E-Hub: Solar Powered Electric Vehicle Charging Station

Electrical system design, Optimisation and Testing

Novy Francis
Cover photo credits: http://www.tudelft.nl/over-tu-delft/onze-campus/
E-Hub : Solar Powered Electric Vehicle Charging Station

Electrical system design, Optimisation and Testing

by

Novy Francis

to obtain the degree of

Master of Science
Sustainable Energy Technology

at the Delft University of Technology,
to be defended publicly on October 25, 2017 at 10:00

Student number: 4477200
Project duration: March, 2017 – October, 2017
Thesis committee: Prof. Dr. Ir. P. Bauer, TU Delft, Supervisor
Prof. Dr. Ir. A. H. M. Smets, TU Delft
Dr. Ir. M. G. Niasar, TU Delft

This thesis is confidential and cannot be made public until January, 2018.

An electronic version of this thesis is available at http://repository.tudelft.nl/
Acknowledgements

This master thesis marks the end of a rewarding journey of my life in Delft for the last two years. This has been because of a supportive group of colleagues, acquaintances, friends and family that have helped and believed in me. Therefore it is fitting to pay my tribute to each and every one of them.

I would like to start by thanking my PhD supervisor, Gautham Ram Chandra Mouli, who undoubtedly shares the same enthusiasm and zeal for renewable energy and electric vehicles. Your guidance has shown me the importance of a skilled mentor. I cherished every friday meeting of ours which have been of great value to me and for always pushing me to perform better at dire of times. I am very thankful for your effort in helping me whenever I had doubts or with the organization of my research despite your busy PhD schedule.

I would like to thank Prof. Pavol Bauer for his help and feedback that have greatly helped me in shaping my research by guiding me in the right direction. Furthermore, I would like to thank my other supervisors, Prof. Arno Smets and Dr. M.G Niasar for their valuable feedback and discussions in the final weeks of my study.

Next, officially my mentors and unofficially my friends Nishant Narayan and Victor Vega. The PhD room of LB.3.680 is very special for always being the place for discussion in every aspect of this thesis, life and what not. Thank you for always helping me whenever I was stuck with a problem and needed advice. We need more late evening snack breaks!

I would like to thank Bob Elders and Sjoerd Moorman from the E-Hub for always guiding and supporting me with this research. Thank you very much for introducing me to the field of electric vehicles and for the cup of coffee every wednesday afternoon which was always the first point on the agenda. A special mention to Dr. Bart Roodenburg, Jr. Joris Koeners and Harrie Olsthoorn for helping me in the Electrical sustainable power lab during the experimental tests with the Tesla Powerwall and SolarEdge systems.

Living together in a house with graduating students and a particularly interesting neighbour can be encouraging and disheartening simultaneously. Therefore, I would like to extend my deepest gratitude to my house-mates Abhi and Sahil who have been a part of this journey celebrating the highs and sharing the lows of a thesis research together in Delft.

I am completely certain that all accomplishments I have reached in life have been a result of the strength my family provides. My gratitude and love for you sees no end. Amma, Papa, Nora and Dojo, without your unconditional love, sacrifice and positive energy I could not have achieved this. This work is dedicated to you.

Novy Francis
Delft, October 2017
The development in technology and increased public interest has attributed to an unprecedented growth of E-mobility in recent years. Electric vehicles (EVs) even though viewed as emission free and environmentally friendly can still contribute towards indirect emissions if charged by using traditional fossil fuels. The integration of renewable energy sources is hence paramount to approach a completely carbon free future of E-mobility integration in the transportation sector.

This thesis project aims at designing and implementing a photovoltaic (PV) based charging station for a fleet of ten EVs in the TU Delft campus. The complete solar powered charging station for EVs is hence called as E-Hub, which aims to facilitate the development of e-mobility in the TU Delft campus by providing charging facilities that can be scaled up along with a competitive business model.

At first, the driving pattern of EV owners in the Netherlands is analysed to categorize employees and visitors. The driving pattern is used to estimate the load profile and the yearly charging demand for the EV fleet in the TU Delft campus. Calendar effects such as holidays and vacations are taken into account to accurately predict the charging demand.

A thorough PV system design is carried out to meet the estimated charging demand, followed by a practical and economic feasibility study. The components required for the E-hub are listed along with an estimation of the initial investment.

Later an optimisation model is used to develop power management algorithms for optimum economical performance based on the designed technical framework. Nine charging strategies are considered for both summer and winter conditions. The performance of each strategy is analysed under the estimated load profile and designed PV system. The model is also extended to explore the integration of battery systems and its effect on the technical and economical performance of the E-Hub. This battery system can hence function as a virtual power plant to supply power back to the grid in times of peak load and facilitate in stabilization of the grid.

A proof of concept is then built to test the developed power management algorithms in the Electrical Sustainable Power Lab (EWI, TU Delft). The Eneco SolarEdge and Tesla Powerwall (ESTP) set-up is used to study the power flow and a system is designed to dynamically control and monitor the ESTP set-up. It was concluded that such a system is technically and economically feasible and can be implemented in the university to provide an environmentally friendly charging infrastructure to electrical vehicles.

This master thesis has been performed within the DC systems, Energy conversion and Storage group of the Faculty of Electrical Engineering, Mathematics & Computer Science of the Delft University of Technology.
# Contents

Abstract v  
List of Figures ix  
List of Tables xi  
Nomenclature xiii  

1 Introduction 1  
1.1 EVs in the Netherlands ......................................................... 1  
1.2 E-Hub .................................................................................. 3  
1.3 Thesis Project ................................................................. 4  
1.3.1 Motivation of the thesis ............................................. 4  
1.3.2 Research questions .................................................. 5  
1.3.3 Scope of research ...................................................... 5  
1.4 Thesis Outline ................................................................... 6  

2 Literature Review 7  
2.1 Thesis Topic ................................................................. 7  
2.2 Core Papers .................................................................. 9  
2.3 Contribution of the Thesis ........................................ 11  

3 Estimating Energy Demand for EV Charging 13  
3.1 Factors affecting EV Energy Demand ................................. 13  
3.2 Number of EVs ............................................................. 15  
3.2.1 Preferred Charging Location ..................................... 15  
3.3 Driving Pattern ............................................................. 15  
3.4 EV Driving Efficiency .................................................. 20  
3.5 Estimating the Yearly Load Demand ................................. 20  
3.6 Conclusion .................................................................. 21  

4 Estimating PV Energy Resources 27  
4.1 Determining the Renewable Energy Source for the E-Hub ................................. 27  
4.2 Scope of Weather Data .................................................. 30  
4.2.1 Irradiance Profiles .................................................. 30  
4.2.2 Ambient Temperature ............................................... 34  
4.2.3 Wind Speed ............................................................ 34  
4.3 Computing Available Energy ........................................... 35  
4.4 Estimating PV Output ....................................................... 35  
4.4.1 PV Modules ............................................................ 35  
4.4.2 Duffie Beckman Model ............................................. 36  
4.5 PV Module Output Power ............................................. 37  
4.6 Conclusion .................................................................. 37  

5 System Design 41  
5.1 PV Module Sizing .............................................................. 41  
5.2 PV Array Layout .............................................................. 42  
5.3 Inverter Selection ............................................................. 44  
5.4 System Architecture ......................................................... 45  
5.5 EV Chargers ................................................................. 46  
5.6 Practical Feasibility ............................................................ 48  
5.7 Financial Study ............................................................... 49  
5.8 Conclusion .................................................................. 53
# Contents

## 6 Power Management 55
6.1 Linear Programming ...................................... 55
6.2 Application of Linear Programming in E-Hub .................. 56
   6.2.1 Upper and Lower Bounds .................................. 56
   6.2.2 Linear Inequalities ....................................... 57
   6.2.3 Grid Prices ............................................... 57
   6.2.4 Equality Constraints ...................................... 57
   6.2.5 Objective Function ...................................... 58

## 7 Case Study 59
7.1 Cases ......................................................... 59
    7.1.1 Case 1: Unregulated Charging in Summer .................. 59
    7.1.2 Case 2: Regulated Charging in Summer .................... 61
    7.1.3 Case 3: Unregulated Charging in Winter ................... 62
    7.1.4 Case 4: Regulated Charging in Winter ..................... 64
    7.1.5 Case 5: Regulated Charging in Winter with peak shaving .... 65
7.2 Cases with Battery .......................................... 66
7.3 Battery State of Charge ...................................... 68
7.4 Case 6: Summer with battery and peak shaving ................. 69
7.5 Case 7: Summer with battery and without peak shaving ........ 71
7.6 Case 8: Winter with battery and peak shaving ................ 73
7.7 Case 9: Winter with battery and without peak shaving ........ 74
7.8 Conclusion .................................................. 78

## 8 Test Model 79
8.1 Lab Set-Up .................................................. 79
8.2 SolarEdge Monitoring Portal ................................. 81
8.3 Charge/Discharge Profile Programming ......................... 81
8.4 Charge/Discharge (C/D) Modes ................................ 83
    8.4.1 Battery OFF .............................................. 83
    8.4.2 Charge excess PV Power .................................. 83
    8.4.3 Charge from PV .......................................... 83
    8.4.4 Charge from PV and Grid ................................ 84
    8.4.5 Discharge to maximize export ............................ 84
    8.4.6 Discharge to minimize import ............................ 85
    8.4.7 Maximize Self-Consumption .............................. 85
8.5 Results ....................................................... 86
8.6 Conclusion ................................................... 90

## 9 Conclusion and Recommendations 91

## A PVDatasheets 95

## B SunPower Module PV Output Parameters 99

## C InverterDatasheets 103

## D EV-Box EVCharging Pole 107

## E TeslaPowerwallDatasheet 109

## F Results of studied cases 111
    F.1 Case 7: Summer without battery and peak shaving .......... 111
    F.2 Case 8: Winter with battery and peak shaving ................ 114
    F.3 Case 9: Winter without battery and peak shaving .......... 116

## G SolarEdge StorEdge InterfaceDatasheet 119

## H Eneco SolarEdge and Tesla Powerwall Interface - Operating Manual 121

## Bibliography 141
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Number of EVs sold in the Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Fraction of EVs in Total car sales in the Netherlands</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Major EV models sold in the Netherlands</td>
<td>2</td>
</tr>
<tr>
<td>1.4</td>
<td>Battery size of major EVs sold in the Netherlands</td>
<td>3</td>
</tr>
<tr>
<td>1.5</td>
<td>Vision of the E-Hub</td>
<td>4</td>
</tr>
<tr>
<td>3.1</td>
<td>Factors effecting energy demand required for an EV</td>
<td>14</td>
</tr>
<tr>
<td>3.2</td>
<td>Factors effecting energy demand required for an EV considered in the mathematical model</td>
<td>14</td>
</tr>
<tr>
<td>3.3</td>
<td>Average distance of each trip based on purpose</td>
<td>16</td>
</tr>
<tr>
<td>3.4</td>
<td>Histogram of maximum distance travelled in a year</td>
<td>16</td>
</tr>
<tr>
<td>3.5</td>
<td>Maximum half trip distance travelled by EV in a year</td>
<td>17</td>
</tr>
<tr>
<td>3.6</td>
<td>Average distance per trip for Employee and Visitor</td>
<td>17</td>
</tr>
<tr>
<td>3.7</td>
<td>Distribution of distance travelled by Employee EV on one random day in a year</td>
<td>18</td>
</tr>
<tr>
<td>3.8</td>
<td>Distribution of distance travelled by Visitor EV on one random day in a year</td>
<td>18</td>
</tr>
<tr>
<td>3.9</td>
<td>Cumulative driving pattern of all EVs in a year</td>
<td>22</td>
</tr>
<tr>
<td>3.10</td>
<td>Cumulative driving efficiency (η) of all EVs in a year</td>
<td>23</td>
</tr>
<tr>
<td>3.11</td>
<td>Energy demand (E_Y) of each EV in a year</td>
<td>24</td>
</tr>
<tr>
<td>3.12</td>
<td>Daily Energy Demand for the EV fleet in a year</td>
<td>25</td>
</tr>
<tr>
<td>4.1</td>
<td>Installation costs of Wind and PV systems</td>
<td>29</td>
</tr>
<tr>
<td>4.2</td>
<td>Operation and maintenance costs for Wind and PV systems</td>
<td>29</td>
</tr>
<tr>
<td>4.3</td>
<td>Lifetime of Wind and PV systems</td>
<td>29</td>
</tr>
<tr>
<td>4.4</td>
<td>Optimum Tilt angle and Azimuth for the chosen location for a year</td>
<td>32</td>
</tr>
<tr>
<td>4.5</td>
<td>Annual Irradiance on the chosen location over the year</td>
<td>32</td>
</tr>
<tr>
<td>4.6</td>
<td>Annual ambient temperature on the chosen location over the year</td>
<td>33</td>
</tr>
<tr>
<td>4.7</td>
<td>Annual Wind-speed on the chosen location over the year</td>
<td>33</td>
</tr>
<tr>
<td>4.8</td>
<td>Annual T_m using DB model against T_a for year 2017</td>
<td>38</td>
</tr>
<tr>
<td>4.9</td>
<td>Annual P_m variation for a single module</td>
<td>38</td>
</tr>
<tr>
<td>4.10</td>
<td>Energy yield per day for a single module for the year 2017</td>
<td>39</td>
</tr>
<tr>
<td>5.1</td>
<td>Annual variation of the designed PV array output power</td>
<td>43</td>
</tr>
<tr>
<td>5.2</td>
<td>Central Inverter PV system architecture</td>
<td>45</td>
</tr>
<tr>
<td>5.3</td>
<td>Overview of EV charging standards</td>
<td>47</td>
</tr>
<tr>
<td>5.4</td>
<td>Ground area comparison of designed PV system and car parking</td>
<td>48</td>
</tr>
<tr>
<td>5.5</td>
<td>Complete cost breakdown of the designed PV system</td>
<td>50</td>
</tr>
<tr>
<td>5.6</td>
<td>Overview of E-Hub system design</td>
<td>52</td>
</tr>
<tr>
<td>6.1</td>
<td>Hourly and seasonal variation of EOU prices</td>
<td>58</td>
</tr>
<tr>
<td>7.1</td>
<td>Case 1: Power flow overview</td>
<td>60</td>
</tr>
<tr>
<td>7.2</td>
<td>Case 1: EV Charging profile</td>
<td>60</td>
</tr>
<tr>
<td>7.3</td>
<td>Case 2: Power flow overview</td>
<td>61</td>
</tr>
<tr>
<td>7.4</td>
<td>Case 2: EV Charging profile</td>
<td>62</td>
</tr>
<tr>
<td>7.5</td>
<td>Case 3: Power flow overview</td>
<td>63</td>
</tr>
<tr>
<td>7.6</td>
<td>Case 3: EV Charging profile</td>
<td>63</td>
</tr>
<tr>
<td>7.7</td>
<td>Case 4: Power flow overview</td>
<td>64</td>
</tr>
<tr>
<td>7.8</td>
<td>Case 4: EV Charging profile</td>
<td>64</td>
</tr>
<tr>
<td>7.9</td>
<td>Case 5: Power flow overview</td>
<td>65</td>
</tr>
<tr>
<td>7.10</td>
<td>Case 5: EV Charging profile</td>
<td>66</td>
</tr>
</tbody>
</table>
7.11 Charging demand for each EV ............................................. 67
7.12 Case 6: Power flow overview ........................................... 69
7.13 Case 6: Battery behaviour ................................................. 70
7.14 Case 6: EV Charging profile ................................................ 70
7.15 Case 7: Power flow overview .............................................. 71
7.16 Case 8: Power flow overview .............................................. 73
7.17 Case 9: Power flow overview .............................................. 74
7.18 EV charging costs for summer and winter day for studied charging strategies ............................................. 75
7.19 Maximum grid import for studied charging strategies .......................................................... 76
7.20 PIF for different charging strategies as compared to unregulated charging ............................................. 76
7.21 Economic analysis with introduction of more Tesla Powerwalls ............................................. 77

8.1 Overview of ESTP set-up .................................................... 80
8.2 SolarEdge monitoring portal dashboard ..................................... 81
8.3 ESTP set-up in the lab .......................................................... 82
8.4 C/D Mode 1: Battery OFF .................................................... 83
8.5 C/D Mode 3: Charge from PV ................................................ 83
8.6 C/D Mode 4: Charge from PV and Grid .................................... 84
8.7 C/D Mode 5: Discharge to maximize export ................................ 84
8.8 C/D Mode 6: Discharge to minimize import ................................ 85
8.9 C/D Mode 7: Maximize Self-Consumption ................................. 85
8.10 Case 1: Power flow in the ESTP set-up ................................. 87
8.11 Case 1: Battery behaviour in the ESTP set-up ......................... 87
8.12 Case 2: Power flow in the ESTP set-up ................................ 89
8.13 Case 2: Battery behaviour in the ESTP set-up ......................... 89

B.1 Annual $T_m$ using DB model against $T_a$ for the year 2017 - Sunpower ............................................. 100
B.2 Annual $P_m$ variation - Sunpower ........................................ 100
B.3 Energy yield per day for the year 2017 - Sunpower .................. 101

D.1 EV-Box Business line charging pole ...................................... 107

F.1 Case 7: Battery behaviour ................................................... 112
F.2 Case 7: EV charging profile ................................................ 113
F.3 Case 8: Battery behaviour ................................................... 114
F.4 Case 8: EV Charging profile ............................................... 115
F.5 Case 9: Battery behaviour ................................................... 116
F.6 Case 9: EV Charging profile ............................................... 117
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Overview of core papers</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Comparison of research attributes of core papers and this thesis</td>
<td>11</td>
</tr>
<tr>
<td>3.1</td>
<td>Days in the year 2017</td>
<td>19</td>
</tr>
<tr>
<td>3.2</td>
<td>EV Driving Efficiency ($\eta$) values from literature</td>
<td>20</td>
</tr>
<tr>
<td>3.3</td>
<td>Results of estimated charging energy demand</td>
<td>21</td>
</tr>
<tr>
<td>4.1</td>
<td>Chosen PV Modules</td>
<td>36</td>
</tr>
<tr>
<td>4.2</td>
<td>PV Modules - Specifications</td>
<td>36</td>
</tr>
<tr>
<td>4.3</td>
<td>Results of estimated energy yield</td>
<td>37</td>
</tr>
<tr>
<td>5.1</td>
<td>Physical layout of the PV array</td>
<td>42</td>
</tr>
<tr>
<td>5.2</td>
<td>Key inverter specifications of SMA Sunny Tripower 20000TL</td>
<td>44</td>
</tr>
<tr>
<td>5.3</td>
<td>Key specifications of kW and 21 kW EV chargers</td>
<td>46</td>
</tr>
<tr>
<td>5.4</td>
<td>Ground area calculation of designed PV system and car parking</td>
<td>48</td>
</tr>
<tr>
<td>5.5</td>
<td>Cost evaluation of the chosen components in the E-Hub system</td>
<td>49</td>
</tr>
<tr>
<td>5.6</td>
<td>Cost estimation for the chosen E-Hub PV System</td>
<td>51</td>
</tr>
<tr>
<td>6.1</td>
<td>Variables used in the Linear programming model</td>
<td>56</td>
</tr>
<tr>
<td>7.1</td>
<td>Nomenclature of cases</td>
<td>59</td>
</tr>
<tr>
<td>7.2</td>
<td>Overview of cases under study</td>
<td>66</td>
</tr>
<tr>
<td>7.3</td>
<td>Battery SOC - Case 6</td>
<td>68</td>
</tr>
<tr>
<td>7.4</td>
<td>Battery SOC - Case 7</td>
<td>68</td>
</tr>
<tr>
<td>7.5</td>
<td>Battery SOC - Case 8</td>
<td>68</td>
</tr>
<tr>
<td>7.6</td>
<td>Battery SOC - Case 9</td>
<td>68</td>
</tr>
<tr>
<td>7.7</td>
<td>EV charging cost for each day</td>
<td>78</td>
</tr>
</tbody>
</table>
Nomenclature

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Source</td>
</tr>
<tr>
<td>RAI</td>
<td>Rijwiel en Automobiel Industrie</td>
</tr>
<tr>
<td>D-INCERT</td>
<td>Dutch Innovation Centre for Electric Road Transport</td>
</tr>
<tr>
<td>DCE&amp;S</td>
<td>DC systems, Energy conversion and Storage research group</td>
</tr>
<tr>
<td>PVMD</td>
<td>Photovoltaic Materials and Devices research group</td>
</tr>
<tr>
<td>V2G</td>
<td>Vehicle to Grid</td>
</tr>
<tr>
<td>MDAS</td>
<td>Mobile Data Acquisition System</td>
</tr>
<tr>
<td>PEV</td>
<td>Plug-in Electric Vehicle</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>PM</td>
<td>Power Matcher</td>
</tr>
<tr>
<td>CCS</td>
<td>Combined Charging Standard</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>LEV</td>
<td>Light Electric Vehicles</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and Maintenance</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>DB</td>
<td>Duffie Beckman Model</td>
</tr>
<tr>
<td>NOCT</td>
<td>Nominal Operating Cell Temperature</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance of Systems</td>
</tr>
<tr>
<td>IRENA</td>
<td>The International Renewable Energy Agency</td>
</tr>
<tr>
<td>NYSERDA</td>
<td>New York Energy Research and Development Authority</td>
</tr>
<tr>
<td>PZI</td>
<td>Permitting, Zoning and Inspection</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>LP</td>
<td>Linear Programming</td>
</tr>
<tr>
<td>EOU</td>
<td>Energy of Use</td>
</tr>
<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
</tr>
<tr>
<td>PIF</td>
<td>Performance Index Factor</td>
</tr>
<tr>
<td>ESTP</td>
<td>Eneco SolarEdge and Tesla Powerwall Set-up</td>
</tr>
<tr>
<td>C/D</td>
<td>Charge/Discharge</td>
</tr>
<tr>
<td>DMI</td>
<td>Discharge to Minimize Import</td>
</tr>
<tr>
<td>MSC</td>
<td>Maximize Self-Consumption</td>
</tr>
<tr>
<td>DME</td>
<td>Discharge to Maximize Export</td>
</tr>
</tbody>
</table>
## List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Mean of the distribution</td>
<td>(-)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
<td>(-)</td>
</tr>
<tr>
<td>$E_Y$</td>
<td>Yearly energy load demand for EV charging</td>
<td>(MWh)</td>
</tr>
<tr>
<td>$\eta_{EV}$</td>
<td>Driving efficiency of EV</td>
<td>(kWh/km)</td>
</tr>
<tr>
<td>$k_t'$</td>
<td>Normalized clearness index</td>
<td>(-)</td>
</tr>
<tr>
<td>$\Delta k_t'$</td>
<td>Stability Index</td>
<td>(-)</td>
</tr>
<tr>
<td>$\beta_m$</td>
<td>Module tilt angle</td>
<td>(°)</td>
</tr>
<tr>
<td>$G_{Global}$</td>
<td>Global irradiance on a module</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$G_{Direct}$</td>
<td>Direct irradiance on a module</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$G_{Diffused}$</td>
<td>Diffused irradiance on a module</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$G_{Albedo}$</td>
<td>Albedo irradiance on a module</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Reflectivity of the ground surface</td>
<td>(-)</td>
</tr>
<tr>
<td>$G_{DHI}$</td>
<td>Diffused irradiance on a horizontal module</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$G_{DNI}$</td>
<td>Diffused normal irradiance</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Incident angle of the direct irradiance beam</td>
<td>(°)</td>
</tr>
<tr>
<td>$E_s$</td>
<td>Energy per unit area</td>
<td>(Wh/m²)</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Module temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>$NOCT$</td>
<td>Nominal operating cell temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>$G_{NOCT}$</td>
<td>Irradiance at NOCT conditions</td>
<td>(800 W/m²)</td>
</tr>
<tr>
<td>$V_w$</td>
<td>Wind speed on the module</td>
<td>(m/s)</td>
</tr>
<tr>
<td>$\eta^\text{nom}_m$</td>
<td>Nominal efficiency of the module</td>
<td>(-)</td>
</tr>
<tr>
<td>$\Xi$</td>
<td>Effective transmittance-absorptance product</td>
<td>(0.9)</td>
</tr>
<tr>
<td>$P_m$</td>
<td>Module output power at MPP</td>
<td>(W)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Power temperature coefficient of the module</td>
<td>(%/°C)</td>
</tr>
<tr>
<td>$P_{STC}$</td>
<td>Rated module power at STC</td>
<td>(W)</td>
</tr>
<tr>
<td>$N_m$</td>
<td>Number of modules</td>
<td>(-)</td>
</tr>
<tr>
<td>$E^\text{Yield}_m$</td>
<td>Annual estimated energy yield from the module</td>
<td>(kWh)</td>
</tr>
<tr>
<td>$E_{DC}$</td>
<td>DC Energy load demand</td>
<td>(Wh)</td>
</tr>
<tr>
<td>$\eta_{inv}$</td>
<td>Efficiency of the inverter</td>
<td>(-)</td>
</tr>
<tr>
<td>$SF$</td>
<td>Sizing factor</td>
<td>(1.1)</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Area of the chosen PV module</td>
<td>(m²)</td>
</tr>
<tr>
<td>$\eta_m$</td>
<td>Efficiency of the chosen PV module</td>
<td>(-)</td>
</tr>
<tr>
<td>$N^S_m$</td>
<td>Number of modules in series</td>
<td>(-)</td>
</tr>
<tr>
<td>$N^P_m$</td>
<td>Number of modules in parallel</td>
<td>(-)</td>
</tr>
<tr>
<td>$V_{\text{STC}}_{oc}$</td>
<td>Open circuit voltage of the PV module at STC</td>
<td>(V)</td>
</tr>
<tr>
<td>$I_{\text{STC}}$</td>
<td>Short circuit current of the PV module at STC</td>
<td>(A)</td>
</tr>
<tr>
<td>$V_{\text{inv}}^\text{max}$</td>
<td>Maximum inverter input voltage</td>
<td>(V)</td>
</tr>
<tr>
<td>$I_{\text{inv}}^\text{max}$</td>
<td>Maximum inverter input current</td>
<td>(A)</td>
</tr>
<tr>
<td>$P_{DC0}$</td>
<td>Nominal DC power of the inverter</td>
<td>(kW)</td>
</tr>
</tbody>
</table>
Introduction

1.1. EVs in the Netherlands

Electric Vehicle (EV) presents a shift in the conventional source of energy for powering the transport sector. A zero-carbon future can hence be realized by effectively integrating EV, Renewable energy sources (RES) and market opportunities. The Netherlands being a part of the 2020 EU goals have to achieve a binding 14% renewable energy use along with a saving of 1.5% per year. The Ministry for Infrastructure and the Environment leads the electrification of transport sector in the Netherlands. This has greatly influenced the greater adoption of EV technology. As of the beginning of 2016, about 1.07% of all passenger cars in the Netherlands were EV, which accounts to 87,531 EVs \[52\]. The year 2016 has seen a greater increase in EV penetration.

The Rijwiel en Automobiel Industrie (RAI) is a Dutch association that carries out the interests of the automotive industry in the Netherlands. RAI hence releases a monthly report which states the number of cars sold per manufacturer along with the numbers sold per model. In Figure 1.1 and 1.2 it can be clearly seen that the sale of EV is steadily increasing which makes the placing of this thesis perfect in the timeline of EV adoption.

![Figure 1.1: Number of EVs sold in the Netherlands](source)
It is also interesting to know the current EVs which are sold in the Netherlands so as to interpret the market share among different manufacturers. In Figure 1.3 the EV market share in the year 2016 is shown with the majority being held by Tesla Model S which amounts to 42% of the total share.
1.2. E-Hub

At present only about one third of Dutch households have access to private parking which creates an obstacle in this constantly growing EV penetration in the transportation sector as home charging which is currently considered as the affordable and convenient charging option [52]. To facilitate the development of E-mobility as mentioned in Section 1.1 it is paramount to scale up the public charging infrastructure. This is hence the core focus of E-Hub and D-INCERT.

The three technical universities of Netherlands - TU Eindhoven, University of Twente and TU Delft along with the Universities of Applied Sciences in Amsterdam, Rotterdam, Arnhem and Nijmegen collectively form the D-INCERT consortium. D-INCERT thus shapes the base that associates scientific and practical research along with technological innovation to expedite the e-mobility transition in the Netherlands. E-Hub aims at providing charging facilities for EVs by presenting a system that can be scaled up along with a competitive business solution. The system should therefore be future ready to accommodate forthcoming technologies. In all, the E-Hub project strives towards a goal to help balance the demand and supply of electricity in the region of implementation with high EV penetration. E-Hub thus presents a multidisciplinary and cross-university research study at the future of charging infrastructure of which this thesis targets the system design challenges from a technical outlook.

Figure 1.4: Battery size of major EVs sold in the Netherlands

Source: Rijwiel en Automobiel Industrie, 2016 [17]
1.3. Thesis Project

This Master thesis project is aimed at designing and realizing the initial E-Hub experimental set-up which could be an innovative solution to overcome the present EV charging infrastructure challenges. The final E-Hub system is proposed to be located within Delft University of Technology (TU Delft) campus. This report explains in detail the concept, design and experimental set-up of the E-Hub from a technical viewpoint.

Project collaborators

In order to realise such a system, inputs from three primary departments within the university were sought after. The electrical system design and experimental set-up was conceived under the DC Systems, Energy Conversion & Storage (DCE&S) group. The inputs for the PV system sizing and design was from the Photovoltaic Materials and Devices (PVMD) group and ultimately the final design and objectives of the E-Hub was under the Dutch Innovation Centre for Electric Road Transport (D-INCERT).

1.3.1. Motivation of the thesis

This thesis was motivated by the substantial growth in the penetration of EV in recent years. It can be seen in Section 1.1 on how the Netherlands has shown an increase in the fleet of EVs along with an acceptance of EV models varying from manufacturer, battery size, price and even the appearance.

The need for such a research is also backed up by the recent motion which was passed by the lower house of the Dutch parliament. The motion calls for a country wide ban on the sales of new petrol and diesel cars from 2025. The motion was initially launched by the labour party of the Netherlands (PvdA) and was also supported by other Dutch political parties and politicians such as D66, GroenLinks, Christian Union, PvdD, SP and Kuzu / Öztürk [1]. If the motion is passed by the Dutch senate then in 8 years only zero-emission cars will be available to be purchased. This thesis hence is a perfect fit into the ‘Sustainable E-mobility’ cognitive framework of the Netherlands.

It is ideally envisioned to design a charging infrastructure for EV such as the E-Hub based on solar energy however it needs to be technically and economically feasible. To arrive at a successful realisation of the project, several research questions needs to be construed.
1.3.2. Research questions

This thesis drives to encompass the various design challenges of the E-Hub from a technical outlook. The following set of research questions therefore is to be answered to succeed in the realisation of the project.

Main research question

What are the main electrical system design parameters that influence the E-Hub system design in urban workplace environment?

Sub-research question

1. What is the yearly charging energy demand for an EV fleet at the TU Delft campus?
2. Which renewable energy sources (RES) are to be utilized in the E-Hub design?
3. Given the intermittent nature of RES. What is the estimated yield for the chosen RES?
4. What is the ideal size and design for the E-Hub?
5. Which power management algorithms are to be implemented in the E-Hub system?
6. Is the chosen E-Hub system design viable for testing with favourable results?

1.3.3. Scope of research

The scope of this thesis can be summarized in six key points since the chosen study is very diverse:

1. To ensure that the thesis fits well with further E-Hub project, this thesis will focus on EV charging infrastructure for 10 cars. Two types of charges will be used to match the different types of users which are:
   (a) Semi-quick AC chargers (Upto 21 kW)
       • 4 in number
   (b) Slow AC chargers (Upto 7 kW)
       • 6 in number
2. This thesis is a study on a system level. An in-depth location based analysis is hence not taken into account while designing the system since E-Hub as mentioned in Section 1.2 is a concept idea, and the final location of the E-Hub can only be decided after inputs from technical, economical and social research is collected. It is for now assumed that the E-Hub is present within the campus of TU Delft with co-ordinates 51.996°North and 4.377°East
3. The designed charging infrastructure does not include the exact driving behaviour of employees and visitors using EV at TU Delft, since such data is confidential. The mobility data\[51\] is hence assumed to hold good for this study
4. In the E-Hub scenario it is assumed that all 10 EVs are present for charging every day of the working calendar. It is also assumed that the EVs are parked for the complete duration from 09:00 - 17:00
5. This thesis does not account the performance of battery in the EV context. It is assumed that battery state of health (SOH) remains constant
6. The challenges mentioned in Section 1.3.2 reveals a scientific gap in the EV-PV charging infrastructure research. Therefore, the scope of this thesis is to enrich the research contribution by testing the feasibility of the designed system with simple control algorithms that can be validated in the laboratory before complex algorithms are adopted.
7. The energy yield from PV is calculated from literature research which is explained in Section 2.2, the energy yield modelling and optimisation is accordingly adopted from previous research. Even though this thesis evaluates the calendar effects in the lifetime of the system to be of year 2017, it is not taken into account during experiments and rather studied as independent timelines.
1.4. Thesis Outline

This research study is divided into 9 chapters as discussed below

Chapter 1: Introduction

An overview of the background and motivation is outlined in this chapter along with the definition of research questions.

Chapter 2: Literature Review

In this chapter the existing literature on EV and EV charging is reviewed. Furthermore, the positioning and contribution of this thesis to the field of EV charging with RES is discussed.

Chapter 3: Estimating Energy Demand for EV Charging

This chapter aims at accurately determining the yearly energy demand for EV charging in the TU Delft campus. The various factors effecting this estimation is outlined along with the chosen approach.

Chapter 4: Estimating PV Energy Resources

In this chapter the various RES for the E-Hub is discussed, followed by the chosen PV as the main RES for E-Hub wherein the yield is calculated for the year 2017 in the chosen location.

Chapter 5: System Design

This chapter proposes the initial E-Hub design. The chosen design is further analysed on its practical and financial feasibility.

Chapter 6: Power Management

In this chapter the optimisation approach is discussed along with the implementation of linear programming to the chosen system design of the E-Hub.

Chapter 7: Case Study

This chapter analyses the various cases based on technical and economical performance.

Chapter 8: Test Model

In this chapter the experimental set-up is explained where the power management algorithms can be tested so as to validate a proof of concept.

Chapter 9: Conclusions and Recommendations

This chapter summarizes the key results of this study by answering the defined research questions. A list of recommendations for further studies are also presented.
Chapter Overview

As mentioned in Chapter 1, this thesis focuses on designing the E-hub system and to build a proof of concept for testing the power management techniques. This chapter explains the literary setting of this topic and is structured as following. The initial section will address the various domains of research that have been taken into account in this thesis along with the recent progress that has been made. The second chapter will discourse the scientific research papers that have been recognized as core reports and the final section will treat the positioning of this thesis research with the studied literature.

2.1. Thesis Topic

This thesis research can be defined as an amalgamation of three fields of research. These are:

1. Grid tied PV charging systems
2. Load demand of electric vehicles in a work place environment
3. Power Management in RES integrated EV charging systems

The above mentioned topics have been researched to a great extent in the recent years, nevertheless this thesis research is unique as it combines these fields together. It has however been noticed that the majority of papers and journals merely look into the possibility of smartly charging EV’s using RES and a cursory study into its potential.

Grid tied PV charging systems

In recent years there has been considerable research on the possibilities to charge EV using RES of which the most conspicuous method is by using a grid tied PV charging system. This method is prominent due to the use of available PV power by utilizing the grid during insufficient availability of PV power or the combination of both to power higher loads. The large scale adoption of EV charging using grid has been studied in Ciwei et.al, 2011 and Dharmakeerthi et.al, 2012 [9, 14]. Grid tied PV charging systems have hence expanded from the need to drive future of green e-mobility by RES especially PV which is corroborated by a steady rise in the affordability of PV modules and wider adoption among other RES. The various advantages to use a PV powered EV charging system are explained in Birnie, D. P et.al, 2009 and Denholm et.al, 2013 [7, 12] which explicates the higher penetration of both EV and PV technology. Therefore, the bulk of such a charging system are still at their nascent stages in either pilot projects or lab set ups.

In Abella et.al, 2003 [2] a demonstration project in Madrid is set up where a 9.24 kW grid tied PV system powers two charging towers for monitoring, controlling and managing the power flow for EV charging. Pioneering studies such as in Locment et.al 2010 and Mesentean et.al, 2010 [28, 31] have looked into experimental
2. Literature Review

Lab set ups where strategies to include local storage in such a charging landscape have been studied. The local storage options such as batteries can be put-upon for both charging and energy storage. This opens possibilities for power management by incorporating smart meters. The local storage also helps the system to reduce its dependency on the grid by which PV can be utilized to its maximum capacity. Another important area of focus is on studies that have been carried out to analyze control of such grid tied PV charging systems such as in Gamboa et al., 2010[20] where system efficiency was greatly improved as a result of energy conversion reduction by control algorithms which are to be implement in a parking lot in Florida, US. A minimal power wastage approach by controlling the charging current is studied in Vaidya et al., 1996[48] where Mobile Data Acquisition System (MDAS) is used to extract battery information from the EV along with data from PV and battery chargers to measure DC-DC and AC-DC efficiency for on-board and off-board charger along with studying the effectiveness of grid interconnection. A vital study that explores the integration of V2G technology are Honarmand et al., 2014 and Huang et al., 2009 [22, 23]. The battery of EV is explored as an energy storage device during rest which provides the owner with an option to monetize such a situation by opening up V2G operation from a micro grid point of view. A national scale integration which includes electricity, transport in supply and demand is studied in Lund et al., 2008 [29].

Load demand of electric vehicles in a work place environment

The load demand for EV begins with the charging requirements, which varies with various charging characteristics such as power levels, modes and type. In Yilmaz et al., 2013 [54], an excellent review of the various charger topologies and standards are presented which aids in perceiving the electrical load demands of an EV or a fleet of EVs. The estimation of load demand is complicated as it depends on various factors such as driving patterns, efficiency of the EV, charging power, incoming state of charge of the EV battery pack and efficiency of charging. It is clear from the rise in popularity of EV in the recent years that the adoption of EV has been foreseen since long as studied in Tanaka et al., 2011 and Trigg T. et al., 2013 [43, 47], yet the study of load demand is still a very new subject.

In Schäuble, J et al., 2017 [41] the researchers simulated EV load models by using comprehensive statistical data by three e-mobility studies in the south-western region of Germany. The simulated EV load profiles were then compared with other available scientific research emulating EV load profiles as in Pasaoglu, G., et al., 2013 and Litzlbauer, M. et al., 2010 [37, 46] to validate the results. These results were then used to study the characteristics of EV load profiles. This was hence the direct outcome of a brilliant scientific examination where e-mobility studies from six countries in Europe were studied to compare controlled and uncontrolled unidirectional charging by accounting driving patterns which are specific to each country from which country specific load profiles were determined as Babrowski, Sonja, et al., 2014 [5]. Another approach to estimate the load profiles of EVs are presented in the relevant study to Plug-in electric vehicles (PEVs) which adopts a probabilistic modelling to address the complex interdependencies between various variables as mentioned in the start of this section. A multivariate distribution function was hence determined by using a copula function based on a stochastic framework as Tehrani, Nima H et al., 2015 [45]. This approach was further expanded in Qian, Kejun, et al., 2011 [39] where the stochastic model is used to study several charging modes based on uncontrolled and smart charging scenarios which are very interesting in this thesis research. One of the main conclusions of the study in [39] is that the EV charging load for the battery is greatly effected by the start time distribution in the modes of charging.

Power Management in RES integrated EV charging systems

The optimisation of power flow in an EV charging infrastructure is a profoundly researched topic. Power management through optimisation algorithms can be carried out for any of the following reasons and a combination of the below listed reasons:

- Maximize profit
- Maximize self consumption
- Minimize operating costs
- Minimize emissions
In this thesis from an economical viewpoint the initial scenario is adopted to maximize the financial revenue for the E-Hub with the aid of RES sources. In van der Meer, D et.al, 2016 [49] an energy management system was designed to allocate optimal power flow by forecasting PV power influx so as to minimize charging cost, increase self consumption of PV, reduce emissions and also to finally reduce the stress on the grid. The designed system was extended to utilize a modular converter for connection of various EVs hence greatly reducing system costs.

In Kemper, P.L et.al, 2017 [26], various smart charging strategies are discussed. A thorough model based on Demand side management (DSM) and PowerMatcher (PM) strategy are discussed. The authors discuss the approach and the analytical solutions for such a strategy. The main conclusions of the study in [26, 49] are self-consumption is greatly increased by adopting DSM. It is suggested that at the present V2G is not economically viable from the discussed strategies due to high battery costs.

2.2. Core Papers

This section covers the various scientific research papers and theses that are set inside the core of this research topic as presented in Table 2.1.

Table 2.1: Overview of core papers

<table>
<thead>
<tr>
<th>1st Author</th>
<th>Year</th>
<th>Title</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouli</td>
<td>2016</td>
<td>System design for a solar powered electric vehicle charging station for workplaces</td>
<td>[34]</td>
</tr>
<tr>
<td>G.Nair</td>
<td>2014</td>
<td>Photovoltaic charging station for Electric bikes and scooters</td>
<td>[35]</td>
</tr>
<tr>
<td>Harikumaran J</td>
<td>2012</td>
<td>Comparison of quick charge technologies for electric vehicle introduction in Netherlands</td>
<td>[21]</td>
</tr>
<tr>
<td>Qian</td>
<td>2011</td>
<td>Modeling of load demand due to EV battery charging in distribution systems</td>
<td>[39]</td>
</tr>
</tbody>
</table>

The reason for selecting the above mentioned papers as the main core for this research are briefly discussed in the following sections.

Mouli et al. [34] have addressed the possibility in utilizing solar energy to charge EV at a workplace environment. This paper is of vital importance in helping to direct this research to its end goals by targeting various challenges such as the preliminary PV system design for the location under study, Dynamic charging of EV by analysing various charging profiles, Grid interactions of such a designed system and finally the introduction of local storage in the means of battery back-up. In the model researchers have taken into account various possibilities such as sun tracking systems to counteract the low PV yield during winter from both the technical and financial point of view, PV converter rating for country specific estimation, Workplace scenarios in a 5days/week and 7days/week, and lastly the battery sizing estimation for such a system.

The results of this study conclude that the sun tracker mechanisms are ineffective in a country like The Netherlands, PV converter can be undersized when compared to the PV array for low intensity insolation locations. Gaussian charging profiles are best suited for such a system as it nearly mimics the solar generation profile and ultimately, integrating even low capacity local storage compared to the system helps in palliating the variations in PV output. It was also noted that the size of the local storage saturates after a particular value hence proving that large sized battery storage options are not necessary. The authors have also suggested future research to be carried out in the area of V2G and DC charging by utilizing the DC standards such as Chademo and Combined Charging Standard (CCS).

G.Nair [35] presented a overview on the design aspects of a PV charging station for electric bikes and scooters. This thesis research was greatly studied for its location analysis as the charging station which was to be designed was chosen to be present at Delft University of Technology (TU Delft), from which the energy yield output of a PV system can be calculated. The PV system model was thoroughly explained in terms of sensitivity based on the following elements:

1. Location
• Inclination angle of the PV modules
• Orientation in terms of azimuth

2. Environment
• Wind speed
• Ambient and module temperature
• Shading

The suggested research for the future by G.Nair are on communication protocols to be integrated into the charging system, smart charging scenarios and estimating the load profiles of the Light Electric Vehicles (LEVs).

Harikumaran J [21] focuses on the charging methods of EVs by comparing fast charging and battery switching technologies. The unique position of this study compared to the others in this section is the usage of mobility survey results for the Netherlands [51] from which a model was created to map the different travel patterns of EVs. The authors worked extensively on the mobility data to quantify the different types of travel in terms of

1. Commute (to work/office)
2. Trips for work (meetings/field visits)
3. Visits/Errands
4. Shopping
5. Education related trips
6. Social and recreation trips
7. Other/miscellaneous

This processed data was indispensable for estimating the EV load demand which is further explained in Chapter 3. The paper then approaches the challenges on how the limited capacity of a EV charging facility by adopting Queuing theory to develop a mathematical model to minimize the number of charging instants by assuming different charging strategies. One of the assumptions which the authors have taken are that the mobility data which is used does not shift when the concentration of EVs increase. As future scope of research the physical and environmental aspects of the car such as weight, temperature, wind should be taken into account which can alter the range of the EV.

Qian et al. [39] presents a modelling strategy to analyse the load demand due to EV battery charging in a distribution system. The authors have enumerated four EV charging scenarios in their stochastically formulated model which are:

1. Uncontrolled domestic charging
2. Uncontrolled off-peak charging
3. Smart domestic charging
4. Uncontrolled public charging

These four scenarios take into account various factors such as static and dynamic electricity tariffs and regulation of EV charging. Since the paper was written before the sudden increase in EV concentration, the studied EV technologies were still in their initial stages of development such as the Lead-acid based EV GM EV1 and Nissan Altra EV which was one of the worlds first EV to use lithium-ion battery technology. This paper was of keen importance to this thesis for their use of probability distribution functions to determine various statistical distributions for the chosen parameters.

It was found that the starting time for EV charging has a striking effect on the load distribution which hence needs to be optimized when adopting smart charging algorithms. The resulting penetration of EV was found to increase the daily peak power demand by a factor for 17.9% for 10% increase in EV with the power demand jumping to 35.8% for 20% EV penetration. This study does not include the use of RES for EV charging or any other ancillary services.
2.3. Contribution of the Thesis

Comparison of reviewed literature

In this section the core papers which were presented in 2.2 are characterized on their respective attributes and compared to this thesis as presented in Table 2.2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EV load demand</td>
<td>✷</td>
<td>.</td>
<td>✷</td>
<td></td>
<td>✷</td>
</tr>
<tr>
<td>PV modeling</td>
<td>✷</td>
<td>✷</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV System study</td>
<td>✷</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV charging scenarios</td>
<td>✷</td>
<td>.</td>
<td>✷</td>
<td></td>
<td>✷</td>
</tr>
<tr>
<td>Power management</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Study of EV fleet</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV model for workplace environment</td>
<td>✷</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local storage estimation</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible charging scenarios</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System design</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation of technical performance</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economic evaluation</td>
<td>✷</td>
<td>✷</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation of charging infrastructure</td>
<td>✷</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental tests for the system design</td>
<td>.</td>
<td>.</td>
<td>.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modeling Tool</td>
<td>MATLAB</td>
<td>MATLAB</td>
<td>MATLAB</td>
<td>MATLAB</td>
<td>MATLAB</td>
</tr>
</tbody>
</table>

2.3. Contribution of the Thesis

This thesis as mentioned in Section 1.2 and Chapter 2 is to design the concept of E-Hub which is aimed at breaking the chicken-egg cycle in the EV and EV charging infrastructure by providing an innovative solution for EV charging, which hence is build upon the literature described in the previous section. The literature examines the accessibility of local RES such as solar energy in an urban environment to charge EV under the presently available technologies along with suggestions to implement smart or dynamic charging from disparate points of view be it in terms of energy availability, power management or profit maximization. A similar approach to Mouli et al. and G.Nair [34, 35] is followed, as this study would in detail model the connection of EV charging with available solar energy specific to TU Delft in order to design the system which could later be validated by performing experiments by conceiving a test bed in the TU Delft DCE&S laboratory.

This thesis hence contributes to the presently available literature on EV load demand analysis and integration of RES in EV charging infrastructure and is distinct from the current literature by:

- Modelling load demand for a fleet of EV in an urban workspace environment such as TU Delft. Moreover, it also accommodates different EV users such as employees and visitors in terms of driving behaviour while taking into account the holidays and weekends.
- Providing a complete PV system design to realize such an EV charging infrastructure along with the required economic evaluation to devise the E-Hub system.
- Combining the acquired system design to implement power management algorithms specific to the E-Hub.
- Charting out the process to realize the experimental set-up and overcome the various practical challenges in both hardware and software.

This thesis research hence comprises of results and insights on a system level and does not encompass the topics related to analysis on PV system sensitivity or impacts on the distribution system caused by EV charging or complex control algorithms for EV charging as they cannot be immediately realized for testing. The application of designed system and the realisation of its feasibility is analysed through experiments in TU Delft DCE&S laboratory.
Chapter Overview

In this chapter the methodology used to calculate the yearly load demand will be discussed. A mathematical model is used as an approximative representation of real life scenario by describing the equations and assumptions, which can then suggest the relationship between variables used in the model. This chapter will adumbrate and state the model used to estimate the yearly load demand for EVs in the TU Delft campus.

3.1. Factors affecting EV Energy Demand

In this thesis, the energy demand of each EV is calculated. In a real life scenario the energy consumption of an EV relies on various factors. The main factors are shown in Figure 3.1.

It is however taken into account after defining the scope of this thesis research as mentioned in Section 1.3.3 that some factors would not be taken into consideration during the charging energy demand estimation. The factors and reasons for their omission are as follows:

1. **Charger Rating**: The peak power of the charger is assumed to be lesser or equal to the peak power of the EV

2. **Departure SOC**: The intention is to charge the EV to complete the journey from home to TU Delft

3. **Battery SOH**: As referred in Section 1.3.3 the Battery SOH is assumed to be constant throughout the lifetime of the vehicles in this study

4. **Battery Size**: An approach to eliminate the requirement to take into account the battery size of the variety of EVs is selected. This helps in approaching a realistic scenario where the charging demand can be estimated.

In light of above assumptions the final mathematical model would be based on the parameters mentioned in Figure 3.2 which would be discussed in the following sections.
3. Estimating Energy Demand for EV Charging

Figure 3.1: Factors effecting energy demand required for an EV

Figure 3.2: Factors effecting energy demand required for an EV considered in the mathematical model
3.2. Number of EVs

In regard to the scope of this thesis as mentioned in Section 1.3.3 the system is designed to cater ten cars. Now to introduce variety in the cars which would be present for charging at the E-Hub with an intent to approach a realistic scenario the factor of preferred charging location is introduced.

3.2.1. Preferred Charging Location

In the ten cars which is decided in previous section the following assumptions are made so as to approach a practical scenario.

Assumptions:

- Number of Employee EVs : 7
- Number of Visitor EVs : 3
- All ten cars are present each day for charging at the E-Hub

The E-Hub would hence be designed to provide charging infrastructure for both the employee and visitor EVs. Employee here refers to EV users who are employees of TU Delft such as Professors, PhD scholars, Administrative staff and even students. The visitors refers to those EV users who visit TU Delft for client meetings or other work related trips. The major difference between the employee and visitors are that the EVs used by employees are same throughout the duration of the year which is a valid assumption since the employees would drive the same EV to their place of work which is TU Delft however the same case does not stand with visitors since the EV driven by the visitor can vary according to each visitor. This is taken into consideration in the mathematical model which is explained in Section 3.4.

3.3. Driving Pattern

The mobility report by the Ministry of Infrastructure and Environment is used to calculate the driving pattern based on different categories as shown in Figure 3.3. The driving pattern of the ten EVs are modelled using the data from [21, 51].

To model the driving pattern for both employees and visitors, normal probability distribution is used. The Probability density function is given by Equation 3.1

\[ f(x|\mu, \sigma^2) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]  

(3.1)

- \( \mu \) refers to mean of the distribution
- \( \sigma \) refers to standard deviation

The following values are hence used in the mathematical model which is derived from Figure 3.3:

1. Daily average round trip commute for employees : 21.5 × 2 = 43 km
   - \( \mu_{\text{Employee}} = 43 \text{ km} \)

2. Daily average round trip commute for visitors EV : 25 × 2 = 50 km
   - \( \mu_{\text{Visitor}} = 50 \text{ km} \)

3. The standard deviation \( \sigma \) is taken to be 20% so as to include the variance and distribution which could regard other miscellaneous activities such as shopping, recreational or others [33].

The above values are used in the mathematical model represented by Equation 3.1, a histogram is then plotted to show the distribution of maximum distance travelled by each EV for both employees and visitors throughout the year as shown in Figure 3.4. It is interesting to note that the variations are taken into account.

1As mentioned in Section 1.3.3
Estimating Energy Demand for EV Charging

![Average distance of each trip based on purpose](source: Harikumaran J et al. (2012) [21])

In Figure 3.5, the maximum half trip distance of EVs are plotted from the distribution obtained in Figure 3.4. The maximum half trip distance can then be compared to Figure 3.6 where the location of employees and visitors can be understood from a geographical viewpoint.
3.3. Driving Pattern

Figure 3.5: Maximum half trip distance travelled by EV in a year

Figure 3.6: Average distance per trip for Employee and Visitor

Source: Google Maps 2017
It can be derived from the theory of standard normal distribution in Equation 3.1 that the probability of finding an occurrence is 68.27% within the first standard deviation. 

\[ z_i = \frac{(x_i - \mu)}{\sigma} \]  

\[ \int_{-1}^{1} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} \, dz = 0.68269 \]  

where \( x_i \) is the specific values in the distribution. In Figure 3.7 and 3.8 Equation 3.1, 3.2 and 3.3 are used to represent the distance travelled by each EV. The figures presents the driving pattern for one day of the entire year. It should be noted that some occurrences are outside the 68.27% probability but well within the 95.45% probability of twice standard deviation.
To depict a practical scenario the weekends and holidays are taken into account. This thesis takes into account the year 2017. The weekends and other holidays of 2017 are considered while plotting the yearly driving distribution of EVs. This assumption is valid since the EVs which are evaluated in this thesis are either employees or visitors which would visit the E-Hub only during the working days of TU Delft. The yearly related data is summarized in Table 3.1.

Table 3.1: Days in the year 2017

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Days</td>
<td>365</td>
</tr>
<tr>
<td>Number of Sundays</td>
<td>53</td>
</tr>
<tr>
<td>Number of Saturdays</td>
<td>52</td>
</tr>
<tr>
<td>Good Friday</td>
<td>April 14&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Easter Monday</td>
<td>April 17&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>King’s Day</td>
<td>April 27&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Remembrance Day</td>
<td>May 4&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Liberation Day</td>
<td>May 5&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ascension Day</td>
<td>May 25&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>White Monday</td>
<td>June 5&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>All Saints Day</td>
<td>November 1&lt;sup&gt;st&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sinterklaas</td>
<td>December 5&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Christmas Day</td>
<td>December 25&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>St.Stephens Day</td>
<td>December 26&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Working days</td>
<td>116</td>
</tr>
<tr>
<td>Total number of holidays</td>
<td>249</td>
</tr>
</tbody>
</table>

It should be noted that only the non weekend holidays are mentioned in Table 3.1 to avoid repetition. This inclusion of holidays is vital later on in the calculation of annual energy demand which is explained in Section 3.5. The cumulative driving pattern of all the ten EVs are hence simulated and shown in Figure 3.9.

The first EVs are employees and they are arranged in order of the employee living closest to TU Delft to the farthest and the final three EVs are the visitors. It can be seen that the variation in visitors are more than that of employees since their point of origin can vary drastically. The variation in employees over the year are to accommodate inclusion of shopping, errands or other miscellaneous activities during their commute to work.
3.4. EV Driving Efficiency

The energy consumption of an EV is given in terms of $kWh/km$ which depends on several factors such as:

- Driving Pattern
- Type and model of EV
- Weather conditions
- Traffic status

The real driving cycles of an EV fleet were studied in Pasaoglu et.al, 2013 [37] from which the following conclusions were derived.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\eta$ in kWh/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average driving $\eta$ range for small EVs</td>
<td>0.14 - 0.19</td>
</tr>
<tr>
<td>Average driving $\eta$ on roads</td>
<td>0.13</td>
</tr>
<tr>
<td>Average driving $\eta$ on motorways</td>
<td>0.20</td>
</tr>
<tr>
<td>Overall minimum driving $\eta$</td>
<td>0.22</td>
</tr>
<tr>
<td>Overall maximum driving $\eta$</td>
<td>0.12</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10%</td>
</tr>
</tbody>
</table>

The values stated in Table 3.2 are utilised to model the EV driving efficiency over the entire year. It should however be noted that it is assumed that the same EV is driven for all the trips mentioned in Figure 3.9 for an employee throughout the year. The EV used by the visitor changes every year with common occurrences in an year which is taken into account in the model. Cumulative distribution of driving efficiency for all EVs are shown in Figure 3.10.

3.5. Estimating the Yearly Load Demand

The energy demand of each EV is calculated using the results from the previous sections. The energy demand is calculated for each EV in terms of $kWh$ from the following equation

$$E_Y = \eta_{EV} \times DrivingPattern$$  (3.4)

- $E_Y$ is the Energy Load Demand for the whole year due to EV charging
- $\eta_{EV}$ the driving efficiency of each EV as discussed in Section 3.4
- $DrivingPattern$ of each EV throughout the year as discussed in Section 3.3

The above equation is then applied on each EV for every day of the year. The calculation also takes into account the holidays as shown in Table 3.1. The energy demand of each EV for the year is shown in Figure 3.11.

**Yearly Load Demand for the EV fleet**

To calculate the gross energy demand for the complete EV fleet at the E-Hub the energy demand for EV present at each day of the year as shown in Figure 3.11 is summed for each day which is depicted in Figure 3.12.
3.6. Conclusion

The results from the calculations to estimate the energy demand for charging are listed in Table 3.3. A load safety factor of 1.1 is taken into account so that the E-Hub system design can accommodate days of increased charging demand from EVs with increased driving distance.

<table>
<thead>
<tr>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum daily charging energy demand</td>
<td>57.9 kW h</td>
</tr>
<tr>
<td>Maximum daily charging energy demand</td>
<td>84.9 kW h</td>
</tr>
<tr>
<td>Average daily charging energy demand</td>
<td>73.28 kW h</td>
</tr>
<tr>
<td>Gross annual energy demand</td>
<td>18.24 MWh</td>
</tr>
<tr>
<td>Safety Load Factor</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Annual estimated energy demand</strong></td>
<td><strong>20.07 MWh</strong></td>
</tr>
</tbody>
</table>
3. Estimating Energy Demand for EV Charging

Figure 3.9: Cumulative driving pattern of all EVs in a year.
3.6. Conclusion

Figure 3.10: Cumulative driving efficiency (E) of all EVs in a year.
Estimating Energy Demand for EV Charging

Figure 3.11: Energy demand ($E$) of each EV in a year.
Figure 3.12: Daily Energy Demand for the EV fleet in a year.
4

Estimating PV Energy Resources

Chapter Overview

In this chapter the potential of Renewable Energy Sources (RES) are discussed. It is essential to determine the possibility of using the chosen RES so as to design the E-Hub from results obtained in Chapter 3. The first section discusses the reasons to choose the determined RES. The effects of weather in the chosen RES is studied in the second section which is followed by calculations used to determine the potential of chosen RES. The fourth section would analyse the power output variations using a defined empirical model. In the final section realistic yearly yield is estimated for the chosen location in the TU Delft campus.

4.1. Determining the Renewable Energy Source for the E-Hub

The E-Hub as discussed in Section 1.2 envisions to establish itself as the charging infrastructure of the future especially in an urban environment. In order to cater the charging needs of EVs in the future the E-Hub needs to account the following primary directions in future energy usage which are:

- Integration of extensive distributed RES
- Large scale penetration of EVs in the mobility sector

There has been considerable research on the impact of grid by the influx of EVs as being the primary mode of transport in the passenger vehicle sector. It is predicted that the impact on the grid due to EV charging would not be substantial at the moment since the majority of EV charging occurs at off-peak hours and at night-time [53]. An influx of 10% EVs in the present mobility sector in UK would lead to less than 2% increase in demand from the utility grid which would be relatively one GW increase as studied in Brown, S et.al, 2010 [8]. When the environmental aspect of the EV cycle is scrutinized it is imperative to account the greenhouse gases and the emissions from air pollutants which are presently identified in regard to the electricity needed for EV charging from existing fossil based power plants. In a study of conventional fossil based utility grid in Alberta, Canada it was noticed that the emergence of EVs in the market would make the grid more emission intensive over the life-cycle of the EV as compared to traditional Internal combustion engine vehicles [8]. This decisive insight hence drives the E-Hub to resort to distributed renewable energy sources to augment the environmental benefits of increased EV use.

The two sources of energy generation that were considered for the E-Hub design are:

- Photovoltaic System
- Wind Turbines

The use of a Wind-PV hybrid system is excellent to satisfy sustained load demand amid varying natural conditions since the generation of PV and Wind help in counteracting variations. The E-Hub is however designed to only incorporate a PV system and not wind turbines as justified in the following section.
Exclusion of Wind Turbines from E-Hub design

This project shaped from the vision of E-Hub as discussed in 1.3 is proposed to be located within the TU Delft Campus. The various constraints which led to the exclusion of Wind turbines in the E-Hub design are discussed in this section.

Dutch Regulations

There are several guidelines that need to be fulfilled during the installation of wind turbines as stated by the Rijkswaterstaat, Ministrie van Infrastructuur en Milieu, Dutch Ministry of Infrastructure and Environment. These regulations impede the inclusion of Wind turbine in the present design of E-Hub which have been heavily regulated by keeping noise, shadowing effects and primarily safety into account. The law states the following with regard to installation of wind turbines [40, 44]:

1. There should be a 500m safeguard zone around the housing of turbine to avoid noise barriers and drop shadowing effects.
2. The distance to the road should be half of the rotor diameter
3. A 30m distance to the road should be maintained if the rotor diameter is less than 60m.
4. The space between two wind turbines should be 5-10 times the rotor diameter
5. Additional safety measures are enumerated for placement of wind turbines next to interchanges, educational institutions and also parking lots

Experimental Set-up

As specified in Section 1.3.2, the final E-Hub system design needs to be viable so that the scaled downed system can be tested in the DCE&S laboratory to implement power management algorithms. However, at the present DCE&S laboratory lacks a wind turbine set-up which can be used as an experimental test-bed. At the present only PV Module emulators are present as explained in Appendix H.

Cost Analysis

The final reasoning in the exclusion of Wind turbine in E-Hub is from an economical viewpoint. The investment and maintenance cost greatly increase for wind systems as compared to PV systems. The Energy Analysis study from National Renewable Energy Laboratory (NREL) [27] is used in this section.

It can be inferred from Figure 4.1 and 4.2 that the average cumulative installation costs of Wind systems are 67.2% greater than PV systems. The trend however decreases for larger project sizes. In regard to operation and maintenance costs(O&M) the average cumulative O&M of Wind systems are 84.82% greater than PV systems and does not necessarily decrement with increased project size [27]. This outcome compels the use of PV system as the RES for the E-Hub from an financial outlook. In relation to lifetime of both Wind and PV systems as shown in Figure 4.3, the average lifetime predicted by [27] is 33 years for PV systems and an average of 17.25 years for Wind systems which again restates the justification in use of PV system to attain a lower payback time for the installed RES system in the E-Hub.
4.1. Determining the Renewable Energy Source for the E-Hub

Figure 4.1: Installation costs of Wind and PV systems

Figure 4.2: Operation and maintenance costs for Wind and PV systems

Figure 4.3: Lifetime of Wind and PV systems
4.2. Scope of Weather Data

The chosen location of the E-Hub as discussed in Section 1.3.3 is within the TU Delft campus at the coordinates 51.996°North and 4.377°East. The meteorological data that is used in this thesis have been acquired from Meteonorm. Meteonorm is a global climate database. The software runs only on the Windows operating system and a license needs to be bought. The following data have been imported from the software for the exact location of 51.996°North and 4.377°East at a hourly resolution for every day of the year:

- Irradiance Profiles \( (W/m^2) \)
- Ambient Temperature (°C)
- Wind Speed \((m/s)\)

4.2.1. Irradiance Profiles

*Determination of radiation components with given global horizontal radiation*

The default mode in Meteonorm software to calculate the radiation components with given global horizontal radiation utilizes the dynamic model stated in [25]. The Perez model [25] derives direct normal radiation in an hourly resolution from hourly global horizontal radiation values. The various inputs taken into the Perez model are:

- Normalized clearness index \( k'_{it} \) which is independent of the zenith angle.
- Zenith angle of the sun
- A stability index \( \Delta k'_{it} \) which is calculated from the time series of \( k'_{it} \).

\[
\Delta k'_{it} = 0.5 \times (|k'_{iti} - k'_{iti+1}| + |k'_{iti} - k'_{iti-1}|) \tag{4.1}
\]

where \( i, i-1 \) and \( i+1 \) refer to present, previous and subsequent hour.

- The model can be extended to include the dew point temperature to estimate the humidity in the atmosphere which affects the absorption and production of aerosols.

*Calculation of Global and Diffuse radiation on inclined surface*

The default model in Meteonorm is again the Perez model which takes into account the isotropic diffused model as studied in [25]. The various equations used in the model are as follows [25, 42]:

\[
G_{Global}^m = G_{Direct}^m + G_{Diff used}^m + G_{Albedo}^m \tag{4.2}
\]

\[
G_{Albedo}^m = \frac{1 - \cos(\beta_m)}{2} \times (\Psi \cdot G_{DHI}) \tag{4.3}
\]

\[
\Psi_{Snow} = \Psi - 0.083 + exp(-0.0049 \times hSS - 1.156) \tag{4.4}
\]

\[
G_{Diffused}^m = G_{DHI}^m \times \frac{1 + \cos(\beta_m)}{2} \tag{4.5}
\]

\[
G_{Direct}^m = G_{DNI}^m \times \cos(\theta_i) \tag{4.6}
\]

where:

- \( G_{Global}^m \) = Global irradiance on the module surface with any tilt and azimuth orientation in \( W/m^2 \)
- \( G_{Direct}^m \) = Direct irradiance incident on a module with a module tilt angle of \( \beta_m \) in \( W/m^2 \)
- \( G_{Diffused}^m \) = Diffused irradiance incident on a module with a module tilt angle of \( \beta_m \) in \( W/m^2 \)
- \( G_{Albedo}^m \) = Albedo irradiance incident on a module with a module tilt angle of \( \beta_m \) in \( W/m^2 \)
4.2. Scope of Weather Data

\[ \Psi = \text{Reflectivity of the ground surface} \]

\[ G^{DHI} = \text{Diffused irradiance incident on a horizontal module with } \beta_m = 0 \]

\[ \Psi_{\text{snow}} = \text{Ground surface reflectivity during snow cover} \]

\[ h_{ss} = \text{hours since last snow fall} \]

\[ G^{DNI} = \text{Direct normal irradiance in } \text{W/m}^2 \]

\[ \theta_i = \text{Incident angle of the direct irradiance beam} \]

The various values of \( \Psi \) taken in the Meteonorm software are:

- \( \Psi = 0.2 \) for concrete surface
- \( \Psi = 0.2 \) for 0cm snow cover
- \( \Psi = 0.5 \) for 5cm snow cover
- \( \Psi = 0.73 \) during snowfall
- \( \Psi = 0.42 \) after 3 days of snow fall
- \( \Psi = 0.1 \) for asphalt surface

The \( \Psi \) values for other scenarios are determined from a database with correction factor based on various parameters such as vertical gradient, vertical scale factor, altitude of location and co-ordinates.

**Optimal tilt and azimuth position**

The PV module tilt angle and azimuth needs to be fixed to obtain the optimum PV module position. The optimisation needs to take into account the location of the PV system and the position of sun through the year in relation to the PV system which varies according to the seasons.

Tilt refers to the angle made by the PV module and the horizontal axis. It is essential that the tilt angle for the PV module at the chosen location be greater than 0° so that the sun faces the module. Azimuth refers to the module orientation which is normally fixed at a constant direction such as the southern direction for northern hemisphere since the highest solar intensity is obtained at the highest altitude.

In this thesis an optimum tilt angle and azimuth position is chosen for maximum performance over the whole year. The results from an in-depth optimisation model in [35] as mentioned in Section 2.2 are shown in Figure 4.4 and can be summed up as:

- Tilt of an angle 28°
- Azimuth orientation due South (180°)

The above mentioned tilt angle and azimuth which are optimized for the whole year are chosen since the E-Hub system is perceived to be a grid tied system with battery backup where maximum PV output throughout the year is preferred since the winter months would be supported by the grid.
4. Estimating PV Energy Resources

Figure 4.4: Optimum Tilt angle and Azimuth for the chosen location for a year

Source: G Nair (2014) [35]

Figure 4.5: Annual Irradiance on the chosen location over the year

Figure 4.5: Annual Irradiance on the chosen location over the year
4.2. Scope of Weather Data

Figure 4.6: Annual ambient temperature on the chosen location over the year

Figure 4.7: Annual Wind-speed on the chosen location over the year
Annual trends

The annual trends of solar irradiance for a module tilted at 28° and facing south is derived from Meteonorm in the chosen location as shown in Figure 4.5, since the E-Hub is envisioned to be implemented in the near future the annual irradiance of the future years until 2021 is predicted from the Meteonorm software. The common trend across the depicted years is a peak in the middle of the year (summer) and drops to almost a third of the peak values corresponding to winter months. The Meteonorm software presents three scenarios as presented by the Intergovernmental panel on climate change (IPCC) which are [30]:

- **B1** This scenario predicts a convergent world with a population peak in mid-century and steady decline thenceforth accompanied by rapid diversity in economic structures with rebate in intensity of materials followed by influx of clean and resource-efficient technologies. The priority is on international solutions to the following fields without additional climate initiatives
  - Economic
  - Social
  - Environmental sustainability
  - Improved equity

- **A1B** This scenario predicts a world of rapid economic growth with a population peak in mid-century and steady decline thenceforth. There is technological emphasis on balance across all energy sources. The priority is on capacity building, increased social and cultural interaction and considerable devaluation in regional differences in per capita income.

- **A2** This scenario predicts a heterogeneous world with increased self-reliance and drive to preserve local identity. There is continuous increase in global population and economic growth is slower as compared to other scenarios.

The default scenario of **B1** is chosen to predict the annual irradiance, Ambient temperature and Wind speeds for the year 2017, 2019 and 2021. The change in forecast for global radiation until 2100 are more scattered when compared to temperature changes.

It is however important to note that the predicted data are subjected to uncertainty due to the presence of several variables in the study of climate system.

4.2.2. Ambient Temperature

The temperature data for the year 2015, 2017, 2019 and 2021 at the chosen location from Meteonorm software is shown in Figure 4.6. The temperature profiles also follow an annual trend as discussed in Section 4.2.1. The ambient temperature data for the year 2017 has been chosen as the year of 2017 has been decided to be used as the reference time-frame to study the PV system in this chapter. Figure 4.6 clearly shows a diurnal and seasonal trend. There exists a wide annual range in temperature varying from -10°C to above 30°C.

The ambient temperature effects the module temperature which consecutively effects the performance of the PV system. The performance of the system greatly diminishes with increase in ambient temperature which has been taken into account while designing the PV system as discussed in Section 4.4.2.

4.2.3. Wind Speed

The wind speed data for the year 2015, 2017, 2019 and 2021 at the chosen location from Meteonorm software is shown in Figure 4.7. It should be noted that more accurate wind data can be obtained from local measured wind data to which the predictive **B1** model can be applied. The present data is used due to the lack of availability of locally measured wind speed data since the presence of building and the locations geographical pattern can greatly effect the wind speeds. Wind speeds follow a yearly trend alike irradiance and ambient temperature discussed in Section 4.2.1 and 4.2.2. The wind speeds differ from still days at 0m/s to above 15m/s on winter months due to greater variation in the barometric pressure during winter months which is a result of higher variation in temperatures during winter.

Wind speeds can have a complimentary impact on the PV modules when compared to the rise in ambient
temperature since the module temperature drops due to wind flow. An accurate model has been taken into account while designing the PV system to account the effect of wind speed on the module temperature as discussed in 4.4.2.

4.3. Computing Available Energy

The available energy can be estimated by using the irradiance profile \(W/m^2\) of Figure 4.5. The following equation is used to calculate the available energy over a defined time period ranging from \(t_i\) to \(t_f\) in hours [42]:

\[
E_s = \int_{t_i}^{t_f} G_{m \leq t} dt
\]

(4.7)

Where:
\(E_s\) = Energy per unit area in Wh/m²

As mentioned in Section 4.2.1 the irradiance profile has an hourly resolution hence Equation 4.7 can be rewritten as:

\[
E_s = \sum_{t_i=1}^{t_f} G_{m < t} \cdot \Delta t
\]

(4.8)

where:
\(\Delta t = t_f - t_i = 8760\) hours

4.4. Estimating PV Output

In this section PV output is calculated. Two PV modules are presented and the PV module for the E-Hub is chosen upon which a mathematical model is applied to take into account the effects of temperature and wind-speed to satisfactorily estimate the PV output.

4.4.1. PV Modules

Two different PV modules are taken into study in this thesis, both the modules mainly vary in terms of:

- Type
  - Monocrystalline
  - Polycrystalline

- Performance
  - High efficiency
  - Low efficiency

- Cost (€/Wp)
  - Expensive
  - Affordable

The chosen PV modules are listed in Table 4.1 while Table 4.2 lists the summary of main specifications of the modules. PV modules of other technologies such as Thin-film and Heterojunction panels are not considered in this thesis project as these technologies are still in their developmental phase.

In perspective to the E-Hub project the Peimar OS-260P PV module is chosen keeping into account the capital investment required to realize the E-Hub project. A thorough analysis is however carried out for both the listed panels in terms of yield and costs. The results of the high performance Sunpower SPR E20-327 PV module are listed in Appendix B.
4. Estimated PV Energy Resources

### Table 4.1: Chosen PV Modules

<table>
<thead>
<tr>
<th>Module No.</th>
<th>Module Name</th>
<th>( P_{\text{max}} ) STC (W)</th>
<th>Type</th>
<th>Price ( \epsilon/W_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sunpower SPR E20 - 327</td>
<td>327</td>
<td>Mono-Si</td>
<td>1.45</td>
</tr>
<tr>
<td>2</td>
<td>Peimar OS 260 P</td>
<td>260</td>
<td>Poly</td>
<td>0.51</td>
</tr>
</tbody>
</table>

### Table 4.2: PV Modules - Specifications

<table>
<thead>
<tr>
<th>Module No.</th>
<th>NOCT (°C)</th>
<th>Area ((m^2))</th>
<th>( \eta_{\text{nom}} ) STC (%)</th>
<th>( V_{\text{oc}} ) STC (V)</th>
<th>( I_{\text{sc}} ) STC (A)</th>
<th>Temp Coeff ( P_{\text{max}} ) (%/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43</td>
<td>1.63</td>
<td>20.4</td>
<td>64.9</td>
<td>6.46</td>
<td>-0.35</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>1.63</td>
<td>15.98</td>
<td>37.9</td>
<td>9.06</td>
<td>-0.43</td>
</tr>
</tbody>
</table>

#### 4.4.2. Duffie Beckman Model

The Duffie Beckman (DB) model is used in this thesis to estimate the module temperature which is an extension of Nominal Operating Cell Temperature (NOCT) model. The DB model takes into account the effect of incident irradiance, ambient temperature and wind-speed at the location as discussed in Section 4.2.1, 4.2.2 and 4.2.3.

However, the following assumptions are made since a thorough PV model was outside the scope of this thesis:

- The module temperature is assumed to be uniform throughout the cells hence the effect of temperature latency is not taken into consideration.
- The module and cell temperature are taken to be same where the effects of temperature increase due to absorption at the cells are not taken into account.

The DB model is given by the following equation [15, 35, 42]:

\[
T_m = T_a + (NOCT - 20°C) \times \frac{G_{\text{Global}}}{G_{\text{NOCT}}} \times \left( \frac{9.5}{5.7 + (3.8 \times V_w)} \right) \times \left( 1 - \frac{\eta_{\text{nom}}}{\Xi} \right) \tag{4.9}
\]

where:

- \( T_m \) = Module Temperature (°C)
- \( T_a \) = Ambient Temperature (°C)
- \( NOCT \) = Nominal Operating Cell Temperature (°C)
- \( G_{\text{NOCT}} \) = Irradiance at NOCT conditions = 800 W/m²
- \( V_w \) = Wind-speed on the module (m/s)
- \( \eta_{\text{nom}} \) = Nominal efficiency of the module
- \( \Xi \) = Effective transmittance-absorptance product = 0.9 [15]

The weather data for the year 2017 is used in the DB Model on the Module 2 from Table 4.2 and 4.1. The results are shown in Figure 4.8.
4.5. PV Module Output Power

In the previous section the module temperature was determined, the PV module output in terms of power and energy yield are determined in this section. The output power of the module is calculated by the following equation at an hourly time resolution [34, 35, 42].

\[ P_m = \left( 1 - \lambda (T_m - 25^\circ C) \right) \left( \frac{G_{Global} p_{STC}}{1000} \right) \]  \hspace{1cm} (4.10)

where:

- \( P_m \) = Output power of the module at maximum power point (W)
- \( \lambda \) = Power temperature coefficient of the module (%/°C)
- \( p_{STC} \) = Rated module power at standard test conditions (STC) (W)

4.6. Conclusion

1. Available Energy
   - The annual available energy was estimated in Section 4.3. The available solar energy irradiation at the chosen location for a module tilted at 28 °and faced due south at 180 °for the year 2017 irradiance profile, amounts to 1.193 MW/h/m².

2. Yield
   - The PV yield was estimated using mathematical models to account the effects of weather variations. The yield results for each of the module under consideration is listed in Table 4.3. The high performance Sunpower module has a higher energy yield as compared to the Peimar module, however as stated in Section 4.4.1, the E-Hub PV system design proceeds with the much cheaper Peimar modules and this choice is not constrained by the restriction of area which is discussed in detail in Section 5.6

Table 4.3: Results of estimated energy yield

<table>
<thead>
<tr>
<th>Module</th>
<th>Yield (kWh)</th>
<th>Yield per area (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 1</td>
<td>386.873</td>
<td>237.345</td>
</tr>
<tr>
<td>Module 2</td>
<td>308.404</td>
<td>189.204</td>
</tr>
</tbody>
</table>
Figure 4.8: Annual $T_{\text{m}}$ using DB model against $T_{\text{a}}$ for year 2017

Figure 4.9: Annual $P_{\text{m}}$ variation for a single module
Figure 4.10: Energy yield per day for a single module for the year 2017
5 System Design

Chapter Overview

In this chapter the design of E-Hub in terms of PV system, the physical layout of the PV modules and the balance of system components are discussed. This chapter is an extension of the last two chapters from which the system is sized accordingly. The chapter begins with the PV system sizing. The layout of the PV system is discussed with the deciding factors. The second section discusses the chosen system topology from the incorporated inverter system in the E-Hub. The third section briefly explains the proposed EV chargers to be used in the final system followed by the final section where the practical and economic feasibility of the chosen system design is examined.

5.1. PV Module Sizing

In Section 4.2.1 and 5.4 it is decided that the E-Hub would be a grid connected PV system. It essential in such an architecture that the estimated charging energy demand and the PV yield should reasonably match over the year. An empirical equation to decide the number of modules required in the PV system is shown in Equation 5.1. It should however be noted that in Equation 5.1 the efficiencies of inverter and sizing factor are not taken into account.

\[ N_m = \frac{E_Y}{E_{Yield}} \]  

(5.1)

where:
\[ N_m = \text{Number of modules} \]
\[ E_Y = \text{The annual estimated energy demand for charging } \text{MW}h \text{ from Table 3.3} \]
\[ E_{Yield} = \text{The annual estimated energy yield from the module } \text{kWh} \text{ from Table 4.3} \]

It can be inferred that by using Equation 5.1 a rough estimate of Peimar PV modules required to satisfy the charging load demand of the E-Hub would be:

\[ N_m = 65.17 \approx 66 \]  

(5.2)

To accurately size the number of PV modules required by taking into account the inverter efficiency and sizing factor the set of following equations are used [42]:

\[ E_{DC} = \frac{E_Y}{\eta_{inv}} \]  

(5.3)

\[ N_m = \frac{E_{DC} \times SF}{G_{Global} \times A_m \times \eta_m} \]  

(5.4)
System Design

\[ N_m = 72.52 \approx 73 \]  
(5.5)

where:

\[ E_{DC} = \text{DC energy load demand (Wh)} \]

\[ \eta_{inv} = \text{Efficiency of the inverter in the system from Table 5.2} \]

\[ SF = \text{Sizing factor} \approx 1.1 \]  
[42]

\[ A_m = \text{Area of the chosen PV module (m}^2\text{)} \]

\[ \eta_m = \text{Efficiency of the chosen PV module} \]

5.2. PV Array Layout

It is fundamental to determine physical layout of the PV array in terms of series\(N_m^S\) and parallel\(N_m^P\) connected modules.

\[ N_m = N_m^S \times N_m^P \]  
(5.6)

The inverter chosen for the E-Hub PV system as stated in Section 5.3 is the SMA Sunny Power 20000TL. The key inverter specifications are listed in Table 5.2 and the detailed data-sheet is in Appendix C. It is desirable to have PV array layout with more modules in series from efficiency viewpoint so that the losses in the cable are low due to small value of DC current. The PV array layout is chosen when the following constraints are met [42]:

\[ N_m^S \times V_{oc}^{STC} < V_{inv}^{max} \]  
(5.7)

\[ N_m^P \times I_{sc}^{STC} < I_{inv}^{max} \]  
(5.8)

where:

\[ V_{oc}^{STC} = \text{Open circuit voltage of the PV module at STC conditions (V)} \]

\[ I_{sc}^{STC} = \text{Short circuit current of the PV module at STC conditions (A)} \]

\[ V_{inv}^{max} = \text{Maximum inverter input voltage (V)} \]

\[ I_{inv}^{max} = \text{Maximum inverter input current (A)} \]

The \(V_{oc}^{STC}\) and \(I_{sc}^{STC}\) are taken into account to design the PV array configuration for the worst case scenario with the upper limit of module voltage and current, from Equations 5.7 and 5.8 the ideal PV array configuration is listed in Table 5.1

<table>
<thead>
<tr>
<th>No. of PV modules</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Series (N_m^S)</td>
<td>25</td>
</tr>
<tr>
<td>Parallel (N_m^P)</td>
<td>3</td>
</tr>
<tr>
<td>Total (N_m)</td>
<td>75</td>
</tr>
</tbody>
</table>

The designed PV system would hence have a watt peak \(W_p^{STC}\) at standard test conditions given by Equation 5.9. The annual variation of power output for the designed PV array layout is shown in Figure 5.1.

\[ W_p^{STC} = N_m \times P_m^{STC} = 19.5kW \]  
(5.9)

where:

\[ P_m^{STC} = \text{Maximum power rating of the PV module at STC conditions.} \]
5.2. PV Array Layout

Figure 5.1: Annual variation of the designed PV array output power.
5.3. Inverter Selection

The inverter chosen for the designed PV system is the SMA Sunny Tripower 20000TL. A pragmatic approach to choose the inverter is based on the PV power at STC. As suggested in [42] the inverter is selected such that the nominal DC power of the inverter is up to 10% of the PV system power at STC\(^1\). The chosen PV inverter is a 3φ inverter\(^2\) since the designed PV system has a

\[
P_{DC0} > 5kW_p^{STC}
\]  \hspace{1cm} (5.10)

\(P_{DC0}\) = Nominal DC power of the inverter.

3φ inverters are ordinarily used in large scale PV systems to prevent asymmetric current flow in the three phases when high power is given as an input to a 1 phase. This would then cause irregularities in the grid. The inverter efficiency is not steady throughout its operation with the PV system. The main factors effecting the inverter efficiency are\(^2\):

1. Input DC voltage
2. Total DC input power

The above mentioned factors are not constant during the operation of the PV system due to irradiance fluctuations. The study into inverter efficiency\(^2\) is beyond the scope of this thesis research, hence the inverter selection is based on 1:1 ratio with the peak PV power. The main specifications of the chosen inverter are given in Table 5.2.

<table>
<thead>
<tr>
<th>Technical Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection phases</td>
<td>3φ</td>
</tr>
<tr>
<td>Maximum input voltage</td>
<td>1000 V</td>
</tr>
<tr>
<td>Maximum input current</td>
<td>33 A</td>
</tr>
<tr>
<td>Rated power at 230V, 50Hz</td>
<td>20 kW</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>98.4%</td>
</tr>
<tr>
<td>European efficiency</td>
<td>98%</td>
</tr>
</tbody>
</table>

\(^1\)This approach is taken to consider the irradiance distribution which is dependent on the climate zone where the PV system is located.

\(^2\)European efficiency calculation for locations based in central Europe by taking into account weighted efficiencies at different nominal power of the inverter [42]
5.4. System Architecture

In the designed PV system in Chapter 5 the PV system architecture chosen for the E-Hub is the Central inverter topology as shown in Figure 5.2.

Central inverter topology experiences various disadvantages when compared to other system architectures however these drawbacks become less eminent in larger applications when taking the following reasons into account which were the deciding factors on the central inverter topology for the E-hub:

- Simple architecture especially for large scale PV systems such as for the E-Hub design
- Reliable and robust system due to lesser components
- High inverter efficiency\(^3\)
- Low specific cost\(^4\)

It is advised to install blocking diodes in order to preclude circulation of current inside parallel strings of PV modules which can be caused by the irradiation variation over the modules.

---
\(^3\) Due to higher power level when compared to string inverters
\(^4\) Cost per kWp of installed PV power
5.5. EV Chargers

The EV charging standards at the present are:

1. IEC 62196 (*Electrical connectors for EVs*)
2. IEC 61851 (*EV supply equipment for charging*)
3. IEC 15118 (*EV communication protocols*)

An overview of the above mentioned standards are depicted in Figure 5.3. The E-Hub as discussed in Section 1.3.3 is envisioned to consist of 7 kW and 21 kW EV chargers. The key specifications of the selected chargers are enumerated in Table 5.3.

Table 5.3: Key specifications of 7 kW and 21 kW EV chargers

<table>
<thead>
<tr>
<th>Technical Data</th>
<th>7 kW</th>
<th>21 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Charging Capacity</td>
<td>7.2 kW</td>
<td>22 kW</td>
</tr>
<tr>
<td>Charger Type</td>
<td>Mode 3</td>
<td>Mode 3</td>
</tr>
<tr>
<td>Socket</td>
<td>Type 2</td>
<td>Type 2</td>
</tr>
<tr>
<td>Charging Level</td>
<td>Level 2</td>
<td>Level 2</td>
</tr>
<tr>
<td>Charger Rating</td>
<td>$32A \times 230V = 7360W$</td>
<td>$32A \times 230V \times 3\phi = 22.08kW$</td>
</tr>
</tbody>
</table>

The suggested EV charger for the E-Hub is the EV-Box Business Charging Pole. The datasheet of the chosen charging pole is attached in Appendix D.

The above mentioned EV charger has been chosen for the following reasons [18]:

- 7 kW and 21 kW charging ports are available per EV charging poles
- Two charging ports per EV charging pole hence saving up on ground space
- Monitoring and tracking capability
- LED lighting to indicate charging status
- Use of personalized or common access cards to enable charging
- Sturdy structure to prevent vandalism, theft and the materials used are rated to non-flammable
- The cost of the charging poles are much cheaper when compared to other EV chargers with the above mentioned specifications which makes its use in the E-Hub more financially viable as explained in Section 5.6

---

5 The charger rating can be configured to buy the appropriate EV charging pole with a possibility for adjustable charging rates

6 Smart charging capability
5.5. EV Chargers

Figure 5.3: Overview of EV charging standards

- **Inductive Charging**
- **Others**
- **Type**
  - **Type 1**: SAE J1772
  - **Type 2**: Mennekes
  - **Type 3**: EV Plug Alliance
  - **Type 4**: CHAdeMO and Combo
- **EV Charging Standards**
  - **Mode 1**
  - **Mode 2**
  - **Mode 3**
  - **Mode 4**
- **Level**
  - **Level 1**: Home Charging
  - **Level 2**: Fast AC Charging
  - **Level 3**: Fast DC Charging
- **Wired DC Charging**
- **Wired AC Charging**
- **Home Charging with EVSE cable**
- **Home Charging without safety measures**

**Ev supply equipment (EVSE)**
Mennekes - VDE-AR-E 2623-2-2
5.6. Practical Feasibility

It is vital to consider if the ground area required for the PV system designed in Section 5 is comparable to the area required to park/charge the 10 EVs. The designed PV system is not necessarily to be placed above the cars as a parking lot roof with solar panels since, as mentioned in Section 1.3.3 the final E-Hub design would be based on inputs from research in the field of industrial design and architecture.

The main ground area requirement is listed in Table 5.4

<table>
<thead>
<tr>
<th>Area for one unit</th>
<th>Number</th>
<th>Total ground area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peimar OS260P PV Module</td>
<td>$0.992 \times 1.640$</td>
<td>75</td>
</tr>
<tr>
<td>Parking space</td>
<td>$2.4 \times 4.8$</td>
<td>10</td>
</tr>
</tbody>
</table>

It is calculated from Table 5.4 that the PV system with 75 Peimar OS260P modules would cover the area\textsuperscript{7} required to park 11 cars [13]. The remaining 1 m\textsuperscript{2} can be foreseen to be used to place EV charging poles which were discussed in Section 5.5. The area calculated is shown in Figure 5.4 after applying a scaling factor to figuratively display the ground area of the E-Hub with such a PV system.

\textsuperscript{7}The spacing of PV modules to eliminate shading is not considered since a rooftop PV system design is not envisioned at the present [50]
5.7. Financial Study

In this section the capital investment required to set-up the E-Hub is estimated using various empirical relations from literature. The cost of the selected components in this Chapter are listed in Table 5.5.

Table 5.5: Cost evaluation of the chosen components in the E-Hub system

<table>
<thead>
<tr>
<th>Price for one unit (€)</th>
<th>Number</th>
<th>Total Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peimar OS260P PV Module</td>
<td>132.6</td>
<td>75</td>
</tr>
<tr>
<td>SMA Sunny Tripower STP 20000 TL</td>
<td>2812.90</td>
<td>1</td>
</tr>
<tr>
<td>EV-Box Business Line 7.4 kW</td>
<td>2359</td>
<td>3</td>
</tr>
<tr>
<td>EV-Box Business Line 22 kW</td>
<td>2479</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>24,793</td>
</tr>
</tbody>
</table>

The calculated cost of 24,793€, however does not take into account the balance of system (BOS) costs. Standard utility scale PV system has a BOS cost which amounts to 40% of the total installation costs [3]. The BOS accounts for such a large margin of the PV system installation costs due to the various components which are present in a complete PV system.

Balance of Systems Costs

As discussed in the previous section the total PV system costs can primarily be constituted of PV module costs and BOS costs. In this section the BOS costs would be analysed with respect to cost estimation study from The International Renewable Energy Agency (IRENA), National Renewable Energy Laboratory (NREL) and New York State Energy Research and Development Authority (NYSERDA) [4, 19, 38].

The BOS breakdown in the following section is calculated from the NREL 2017 Benchmark BOS model [19] where a 19.5 kWp PV system is classified as a commercial PV system. The BOS costs can be generally divided into three categories which have further sub-categories [3, 4, 19, 27, 38].

1. Hardware and Material Costs
   (a) Module : Cost of the PV modules which amounts to 9945€ from Table 5.5
   (b) Inverter : Cost of the inverter used which is 2812.90€ as listed in Table 5.5
   (c) Structural BOS : Costs incurred from the structural components used such as racking systems, mounting systems. The prices taken into account are usually factory prices for commercial PV systems
   (d) Electrical BOS : Costs from conductors, conduit and fittings such as transition boxes, switchgear, panel boarding and wiring.

2. Soft BOS costs : These are provoked from non-hardware costs. These costs can be reduced from scaling hence are lower for commercial PV systems when compared to residential systems.
   (a) Permitting, Zoning and Inspection (PZI)
   (b) Interconnection
   (c) Installation labour
   (d) Design and Engineering

---

8 This cost is outside the BOS cost evaluation but is included to structure the complete PV system cost
3. Other BOS costs\(^9\)

   (a) Sales Tax: The average tax rate for the region\(^9\)
   (b) Contingency
   (c) Engineering, procurement and construction (EPC) costs.

---

\(^9\)These costs are taken from the tax rules and regulations set in place in the US and would differ from the European policies

\(^{10}\)USD to € with a conversion factor of 0.85
### 5.7. Financial Study

Table 5.6: Cost estimation for the chosen E-Hub PV System

Source: [3, 4, 19, 27, 38]

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Estimated unit cost ($/W)</th>
<th>Estimated Total Cost ($)</th>
<th>Costs as per Table 5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardware and Material Costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module</td>
<td>0.544</td>
<td>10608</td>
<td>9945</td>
</tr>
<tr>
<td>Inverter</td>
<td>0.1105</td>
<td>2210</td>
<td>2812.90</td>
</tr>
<tr>
<td>Structural BOS</td>
<td>0.1445</td>
<td>2817.75</td>
<td>-</td>
</tr>
<tr>
<td>Electrical BOS</td>
<td>0.136</td>
<td>2652</td>
<td>-</td>
</tr>
<tr>
<td><strong>Soft BOS Costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZI</td>
<td>0.02125</td>
<td>414.375</td>
<td>-</td>
</tr>
<tr>
<td>Interconnection</td>
<td>0.02125</td>
<td>414.375</td>
<td>-</td>
</tr>
<tr>
<td>Installation labour</td>
<td>0.1615</td>
<td>3149.25</td>
<td>-</td>
</tr>
<tr>
<td>Design and engineering</td>
<td>0.3655</td>
<td>7127.25</td>
<td>-</td>
</tr>
<tr>
<td><strong>Other BOS Costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sales tax</td>
<td>0.0595</td>
<td>1160.25</td>
<td>-</td>
</tr>
<tr>
<td>Contingency</td>
<td>0.051</td>
<td>994.5</td>
<td>-</td>
</tr>
<tr>
<td>EPC</td>
<td>0.17</td>
<td>3315</td>
<td>-</td>
</tr>
<tr>
<td><strong>EV Chargers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV-Charger (7.4 kW × 3)</td>
<td>-</td>
<td>-</td>
<td>7077</td>
</tr>
<tr>
<td>EV-Charger (22 kW × 2)</td>
<td>-</td>
<td>-</td>
<td>4958</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tesla Powerwall 1</td>
<td>-</td>
<td>-</td>
<td>3500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>34862.65</strong></td>
<td><strong>50397.75</strong></td>
</tr>
</tbody>
</table>
Figure 5.6: Overview of E-Hub system design

- Fuse
- PV Array
- DC/AC Inverter
- Electric Vehicle
- AC/DC unidirectional charger
- AC/AC bidirectional charger
- E-Hub
- Powerwall
- Utility Grid
5.8. Conclusion

System Design

The Peimar 260OS PV modules are used in the PV system design of the E-Hub. The final PV system would hence consist of 75 panels which are arranged in a layout of 25 panels in series and 3 in parallel. The rated Watt peak of the PV system at STC is 19.5 kW. A central inverter topology is chosen to realize a reliable and simple system design. The proposed inverter is the SMA Sunny Tripower 20000TL. The EV chargers for the E-Hub need to cater the designed 7 kW and 21 kW charging demand. The E-Box business pole is suggested (refer 5.5).

Practical Feasibility

The total ground area required to park and charge 10 EVs is estimated to be 115.2 $m^2$ and the designed PV system would cover an area of 122 $m^2$. The extra area can hence be used to place the EV chargers and other auxiliary devices\textsuperscript{11} as implied in Figure 1.5.

Financial Analysis

It is imperative to carry out a thorough appraisal of the initial investment costs of the E-Hub. The suggested components in Chapter 5 costs 24.793 €. It is seen in Figure 5.5 that Module and Inverter costs account to only 37% of total PV system costs. The total E-Hub initial investment is hence calculated to be 50397.75 €(refer Table 5.6).

\textsuperscript{11}E-Hub Control unit
Chapter Overview

In this chapter the power management algorithms are discussed from the E-Hub context. This approach is pursued to control the EV charging which is now referred as 'Smart Charging'. The initial section discusses the optimisation model that is implemented along with the mathematical equations which define the power management algorithm. The final section later identifies the mathematical equations which build the linear programming algorithm implemented in this thesis project.

6.1. Linear Programming

To approach an implementation of power management algorithms in the designed E-Hub system it is essential to identify mathematical programming models to find an optimal channel to manage the power flow. In the E-Hub background, power management scenario can be translated to mathematical equations which formulate [10, 33]:

- Maximizing/Minimizing an objective - Criteria for performance
- Limited resources - Decision variables
- Competing constraints

Since in the E-Hub scenario the above mathematical equations have constraints that can be specified as equalities/inequalities, Linear programming (LP) optimisation model is adopted. As mentioned in Table 2.2 LP is modelled using the 'linprog' solver in MATLAB.

The LP problem can now be defined mathematically in Equation 6.1

\[
\min_{x} f^T x \quad \text{s.t.} \quad A x \leq b \quad A_{eq} x = b_{eq} \quad lb \leq x \leq ub
\]  

(6.1)

where:
- \( f \) is the objective function (vector)
- \( x \) is the design variable which is being calculated (vector)
- \( lb \) and \( ub \) are the lower and upper bounds of the constraints (vectors)
- \( b_{eq} \) and \( A_{eq} \) are the linear equality constraints which are vector and matrix respectively
- \( b \) and \( A \) are the linear inequality constraints which are vector and matrix respectively
6.2. Application of Linear Programming in E-Hub

In this section the model of LP is discussed and how LP can be adopted to achieve smart charging of EVs in the E-Hub. Smart charging is hence a charging strategy where the EV owners or EV charging facility shares data such as available charging time, available local RES generation with the grid operator to have an optimal charging schedule to increase profits or minimize the loss during the EV charging operation [31].

It should be noted that the following statements hold true for LP modelling in this section:

- Uncertainty about the prediction of load and supply is considered to be nil.
- The load and supply data from Chapter 3 and 4 are held true.
- The time step for the model is one hour. Hence the LP model is carried out for a period of 24 hours with 24 samples.

The various variables used in the LP model are listed in Table 6.1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>Number of EV</td>
<td>-</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
<td>Hour</td>
</tr>
<tr>
<td>( \theta_t )</td>
<td>Exchange with the grid</td>
<td>kW</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Maximum import from grid</td>
<td>kW</td>
</tr>
<tr>
<td>( EV_t )</td>
<td>Total power to charge the EV fleet</td>
<td>kW</td>
</tr>
<tr>
<td>( PV_t )</td>
<td>Output power from the PV array</td>
<td>kW</td>
</tr>
<tr>
<td>( PW_t )</td>
<td>Battery charge/discharge power</td>
<td>kW</td>
</tr>
<tr>
<td>( \chi_{n,t} )</td>
<td>EV charging power</td>
<td>kW</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>Energy of use price of grid</td>
<td>€/kWh</td>
</tr>
<tr>
<td>( \Omega_t )</td>
<td>SOC of the battery</td>
<td>%</td>
</tr>
<tr>
<td>( C )</td>
<td>Capacity of the battery</td>
<td>kWh</td>
</tr>
<tr>
<td>( \eta )</td>
<td>Efficiency of EV charger</td>
<td>%</td>
</tr>
</tbody>
</table>

6.2.1. Upper and Lower Bounds

The \( ub \) and \( lb \) of the variables listed Table 6.1 as shown in Equation 6.1 are discussed in this section.

\[-22.15 \leq \theta_t \leq \kappa \quad \forall t \quad (6.2)\]

The electricity price paid by a customer accounts two components which are:

1. **Energy of use charge** (EOU) : Is the amount levied on the customer for energy usage over the billing period in terms of €/kWh. This EOU price hence depends on the peak and off-peak prices which fluctuates hourly and seasonally throughout the year.

2. **Demand charges** : These charges are of particular importance to industrial and commercial customers such as the E-Hub. Demand charges are levied on the customer based on the peak usage from the grid (kW) during the billing period in terms of €/kW.

If the peak shaving case is taken into account for the reduction of demand charges then,

\[ \kappa = 10 \quad (6.3) \]

or for cases without peak shaving

\[ \kappa = \infty \quad (6.4) \]

\(^{1}\)The model is considered to be deterministic.
The value of 22.15 kW is the maximum PV output obtained as observed in Figure 5.1.

The battery charge and discharging bounds are specified in Equation 6.5 from Appendix E. The battery system which is hence discussed in this section is the Tesla Powerwall 1 as mentioned in Chapter 8.

\[-3.3 \leq PW_t \leq 3.3 \quad \forall t\]  

It is essential to bear the lifetime of battery when considering the range to which the battery can be charged and discharged. The range is specified in Equation 6.6 [16, 32, 55]. It should also be noted that the battery management software (BMS) limits overdischarge and overcharge of the battery hence the assumed range accounts to 65% of the battery capacity C.

\[0.15 \leq \Omega_t \leq 0.80 \quad \forall t\]  

The upper limit of the total EV charging power is

\[EV_{MAX} = 7 \times 6 + 21 \times 4 = 126kW\]  

The individual chargers have the following relation as shown in Equation 6.9

\[\chi_{n,t} \cup \left\{ \begin{array}{ll} 0 \leq \chi_{i,t} \leq 7 & \forall i \in (1,2,3,4,5,6) \\ 0 \leq \chi_{j,t} \leq 21 & \forall j \in (1,2,3,4) \end{array} \right\} \]  

\[\Delta \Omega = \frac{1}{C} \int_{t_1}^{t_2} PW_t \cdot dt \]  

where:

\[C = 6.4 \text{ kWh} \text{ from Appendix E}\]

\[t_1 \text{ and } t_2 \text{ are charge/discharge time period in hours}\]
6.2.5. Objective Function

The objective function used in the LP model is

\[
\min_{\theta_t} \quad f (\theta_t \times \Lambda_t)
\]  

(6.14)

The grid insertion price is taken to be 2% lesser than the EOU price (\(\Lambda_t\)).

The above mentioned mathematical relations are then inserted in the LP model using the 'linprog' solver in MATLAB. The results are discussed in the following sections.
Chapter Overview

In this chapter, the first two sections identifies and analyses cases for winter and summer for different EV charging strategies. The chapter concludes with a technical and economical analysis of the studied cases along with an extension to the possibility of including more batteries in the E-Hub design and its effect on the revenue.

7.1. Cases

In this chapter, nine different scenarios are discussed for both summer and winter conditions. The above mentioned cases are analysed to compare the E-Hub design with and without a battery back-up system. In unregulated charging, optimisation algorithms discussed in Chapter 6 are not applied. The nine cases which would hence be examined on their technical and economical performance are listed in Table 7.1. Each case satisfies the charging demand required for the fleet of 10 EVs as shown in Figure 7.11.

<table>
<thead>
<tr>
<th>Name</th>
<th>Charging strategy</th>
<th>Season</th>
<th>Peak Shaving</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Unregulated</td>
<td>Summer</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 2</td>
<td>Regulated</td>
<td>Summer</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 3</td>
<td>Unregulated</td>
<td>Winter</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 4</td>
<td>Regulated</td>
<td>Winter</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 5</td>
<td>Regulated</td>
<td>Winter</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Case 6</td>
<td>Regulated</td>
<td>Summer</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Case 7</td>
<td>Regulated</td>
<td>Summer</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Case 8</td>
<td>Regulated</td>
<td>Winter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Case 9</td>
<td>Regulated</td>
<td>Winter</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

7.1.1. Case 1: Unregulated Charging in Summer

As mentioned in Section 7.1, in this scenario power management algorithms are not applied. It should be noted that positive power values are import from the grid and negative values are export to the grid. The power flow in such a system is shown in Figure 7.1.

It can be noticed that the total EV charging demand for the day which amounts to 83.45 kWh is satisfied at the earliest, irrespective of the change in grid EOU prices and available PV power. Unregulated charging is hence not advisable for generating revenue and for efficient utilization of RES. This leads to a massive import from the grid as seen in Figure 7.1 and 7.2.
The EV chargers (7 kW) function at their maximum capacity during the initial hour. It can also be inferred that in Figure 7.1 an introduction of battery back-up helps in exporting the available PV power later on in the day (20:00-00:00) when the grid EOU prices are high.
7.1. Cases

Results

The main conclusion from the studied scenarios are:

1. The RES source (PV) is not effectively utilized
2. Grid EOU prices are not taken into account while charging which results in high costs
3. There is stress on the grid due to higher import at peak EOU price hours
4. The maximum import from the grid amounts to 76.84 kW

In summer with unregulated charging the E-Hub achieves a revenue of \(1.96\ \text{€}\). It should however be noted that higher demand charges will be levied due to higher peak grid demand which would lead to a revenue much lesser than the calculated value.

7.1.2. Case 2: Regulated Charging in Summer

In this section, regulated charging with optimisation algorithms discussed in Chapter 6 is analysed. The power flow in such a scenario is shown in Figure 7.3.

Regulated charging clearly introduces effective utilization of available PV along with the grid EOU to maximize revenue. The EV charging is shifted to match the generation of PV. The E-Hub with regulated charging achieves grid independence. The maximum charging demand from EV chargers are below 2 kW due to regulated charging over the duration of the day to match the PV output. A battery back-up would help to postpone grid export during high EOU prices.

Results

1. Smart charging is implemented
2. The E-Hub has achieved grid independence
3. Greater revenue (No demand charges levied)
4. The maximum charging power requirement from a single EV charger is much lower than the listed 7 kW and 21 kW EV charger design proposed for the E-Hub.

In summer with regulated charging the E-Hub can achieve a revenue of \textbf{2.2031 €}.

7.1.3. Case 3: Unregulated Charging in Winter

In this section the unregulated charging scenario for winter is analysed in the same fashion as Section 7.1.1. The results are enumerated in the following below.

**Results**

1. The available PV power is not utilized
2. High stress on the grid due to peak import at peak EOU price hours
3. The maximum grid import amounts to 83.27 kW
4. The EV chargers (7 kW) function at their maximum power capacity

On a winter day with unregulated EV charging, the E-hub incurs a cost of \textbf{3.174 €}. The calculated cost does not include the peak demand charge costs which collectively increase the gross cost in winter.
7.1. Cases

Figure 7.5: Case 3: Power flow overview

Figure 7.6: Case 3: EV Charging profile
7.1.4. Case 4: Regulated Charging in Winter

The regulated charging scenario for a winter day is analysed similarly to Section 7.1.2 and the results are listed in the following section.

Figure 7.7: Case 4: Power flow overview

Figure 7.8: Case 4: EV Charging profile
7.1. Cases

Results

1. A fraction of EV charging is shifted to lower EOU prices
2. There is high grid import due to lack of PV output

On a winter day with regulated charging the E-Hub incurs a cost of €3.125. The cost incurred is only 1.54% lower than unregulated charging discussed in Section 7.1.3.

7.1.5. Case 5: Regulated Charging in Winter with peak shaving

It is seen in case 4 in Section 7.1.4 that the maximum grid import of 83.27 kW occurs at 09:00 when the grid EOU prices are the lowest during the 09:00-17:00 period (refer Figure 7.5). It is hence interesting to investigate implementation of peak shaving.

The results are shown in Figure 7.9 and 7.10.

![Figure 7.9: Case 5: Power flow overview](image)

In contrast to case 4, the EV charging profile has a more power distribution over the 09:00-17:00 time period. The main results are enumerated below.

Results

1. EV charging demand is met with a peak shaving of 10 kW
2. Grid import occurs at low grid EOU prices
3. The maximum grid import reduces by 88% as compared to Case 3 and 4
4. Individual charging demand for EV chargers has reduced greatly when compared to Case 3 and 4

On a winter day with regulated charging and peak shaving the E-Hub incurs a cost of €3.327.
7.2. Cases with Battery

To study the technical operation of the designed system along with its economic potential four different scenario are outlined. These scenarios deviate in terms of weather and restriction on grid import. The four cases which will be studied in this chapter are:

1. Summer day with peak shaving - Case 6
2. Summer day without peak shaving - Case 7
3. Winter day with peak shaving - Case 8
4. Winter day without peak shaving - Case 9

The above mentioned scenarios are taken to understand how the E-Hub varies according to weather which would effect the EV charging capability which further helps in interpreting the exchange with grid and battery system. The scenarios are simulated using the optimisation approach adumbrated in Chapter 6.

Table 7.2: Overview of cases under study

<table>
<thead>
<tr>
<th>Case</th>
<th>Grid prices (€/kWh)$^3$</th>
<th>PV output (kW)$^4$</th>
<th>EV load demand (kWh)$^5$</th>
<th>Maximum grid import (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Averaged price of July</td>
<td>July 3rd</td>
<td>July 3rd</td>
<td>10</td>
</tr>
<tr>
<td>1,2 &amp; 7</td>
<td>Averaged price of July</td>
<td>July 3rd</td>
<td>July 3rd</td>
<td>$\infty$</td>
</tr>
<tr>
<td>5 &amp; 8</td>
<td>Averaged price of January</td>
<td>January 9th</td>
<td>January 9th</td>
<td>10</td>
</tr>
<tr>
<td>3,4 &amp; 9</td>
<td>Averaged price of January</td>
<td>January 9th</td>
<td>January 9th</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

$^1$PV output variation
$^2$Cases in study are for the year 2017
$^3$Calculated in Section 6.2.3
$^4$Calculated PV output as shown in Figure 5.1
$^5$Simulated in Section 3.5
The charging demand for each EV was calculated in Section 3.5. The individual charging demand for each EV for each case mentioned in Table 7.2 is listed in Figure 7.11.

Figure 7.11: Charging demand for each EV

Source: Figure 3.11
It was decisive to calculate the starting state of charge \( \text{(SOC)} \) of the battery at start of EV charging. The starting SOC is hence not listed in Table 7.2. The SOC required by the battery at the start of the day for every case is calculated by the optimization algorithm listed in Chapter 6 with the Equations 6.6 and 6.14. The results are enumerated in the tables below.

### Table 7.3: Battery SOC - Case 6

<table>
<thead>
<tr>
<th>Starting SOC</th>
<th>Gross Profit (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td><strong>2.4409</strong></td>
</tr>
<tr>
<td>0.7</td>
<td>2.2682</td>
</tr>
<tr>
<td>0.6</td>
<td>2.2633</td>
</tr>
<tr>
<td>0.5</td>
<td>2.2579</td>
</tr>
<tr>
<td>0.4</td>
<td>2.255</td>
</tr>
<tr>
<td>0.3</td>
<td>2.2492</td>
</tr>
<tr>
<td>0.2</td>
<td>2.3492</td>
</tr>
<tr>
<td>0.15</td>
<td>2.2407</td>
</tr>
</tbody>
</table>

### Table 7.4: Battery SOC - Case 7

<table>
<thead>
<tr>
<th>Starting SOC</th>
<th>Gross Profit (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td><strong>2.4928</strong></td>
</tr>
<tr>
<td>0.7</td>
<td>2.2561</td>
</tr>
<tr>
<td>0.6</td>
<td>2.3883</td>
</tr>
<tr>
<td>0.5</td>
<td>2.4513</td>
</tr>
<tr>
<td>0.4</td>
<td>2.4525</td>
</tr>
<tr>
<td>0.3</td>
<td>2.4691</td>
</tr>
<tr>
<td>0.2</td>
<td>2.2455</td>
</tr>
<tr>
<td>0.15</td>
<td>2.2299</td>
</tr>
</tbody>
</table>

### Table 7.5: Battery SOC - Case 8

<table>
<thead>
<tr>
<th>Starting SOC</th>
<th>Gross Loss (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td><strong>3.1414</strong></td>
</tr>
<tr>
<td>0.7</td>
<td>3.1563</td>
</tr>
<tr>
<td>0.6</td>
<td>3.1711</td>
</tr>
<tr>
<td>0.5</td>
<td>3.1858</td>
</tr>
<tr>
<td>0.4</td>
<td>3.2006</td>
</tr>
<tr>
<td>0.3</td>
<td>3.2155</td>
</tr>
<tr>
<td>0.2</td>
<td>3.2322</td>
</tr>
<tr>
<td>0.15</td>
<td>3.2408</td>
</tr>
</tbody>
</table>

### Table 7.6: Battery SOC - Case 9

<table>
<thead>
<tr>
<th>Starting SOC</th>
<th>Gross Loss (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td><strong>2.9353</strong></td>
</tr>
<tr>
<td>0.7</td>
<td>2.9455</td>
</tr>
<tr>
<td>0.6</td>
<td>2.9558</td>
</tr>
<tr>
<td>0.5</td>
<td>2.9659</td>
</tr>
<tr>
<td>0.4</td>
<td>2.9761</td>
</tr>
<tr>
<td>0.3</td>
<td>2.9863</td>
</tr>
<tr>
<td>0.2</td>
<td>3.0016</td>
</tr>
<tr>
<td>0.15</td>
<td>3.0098</td>
</tr>
</tbody>
</table>

It can be inferred from the above results that the best economic potential is extracted when the battery is completely charged (80% SOC) at the start of EV charging. The results listed in the above tables also take into account the money expended outside the charging duration which is 17:00 of present day to 09:00 the next day.

In line with the obtained results, in the power management algorithm for the four cases the following constraint is added:

\[
\text{SOC}_{\text{initial}} = 0.8
\]  

(7.1)
7.4. Case 6: Summer with battery and peak shaving

The power management algorithms contrived in Chapter 6 is applied in Case 6 which is listed in Table 7.2. It should be noted that the positive power values are import from the grid and negative values are export to the grid.

The results are shown in Figure 7.12.

If the region between 09:00 - 17:00 is analysed it can be inferred that when the grid prices are high the following actions take place:

- The battery discharges if there is sufficient capacity
- The PV output is fed to the grid

The above actions take place to maximize profit by selling the power to grid and shifting the EV charging demand to the time period when the grid prices are relatively low during the 09:00 - 17:00 time-frame. When the grid prices are relatively low the following actions take place:

- EV charging
- Battery charging
  - With PV (if there is available PV output)
  - With grid (if the prices are cheap and below the maximum grid import)

In Figure 7.13 the battery behaviour is shown, as discussed in Section 7.3. It can be noticed that the battery discharges when the grid prices are high. The battery hence acts as a back up source to aid not only EV charging but also to export back to the grid during peak grid price period. It is also observed that at the end of the working day (17:00) the battery is completely discharged. The battery gets back to its designated capacity (80%) at the start of the day (09:00) after charging/discharging throughout the night to maximize profit.
From the implemented power management algorithms, the concept of 'smart charging' as envisioned in Section 6.1 is achieved. The results are presented in Figure 7.14. It can be observed that the charging of EV has shifted to 13:00 - 17:00 period when the grid prices are relatively lower due to the off-peak time period. The
maximum total EV charging power is 30 kW and the maximum charging power from a single charger is 4.628 kW.

Results
The main conclusions from the studied Case 6 are:

1. Smart charging is implemented
2. The E-Hub system has greatly reduced its dependency on the grid during summer day with grid import only at the minimum grid price during the 09:00 - 17:00 period
3. Greater revenue from RES (Solar power) due to selling of PV power at peak prices
4. The retail price payment has significantly reduced which now follows the general wholesale EOU prices
5. There is less stress on the grid, since the charging has shifted towards off-peak prices/time-period
6. The maximum charging power requirement from a single EV charger is much lower than the listed 7 kW and 21 kW EV charger design proposed for the E-Hub

In the summer with peak shaving the E-Hub can achieve a revenue of \(2.4409\) €.

7.5. Case 7: Summer with battery and without peak shaving

In this section the second case as listed in Table 7.2 is discussed. The complete set of results are attached in Appendix F.1. The overview of Case 7 is shown in Figure 7.15

The results are analysed in the same fashion as Case 6 and the results are enumerated in the following section.
Results

1. The maximum grid import occurs at 16:00 when the grid EOU price is the minimum and amounts to 53.43 kW

2. The EV charging hence shifts to the time period when the grid EOU price has its local minima in the 09:00 - 17:00 time-frame

3. The maximum charging power required by the EV chargers are greater as compared to Case 6

4. For the EVs being charged with 7 kW charger, the charging begins earlier than the EVs being charged from the 21 kW charger.

5. The maximum charging demand from the 7 kW charger is 6.47 kW

6. The maximum charging demand from the 21 kW charger is 11.31 kW

7. The battery is completely discharged at 17:00 and charges with PV power after 17:00 and when the grid EOU prices are lower comparatively

In the summer without peak shaving the E-Hub can achieve a revenue of 2.4928 €.

The revenue in Case 7 is 0.0571 € greater than Case 6. This increase is negligible since the charges paid for the grid import higher than 10 kW leads to greater demand charges which would result in a lower profit while calculating the gross revenue.
7.6. Case 8: Winter with battery and peak shaving

It is interesting to notice the power flow in the E-Hub during winter. As seen in Figure 7.16 the maximum PV power output is 10.42 kW as compared to 20.612 kW in summer. The EV charging behaviour mimics the PV output pattern with exemption when the grid EOU prices are high where in the available PV and battery power is exported to the grid to maximize revenue. The complete set of results for Case 8 are attached in Appendix F2.

![Figure 7.16: Case 8: Power flow overview](image)

It should be noted that in winter the strategy is to minimize losses unlike in summer since the E-Hub is not designed to be grid-independent system. The results are analysed in the similar approach as in Case 6 and the main results are listed below.

**Results**

1. The maximum grid import is limited to 10 kW and occurs during off-peak EOU price period at 09:00 and 12:00 - 16:00

2. The EV charging mimics the availability of PV except when the grid EOU prices are high

3. The battery is completely discharged at 17:00 and charges only during off-peak EOU prices to reach back to the destined SOC at 09:00 the next day through optimisation algorithms

4. The battery helps in improving revenue by discharging to the grid during high EOU prices especially at 19:00 where the highest EOU price is achieved mainly due to the cumulative heating demands during winter

5. The maximum EV charging demand is 20.53 kW with maximum power demand from a single EV charger at 3.033 kW

6. The maximum charging power requirement from a single EV charger is much lower than the listed 7 kW and 21 kW EV charger design proposed for the E-Hub

In winter with peak shaving the E-Hub incurs a cost of \(3.1414\) €.
7.7. Case 9: Winter with battery and without peak shaving

In this section the final case is examined. The overview of the power flow with respect to winter grid EOU prices are shown in Figure 7.17. In this case, the EV charging behaviour mimics the grid prices as can be seen with spike in grid import at 09:00 due to the local minima of grid EOU price in the 09:00 - 17:00 time-frame. The complete set of results are attached in Appendix F.3. The results are analysed in the similar fashion as the previous cases and the results are catalogued in the following section.

![Figure 7.17: Case 9: Power flow overview](image)

**Results**

1. The maximum grid import occurs at 09:00 and amounts to 83.27 kW
2. The bulk of EV charging occurs at the above mentioned time period when the local minima of grid EOU price is encountered
3. The maximum charging power required by the EV chargers are much higher than case 3 and amounts to 83.27 kW. It is hence noticed that the entire import from the grid is utilized to charge the EV fleet since there is no available PV and the battery is saved to be utilized later when the EOU prices are higher
4. Of the six 7 kW chargers, five of them function at maximum capacity at 09:00
5. Of the four 21 kW chargers, the maximum required charging demand is 13.414 kW and the complete charging of these four EVs occur in one hour (09:00 - 10:00)
6. The EV chargers are utilized to their capacity in this case
7. The battery is completely discharged at 17:00 and is utilized to maximize revenue as observed in the previous cases

In winter without peak shaving the E-Hub incurs a cost of **2.9353 €**.

The incurred cost in Case 9 is 0.6486 €less than case 3, however the grid import of 83.27 kW would lead to exorbitant costs due to higher demand chargers.
Technical and economical analysis

The economic performance is examined on basis of profit/loss during operation for a particular charging strategy as referred in Table 7.1. These costs however do not include the demand charges levied due to peak electricity usage and the cost of battery storage system. As mentioned in Section 6.2.1 demand charges are billed on a €/kW basis. The technical performance is reviewed on the peak grid import for a particular charging strategy as referred in Table 7.1. The energy usage of a particular charging strategy is more technically and economically feasible under lower peak demands.

The operating costs for EV charging for a day both in summer and winter conditions for various charging strategies are shown in Figure 7.18.

The results seen in Figure 7.18 depict ‘Regulated charging without peak shaving and with battery’ which are Case 7 and 9 as the economically optimum charging strategy for summer and winter. However as discussed before, Case 7 and 9 would encounter high demand charges due to peak grid import along with cost of battery systems. It is hence necessary to analyse the maximum grid import during the operation of the particular charging strategy. In Figure 7.19, the above mentioned scenario of ‘Regulated charging without peak shaving and with battery’ (Case 7 and 9) have high maximum grid import during the day\(^6\). In order to effectively compare the performance of each strategy, a performance index factor (PIF) is defined as:

\[
PIF_i = \frac{\kappa_i}{\theta_i}
\]

where:
- \(i\) = The case under study (from 1 to 9 in Table 7.1)
- \(PIF_i\) = Performance index factor in kW/€
- \(\kappa_i\) = Maximum import from grid in kW
- \(\theta_i\) = Overall cost of EV charging for one day in €

PIF accounts the maximum grid import and the profit/loss incurred during EV charging for the particular day of operation. The performance of studied cases are compared with respect to the performance of the base case of unregulated charging.

\(^6\)except unregulated charging scenario
It is seen in Figure 7.20 that for summer, 'Regulated charging with and without peak shaving' performs better than 'Regulated charging with peak shaving and with battery' by a factor of 0.05.

In winter 'Regulated charging with peak shaving and battery' and 'Regulated charging with peak shaving' perform at the same PIF as compared to unregulated charging.

Grid independent in summer
Introduction of more batteries

It can be distinctly noticed in the previously studied cases that Peak shaving is more technically and economically viable. It was hence critical to inspect inclusion of more batteries\(^7\) in the E-Hub and how such an involvement would effect the economics discussed in the previous sections.

The first case to be analysed in the scenario is Case 7.4 with more than 1 Tesla Powerwall, the results of which are shown in Figure 7.21a. The revenue increases with introduction of more batteries, however the profits gained outside the working hours in the day are dormant which can be reasoned due to the costs incurred on charging in time period (17:00 - 09:00) where the only opportunity to charge the battery is from the grid due to non-existence of PV output power.

The increase in revenue from introduction of more batteries is however not the case from a realistic scenario when the costs of battery and auxiliary components are taken into account. In Figure 7.21b the scenario for case 7.6 is examined. The gross costs incurred in winter linearly reduces with introduction of more Tesla powerwalls however the costs to charge the batteries outside working hours increases due to the increased charging demand. This negates the previous effect.

It can therefore be concluded that for the conditions stated in Section 7.3, the E-Hub system performs at the economic optimum scenario throughout the year with one Tesla Powerwall which is fully charged (80% SOC) at 09:00 every day.

---

\(^7\)Tesla Powerwall 1
7.8. Conclusion

The power management algorithms designed in Chapter 6 is applied on nine different cases mentioned in Table 7.1. The power management algorithms are designed for optimum economic performance during summer and winter. The power flow for each charging strategy is analysed along with the corresponding EV charging profile. The cost of operation for each day in summer and winter is calculated. The results are listed in Table 5.5.

Table 7.7: EV charging cost for each day

<table>
<thead>
<tr>
<th>Case</th>
<th>Profit (€)</th>
<th>Loss (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.96</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2.203</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>3.174</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>3.125</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>3.327</td>
</tr>
<tr>
<td>6</td>
<td>2.44</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>2.492</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>3.141</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>2.935</td>
</tr>
</tbody>
</table>

A performance index factor is defined to compare the techno-economic performance of different EV charging strategies with respect to case of unregulated charging.

The results from Figure 7.20 show that the increase in techno-economic performance by introduction of battery is negligible when the cost of battery and auxiliary components of storage are accounted.
8

Test Model

Chapter Overview

In Chapter 6 and 7 the various power management algorithms were implemented in idealized test cases. In this chapter the practical evaluation of the designed algorithms on an experimental test set-up is attempted. This test set-up hence provides a proof of concept to analyse behaviour of the various components of the E-Hub system in terms of power flow. The direct implementation of chosen E-Hub components are at present not conceivable due to constraints of investment and space. Therefore the tests are carried out in a scaled down set-up as mentioned in Section 8.1 at the Electrical Sustainable Power Lab in EWI, TU Delft.

A detailed manual which explains the procedure required to carry out the tests mentioned in this chapter is attached in Appendix H.

8.1. Lab Set-Up

It was essential to have a system which can be controlled to follow custom user defined settings to respond to a dynamic charging and discharging profile. The Eneco SolarEdge and Tesla Powerwall (ESTP) set-up was hence chosen as the test bed to implement the power management algorithms of Chapter 6 and 7.

The following requirements hence needs to be satisfied:

• The system should be able to communicate with the various components in ESTP in real time
• The status information of ESTP should be displayed in real time and must be viable to be logged for data processing
• A real time user defined controlling command can be operated by the system
• Remote control of the complete set-up should be viable
• Ease of use for customers
• The system should be easily scalable for future requirements
• The system permits configurable choice of settings for custom power management profiles

The components of ESTP are shown in Figure 8.1.

PV Emulators

In the absence of solar panels in Electrical Sustainable Power Lab, eight 30V DC power supplies with control PCB’s are utilized as PV emulators to mimic the behaviour of a real solar panel. Each emulator is connected to a P404 SolarEdge DC optimizer to regulate a voltage to 50V DC to achieve a 400V DC bus as shown in Figure 8.1. The emulators are connected in series and the DC power output is directly fed to the inverter.

It should therefore be noted that in this chapter PV modules refer to these PV emulators.
Inverter

The **SolarEdge SE3500** solar inverter is used in the ESTP set-up, the datasheet of the inverter is attached in Appendix C. The connection between the 400V DC bus to the 230V AC grid is realised with the SolarEdge SE3500 solar inverter.

StorEdge Interface

As show in Figure 8.1 this module interfaces the 400V DC bus and the RS485 communication module of the battery and SolarEdge inverter. The datasheet of StorEdge Interface is attached in Appendix G.

Battery

The Li-ion battery used in the ESTP set-up is the **Tesla Powerwall 1**. The powerwall is directly connected to the 400V DC bus and communicates with the RS485 communication module of StorEdge interface. The datasheet of Tesla Powerwall 1 is attached in Appendix E.

AC Load

The ESTP is mounted on a trolley as shown in Figure 8.3. At the backside of the trolley there are two lamps connected with the following power rating:

- 500W × 2
  
  To include more loads the set-up now consists of
  
  - 400W × 2

In this chapter as mentioned in the overview these lamps are considered as EV present for charging. The manual for the connection and control of the AC loads are explained in detail in Appendix H.
8.2. SolarEdge Monitoring Portal

In line with the discussed functional goals of the system in Section 8.1, the SolarEdge monitoring portal serves as the perfect medium to achieve a dynamic controllable set-up with the ESTP. The monitoring portal can be accessed at https://monitoring.solaredge.com/solaredge-web/p/login or by a mobile application for the Android and iOS platform.

The portal can be used to read real time data from the components discussed in Section 8.1 and also to control and configure custom user defined profiles which is explained in Section 8.3. The SolarEdge monitoring portal is cloud based platform which therefore presents a remote monitoring solution. This service was extensively used in this thesis research to control the ESTP set-up to achieve the required results. A typical screen layout is shown in Figure 8.2 where the set-up is in idle mode.

![SolarEdge monitoring portal dashboard](https://monitoring.solaredge.com/solaredge-web/p/login)

8.3. Charge/Discharge Profile Programming

The charge/discharge (C/D) profile can be constructed from a set of seven available modes. Each mode has a custom purpose which can then be selected to create the overall user profile as explained in the Manual in Appendix H [24]. The C/D profile is programmed on an annual basis. The annual profile consists of three parts:

1. **Daily Profile**: The C/D variations in the day can be programmed here for various user preferences such as
   (a) Weekday
   (b) Weekend
   (c) Summer weekday
   (d) Winter weekend
   (e) Holidays

2. **Seasonal Profile**: The variations of C/D profile for the week are programmed here. Each day of the week can then be chosen from the 'Daily Profile' which is programmed before hence shaping a week
according to Weekday/Weekend/Holiday etc. These seasonal profiles can be used to denote specific periods of the year such as:

- Summer
- Winter
- Holidays/Vacation

It should be noted that the Seasonal Profile should cover the entire year. The seasonal profile could then be

- Annual (Jan 1st - Dec 31st) : Then the whole year would be a repetition of the weekly profile.
- Annual with seasonal variations : Here the specific seasons would each have a seasonal profile of its own. For the case mentioned below the seasonal profile start and end dates would be as mentioned below. It can hence be used to create profiles which would then correspond to changes in the grid prices specific to each season. It should again as mentioned before checked that the seasonal profile covers the entire year.
  (a) Spring - March 1 to May 31
  (b) Summer - June 1 to August 31
  (c) Fall - September 1 to November 30
  (d) Winter - December 1 to February 28

3. **Special day type** : The exceptions of the year are programmed here. The day profile in the special day type denoted dates that should have the said profile instead of the seasonal profile programmed during that period. Special days can be set as one-time events or as recurring events [24].

![Figure 8.3: ESTP set-up in the lab](image)
8.4. Charge/Discharge (C/D) Modes

The seven charging and discharging modes are discussed in this section. The monitoring portal dashboard figures shown in each sub-section of this section were taken during the tests the results of which are depicted in Section 8.5.

8.4.1. Battery OFF

In this mode, Tesla Powerwall is disabled through the StorEdge interface. The battery is hence not charged or discharged. This mode is applied when the lifetime of the battery needs to be extended by minimizing shallow C/D cycles which is prevalent in night-time and winter [24].

This mode can hence be applied in the regions where battery is not utilized in Figure 7.12, 7.15, 7.16 and 7.17.

![Battery OFF without load](image1)

![Battery OFF with load](image2)

(b) Battery OFF with load

Figure 8.4: C/D Mode 1 : Battery OFF

In Figure 8.4, the dashboard of SolarEdge Monitoring portal is shown when the Battery OFF mode is activated.

8.4.2. Charge excess PV Power

In this mode, the PV power which is not self consumed is used for charging the Tesla Powerwall [24]. This mode can be used especially in summer where the excess PV power is used to charge the battery in Figure 7.12 and 7.15.

8.4.3. Charge from PV

This mode is implemented when the battery needs to be charged with all the available PV power until the mode is activated. The priority is hence given to charge the battery and the PV power is not used for self-consumption [24].

This mode is used extensively in the studied scenarios in Figure 7.12, 7.15, 7.16 and 7.17 when the import grid EOU prices are high.

![Charge from PV](image3)

![Figure 8.5: C/D Mode 3 : Charge from PV](image4)

It is however seen in Figure 8.5 that even when the present mode is activated a tiny fraction of PV power amounting to an average of 50W is used for self-consumption. This is due to the internal programming of the SolarEdge inverter as stated in Appendix C.
8.4.4. Charge from PV and Grid

In this mode, the priority is given to charge the Tesla Powerwall with all available PV power and imported power from the grid. This mode is again extensively used in scenarios shown Figure 7.12, 7.15, 7.16 and 7.17. It is hence activated when the grid EOU are low.

![Figure 8.6: C/D Mode 4: Charge from PV and Grid](image)

It is seen in Figure 8.6 that the battery is charged even in the presence and absence of local load. It is hence crucial to limit the import rate from the grid \(^1\).

The SolarEdge monitoring portal allows programming of this charging import limit from the grid which is explained in Section 8.2 of the manual attached in Appendix H.

8.4.5. Discharge to maximize export

This mode is activated when the battery is sufficiently charged and the grid EOU prices are high, since the battery is completely discharged until the AC limit of the inverter is reached \([24]\). The Tesla Powerwall has a maximum discharge capacity of 3.3 kW which is seen in Figure 7.12, 7.15, 7.16 and 7.17 as stated in the datasheet from Appendix E.

![Figure 8.7: C/D Mode 5: Discharge to maximize export](image)

It is seen that the maximum discharge power capacity is limited to 3.26 kW by the internal safety mechanism in the SolarEdge inverter as stated in Appendix C.

\(^1\)Peak Shaving to minimize demand charges
8.4.6. Discharge to minimize import

In this mode, the battery is discharged only for self-consumption. This mode is hence activated when the grid EOU prices are high and is extensively used in the studied scenarios of Chapter 7.2. The battery is hence not discharged for export to the grid as seen in the previous mode [24].

![Figure 8.8: C/D Mode 6: Discharge to minimize import](image)

It is seen that even though the battery is discharged only for self-consumption an average of 100W which is 22.7% of the total power-flow in Figure 8.8 is exported to the grid due to the internal reading of the wattnode-meter and losses as stated in the datasheet. (Appendix G)

8.4.7. Maximize Self-Consumption

Maximize Self-Consumption (MSC) is the default mode of ESTP. In MSC mode, the battery is charged or discharged as needed to maximize self consumption with the amount of available PV power output [24].

![Figure 8.9: C/D Mode 7: Maximize Self-Consumption](image)

In this mode the system tries to be grid independent as seen in Figure 8.9.
8.5. Results

The above discussed modes are tested using the ESTP set-up to analyse the power flow. Two cases are presented in this section which cumulatively cover the seven C/D modes.

Case 1

The following modes are analysed in this case with respect to the results depicted in Figure 8.10 and 8.10:

- **DMI**: Discharge to minimize import

  The ESTP is started with DMI and in the absence of load. It can hence be seen the PV output is exported to the grid.

- **Charge from PV**

  This mode is activated at 10:00, the battery SOC is steadily increasing due to charging from total available PV power and the load of 1 kW is hence satisfied from the grid.

- **Battery OFF**

  The battery SOC is constant and the load is now satisfied with available PV output power. There is import from the grid since the load is greater than the available PV power.

- **MSC**: Maximize self-consumption

  In MSC, the battery is discharged with respect to the load. The battery power is hence the difference of PV output power and load demand\(^2\). The battery SOC therefore drops from 81.6% to 74.95%.

- **Charge from PV**

  Battery again charges from total available PV power and the load is satisfied with the power imported from the grid.

- **DME**: Discharge to maximize export

  In this mode, the battery is discharged to its maximum capacity of 3.26 kW which results in battery SOC dropping rapidly from 76.49% to 20.24%.

\(^2\) in kW
8.5. Results

Figure 8.10: Case 1: Power flow in the ESTP set-up

Figure 8.11: Case 1: Battery behaviour in the ESTP set-up
Case 2

The following modes are analysed in this case with respect to the results depicted in Figure 8.11 and 8.11:

- **Charge from PV and Grid**

  The battery is charged at its maximum charging capacity of 3.26 kW. This leads the battery SOC to rapidly rise from 26.34% to 39.8%. The introduction of AC load at 10:00 AM leads to an increase in import from the grid

- **Battery OFF**

  Battery SOC is constant and the load is satisfied from the available PV output power and grid.

- **Charge from PV and Grid**

  Battery is again charged at its maximum power capacity leading to a rapid increase in SOC from 39.8% to 100% 3.

- **DME**

  The battery is discharged at its maximum power capacity, leading to a rapid drop in SOC. It should be noted that rapid cycles of Charge from PV and Grid and DME can lead to degradation of battery life due to rapid C/D.

- **Battery OFF**

  The battery SOC is again constant. It can be seen that in the absence of a load, the available PV power is exported to the grid.

- **Charge excess PV**

  Follows the same profile as in Charge from PV mode, due to the undersized PV system 4 design in the Electrical Sustainable Power Lab.

- **DMI**

  In this mode, the priority is to attain grid independence. It can hence be observed that the fluctuation of load is satisfied by the dynamic battery discharge profile. This leads to a drop in battery SOC from 67.38% to 51.18%.

---

3 The internal safety mechanism of StorEdge and Tesla Powerwall prevents overcharge and deep discharge (Appendix G and E)

4 Using PV emulators
8.5. Results

Figure 8.12: Case 2: Power flow in the ESTP set-up

Figure 8.13: Case 2: Battery behaviour in the ESTP set-up
8.6. Conclusion

The experimental test set-up is outlined along with its present technical competence and constraints. The ESTP set-up provides a platform as a battery back up system for the E-Hub as seen in this chapter. However the ESTP is not viable for dynamic control as envisioned in the power management algorithms of Chapter 6 and 7.

The ESTP set-up functions on pre-programmed C/D profiles as outlined in Appendix H, hence for decisive functioning of the battery system a thorough EV charging pattern of the location under study needs to be analysed to program the C/D profiles.

Remote control and monitoring of the set-up is achieved by the use of SolarEgde monitoring portal. This cloud based portal therefore provides a means to log the data of corresponding parameters along with effective monitoring of the PV system, Inverter and the battery.

The seven different C/D modes were discussed along with their testing on the ESTP set-up under different loads and PV output throughout the day.
Conclusion and Recommendations

The objective of this thesis research was to design a solar based EV charging station in the TU Delft campus by analysing various charging strategies and to build a proof of concept to implement the designed charging strategies. The charging demand for a fleet of 10 EVs were calculated followed by a thorough PV system design for the E-Hub. Calendar effects were incorporated in the EV driving profile and PV module to accommodate environmental effects on the PV system.

Conclusion

To successfully attain a technical and economical feasible realisation of the E-Hub project, several research questions were outlined in Section 1.3.2, which are now answered based on the results of this research study.

1. What is the yearly charging demand for an EV fleet at the TU Delft campus?

The EV fleet was categorized as employees and visitors. The Dutch mobility report by Ministry of Infrastructure and the Environment was used to mathematically model the driving pattern of an EV fleet. The gross annual charging demand was calculated to be 18.24 MWh with an average daily charging energy demand of 73.28 kWh.

2. Which renewable energy sources (RES) are to be utilized in the E-Hub design?

A hybrid Photovoltaic and Wind turbines system were considered in the preliminary E-Hub design however after examining the law and legislatures outlined by Dutch Ministry of Infrastructure and the Environment for Wind turbine in urban spaces, a PV system was decided to be the RES for the E-Hub. An analysis into installation costs, operation and maintenance costs and lifetime of wind and PV system further drove the choice of a PV system for the E-Hub.

3. Given the intermittent nature of RES. What is the estimated yield for the chosen RES?

It was found that for a module inclination of 28° facing south the estimated yield was calculated to be 1.19 MWh/m². Two different PV modules were considered in the PV system design. The estimated yield for the chosen PV module (Peimar OS 260P) amounts to 308.4 kWh.

4. What is the ideal size and design for the E-Hub?

The PV system for E-Hub consists of 75 PV modules arranged in a layout of 25 modules in series and 3 modules in parallel. The watt peak rating of the PV system is hence 19.5 kW at STC. A central inverter topology is recommended with the SMA Sunny Tripower 20 kW inverter. A set of 5 EV chargers are outlined with the respective charging capacity of 7 kW and 21 kW. The total ground area for the PV system is calculated to be 122 m² and the area required to park 10 EVs amounts to 115.2 m².

The initial investment for the E-Hub is calculated to be 50,398 €.
5. **Which power management algorithms are to be implemented in the E-Hub system?**

A linear programming model is implemented to design power management algorithms. The main objective of the algorithms is to achieve an economically optimum performance in summer and winter. The designed power management algorithms are implemented on nine different EV charging strategies. A performance index factor (PIF) is defined to analyse the charging strategies on both technical and economic performance.

6. **Is the chosen E-Hub system design viable for testing with favourable results?**

Yes. It was found that the designed power management algorithms can be tested on the **Eneco SolarEdge and Tesla Powerwall** (ESTP) set-up in the Electrical Sustainable Power Lab (EWI, TU Delft). The experiments were run and monitored in real time. The present capabilities and constraints of the ESTP set-up were outlined in a detailed **manual** for the Electrical Sustainable Power Lab (refer Appendix H).

It is seen from Chapter 7 that the introduction of Tesla Powerwall as a battery system opens up many technical and economical possibilities, however at the present such a system is not economically viable due to negligible increase in profits due to high installation and equipment costs. It should however be noted that with the steady increase in battery technology especially with the research and penetration of EV technology the battery costs are expected to become more cost competitive in correlation with the learning curve. The E-Hub system design with the Tesla Powerwall then would be economically feasible to be implemented.
Recommendations

This thesis research although comprehensive, a scope was defined in Section 1.3.3 to achieve the various objectives outlined in the above section. Naturally, there are opportunities for follow-up study on EV charging and EV charging infrastructure in the RES framework in urban spaces that would be capable of accommodating present and future needs.

Load profile

The load profile used in this thesis study was based on Dutch mobility report by Ministry of Infrastructure and the Environment which is calculated by user survey and statistics. The actual load profile in the TU Delft campus would be different. A complete driving profile of EVs in the university campus would provide a realistic profile that can drastically improve the performance assessment of E-Hub.

Location analysis

Once the location of E-Hub is finalized, a thorough location analysis can be carried out to examine the effects of shading. The design changes can then be implemented to improve the performance of E-Hub.

Scalability

The E-Hub is currently envisioned for 10 EVs, however with rise in penetration of EVs the E-Hub should be scalable to accommodate more EVs.

Time resolution

As seen in Chapter 7 the time resolution is presently on a hourly basis. The hourly time resolution greatly averages the PV output power. It is hence recommended in future research to have a more finite minutely resolution to have an improved dynamic control over the power management algorithms.

Case Study

In line with the scope of the thesis a the designed charging strategies are studies only for one single day of summer and winter to examine technical and economical performance. The results from such a study would only present an overview of the yearly performance. To accurately assess the financial competitiveness of the system an yearly study of the designed charging strategies is recommended.

PV System Protection - Fault detection

It is crucial to account fault detection mechanism in the designed PV system. A thorough electrical layout design is suggested to size and choose the appropriate components such as:

- PV sub array combiner boxes
- PV string disconnection devices
- String overcurrent protection devices
- Overvoltage protection devices
- PV array combiner boxes
- Main DC disconnection devices

Economic and environmental analysis

In this thesis, the economic analysis was analysed for a day in summer and winter. It would be interesting to study the complete yearly economic performance of the designed charging strategies for the E-Hub. The economic analysis can be extended to include the effects of battery degradation. Environmental analysis can be carried out to estimate the CO$_2$ emissions saved and extended to the environmental costs for EV charging, EV charging infrastructure and PV system.

Charging technologies

The area of Vehicle to grid (V2G), DC fast charging and Wireless charging can be explored to be implemented in the E-Hub design. Investment of these technologies in the E-Hub opens up research in design, technical, economical and architectural fronts.
PV Datasheets

The relevant pages of the chosen PV Module datasheets are attached here.

SunPower E20-327

SunPower® E-Series Residential Solar Panels | E20-327

More than 20% Efficiency
Ideal for roofs where space is at a premium or where future expansion might be needed.

High Performance
Delivers excellent performance in real-world conditions, such as high temperatures, clouds, and low light. 1,2

Proven Value
Designed for residential rooftops. E-Series panels deliver the features, value and performance for any home.

Maxeon® Solar Cells: Fundamentally better
Engineered for performance, designed for durability.

Engineered for Peace of Mind
Designed to deliver consistent, trouble-free energy over a very long lifetime. 3,4

Designed for Durability
The SunPower Maxeon Solar Cell is the only cell built on a solid copper foundation. Virtually impervious to the corrosion and cracking that degrade conventional panels. 3,9

#1 Rank in Fraunhofer durability test. 9
100% power maintained in Atlas 25+ comprehensive durability test. 7,10

High Efficiency
Generate more energy per square foot
E-Series residential panels convert more sunlight to electricity by producing 51% more power per panel and 60% more energy per square foot over 25 years. 1,2,3

High Energy Production
Produce more energy per rated watt
High year-one performance delivers 7-9% more energy per rated watt. This advantage increases over time, producing 20% more energy over the first 25 years to meet your needs. 2

High Performance & Excellent Durability

High Efficiency

Generate more energy per square foot

More energy per rated watt

Engineered for Peace of Mind

Designed for Durability

Maxeon® Solar Cells: Fundamentally better

Engineered for performance, designed for durability.

Designed for Durability

The SunPower Maxeon Solar Cell is the only cell built on a solid copper foundation. Virtually impervious to the corrosion and cracking that degrade conventional panels. 3

#1 Rank in Fraunhofer durability test. 9
100% power maintained in Atlas 25+ comprehensive durability test. 7,10

Designed for Durability

Maxeon® Solar Cells: Fundamentally better

Engineered for performance, designed for durability.

Engineered for Peace of Mind

Designed to deliver consistent, trouble-free energy over a very long lifetime. 3,4

Designed for Durability

The SunPower Maxeon Solar Cell is the only cell built on a solid copper foundation. Virtually impervious to the corrosion and cracking that degrade conventional panels. 3

#1 Rank in Fraunhofer durability test. 9
100% power maintained in Atlas 25+ comprehensive durability test. 7,10

High Performance

High year-one performance delivers 7-9% more energy per rated watt. This advantage increases over time, producing 20% more energy over the first 25 years to meet your needs. 2

High Efficiency

Generate more energy per square foot

More energy per rated watt

Engineered for Peace of Mind

Designed for Durability

Maxeon® Solar Cells: Fundamentally better

Engineered for performance, designed for durability.
SunPower® E-Series Residential Solar Panels | E20-327

SunPower® Offers The Best Combined Power And Product Warranty

<table>
<thead>
<tr>
<th>Power Warranty</th>
<th>Product Warranty</th>
</tr>
</thead>
<tbody>
<tr>
<td>More guaranteed power: 95% for first 5 years</td>
<td>Combined Power and Product defect 25-year coverage</td>
</tr>
</tbody>
</table>

### Electrical Data

<table>
<thead>
<tr>
<th>Description</th>
<th>E20-327</th>
<th>E20-320</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power (Nom)</td>
<td>327 W</td>
<td>320 W</td>
</tr>
<tr>
<td>Power Tolerance</td>
<td>+5%/-0%</td>
<td>+5%/-0%</td>
</tr>
<tr>
<td>Avg. Panel Efficiency¹</td>
<td>20.4%</td>
<td>19.9%</td>
</tr>
<tr>
<td>Rated Voltage (Vpp)</td>
<td>54.7 V</td>
<td>54.7 V</td>
</tr>
<tr>
<td>Rated Current (Imp)</td>
<td>5.98 A</td>
<td>5.86 A</td>
</tr>
<tr>
<td>Open-Circuit Voltage (Voc)</td>
<td>64.8 V</td>
<td>64.8 V</td>
</tr>
<tr>
<td>Short-Circuit Current (Iss)</td>
<td>6.46 A</td>
<td>6.24 A</td>
</tr>
<tr>
<td>Max. System Voltage</td>
<td>600 V UL &amp; 1000 V IEC</td>
<td></td>
</tr>
<tr>
<td>Maximum Series Fuse</td>
<td>15 A</td>
<td></td>
</tr>
<tr>
<td>Current Temp Coef.</td>
<td>-0.35% / °C</td>
<td></td>
</tr>
<tr>
<td>Voltage Temp Coef.</td>
<td>-176.6 mV / °C</td>
<td></td>
</tr>
</tbody>
</table>

### Notes and Restrictions

1. All comparisons are SPR-E20-327 vs. a representative conventional panel: 250 W, approx. 1.6 m², 15.3% efficiency.
4. "SunPower Module 40-Year Useful Life" Sunpower white paper, May 2015. Useful Life is 99 out of 100 panels operating at more than 70% of rated power.
6. 6.6% more energy than the average of the top 10 panel companies tested in 2012 (151 panels, 92 companies). Photon (international) Feb 2013.
8. Some restrictions and exclusions may apply. See warranty for details.
9. Ratings are based on average from a comprehensive laboratory testing of five panels.
10. Limited to panels manufactured after 2014.
15. Compared with the top 5 manufacturers tested in 2012 (151 panels, 92 companies). Photon (international) Feb 2013.
17. Compared with the top 5 manufacturers tested in 2012 (151 panels, 92 companies). Photon (international) Feb 2013.
23. Compared with the top 5 manufacturers tested in 2012 (151 panels, 92 companies). Photon (international) Feb 2013.
25. Compared with the top 5 manufacturers tested in 2012 (151 panels, 92 companies). Photon (international) Feb 2013.
27. Compared with the top 5 manufacturers tested in 2012 (151 panels, 92 companies). Photon (international) Feb 2013.
Peimar OS260P

PEIMAR polycrystalline solar panels made in Italy provide customers with a perfect combination of high-efficiency and versatility. Thanks to the use of high-quality solar cells, our panels achieve outstanding performance and ensure maximum production output even under poor lighting and weather conditions. The strong yet ultra-light frames, available in silver or black make installation easy but robust in either residential, commercial or large-scale settings.
### ELECTRICAL Characteristics (STC)*

<table>
<thead>
<tr>
<th></th>
<th>OS250P</th>
<th>OS260P</th>
<th>OS270P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Output (Pmax)</td>
<td>250 W</td>
<td>260 W</td>
<td>270 W</td>
</tr>
<tr>
<td>Flash Test Power Tolerance</td>
<td>0/+5 W</td>
<td>0/+5 W</td>
<td>0/+5 W</td>
</tr>
<tr>
<td>Voltage at Pmax (Vmp)</td>
<td>30.5 V</td>
<td>30.8 V</td>
<td>31.1 V</td>
</tr>
<tr>
<td>Current at Pmax (Imp)</td>
<td>8.20 A</td>
<td>8.45 A</td>
<td>8.69 A</td>
</tr>
<tr>
<td>Open Circuit Voltage (Voc)</td>
<td>37.8 V</td>
<td>37.9 V</td>
<td>38.0 V</td>
</tr>
<tr>
<td>Short Circuit Current (Isc)</td>
<td>8.87 A</td>
<td>9.06 A</td>
<td>9.25 A</td>
</tr>
<tr>
<td>Maximum System Voltage</td>
<td>1000 V</td>
<td>1000 V</td>
<td>1000 V</td>
</tr>
<tr>
<td>Maximum Series Fuse Rating</td>
<td>15 A</td>
<td>15 A</td>
<td>15 A</td>
</tr>
<tr>
<td>Cell Efficiency</td>
<td>17.12 %</td>
<td>17.31 %</td>
<td>17.49 %</td>
</tr>
<tr>
<td>Module Efficiency</td>
<td>15.37 %</td>
<td>15.38 %</td>
<td>16.60 %</td>
</tr>
</tbody>
</table>

*STC: Standard Test Conditions (irradiance 1000W/m², Module Temperature 25°C, Air Mass 1.5)

### MECHANICAL Characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cells</td>
<td>60 (6x10) polycrystalline</td>
</tr>
<tr>
<td>Solar Cells Size</td>
<td>158x156 mm / 6x6&quot;</td>
</tr>
<tr>
<td>Front Cover</td>
<td>3.2 mm / 0.12&quot; thick, low iron tempered glass</td>
</tr>
<tr>
<td>Back Cover</td>
<td>TPT (Tedlar PET Tedlar)</td>
</tr>
<tr>
<td>Encapsulant</td>
<td>EVA (Ethylene vinyl acetate)</td>
</tr>
<tr>
<td>Frame</td>
<td>Anodized aluminum alloy, double wall</td>
</tr>
<tr>
<td>Frame finishing</td>
<td>Silver/Black</td>
</tr>
<tr>
<td>Backsheet finishing</td>
<td>White</td>
</tr>
<tr>
<td>Diodes</td>
<td>3 Bypass diodes serviceable</td>
</tr>
<tr>
<td>Junction Box</td>
<td>IP66 rated</td>
</tr>
<tr>
<td>Connector</td>
<td>MC4 or compatible connector</td>
</tr>
<tr>
<td>Cables Length</td>
<td>900 mm / 36&quot;</td>
</tr>
<tr>
<td>Cables Section</td>
<td>4.0 mm² / 0.006&quot;</td>
</tr>
<tr>
<td>Dimensions</td>
<td>1640x992x40 mm / 64.5x39x1.57&quot;</td>
</tr>
<tr>
<td>Weight</td>
<td>18 kg / 39.7 lb</td>
</tr>
<tr>
<td>Max. Load</td>
<td>Certified to 5400 Pa</td>
</tr>
</tbody>
</table>

### TEMPERATURE Characteristics

<table>
<thead>
<tr>
<th>Condition</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOCT**</td>
<td>45±2 °C</td>
</tr>
<tr>
<td>Temperature Coefficient of Pmax</td>
<td>-0.43 %/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of Voc</td>
<td>-0.32 %/°C</td>
</tr>
<tr>
<td>Temperature Coefficient of Isc</td>
<td>0.047 %/°C</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40 °C ~ +85°C</td>
</tr>
</tbody>
</table>

**NOCT: Nominal Operation Cell Temperature Sun 800W/m²; Air 20°C; Wind speed 0 m/s

### PACKAGING***

- Pallet dimensions: 1700x1100x1200 mm / 67x43x47"
- Pieces per pallet: 27
- Weight: 516 Kg / 1138 lb

***Pallets can be stacked up to two

### CERTIFICATIONS

- Pre-Resistance Rating: 1 (IEC61737)

### CURRENT/VOLTAGE Characteristics

- Values apply to panel OS250P

---

**REV 2_02/2017**

It is important to point out, that all technical specifications, information and figures contained in this datasheet are estimated values. Peimar reserves the right to change the technical specifications, information and figures contained in this document at any time and without notice.
SunPower Module PV Output Parameters
Figure B.1: Annual $T_m$ using DB model against $T_a$ for the year 2017 - Sunpower

Figure B.2: Annual $P_m$ variation - Sunpower
Figure B.3: Energy yield per day for the year 2017 - Sunpower
# Inverter Datasheets

**SolarEdge SE3500 Solar Inverter Datasheet**

## Specifications

### Output

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SE3000-16A</th>
<th>SE3500-16A</th>
<th>SE4000-16A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated AC Power Output</td>
<td>3000</td>
<td>3500</td>
<td>3680</td>
</tr>
<tr>
<td>Maximum AC Power Output</td>
<td>3000</td>
<td>3500</td>
<td>4000</td>
</tr>
<tr>
<td>AC Output Voltage (Nominal)</td>
<td>220/330 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Output Voltage Range</td>
<td>184-264.5 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Frequency (Nominal)</td>
<td>50/60 ±5 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Continuous Output Current</td>
<td>16 A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual Current Detector</td>
<td>300/30 mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Configurable Thresholds</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Additional Features

- **Safety**: IEC-62109 (EN61720), IEC-62109
- **Grid Connection Standards**: VDE 0126-1-1, VDE-AR-N-4105, AS-4777, RD-1663, DK 5940
- **Emissions**: IEC61000-6-2, IEC61000-6-3, IEC61000-3-11, IEC61000-3-12, FCC part15 class B
- **RoHS**: Yes
- **Establishment Compliance**: Export Limitation, StorEdge applications
- **Supported Communication Interfaces**: RS485, Ethernet, ZigBee (optional), Wi-Fi (optional), Built-in GSM (optional)
- **Smart Energy Management**: No

### Installation Specifications

- **AC Output**: Cable Gland - diameter 9.16 mm
- **DC Input**: 1 MC4 pair
- **Dimensions (HxWxD)**: 540 x 315 x 172 mm / 540 x 315 x 191 mm
- **Weight**: 20.2 kg / 21.7 kg
- **Cooling**: Natural Convection
- **Noise**: <25 dBa
- **Operating Temperature Range**: -20 to +50°C (MM4 version -40 to +50°C)
- **Protection Rating**: IP65 - Outdoor and Indoor
- **Bracket Mounted (Bracket Provided)**: Yes

---

1. SE3500-16A & SE3500-16B for United Kingdom, Ireland, Latvia, Portugal and Poland should be set to country code GB, IE, LV, PT in MOS respectively to limit to 16A. For other countries contact SolarEdge.
2. SE3500-16A & SE3500-16B for Denmark, Ireland, Latvia, Portugal and Poland should be set to country code GB, IE, LV, PT or MOS respectively to limit to 16A. For other countries contact SolarEdge.
3. Refer to Datasheets > Communications category in Downloads page for specifications of optional communication options: [http://www.solaredge.com/groups/support/downloads](http://www.solaredge.com/groups/support/downloads)
SMA Sunny Tripower 20000TL Inverter Datasheet

SUNNY TRIPOWER
15000TL / 20000TL / 25000TL

Efficient
• Maximum efficiency of 98.4%

Safe
• DC surge arrester (SPD type II) can be integrated

Flexible
• DC input voltage of up to 1000 V
• Multistring capability for optimum system design
• Optional display

Innovative
• Cutting-edge grid management functions with Integrated Plant Control
• Reactive power available 24/7 (Q on Demand 24/7)

SUNNY TRIPOWER
15000TL / 20000TL / 25000TL

The versatile specialist for large-scale commercial plants and solar power plants

The Sunny Tripower is the ideal inverter for large-scale commercial and industrial plants. Not only does it deliver extraordinary high yields with an efficiency of 98.4%, but it also offers enormous design flexibility and compatibility with many PV modules thanks to its multistring capabilities and wide input voltage range.

The future is now: the Sunny Tripower comes with cutting-edge grid management functions such as Integrated Plant Control, which allows the inverter to regulate reactive power at the point of common coupling. Separate controllers are no longer needed, lowering system costs. Another new feature—reactive power provision on demand (Q on Demand 24/7).
### Technical Data

<table>
<thead>
<tr>
<th>Input (DC)</th>
<th>Sunny Tripower 20000TL</th>
<th>Sunny Tripower 25000TL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. DC power (at cos φ = 1) / DC rated power</td>
<td>20440 W / 20440 W</td>
<td>25550 W / 25550 W</td>
</tr>
<tr>
<td>Max. input voltage</td>
<td>1000 V</td>
<td>1000 V</td>
</tr>
<tr>
<td>MPP voltage range / rated input voltage</td>
<td>320 V to 800 V / 600 V</td>
<td>390 V to 800 V / 600 V</td>
</tr>
<tr>
<td>Min. input voltage / start input voltage</td>
<td>150 V / 188 V</td>
<td>150 V / 188 V</td>
</tr>
<tr>
<td>Max. input current input A / input B</td>
<td>33 A / 33 A</td>
<td>33 A / 33 A</td>
</tr>
<tr>
<td>Number of independent MPP inputs / strings per MPP input</td>
<td>2 / A: 3; B: 3</td>
<td>2 / A: 3; B: 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output (AC)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (at 230 V, 50 Hz)</td>
<td>20000 W</td>
<td>25000 W</td>
</tr>
<tr>
<td>Max. AC apparent power</td>
<td>20000 VA</td>
<td>25000 VA</td>
</tr>
<tr>
<td>AC nominal voltage</td>
<td>3 / N / PE: 220 V / 380 V</td>
<td>3 / N / PE: 230 V / 400 V</td>
</tr>
<tr>
<td>AC voltage range</td>
<td>3 / N / PE: 240 V / 415 V</td>
<td>180 V to 280 V</td>
</tr>
<tr>
<td>AC grid frequency / range</td>
<td>50 Hz / 44 Hz to 55 Hz</td>
<td>180 Hz / 230 V</td>
</tr>
<tr>
<td>Rated power frequency / rated grid voltage</td>
<td>60 Hz / 54 Hz to 65 Hz</td>
<td>50 Hz / 230 V</td>
</tr>
<tr>
<td>Max. output current / Rated output current</td>
<td>29 A / 29 A</td>
<td>36.2 A / 36.2 A</td>
</tr>
<tr>
<td>Power factor at rated power / Adjustable displacement power factor</td>
<td>1 / 0 overexcited to 0 underexcited</td>
<td>≤ 3%</td>
</tr>
<tr>
<td>THD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed-in phases / connection phases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>98.4% / 98.0%</td>
<td>98.3% / 98.1%</td>
</tr>
</tbody>
</table>

### Protective devices

- DC-side disconnection device
- Ground fault monitoring / grid monitoring
- DC surge arrester (Type II) can be integrated
- DC reverse polarity protection / AC short-circuit current capability / galvanically isolated
- All-pole sensitive residual-current monitoring unit
- Protection class (according to IEC 62109-1) / overvoltage category (according to IEC 62109-1)
  - | / AC: III; DC: II

### General data

- Dimensions (W / H / D) | 661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)
- Weight | 61 kg (134.48 lb)
- Operating temperature range | −25 °C to +60 °C [-13 °F to +140 °F]
- Noise emission [typical] | 51 dB[A]
- Self-consumption (at night) | 1 W
- Topology / cooling concept | Transformerless / Opticool
- Degree of protection (as per IEC 60529) | IP55
- Climatic category (according to IEC 60721-3-4) | 4K4H
- Maximum permissible value for relative humidity (non-condensing) | 100%

### Features / function / Accessories

- DC connection / AC connection | SUNCLIX / spring-cage terminal
- Display | |
- Interface: RS485, Speedware/Webconnect
- Data interface: SMA Modbus / SunSpec Modbus
- Multifunction relay / Power Control Module
- OptiTrack Global Peak / Integrated Plant Control / Q on Demand 24/7
- OBC Grid capable / SMA Fuel Save Controller compatible
- Guarantee: 5 / 10 / 15 / 20 years
- Certificates and permits (more available on request)
  - IEC 60548, NBR 1271, IEC 61727, IEC 61215/2, IEC 6216, MEA 2013, NER 16149
  - IEC 60548, NBR 1271, IEC 61727, IEC 61215/2, IEC 6216, MEA 2013, NER 16149, NEN-EN 50348, NBR 1271, IEC 61727, IEC 61215/2, IEC 6216, MEA 2013, NER 16149
  - IEC 60548, NBR 1271, IEC 61727, IEC 61215/2, IEC 6216, MEA 2013, NER 16149

| Type designation | STP 20000TL-30 | STP 25000TL-30 |
EV-Box EV Charging Pole

The Business line series of EV charging pole EV Box is shown in Figure

Figure D.1: EV-Box Business line charging pole

The relevant pages of the EV charger data-sheet is attached here.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical features</strong></td>
<td></td>
</tr>
<tr>
<td>Charging capacity per connector</td>
<td>3.7kW, 7.4kW, 11kW, 22kW</td>
</tr>
<tr>
<td>Charge mode</td>
<td>Mode 3, Z.E. Ready</td>
</tr>
<tr>
<td>Connector type</td>
<td>Type 2</td>
</tr>
<tr>
<td>Number of connectors</td>
<td>1 or 2</td>
</tr>
<tr>
<td>CE certified</td>
<td>Yes</td>
</tr>
<tr>
<td>Outpower power</td>
<td>1-phase or 3-phase, 230V – 400V, 16A and 32A</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-25°C to +60°C</td>
</tr>
<tr>
<td>Moisture (non-regulating)</td>
<td>Max. 95%</td>
</tr>
<tr>
<td>Authorization</td>
<td>Auto START / Keyfob / RFID card</td>
</tr>
<tr>
<td>Information status</td>
<td>LED ring</td>
</tr>
<tr>
<td>Communication</td>
<td>GPS / GSM / UMTS / GPRS Modem / controller with RFID reader</td>
</tr>
<tr>
<td>Communication protocol</td>
<td>OCPP 1.2, 1.5 and 1.6</td>
</tr>
<tr>
<td><strong>Physical properties</strong></td>
<td></td>
</tr>
<tr>
<td>Designed according to IEC</td>
<td>IEC 61851-1 (2010), EC 61851-22 (2002), Renault Z.E. Ready guidelines</td>
</tr>
<tr>
<td>Protection</td>
<td>IP54, IK09</td>
</tr>
<tr>
<td>Housing</td>
<td>Polycarbonate (Bayblend)</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>600 x 255 x 410 (L x W x H / double socket)</td>
</tr>
<tr>
<td>Weight</td>
<td>11 kg (max.)</td>
</tr>
<tr>
<td>Mounting</td>
<td>Wall or pole</td>
</tr>
<tr>
<td>Standard colors</td>
<td>RAL 6024 (light green), RAL 6007 (dark green), RAL 5017 (blue), RAL 7042 (light grey), RAL 7016 (dark grey), RAL 9016 (white)</td>
</tr>
<tr>
<td>Optional</td>
<td>6 or 8 meter fixed cable</td>
</tr>
<tr>
<td>All online charging stations include a MID-certified kWh meter.</td>
<td></td>
</tr>
</tbody>
</table>
The Tesla Powerwall is a wall-mounted battery system for residential or light commercial use. Its rechargeable lithium-ion battery pack provides energy storage for solar self-consumption, load shifting, backup power, or any high-throughput application. Powerwall’s electrical interface is provided by an internal isolated bi-directional DC/DC converter controlling the charge and discharge of the battery for integration with utility-interactive inverters.

Powerwall achieves unprecedented levels of safety in home energy storage. It is a factory assembled, fully-certified unit that contains no user serviceable parts. The microprocessor controlled DC/DC converter is electrically isolated from the internal battery and eliminates user access to live terminals during installation or service.

### ELECTRICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, continuous and peak</td>
<td>3.3 kW</td>
</tr>
<tr>
<td>Energy*</td>
<td>6.6 kWh</td>
</tr>
<tr>
<td>Internal Battery Voltage</td>
<td>&lt; 50 VDC</td>
</tr>
<tr>
<td>System Operating Voltage</td>
<td>350 V–450 V</td>
</tr>
<tr>
<td>Voltage in OFF State</td>
<td>0 VDC</td>
</tr>
<tr>
<td>Current</td>
<td>9.5 ADC</td>
</tr>
<tr>
<td>Round Trip Efficiency*</td>
<td>92.5% (for a 400 V–450 V DC bus)</td>
</tr>
<tr>
<td>Depth of Discharge</td>
<td>100%</td>
</tr>
<tr>
<td>Equivalent Cycles</td>
<td>Unlimited cycles</td>
</tr>
<tr>
<td></td>
<td>(provided Powerwall is only used for solar self-consumption and backup)</td>
</tr>
</tbody>
</table>

* Values provided for 25°C (77°F), 2 kW charge/discharge power

### ENVIRONMENTAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>-20° C to 50° C (-4°F to 122°F)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>100% conditioned</td>
</tr>
<tr>
<td>Maximum altitude</td>
<td>3000 m (9843 ft)</td>
</tr>
<tr>
<td>Impact Rating</td>
<td>IK09</td>
</tr>
<tr>
<td>Ingress Rating</td>
<td>IP20 &amp; NEMA 3R (Powerwall) / IP67 (Battery Pod)</td>
</tr>
</tbody>
</table>

### MECHANICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>1302 mm (51.3 in) x 862 mm (34 in) x 183 mm (7.2 in)</td>
</tr>
<tr>
<td>Weight</td>
<td>97 kg (214 lbs)</td>
</tr>
</tbody>
</table>

### CERTIFICATIONS

- Powerwall: UL 9540, AC156 seismic certification, IEEE 693-2005 seismic certification, FCC Part 15 Class B, IEC/EN 61000 Class B
Results of studied cases

F.1. Case 7: Summer without battery and peak shaving
Case 7: Overview

Figure E.1: Case 7: Battery behaviour
Case 7: Summer without battery and peak shaving

Figure F.2: Case 7: EV charging profile
E.2. Case 8: Winter with battery and peak shaving

Figure E3: Case 8: Battery behaviour
Figure F.4: Case 8: EV Charging profile
E.3. Case 9: Winter without battery and peak shaving

Figure E.5: Case 9: Battery behaviour
E3. Case 9: Winter without battery and peak shaving

Figure E6: Case 9: EV Charging profile
SolarEdge StorEdge Interface Datasheet

## BATTERY DC INPUT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Batteries per Interface*</td>
<td>1</td>
</tr>
<tr>
<td>Max Input Voltage</td>
<td>1000 Vdc</td>
</tr>
<tr>
<td>Max Input Current</td>
<td>8.5 Adc</td>
</tr>
<tr>
<td>DC Fuses on Plus and Minus</td>
<td>12A (field replaceable)</td>
</tr>
</tbody>
</table>

## ADDITIONAL FEATURES

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Communication Interface</td>
<td>RS485</td>
</tr>
<tr>
<td>Meter Communication Interface</td>
<td>RS485</td>
</tr>
<tr>
<td>Battery Power Supply</td>
<td>Yes, 12V / 5.3W</td>
</tr>
</tbody>
</table>

## STOREEDGE INTERFACE POWER SUPPLY

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Input Voltage (Nominal)</td>
<td>220 / 230 Vac</td>
</tr>
<tr>
<td>AC Input Voltage Range</td>
<td>184 - 264.5 Vac</td>
</tr>
<tr>
<td>AC Frequency (Nominal)</td>
<td>50 / 60 ± 5 Hz</td>
</tr>
<tr>
<td>Max AC Input Current</td>
<td>300 mA</td>
</tr>
</tbody>
</table>

## INSTALLATION SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC input gland cable diameter / wire cross section</td>
<td>6-13mm / 1-2.5mm²</td>
</tr>
<tr>
<td>DC input</td>
<td>1 MC4 pair</td>
</tr>
<tr>
<td>Dimensions (HxWxD)</td>
<td>206.6 x 316 x 117.5 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>3 kg</td>
</tr>
<tr>
<td>Min - Max Operating Temperature</td>
<td>-20 to +60 °C</td>
</tr>
<tr>
<td>Protection Rating</td>
<td>IP65</td>
</tr>
<tr>
<td>Installation</td>
<td>Wall mounted</td>
</tr>
</tbody>
</table>

*For more batteries per Interface, contact SolarEdge.
Eneco SolarEdge and Tesla Powerwall Interface - Operating Manual
STORED EDGE
CHARGE/DISCHARGE
PROFILE PROGRAMMING
Eneco SolarEdge & Tesla Powerwall setup at the DCE6S Lab,
TU Delft
NOVY FRANCIS
September 2017

CONTENTS
1 Objective 2
2 Introduction 2
  2.1 Auxiliary Components ........................... 2
3 SolarEdge Monitoring Portal 5
4 C/D Modes 5
5 C/D Profile [1] 5
6 Default ESTP C/D Mode 7
7 Inverter Programming 7
  7.1 Procedure to change the Energy control of SolarEdge SE3500 Inverter ........................................ 7
8 Configuring C/D Profile 9
  8.1 Uploading the C/D Profile ............................ 9
  8.2 Additional inverter programming ...................... 12
9 Appendix A 13

LIST OF FIGURES
Figure 1 ESTP set-up in the lab ................................ 3
Figure 2 Solar emulators with SolarEdge optimisers .......... 3
Figure 3 ESTP PV system layout overview from SolarEdge monitoring portal .............................................. 4
Figure 4 C/D Modes [1] ...................................... 6
Figure 5 Entering configuration menu of SolarEdge SE3500 ... 8
Figure 6 Time of use selection .................................. 8
Figure 7 Password entry prompt ................................ 9
Figure 8 Entering configuration menu ........................... 9
Figure 9 Selecting power control ................................ 10
Figure 10 Selecting energy manager ............................ 10
1 OBJECTIVE

This document explains in detail the procedure required to program the ‘Charging and Discharging’ of the Eneco SolarEdge & Tesla Powerwall (ESTP) set-up for custom profiles in the DCE&S lab. This document is an extension of the Setup description [2] which can be found in the "Knowledge drive of DCE&S".

It was essential to have a system which can be controlled to follow custom user defined settings to respond to a dynamic profile. The following chapters explain the default profile of the ESTP with respect to battery charging/discharging (C/D) profile followed by the procedure to set up the monitoring portal of SolarEdge and later on the method to program the C/D which is based upon [1]. C/D can be utilized for enabling energy independence by programming the battery to user defined behavior patterns. The user defined C/D profile can be created in an annual basis which would then be repeated for 20 years if no changes are made to the profile [1].

2 INTRODUCTION

The ESTP set-up is shown in Figure 1. The StorEdge set up as shown in Figure 1 consists of the Tesla Powerwall 1, SolarEdge single phase inverter SE3500 and the StorEdge interface. It should also be noted that the Wattnode Smartmeter is placed at the back of the mounted trolley structure. In the absence of the solar panels, a set of 8 solar emulators are available which are connected to the SolarEdge PV optimisers as shown in Figure 2.

2.1 Auxiliary Components

The ESTP set-up consists of the following auxiliary components:

1. StorEdge Interface Module
2. PV power optimisers connected to the Solar emulators
3. AC Load components
4. AC power meter

In the constraints of the lab set-up at the present, the recreation of a real life scenario such as the variation in PV output and AC load during the day was carried out in the following manner.
2.1.1 PV output variation

The solar optimisers in the ESTP set-up are each connected to the P404 SolarEdge Power Optimiser. The power optimiser is a DC/DC converter to boost the DC output voltage from the module and also performs MPPT tracking. The optimisers are used in the ESTP set-up for:

- Performance monitoring
- Safety (Automatic shut down when the inverter or grid is down)
- Maintaining constant string voltage
- Temperature monitoring
- Communication with the SolarEdge inverter and monitoring portal.
The ESTP consists of a 400V DC bus via which the solar panels, battery and inverter are connected. The 8 solar emulators along with the P404 regulated the voltage to 50V DC to each optimiser.

To simulate a slight variation in PV output, the solar emulators can be switched off, but this would then cause the P404 to maintain the 400V DC bus with the emulators that are switched on. The P404 datasheet limits the absolute maximum operating voltage to 80V. This limits the maximum number of solar emulators to be switched off to 3.

\[ 5 \text{(Modules)} \times 80V = 400V \]

It is however advised that at a minimum of 6 solar emulators are operating so as to keep the P404 operating voltage below 75V. In figure 3, the energy produced from each module can be viewed. The colour shading scheme is used to denote cases of shading or malfunction of the module. The darker the shade of blue, the more the module is subjected to shading or other issues hampering the output of the module. It can be seen that in figure 3 the first two modules have darker shade of blue, these two modules were switched ON and OFF on purpose, during the experiments to vary the output of PV system to mimic variations in PV output.

The layout tab can also be accessed to extract live information from the modules such as:

1. Current
2. Optimiser voltage
3. Power
4. Voltage
5. Energy

The time resolution of the reading is once in every 15 minutes.
2.1.2 AC Load

The ESTP is mounted on a trolley as shown in Figure 1. At the backside of the trolley there are two Lamps connected with the following power rating:

- 500W x 1
- 500W x 1

To include more loads the set-up now consists of more lamps

- 400W x 1
- 400W x 1

To include more AC loads kindly contact the lab-supervisors.

3 SOLAR EDGE MONITORING PORTAL

The solarEdge monitoring portal can be accessed at https://monitoring.solaredge.com/solaredge-web/p/login. The user ID which is associated with the Admin access to control the C/D of the ESTP is:

- tudelftdces@nol.com

Researchers can get the password for the above admin account via the lab-supervisors to program and extract the data from ESTP. The monitoring portal can also be accessed by a mobile application for the Android and iOS platform using the above mentioned credentials.

4 C/D MODES

The C/D profile can be constructed from a set of 7 available modes. Each mode has a custom purpose which can then be selected to create the overall user profile which is explained in Section 5. The modes can be programmed for economic, environmental gain etc.

5 C/D PROFILE [1]

As mentioned in Section 1 the C/D profile is programmed on an annual basis. The annual profile consists of three parts:

1. Daily Profile: The C/D variations in the day can be programmed here for various user preferences such as
   a) Weekday
   b) Weekend
   c) Summer weekday
d) Winter weekend

e) Holidays

2. **Seasonal Profile**: The variations of C/D profile for the week are programmed here. Each day of the week can then be chosen from the 'Daily Profile' which is programmed before hence shaping a week according to Weekday/Weekend/Holiday etc. These seasonal profiles can be used to denote specific periods of the year such as:

- Summer
- Winter
- Holidays/Vacation

It should be noted that the Seasonal Profile should cover the entire year. The seasonal profile could then be

- **Annual (Jan 1st - Dec 31st)**: Then the whole year would be a repetition of the weekly profile.
- **Annual with seasonal variations**: Here the specific seasons would each have a seasonal profile of its own. For the case mentioned below the seasonal profile start and end dates would be as mentioned below. It can hence be used to create profiles which would then correspond to changes in the grid prices specific to each season. It should again as mentioned before checked that the seasonal profile covers the entire year.
  a) Spring - March 1 to May 31
  b) Summer - June 1 to August 31
  c) Fall - September 1 to November 30
  d) Winter - December 1 to February 28

3. **Special day type**: The exceptions of the year are programmed here. The day profile in the special day type denoted dates that should have the said profile instead of the seasonal profile programmed during that period. For example, if you defined a seasonal profile from Dec. 15 to
Jan. 15 but want the system to have a different daily profile for New
Years, define a special day. Special days can be set as one-time events
or as recurring events [1].

6 DEFAULT ESTP C/D MODE

The default mode of the ESTP is Maximize self-consumption (MSC). MSC
mode satisfies the load with PV and Battery (upto maximum battery power
output capacity\(^1\)). If the load cannot be satisfied with the available PV and
battery state of charge (SOC) only then the grid is utilized. MSC is also
described in figure 4.

7 INVERTER PROGRAMMING

It is essential to program the inverter before a custom C/D profile is up-
loaded. The inverter is by default programmed to MSC mode. The inverter
Energy control model needs to be changed from Max Self-Consume to Time
of Use to undertake custom C/D profiles.

7.1 Procedure to change the Energy control of SolarEdge SE3500 In-
verter

To access the Energy Control section of the inverter, the front panel of the
inverter needs to removed \(^2\) with the help of a Hex key, make sure that
inverter is switched off\(^3\).

1. Switch OFF the inverter
2. Wait for the DC voltage to drop from 400V DC to below 10V DC
3. Open the front panel of the inverter
4. Hold the button which is encircled in red in Figure 5 for three seconds
   and release

   This leads to the Configuration menu of the inverter.

5. A prompt to enter the password\(^4\) appears, the password should be
   entered by using the analog buttons depicted as ‘1’, ‘2’ and ‘3’ in Figure
   5

6. The choices in the menu can be accessed by using the \(\rightarrow\) analog but-
   ton shown in Figure 5

7. Select Power control

---

\(^1\) The maximum Tesla powerwall charging/discharging power capacity is 3.3 kW
\(^2\) Kindly seek the supervision of the lab supervisors
\(^3\) The DC bus voltage is 400V, the DC bus voltage w.r.t ground is between -200V DC to +200V
DC, be aware of your safety
\(^4\) Researchers can get the password from the lab supervisors
8. Select Energy Manager

9. Change from Max Self-Consumption to Time of Use.

Now the inverter is ready to accept custom C/D profiles.

10. To make sure the inverter is in Time of Use energy control, the menu shown in Figure 6 should appear when shuffling between the menus on the inverter LCD screen.

Figure 5: Entering configuration menu of SolarEdge SE3500

Figure 6: Time of use selection
8 Configuring C/D Profile

The relevant pages from SolarEdge application note [1] are attached in Appendix A [5].

8.1 Uploading the C/D Profile

After the Profile has been created. The following procedure needs to be followed.

1. Switch OFF the inverter

5 Night mode of the inverter
2. Select the Admin Tab in the SolarEdge monitoring portal
3. Select the Energy Manager option
4. Check the 'Apply this profile' option.
5. The saved custom C/D profile would now be visible in the dropdown menu
6. ‘Save’
7. In the inverter profile option, the updated profile would show the following message
8. If the profile has been successfully uploaded the ‘Storage profile name’ would now show the name of the custom C/D profile made.

9. The above step can be verified when the inverter is switched ON, the inverter menu shown in Figure 6 should now show the last sync time.

6 The profile upload can take up to an hour
7 The time when the profile was uploaded
8.2 Additional inverter programming

If the profile has the following option ‘Charge from PV and Grid’ from Figure 4. The maximum limit of the grid intake to charge the battery needs to be specified when creating the profile in the ‘Storage profile’ tab. The maximum AC charge limit can be chosen from the following constraints:

1. No limit
2. Annual limit Limit to % of annual production
3. Not allowed

The above mentioned mode would only work if the option is enabled in the inverter. The procedure is the same as mentioned in Section 7.1. The AC charge should then be enabled. If the inverter AC charge is enabled the option shown in Figure 13 should be visible in the inverter.

![AC charge mode enabled](image)

**Figure 13: AC charge mode enabled**

REFERENCES


---

8 This will change the mode to charge from PV
9 APPENDIX A

In this section the relevant pages of application note from SolarEdge for the StorEdge interface is attached [1]. The steps to create a profile with the discussed modes in Section 5 are enumerated.
Configuring a Profile

This procedure can be completed before the system is installed or connected to the portal, that is, the site was defined in the monitoring portal but not connected.

► To create a storage profile:

1 In the monitoring portal home page, click My Account and select the Storage Profiles tab.

![Figure 1: Storage Profiles tab and Add Storage Profile button](image)

2 Click Add Storage Profile. The following window is displayed:

![Figure 2: Add Storage Profiles](image)

3 Fill in the profile details: name, country and optionally a profile description.

4 In the Backup reserve field enter the battery capacity portion to reserve for backup (in %). This is applicable only to StorEdge systems with backup.
5 Create daily profiles:
   a. Click **Add Daily Profile Type**. The following window is displayed:

   ![Figure 3: Add Daily Profile](image)

   b. Fill in the profile details: name and optionally a profile description.
   c. Select the profile default mode from the dropdown list. The default mode will apply to the entire day; you can then set different modes for selected timeslots.

   ![Figure 4: Profile modes](image)

d. Click **Create**. The Daily Profile Details window is displayed:

   ![Figure 5: Daily Profile Details](image)
e. You can set different modes for selected time slots, either by clicking **Change Schedule**, or by selecting a time slot in the window. The Change Schedule window is displayed.

![Change Schedule](image)

Figure 6: Changing the schedule in a daily profile

- Select the mode from the **Schedule** drop down and optionally add a description.
- Click **Save**.
- Click **Update** in the Daily Profile Details window.

f. Click **Create**. The daily profile is added to the Storage Profiles window.

![Storage Profile Details](image)

Figure 7: Daily profile types

- To create additional daily profiles, click **Add Profile Type**. Repeat the steps above to create as many profile types as needed. For example, you can use Maximize Self-consumption mode on the weekend, Charge from PV mode in summer mornings, or Charge from PV mode in autumn noon hours.

6 Create seasonal profiles:

a. In the Storage Profiles window, click **Add Seasonal Profile**.

![Seasonal Profiles](image)

Figure 8: Add Seasonal Profiles in the Storage Profiles window
The following window is displayed:

![Charge/Discharge Profile Programming through the Monitoring Portal – Application Note](image)

**Figure 5: Adding Seasonal Profiles**

b. Fill in the profile details: name, optionally a profile description, and the start and end dates of the period when the profile should be used.

c. For each day of the week, select a daily profile from the dropdown list. This weekly profile will recur each week of the defined period.

d. Click **Create**. The profile is added to the Storage Profiles window.

e. To create additional seasonal profiles, click **Add Profile Type**. Repeat the steps above to create as many profile types as needed.

**NOTE**

The seasonal profiles must cover the entire year, from Jan 1st to Dec 31st.
7 Optionally, create specific day profiles for holidays and other days requiring a different profile:
   a. In the Storage Profiles window, click Add Special Day. The following window is displayed:

   ![Special Days Window](image)

   Figure 10: Creating a special day profile

   f. Fill in the profile details: name and optionally a profile description.

8 Click in the Date field. Enter a single date or click the calendar icon to select a date or a period that should be defined with the same settings.

   ![Calendar](image)

   Figure 11: Calendar

   g. To repeat the profile yearly, select the recurring check box.
   h. Select a daily profile from the dropdown list.
   i. Click Create. The profile is added to the Storage Profiles window.

9 Click Create. The profile is saved.
Bibliography


[44] Stamati T.E. Sustainable microgrid for charging electric vehicles from on-road contactless power transfer systems, November 2012.


