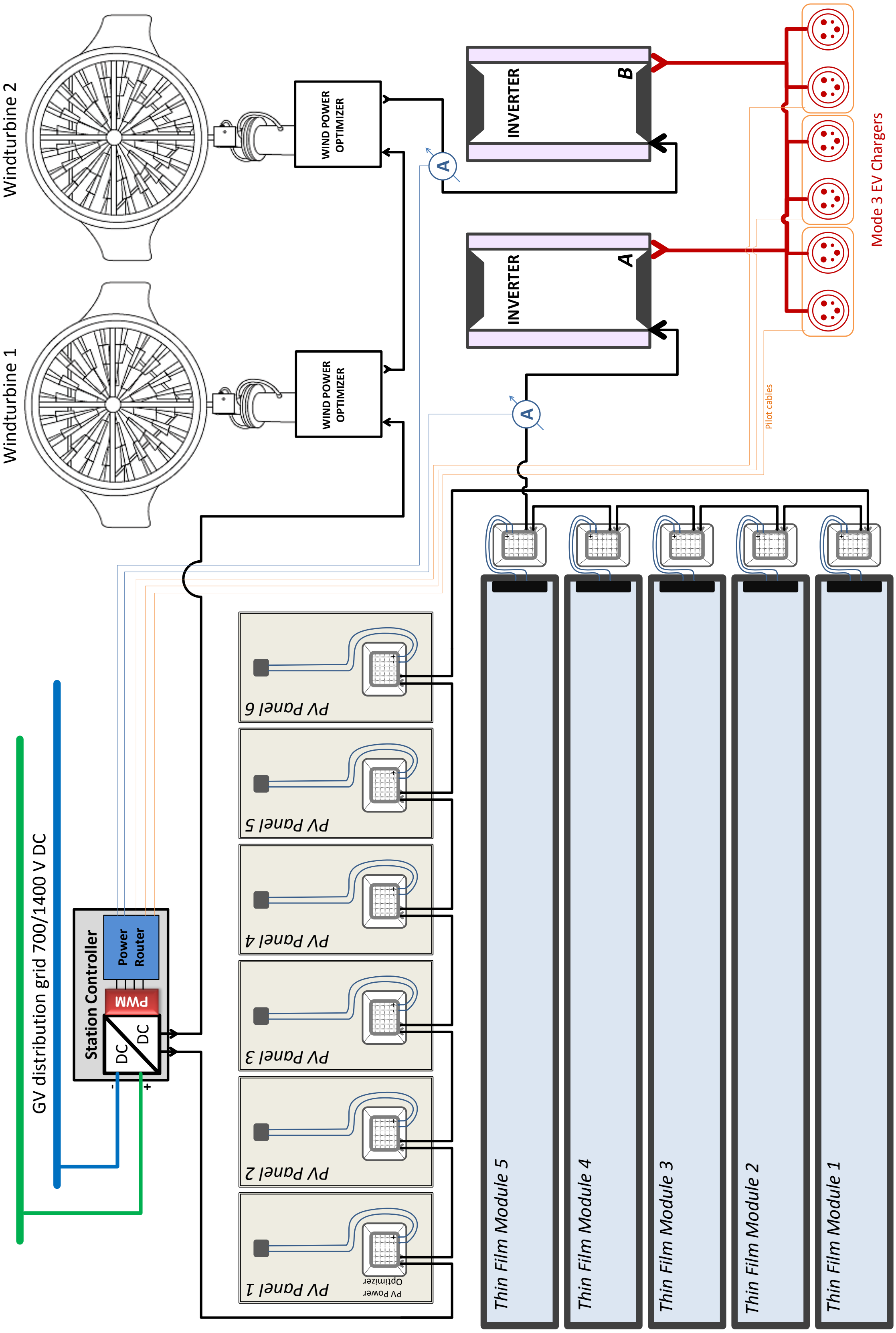
Source: http://www.directcurrent.nl/en/vision

Appendix Q : DC B.V. MVDC/LVDC Converter



Source: http://www.directcurrent.nl/en/projects/mvdc-lvdc-converter

Appendix R : Wiring



Wiring and interconnection schematic