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The potential integration of alternative energy solutions in charging plazas for electric construction equipment

An in-depth analysis of the impact of alternative energy solutions on charging plazas for electric construction equipment

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An in-depth analysis of the impact of alternative energy solutions on charging plazas for electric construction equipment

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by

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Executive summary

Background

ProRail has set an objective to have solely emission-free construction sites by 2030. To fulfill this objective, construction equipment of contractors needs to become electric. Electric construction equipment requires enough grid capacity and/or alternative energy solutions. There should be enough energy supplies available for charging construction equipment to start construction processes.
Charging plazas are considered the best option for charging infrastructure in the transition to electric construction equipment. Advantages of charging plazas are that they are less time-consuming, more cost-efficient and improve system efficiency in comparison with a single charging station.

The research objective of this study is hereby,

> *To gain understanding on the impact that alternative energy solutions could have on different types of charging plazas from ProRail for electric construction equipment.*

Methods

Within searched academic literature and during conversations with experts in the field of energy supply and charging plazas, there exists a lack of knowledge on alternative energy solutions that can be of value for charging plazas containing electric construction equipment. Factors such as what and how these solutions can be integrated into various scenarios is researched in this project. This is relevant because of the fact that grid capacity might not fulfill entire demand of a charging plaza due to congestion in the electricity grid. Alternative energy solutions can help out in generating or storing electricity. The main research question to be answered in this thesis is:

> *"What impact could alternative energy solutions have on charging plazas for electric construction equipment from ProRail by 2030?"*

To begin with, the ins and outs of a charging plaza and alternative energy solutions are presented. As a result, a good understanding of the subject in this thesis project is given. The full picture of charging plazas is given by an introduction to charging plazas including an illustration of what a charging plaza looks like, examples of requirement factors and assessment factors to design a plaza. The approach in obtaining relevant information is by desk research and (semi-structured) interviews with experts in the field of charging plazas and construction equipment. When this was examined, it was important to get an understanding of how charging plazas can be supplied. From interviews, alternative energy solutions were proposed to be installed on charging plazas. The proposed alternative energy solutions are analyzed by a SWOT-analysis. In creating scenarios, morphological charts, realization tables and combinations tables are made in collaboration with experts from Movares. This helped to ensure realistic scenarios based on real life examples. The created scenarios are recreated in Excel to obtain results and see whether alternative energy solutions can supply charging demand of charging plaza scenarios.

Results

From the SWOT-analysis, it resulted that each scenario would include battery storage and solar carports. Wind energy was optional if it is considered economically feasible. However, hydrogen and vehicle-to-load were excluded from the alternative energy solutions, because of the fact that interviews and desk research mentioned the immaturity of both technologies. Hydrogen has a very inefficient production process and this production process needs to be in a further stage to be able to have sufficient amount of supplies. Vehicle-to-load is only offered by two car manufacturers and interviewees do not expect it to play a role in the coming years due to lack of regulation.

The scenarios that are created are the following:

- Scenario 1: A long-term project (~20 years). This scenario does not receive grid connection as the rail access point is close to a substation. There will be a battery storage capacity of 120 kWh, 2000 Wp of PV panels capacity is present as well as a wind turbine of 100 kW.
- Scenario 2: A 5-year project. This scenario receives a grid connection that fulfils in 75% of total charging demand of the charging plaza. Battery storage capacity of 500 kWh is present as well as 16,000 Wp of PV panels capacity and 350 kW of wind turbine capacity.
- Scenario 3: A 6-month project. This scenario receives a grid connection that meets total charging demand of the plaza up to 50%. There is no wind capacity available as permits and licenses cannot be granted due to the short period of time. Battery storage capacity of 350 kWh is present as well as 8,000 Wp of PV panels capacity.

These scenarios are recreated in Excel to show to what extent the alternative energy solutions can fulfil the energy demand of the charging plaza scenarios.

For a long-term project (~20 years), it became clear that without the help of grid connection and usage of battery storage, wind and solar sources, charging demand of present construction equipment is met in time. Also, an overview of total costs of this scenario is given. For a five-year project, there exists a high charging demand of all construction equipment. Wind and solar sources generate sufficient amount to meet charging demand in this scenario with made assumptions. However, in real life, wind and solar sources are more fluctuant which would lead to a less reliable outcome. Also for this case, an overview of total costs is given, which shows that battery storage is relatively more expensive due to the higher capacity that is necessary, compared to scenario 1. For a six-month project, alternative energy solutions are not able to meet demand of the charging plaza any time without the help of a grid connection. This is due to the fact that wind energy cannot be integrated for such a short period of time.

Conclusions and recommendation

For short-term charging plaza projects (shorter than five years), alternative energy solutions cannot meet demand without the addition of sufficient grid capacity. PV panels do not generate an effectual amount of energy for such projects and wind energy is not an option as it does not have a positive business case.

Projects with a longer durance (equal to or longer than five years) show that alternative energy solutions can be integrated successfully to charging plazas. With the help of battery storage, wind energy and solar energy, demand of charging plazas is able to be met. In these scenarios, wind energy was key to generate sufficient amount of energy supplies. Without wind energy, both scenarios would not have been able to fulfil in the need of the charging plaza because PV panels seemingly generate a small fraction of what is necessary in demand. In addition, it is preferable to have a battery as big as possible to store during the day and night. A smaller battery means that a great deal of time is put in to charging the battery. In these scenarios it is assumed that the battery gets filled up with either grid capacity or wind/solar energy, but in real life scenarios, it is uncertain if the wind blows or the sun is shining.

The main suggestion for future research would be of added value is to include hard data. The scenarios that have been created are based on assumptions in one type of construction equipment (e-krol), and averages in generation of alternative energy solutions and charging demand. This could be made more specific. For example, a study could be set up on designing a charging plaza on a specific location with certain types of construction equipment. If more data becomes available on capacity of different battery packs of construction equipment, obtained results would be more practical and closer to *real life.*

Keywords: Charging plaza; Charging infrastructure; (Electric) construction equipment; Alternative energy solutions.

Acknowledgement

This thesis marks the end of my journey at the MSc Complex Systems Engineering & Management program at TU Delft. I experienced the thesis work as a very valuable project that was both fun and interesting. Energy transition has always been my field of interest. Therefore, I enjoyed to do my research about the integration of alternative energy solutions in designing charging plazas to make a transition in construction equipment. The construction sector has a long way to go when it comes to this transition but big steps are being made. In these final months of my study, I have learned how to conduct research and how to write a thesis.

This thesis project has been with ups and downs. I wish to acknowledge the assistance of many that have made this possible.

To start with, I would like to thank my supervisors from Movares. Both Sjaak den Breeje and Florian Simonsen have been of great importance in guiding me along the way. They have reviewed my thesis multiple times, and provided critical feedback. Also, they helped me when the focus of my research project had to change. In some moments, it is hard to head into the right direction and easy to lose sight. In addition, I want to thank my other colleagues from Movares. I really enjoyed being part of the Energy department for a couple of months. I truly believe that Movares is a very modern engineering company that will be of great value to our country’s development.

Second, I want to thank my committee for all effort they have put in advising me about my research. First and foremost, Dr. Jan Anne Annema for his clear advice and result-oriented approach. Along the way, you have been my first contact with TU Delft, which I experienced as a professional and fruitful collaboration. Second, thanks to Dr. Wijnand Veeneman for his critical feedback and added value to the method section. Third, I want to thank Prof. dr. Bert van Wee for being the chair of my committee.

Also, I would like to express my gratitude to all the experts in the field of construction equipment and charging infrastructure who were willing to provide me with necessary information. Their help and enthusiasm about my topic made me feel that I was doing an useful research project.

Sander Baltes
Delft, February 2023

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Acronyms

A	Ampere
AC	Alternative current
CO_2	Carbon dioxide
CoSEM	Complex Systems Engineering and Management
DC	Direct current
EV	Electric vehicle
I&M	Ministry of Infrastructure and Environment
e-krol	electric kraan op lorries
kV	kilo Volts
kW	kilo Watt
kWh	kilo Watt hour
LP	Linear programming
Mton	Mega tonnes
NKL	Nationaal Kennisplatform Laadinfrastructuur
PHS	Programma Hoogfrequent Spoor
RQ	Research question
SoC	State of Charge
SWOT	Strengths, Weaknesses, Opportunities, Threats
TCO	Total cost of ownership
V2G	Vehicle to Grid
V2L	Vehicle to Load
W	Watt
Wp	Watt peak (nominal power)
ZE	Zero-emission

I. Introduction

In this introductory chapter, the research topic and scope is presented. First, a brief overview of the context is given in section 1.1. In section 1.2, the problem statement is discussed, which consists of the identification of scientific knowledge gaps and the research objective. From the identified scientific knowledge gaps the main research question and four sub questions were derived in section 1.3. In section 1.4, the societal and scientific relevance of the research project is given. At last, section 1.5 presents the outline of the thesis project.

1.1 Context

1.1.1 Climate agreements and the construction sector

With the signing of the Paris Agreement in 2015, 195 countries pledged to reduce the amount of carbon dioxide emissions and other greenhouse gases, as well as to adapt to impacts of climate change (IRENA, 2020). It aims to limit the rise of average global surface temperature in this century to well below 2.0 degrees Celsius, and ideally below 1.5 degrees Celsius above pre-industrial levels. The Dutch government has translated the goals of the Paris Agreement into the Dutch Climate Agreement of 2019, which states that the national CO_2-emissions have to be reduced by at least 49% in 2030 compared to 1990 (Kabinet Rutte III, 2019). In many countries, enterprises are undergoing a period of reformation. The goals and ambitions of companies are adjusted or expanded to put climate change at the heart of business operations. The construction sector also faces the challenge of realizing a transition to zero emissions. This transition is necessary to achieve the agreed climate goals. The following objectives for the construction sector have been set in this agreement (CE Delft, 2022):

- 60% nitrogen reduction in the construction sector in 2030 compared to 2018;
- 0.4 Mton less CO_2- emissions in 2030 compared to 2019;
- 75% less damage to health in 2030 compared to 2016.

In order to achieve these objectives, various programs and strategies have been drawn up, such as the Climate Neutral and Circular Government Infrastructure Projects, with the aim of ensuring that all construction equipment for government infrastructure projects is emission-free by 2030 (Ministerie van Infrastructuur en Waterstaat, 2020). In the construction sector, electrification of equipment is set to be the trend that most contractors seem to follow (ElaadNL, 2021). This is due to the fact that prices of renewable electricity and electric equipment continue to drop. Companies can capture cost-saving and opportunities to reduce their greenhouse gas emissions by planning the electrification of their operations (Roelofsen et al., 2020). However, developments in the transition to electrification of construction equipment is in an early stage all over the world. More knowledge and experience is necessary to speed up this transition. Therefore, this report will first focus on how the transition to emission-free construction sites could be made, especially with a focus on ProRail. Later on, results are reflected upon broader application to make recommendations to other groups or context who can use the results of this thesis.

1.1.2 ProRail and zero-emission construction equipment

ProRail, a Dutch government organisation, is responsible for the maintenance and extension of national railway network infrastructure, other than the metro and tram. In the context of climate change, ProRail must also make a transition to zero-emission (ZE) business processes in the coming years.

In order to do so, ProRail established a so-called CO_2 performance ladder (ProRail, 2022). This ladder consists of a certificate that aims to stimulate sustainable working, to emit less CO_2 and make efficient usage of energy. Clients of ProRail gain a higher score on the certificate if working processes are more environmentally aware and responsible. As a result, it is said that ProRail gives contractors an advantage in any tender if they make use of emission-free construction equipment.
ProRail has set an objective to have solely emission-free construction sites by 2030. To fulfill this objective, ProRail wants construction equipment of contractors to become electric. Figure 1 shows that a fairly large share of construction equipment will contain an electric version by 2030. Not every contractor will convert their equipment to electric versions, but this does not mean that ProRail will not be able to create zero-emission construction sites. Due to their performance ladder, they are in charge to choose the best economic, environmental and technical option on factors between contractors.

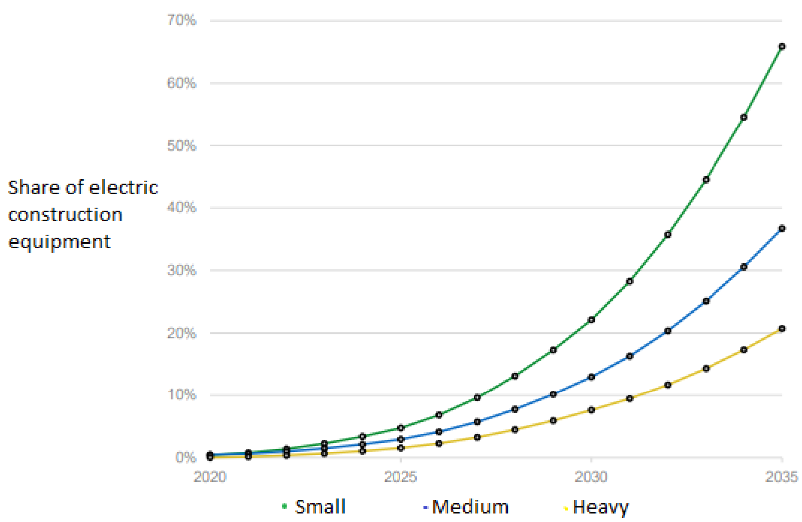


Figure 1: Estimations of the share of electric construction equipment in upcoming years (ElaadNL, 2021).

According to Jan van Rookhuijzen (*Interview Jan van Rookhuijzen (ElaadNL)*, 2022), all shares of electric construction equipment, as is shown in the figure above, have increased by developments in 2022. The performance ladder from ProRail helps to stimulate contractors to invest in electric construction equipment. In addition, the construction sector also aims to become more sustainable. The sector is responsible for approximately 40% of all our national CO_2-emissions (Arcadis, 2022). Due to the Dutch Climate Agreement, new construction prescriptions are put forward in the Dutch Building decision. This contains prescriptions related to safety, energy efficiency and environment (BUVA, 2021).
Electric equipment requires charging infrastructure. Therefore, charging plazas are considered to be a solution in offering enough charging stations (Carstens et al., 2022). A charging plaza contains multiple charging stations on one location with one single connection to the grid, which is considered to be more efficient than single charging stations. This is due to a number of reasons.

First, the contractor can build more charging points at the same time in less time and the grid operator only has to perform work on site for several charging stations once. Also, in general a charging plaza is scalable. There is often the possibility to add more points in the future (Nationaal Kennisplatform Laadinfrastructuur, 2021).

1.2 Problem exploration

This chapter presents the scientific knowledge gaps and research objective. This was explored by a conducted literature review. First, two current issues that influence the energy transition are introduced. Second, the findings of the literature review is described, which resulted in the identification of scientific knowledge gaps and the research objective. Based on the identified scientific knowledge gaps and research objective, a main research question and four research questions (RQs) are proposed in section 1.3. Answers to the four sub questions aim to produce an answer to the main research question.

1.2.1 The problem of insufficient grid capacity and congestion

It is important to emphasize that future goals start by today's actions. Electric construction equipment will require enough grid capacity and energy supplies. There should be enough energy supplies available for charging construction equipment to start construction processes. ProRail possesses two types of connections to the electricity grid:

1) connections for the traction network;
2) connections for other (rail infrastructure) power supplies.

The traction network supplies the overhead lines of the track that is used to drive trains, train security systems and business operations. The connections for other (rail infrastructure) power supplies are used for facility purposes. Examples of such purposes are the escalators or lighting at train stations. ProRail wants to supply charging plazas through its connections to the public electricity grid, but the question is whether sufficient capacity is available to meet their charging needs (CE Delft, 2022).
The increase of renewable energy sources and the rise of electrification cannot always be processed properly by the electricity grid. This phenomenon is called *congestion.* A widely used metaphor is that traffic jams should not occur on high voltage lines. In nine out of ten times there is no congestion on the grid, but as renewable energy sources are highly volatile, peaks in energy generation result in reaching the maximum capacity of transport of electricity on the grid (RVO, 2021).

If a request for building a connection is approved, there may be no room to purchase power from the grid operator due to grid congestion. To build a connection to the grid is time-consuming due to the great deal of requests that the grid operator receives at the moment. Both causes make it difficult for companies to make progress on their sustainability goals (NAL, 2022).

1.2.2 Scientific knowledge gap and research objective

A literature review has been conducted to identify scientific knowledge gaps in the field of charging plazas and alternative energy solutions. During the literature review, there was made use of databases of search engines Google Scholar, Science Direct and Scopus as well as obtained private documentation from expert parties such as CE Delft, TNO and ProRail. **Core concepts** that obtained subject specific articles were "Alternative energy solutions", "Charging infrastructure", "Charging plazas" and "Charging stations" and "(electric) construction equipment". A more elaborate description of the literature review can be found in Appendix A.

Charging plazas must supply demand of **electric construction equipment**. Currently, it is a major challenge for the contractors to switch to emission-free construction equipment. Lots of construction equipment still contain diesel engines. A research conducted by Un-Noor (2021) shows that from 17 off-road vehicles across six equipment types, four types of equipment can be electrified to a significant extent using battery electric powertrains, while the remaining two types are more suitable for hybridization. They collected data to investigate the electrification potential of six equipment types (Un-Noor et al., 2021). This research shows that electrification is a good option for construction equipment to reduce its emissions. This is also shown on the market as BAM has expanded its electric family with the electric kraan op lorries (e-krol) after the electric roller, the hybrid CPT truck and the electric asphalt spreader (Royal BAM Group, 2022).
According to TNO (2022), the *total cost of ownership* (TCO) of electrical vehicles is still higher compared to controversial options and so a sharp decrease in the cost of electricity supply and the prices of batteries would be highly valued to become more attractive. Due to technological developments, the presence of new models and scaling up production, electric options are becoming increasingly interesting compared to diesel (ElaadNL, 2021).

Many European countries have made considerable efforts to increase the share of electrification in the transport sector. Crucial to a successful rollout of a transition to electrification is the provision of sufficient **charging infrastructure**. The understanding of the charging behaviors of electric vehicles or equipment in terms of when they charge, how much they consume, how long they charge for, and their choice of charging infrastructure type is relevant (Morrissey et al., 2016).
Also sufficient energy capacity must be available. Smart charging, battery storage and **charging plazas** are part of mitigating measures that offer perspective in a situation with an insufficient grid capacity connection (van Cappellen et al., 2022). For example, **charging stations** with smart charging technology are considered to optimize the effect on objectives such as reduction of net impact by electric vehicles, minimizing energy costs or matching with renewable energy generation (Bons et al., 2020).

Also, battery storage increases the efficiency and effectiveness of transmission and distribution of electricity (Trahey et al., 2020). As an addition to grid capacity, battery storage can expand the available capacity on charging plazas. They can be filled with energy from the grid or by solar and/or wind energy (van Cappellen et al., 2022). Sources that can relieve the electricity grid and provide construction projects with their electricity demand on time are referred to as **alternative energy solutions**. Alternative energy solutions are a rising concept with many promissory benefits.

However, not many articles were found that contained multiple core concepts, such as charging plazas, electric construction equipment or alternative energy solutions. As a result, the following scientific knowledge gaps were identified:

Knowledge gap 1: The understanding on what alternative energy solutions can be used to supply power for charging plazas for electric construction equipment;

Knowledge gap 2: The understanding of what scenarios of charging plazas for charging electric construction equipment.

Answers that could fill these knowledge gaps would help speed up the transition to electric construction equipment and help ProRail to accomplish their objective as explained in section 1.1.2. The research objective of this thesis project is hereby,

To gain understanding on the impact that alternative energy solutions could have on different types of charging plazas from ProRail for electric construction equipment.

1.3 Main research question and sub questions

Based on the current state of scientific knowledge in the research area, the identified knowledge gaps and the presented research objective, the following main research question is defined:

What impact could alternative energy solutions have on charging plazas for electric construction equipment from ProRail by 2030?

As ProRail has set targets on having emission-free construction sites by 2030, the research project will focus on this period of time. Also, it is assumed that no significant difference will occur if the period of time would be extended since the current trend in the construction sector is electrification (*Interview Jan van Rookhuijzen (ElaadNL)*, 2022). Therefore, the focus is set on charging plazas that are relevant to ProRail, which contain electric construction equipment.

The main research question is answered with the help of the following sub questions:

***RQ1**: What do charging plazas look like and what needs to be considered in designing charging plazas?*

RQ1 aims to provide an answer on why specifically is chosen for charging plazas, what a plaza contains and what needs to be taken into account when designing it.

***RQ2**: What are potential alternative energy solutions for charging plazas and what are their characteristics?*

RQ2 aims to gather all relevant information from literature and expert knowledge to create an overview of potential alternative energy solutions that can serve a function on charging plazas. The ins and outs of potential alternative energy solutions are discussed.

***RQ3**: What are realistic charging plaza scenarios for ProRail and what assumptions do they contain?*

RQ3 aims to provide the basement for building a model in Excel by making assumptions and creating realistic scenarios for ProRail. As knowledge gap 2 states, no scenarios are created yet.

***RQ4**: How do the charging plaza scenarios for ProRail fulfil in charging demand and what are their total costs?*

The created charging plaza scenarios and assumptions of RQ3 are used to build a model in Excel. The last sub question aims to provide graphic representations to determine to what extent alternative energy solutions fulfill in demand of each scenario. Feasible results of scenarios contain an indication of the total costs as well.

1.4 Scientific and societal relevance of this study

Un-Noor (2021) already examined that electrification is a good option for construction equipment to reduce its emissions; van Cappellen et al. (2022) examined measures and methods to charge vans or trucks with restricted grid capacity available. Although these studies are highly relevant, the aim of this study is to determine what alternative energy solutions could contribute to the integration of charging plazas in various different scenarios. This is relevant because of the fact that grid capacity might not fulfill entire demand of a charging plaza. Alternative energy solutions can help out and generate or store electricity to fulfill this need. Therefore, it is very useful to gain understanding in the developments of construction equipment. Also, the trends in the realization of charging plazas in relation to alternative energy solutions. As of today, most charging plazas are realized for buses or electric vehicles. There is not much information on both charging plazas and electric construction equipment for rail purposes.

The societal relevance of this study lies in lessons learned from the results. Each scenario provides an unique outcome and can be taken into account in the design process of charging plazas. Due to the assumptions made, it is not likely to be used for future purposes but it gives an indication. From the perspective of related organizations, a better estimation can be made when charging demand of different charging plazas is known with present construction equipment.
Also, congestion is a big problem throughout the whole country. Not only ProRail is in need of power for short-term projects, but more companies working on infrastructure or buildings do. In addition, not only contractors working for ProRail are exposed to this problem, but the entire market. The fact that projects with a durance of more than five years can have a positive business case, might be relating to other infrastructural construction purposes other than rail.

1.5 Thesis Structure

The thesis report is structured as presented in the research flow diagram in section 2.3. Each sub question is focused on in a single chapter. First, chapter 2 provides the research approach and methods being used throughout the research project to obtain an answer to the main research question.

Chapter 3 focuses on answering sub question 1, which gives an indication on what charging plazas look like and what factors need to be considered when designing charging plazas. Chapter 4 contains a SWOT-analysis of proposed alternative energy solutions for charging plazas. This results in the inclusion and exclusion of these solutions to the rest of project. In chapter 5, assumptions and scenarios are presented. Arguments that support the choice of types of alternative energy solutions is given. Results are discussed in chapter 6. The results show whether the created scenarios are able to fulfil in demand of the particular charging plaza scenario. If it does meet demand, an indication of the total costs of the scenario is made as well as the benefits in comparison with past circumstances. The report ends with conclusions to all research questions, scientific contributions, recommendations on future research and the link between the master thesis and master program in chapter 7.

2. Research approach and methods

This chapter consists of an elaboration on the in-depth analysis that is executed during the thesis project. From this chapter, it is important to take out the structure and approaches within the project. Examples of questions being answered in this chapter are: *What are the sub questions of this research project? What methods are used to gather information and data? What is the research flow within this project?* The chapter starts with the approaches used in the project. Then, methods that have been used to obtain answers to the sub questions are discussed in paragraphs 2.2 and 2.3. At last, the Research Flow Diagram is presented, which shows the steps that are taken throughout the project.

2.1 Research approach

In order to attain the proposed research objective in chapter 1.2.3, a research approach is required to help structure and divide the project into smaller components. In the figure below, the smaller components are given as the research questions and their deliverables. The main research question is split up into four research questions.

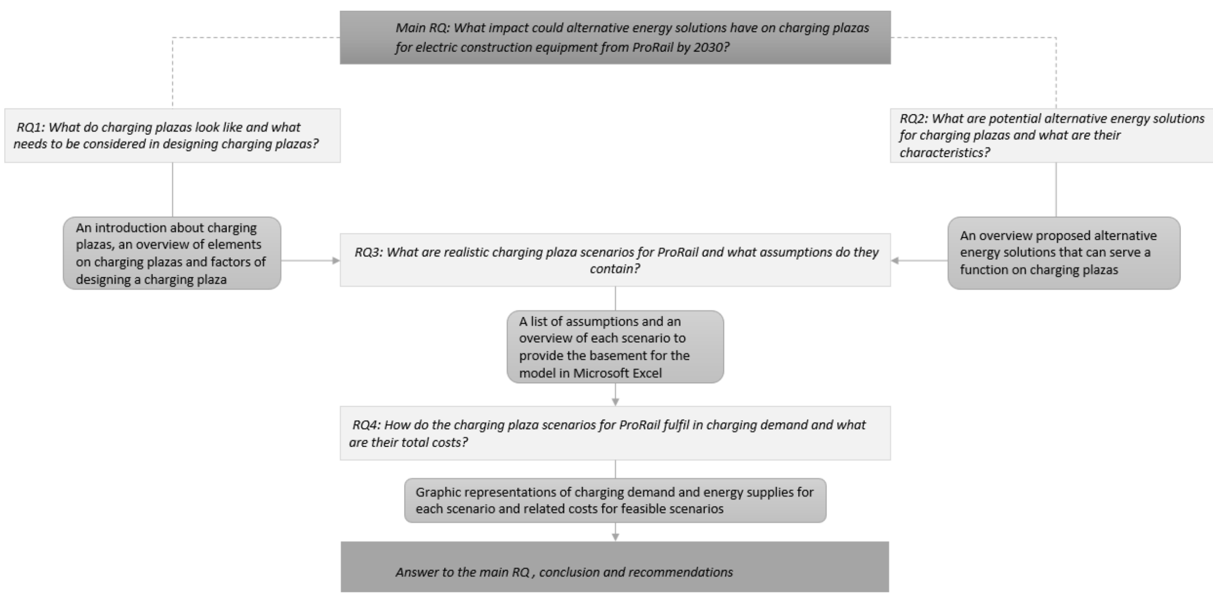


Figure 2: An overview of the contribution of deliverables of RQ's and the structure in this thesis project.

Each research question is given its own chapter. A good understanding of the subject in this thesis project is explicated by research question 1 and research question 2. Research question 1 elaborates on why charging plazas are part of the transition to emission-free construction equipment. Therefore, advantages of charging plazas are listed. Also, requirements that need to be considered in designing it as well as assessment factors are given. This is because it provides a better picture of important factors in engineering a charging plaza, which is done in RQ4. For RQ1, a distinction is made between the situation on previous occasions and what the integration of a charging plaza changed to the situation. This is in regard to construction equipment, infrastructure to refuel equipment and means of supply of fuel. In RQ2, an overview of relevant information on potential alternative energy solutions for charging plazas is given.

The full picture of charging plazas and alternative energy solutions is used as the basement in answering RQ3 and RQ4. In RQ3, the foundation of a model is made to recreate *real life* scenarios of projects in which charging plazas could serve a function. The foundation consists of assumptions in alternative energy solutions and other parameters to build a model and scenarios of charging plazas. In RQ4, a graphic representation is made in Excel of each scenario to see whether charging demand can be met with present alternative energy solutions. For scenarios with a positive demand-supply ratio, an analysis of total costs during the entire project is made.

2.2 Research methods and questions

In this section, the research design for the mentioned problem setting is presented. First, an overview and description is given on the selection of articles and interviews. Second, this paragraph focuses on the tools or techniques that are used to obtain answers to all sub questions.

This project is a qualitative research project as it involves collecting and analyzing non-numerical data to understand concepts or opinions. It is used to gather in-depth insights. Both desk research and interviews are examples of such methods.

The use of desk research started with a literature review, as mentioned in section 1.2.2., to identify scientific knowledge gaps. Figure 3 shows the entire methodology in which the steps in selecting articles can be derived. The methodology is split up in four phases: identification, screening, eligibility and selected. In the identification phase, the key terms “Alternative energy solutions”, “Charging infrastructure”, “Charging stations”, “Charging plazas” and “(electric) construction equipment” were searched. This resulted in 16 articles for the screening phase. In the screening phase, the suitability of the articles was examined. Only selecting articles published after 2010 resulted in 14 articles being included in the literature review. Afterwards, backward snowballing, referred to as making use of references to obtain new (relevant) articles, resulted in one extra related paper. In the end, a total of 15 articles were selected for the literature review.

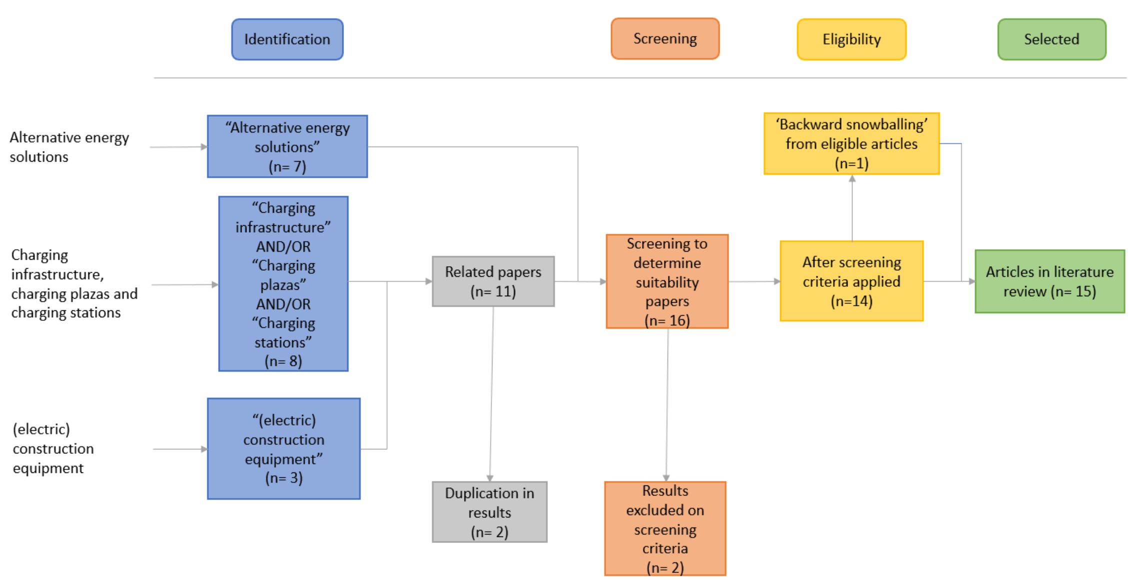


Figure 3: An overview of the methodology in the literature review process.

For the interviews, there has been chosen for interviewees that have affinity with the core concepts as presented in section 1.2.2. In most cases, an email was sent to candidates at first to invite them for an interview after encountering their names in literature, which can be found in Appendix B1. The articles that were found must have affinity with at least one core concept and/or their current function and company is considered very much related to the research topic. This led to a total of eight interviewees to gather insights from different perspectives in the field of construction, charging plazas and alternative energy solutions. The idea was to find at least one person for each core concept or included alternative energy solution. Beforehand, a list of relevant questions was prepared, either to guide the interview (semi-structured) or lead the interview (structured). The interviews with Rob de Jeu, Robert Daems and Daan Geldermans are conducted offline. All interviews were recorded in order to be able to focus on the conversation rather than documenting results. The recorded tapes resulted in a summary of themes and their key take aways. An overview of all conducted interviews and brainstorm session during the thesis project is given in table 1 below. A summary of each interview can be found in Appendix B.

Table 1: An overview of all conducted interviews and brainstorm sessions during the thesis project. An elaboration of each interview in the form of a summary can be found in appendix B.

Name	**Company**	**Output (addressed subjects)**
Rob de Jeu	ProRail	- Technical and organizational aspects of realizing charging infrastructure
Jan van Rookhuijzen	ElaadNL	- The electrification of construction equipment - Developments of alternative energy solutions (hydrogen, vehicle-to-load) - Insufficient grid capacity and grid connection
Roy Kat	BAM	- The electrification of construction equipment - Developments of alternative energy solutions (hydrogen, vehicle-to-load) - Criteria and limitations of charging plazas
Robert Daems	ABB	- Charging stations - Battery containers - Potential of vehicle-to-load
Robbie Blok	NKL Nederland	- Requirements, assessment and pros/cons of charging plazas - Alternative energy solutions in regard to charging plazas (wind energy, hydrogen, electrification, vehicle-to-load)
Daan Geldermans	Skoon Energy	- Specific information on battery storage, e.g. charging time and application
Maarten Deutekom	Wind Energy Solutions	- Specific information on wind turbines, e.g. the total costs of various types of turbines
Anna Visser	GroenLeven	- Specific information on solar carports, e.g. its pros and cons
Brainstorm session	Movares	- A discussion on the continuation of the thesis project including useful tips on assumptions and the creation of scenarios

2.2.1. Research methods sub question 1

***RQ1**: What do charging plazas look like and what needs to be considered in designing charging plazas?*

For answering RQ1, desk research helped to gain knowledge about both electric construction equipment and charging plazas. From desk research, experts had been contacted to be interviewed. A limitation of interviews is that only a restricted amount of people can be included. The literature provided evidence that the experts had sufficient expertise in the core concepts and made me develop questions. As a result, five interviewees from ProRail, contractors, NKL Nederland and ABB were interviewed, see table 1 above. NKL has executed multiple pilots of charging plazas, for example in Utrecht. They are familiar with requirements for engineering charging plazas and assessing whether a charging plaza is a suitable option. Because of the fact that this thesis covers the designing/engineering of charging plazas, examples of assessment factors and requirements of charging plazas are given. ProRail and contractors have provided information about requirements from construction equipment and desires in designing charging plazas. ABB has given information on charging stations.

All interviews are conducted in a semi-structured way in order to collect information and insights on relevant topics. This also made it possible to explore further as some interviewees have expertise and knowledge about multiple core concepts. Afterwards, a qualitative analysis is performed to interpret and summarize the interview results. The interview results are summarized and can be found in Appendix B.

2.2.2. Research methods sub question 2

***RQ2**: What are potential alternative energy solutions for charging plazas and what are their characteristics?*

For answering RQ2 in chapter 4, conducted semi-structured interviews from RQ1 also tackled the subject of alternative energy solutions on charging plazas. For instance, Roy Kat and Robbie Blok (2022) have given insights on developments on charging plazas in relation to alternative energy solutions. This resulted in a total of five solutions that could be used for the model in RQ4. However, the inclusion of all five solutions would not make it a reliable situation on a charging plaza. Therefore, it was decided to include three alternative energy solutions into the Excel model.

In order to decide which alternative energy solutions would be included into the model in Excel, a SWOT-analysis was made to provide insights into the proposed five alternative energy solutions. A SWOT-analysis identifies the strengths, weaknesses, opportunities and threats of different alternative energy solutions. It is useful in examining the contribution of an alternative energy solution to desired performance, along with approximations of the degree to which each factor is or is not within the performance (Mercieca et al., 2019). The analysis of alternative energy solutions resulted in the inclusion and exclusion of alternative energy solutions to the integration of charging plazas. The bottom line of the interviews came down to similar answers. In addition, desk research provided a great deal of information and knowledge about the characteristics of the alternative energy solutions.

2.2.3. Research methods sub question 3

RQ3: *What are realistic charging plaza scenarios for ProRail and what assumptions do they contain?*

For answering RQ3 in chapter 5, the research findings to RQ1 and RQ2 as well as desk research are used to develop assumptions in alternative energy solutions in order to develop scenarios. Examples of assumptions are the amount of grid capacity available on different charging plaza sites or the type of PV panel and its wattage. These assumptions are made, based on structured interviews with specialists in the type of field that the assumption concerns. In these structured interviews, a prepared list of questions was followed during the interview, which was necessary for building the model in Excel. For example, interviews had taken place with an expert of a solar carport company and wind energy company, see table 1. An example of an assumption for wind energy is that each day has a specific amount of full load hours in which energy is generated. This determines the total generated wind energy on a day.
For the creation of scenarios, morphological charts, realization tables and combination tables were made. The morphological charts contain five dimensions of five different types of means and five different time spans of projects. For three time span projects, a scenario with specific charging demand, capacities of alternative energy solutions and available grid capacity were picked. For each scenario, a realization table containing the uncertainties of the scenario was made. The combination table is a combination of the alternative energy solutions and their uncertainties showing the potential impact. The creation of these tables has been done in collaboration with experts from Movares to make it as realistic as possible and similar to *real-life* scenarios of charging plazas. For instance, a wind turbine is not an option for a project with a 6 month time span as it has a negative business case. The tables (morphological chart, realization table and combination table) are given in Appendix C, whereas assumptions in the scenarios are listed in Appendix D.

2.2.4. Research methods sub question 4

RQ4*: How do the charging plaza scenarios for ProRail fulfil in charging demand and what are their total costs?*

For answering RQ4 in chapter 6, each charging plaza scenario is recreated in Microsoft Excel according to the made assumptions in chapter 5. This includes the charging pattern of charging stations and to what extent the energy supplies can meet charging demand on a regular day. The results are presented by means of graphs which show how each scenario fulfills in demand of the charging plaza with integrated alternative energy solutions. The results are discussed. Besides, linear programming is used to determine optimal capacity for relevant alternative energy solutions. The Solver function in Microsoft Excel is able to make use of this method by means of decision variables, constraints and an objective function. A more elaborate explanation and an example of linear programming can be found in Appendix E.
Also, the total costs are accounted for feasible scenarios. This is based on assumptions and estimations from desk research or obtained information from interviews with experts in the concerned field of work. For example, Maarten Deutekom (2022) provided the costs of various capacities of wind turbines. These costs contain costs incurred during the projects time span, which includes the investment costs (Capex), operation and maintenance costs (Opex) and installation costs.

2.3 Research Flow Diagram

The entire research project is summarized in a so-called Research Flow Diagram (RFD) as shown in figure 3 below. This diagram provides an overview of the steps that are taken during the project. The outcomes of the different sub questions provide an answer to the main research question. In the figure, the input, activity and output is given of each upcoming chapter. Also, it shows the chapters in which certain research questions are covered. The answers to RQ1 and RQ2 serve as input to RQ3, which is why the arrows of RQ1 and RQ2 end up at RQ3.

From the results of the interviews, answers are given to RQ1 and RQ2. Also, the foundation of a model in Excel is based on assumptions from the input of interviewees. The model Excel developed the results of which the conclusion is made.

After all, this research project aims to contribute to the state of the art by fastening the transition to emission-free construction equipment by determining how alternative energy solutions could be integrated into charging plaza scenarios. An indication is made of how alternative energy solutions are able to meet charging demand with or without grid capacity. The project focuses in particular on rail purposes that are of interest to ProRail.

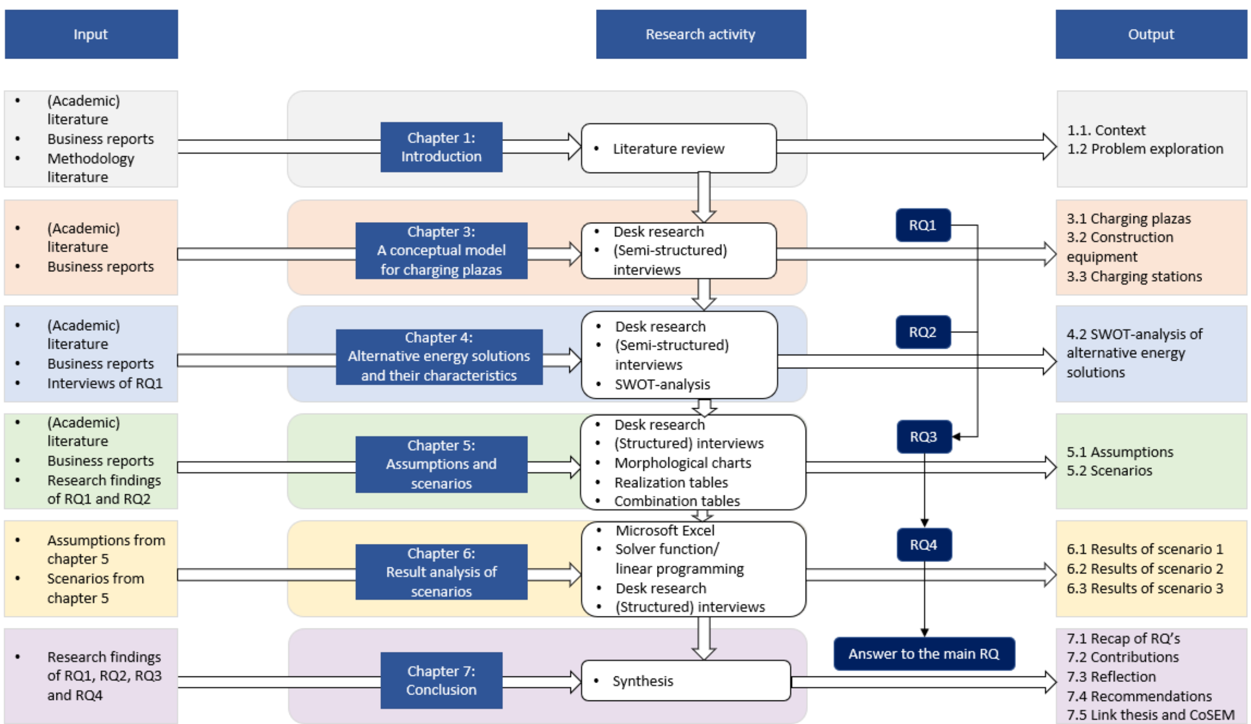


Figure 4: The Research Flow Diagram provides an overview of the proceedings of the research project.

3. The ins and outs of charging plazas

From the identified knowledge gap and the research objective in section 1.2.2, this chapter addresses RQ1: *What do charging plazas look like and what needs to be considered in designing charging plazas?* In order to answer this question, multiple interviews were held with experts to get an understanding of charging plazas, charging stations and factors that need to be considered in assessing or designing a plaza. In addition, desk research has provided further in-depth knowledge to these subjects.
First, an introduction is given about charging plazas, which is followed by an explanation of factors that assess the suitability of choosing for a charging plaza and requirements for engineering a charging plaza. Then, an overview is given of traditional and electric track construction and maintenance equipment. Lastly, a brief description of charging stations is given.

3.1 Charging plazas

3.1.1 Introduction of charging plazas

In the transition from fossil fuels to electrification, one of the common goals is to make (public) charging an everyday activity in 2025, just like filling up at a gas station is today. The mobility sector aims to have 1.9 million electric vehicles on the road by 2030. As the usage of electric vehicles is rapidly growing, charging infrastructure has become very important. This rapid increase in electric vehicles would stagnate if electric vehicles would not have sufficient amount of available charging points. This is the reason why the mobility sector's objective is that by 2025 electric vehicle drivers can charge without any surprises as they do not have to dedicate a large amount of time to research and find information on charging points. The objective aligns to 1.7 million charging stations in the Netherlands. One of the fastest and most efficient ways to fulfil in the charging demand is to construct charging plazas (Duurzaam Ondernemen, 2021).

The definition of a charging plaza is as follows (Cui et al., 2022, p. 1):

"A charging plaza consists of one grid connection with several (more than two) charging stations."

The Ministry of Infrastructure and Environment (I&M) has started an initiative in the form of 'the Pilot of Smart Charging Plazas'. In this pilot, 46 charging plazas are realized in 19 municipalities. The most important goal is to share knowledge in order to develop more advanced and attractive charging plazas. For example, smart charging and vehicle-to-grid (V2G) are installed to examine their best way of application (Duurzaam Ondernemen, 2021).

From a systems perspective, charging plazas' mission is to charge as many equipment as possible. There are numerous advantageous of constructing charging plazas (*Interview Robbie Blok (NKL)*, 2022):

- *More cost-efficient:*
  - It is cheaper to connect one or more objects to a single grid connection than connect each charging point to a single grid connection. This is due to less usage of material and less costs to connect to the grid.

- Period costs for the grid connection can be shared between multiple objects instead of one. Also, when placing several charging points on one grid connection, the energy tax can be lower as a result of higher consumption on one grid connection.

- *Less time-consuming:*
  - The municipality does not have to perform an analysis to determine the location of each wanted charging station individually
  - The grid operator only has to execute construction work once for multiple charging stations
- *Increases the system efficiency and charging security:*
  - The higher concentration of charging points on one location reduces the burden on public space
  - Charging plazas can easier be connected to local renewable energy sources
  - A charging plaza is in most cases easier to expand. In addition, by clustering charging stations, the pressure on the public space are shifted to locations that are most suitable for it.
  - More available charging stations should secure more options to drivers in charging their vehicle.

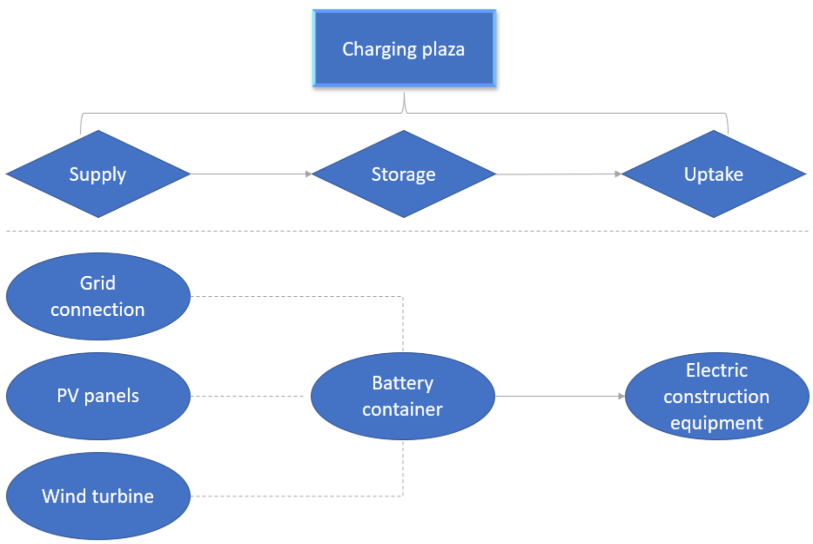


Figure 5: A conceptual model of a charging plaza for ProRail.

In general, a charging plaza consists of multiple charging stations, battery storage, PV panels for charging electric vehicles (EV) or construction equipment. In general, wind turbines are not used as they generate a lot of energy that is not necessary for the relatively small charging demand of EV's. Electric construction equipment have a much higher charging demand in comparison with EV's. Therefore, it is possible that wind turbines are used to generate enough power for electric construction equipment. In figures 5 and 6 is a conceptual model and an illustration of a charging plaza for ProRail shown. Important to note here that in figure 5, the supply and storage artefacts are examples. This is elaborated on in chapter 4.

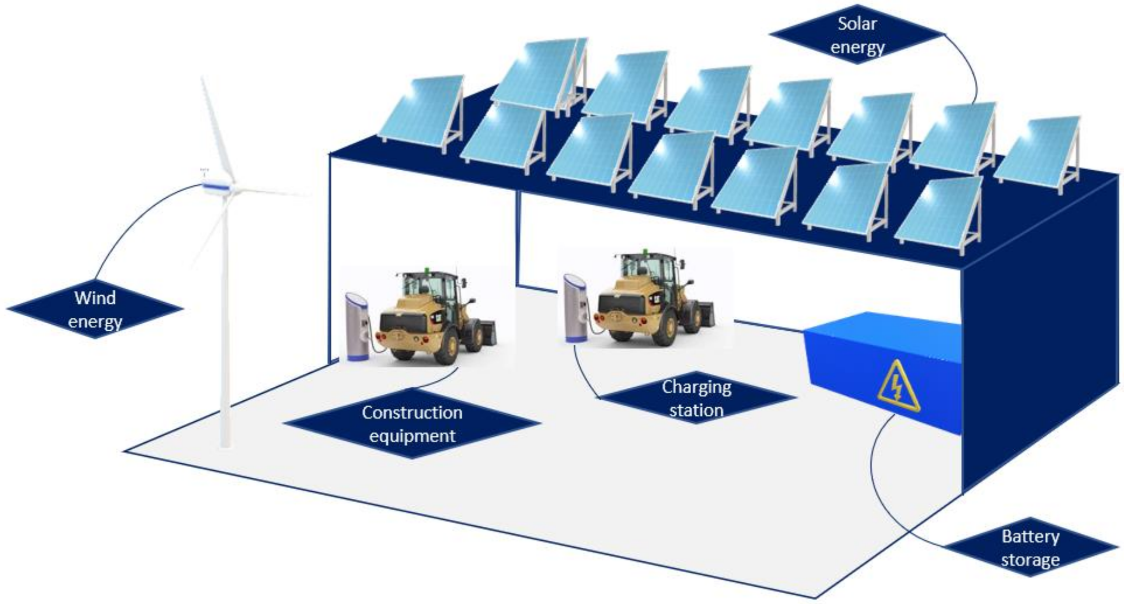


Figure 6: An overview of what a charging plaza looks like.

3.1.2 Factors in the assessment of charging plazas

Chapter 3 is about the ins and outs of charging plazas. As the advantages have been listed in previous paragraph, it is also important to understand what factors need to be taken into account to determine if a charging plaza is a suitable option. Examples of factors that the assessment takes into consideration are:

- *Spatial planning:*
  A charging plaza can benefit the quality of public space. One grid connection is required and offers multiple advantages to quality of public space. For example, grid connection and control systems can be housed in a distribution box rather than in each separate charging station (NKL Nederland, 2019).
- *Streamlining traffic flows:*
  A charging plaza generates a flow of traffic to one place rather than traffic circulating in search of different charging locations (NKL Nederland, 2019).
- *Scalability:*
  The work to provide a grid connection for a charging plaza or charging station is the same. As a result, it is easy to expand a charging plaza. This must be taken into consideration during the construction of the charging plaza by installing the necessary infrastructure (e.g. cables and pipes) (NKL Nederland, 2019).
- *Reliability of charging point availability :*
  At a charging plaza, it is possible to offer different charging needs (AC/DC). A charging plaza can facilitate a large number of users at the same time at a single location (*Interview Roy Kat (BAM)*, 2022).

- *Financial considerations:*
  The business case for a charging plaza is potentially more favourable than for a charging station. This is in relation to the effort necessary to provide infrastructure and also because capacity charge of one single grid connection has to be paid in both cases (*Interview Robbie Blok (NKL)*, 2022).
- Charging process management:
  The grid operator and site owner can optimally cater for construction equipment their charging requirements. This means that power can be more efficiently distributed between charging stations, which could reduce the peak load on the grid (*Interview Robert Daems (ABB)*, 2022).

3.1.3 Requirements for designing a charging plaza

If charging plazas are going to be realised for ProRail, a set of requirements are drawn to achieve desired performance. In this paragraph, an overview is provided of an example of categories including of requirements and options that must be considered in making agreements in relation to a charging plaza. These examples of requirements are randomly picked to provide an understanding of factors that need to be considered when designing a charging plaza. However, all categories of requirements are included, such as functionality and design, but not all examples are given. As this research project is about the development of charging plazas for construction equipment, it is useful to gain understanding on what factors are important in engineering such plazas.

Table 2: An overview of categories including examples of requirements and options in relation to a charging plaza (NKL Nederland, 2019b).

Category of requirement	**Examples of requirements**	**Description**
Functionality	Availability of new charging session	After the user has logged out, each charging point must be immediately available for new charging session
	Providing charging services	The charging infrastructure delivers energy generated from the charging plaza (e.g. connection, battery, PV, wind)
	Locking of plugs	The plug must be locked in the outlet from the moment the user logs in until they log out
Design	Appearance and materials	The charging infrastructure must be manufactured to high quality without sharp edges
	Charging station data	Information must be provided: phone number for malfunctions and other services, a reference to terms of service
Engineering and safety	Protection	The connection between the outlet and the isolator switch is protected according to standards
	Safety	The charging station must be able to withstand an impulse current of 4 kV

Smart charging	Local load balancing	The charging station must divide available energy over connected charging stations
	Charging session	Users must be able to control the charging session
Environment and location	Distance to main cable	The charging station should preferably be placed within 25 meters of the main cable
	Clean soil	The charging station should be placed in a location for which it is known that there is a clean soil statement
Security	Security	Cyber security must comply with the EV Charging Systems Security Requirements
Management and monitoring	Maintenance	The contractor is responsible for maintaining the charging infrastructure and must actively monitor its status
	Repair service	The contractor must ensure a service enabling malfunctions to be remedied remotely via a free telephone number
Application and construction	Accessible components	The service hatch for charging infrastructure must be open at all times
	Work and execution	The construction work must meet the requirements of the guidelines for work and execution
Standards and requirements	Grid operator requirements	The charging stations must be connected to a requested grid connection by the contractor of the grid operator
	Standardized charging protocol	Charging of electric equipment must take place according to protocols from the government

3.2 Construction equipment: then vs. now

The construction sector can be divided into housing, utility construction (offices, schools, etc.) and infrastructure projects. Within infrastructure projects, the focus is on different construction equipment that are used for track construction and maintenance. For instance, this concerns work around ballast, rails, sleepers and overhead lines. Railway equipment are mostly specialized machines. There is a wide variety in equipment. However, construction work around the railway is also being executed with more regular equipment as goes for works of art, tunnels and at train stations. A rough distinction can be made in the following track specific equipment (TNO, 2022):

- <u>Work trains</u>
  A work train is (often) a diesel locomotive intended for the transport of construction or maintenance materials. These trains can be used for construction work as well as for regular freight transport.

- Specialist railway equipment
  This concerns, for example, tamping machines, railway cranes, conversion cranes, inspection and measurement trains, grinding and milling trains and aerial platforms.
- Rail-road vehicles
  This concerns, for example, curls (excavator on rails) and welding bushes. The krol in particular is often used for railway works.
- Track-specific small equipment
  This concerns, for example, collar bolt machines, (small) grinders milling machines and screw and drilling machines.

Based on the rough distinction of equipment above, a categorization can be made. The categorization is shown in the table below.

Table 3: The categorization of construction equipment by means of power and size (J. Guldenaar, 2022).

Category	**Power**	**Examples of equipment**
Mini	< 19 kW	Vibration plates, mini diggers
Small	19-56 kW	Smaller excavators, generators
Medium	56-130 kW	Medium-sized specialistic railway equipment, mobile cranes
Large	130-560 kW	Rail-road vehicles, bulldozers
Very large	> 560 kW	Work trains, very large specialistic railway equipment

Nowadays, construction equipment runs on diesel engines. Construction equipment is parked on construction sites. Construction sites are the location at which the project of infrastructure is executed. Also, work sites around the tracks are used for the supply and removal of materials and to store equipment that is used by the contractor.

As ProRail has set the objective of having emission-free construction equipment by 2030, a transition has to be made. it is assumed that no significant difference will occur, if the period of time would be extended to 2040, for example, since the current trend in the construction sector is electrification (*Interview Jan van Rookhuijzen (ElaadNL)*, 2022). Therefore, the focus is set on charging plazas. These plazas will take over the function of construction sites and other work sites to store equipment.
In order to charge electric construction equipment, sufficient charging infrastructure should be installed. Therefore, charging plazas are considered to be the most attractive option in facilitating this transition. A new generation of electric construction equipment plugs in for greener construction sites. Gammon Construction launched one of its first all-electric construction equipment projects in Hong Kong. Many heavy equipment manufacturers, including Doosan Bobcat and Volvo, are beginning to roll out electric construction equipment. Examples of electric construction equipment include: excavators, loaders, forklifts and rail-road vehicles. An example of a rail-road vehicle is the e-krol. An e-krol from BAM is currently one of the heaviest electric construction equipment.

This e-krol has a capacity of 240 kWh consisting of four interchangeable battery packs of 60 kWh. The entire battery capacity endures eight hours of work (Royal BAM Group, 2022).
There are plenty of advantages to the usage of electric construction equipment: a reduction in fumes, noise, emissions, energy costs and operating costs (Sisson P., 2022). Heavy construction equipment requires power levels over 150 kW which is not too far away due to DC high power charging (RMI, 2020).

3.3 Charging station

Until now, both concepts of charging plaza and electric construction equipment have been discussed. In between these two artefacts is a charging station located in the supply chain. In this section, the utility of charging stations is discussed.
There are two different options in charging stations: alternative current (AC) or direct current (DC). The charging stations with alternative current are used for regular charging concerning charging power between 3.7 kW and 22 kW. Within charging by alternative current are three modes (Deltrix Chargers, 2019).

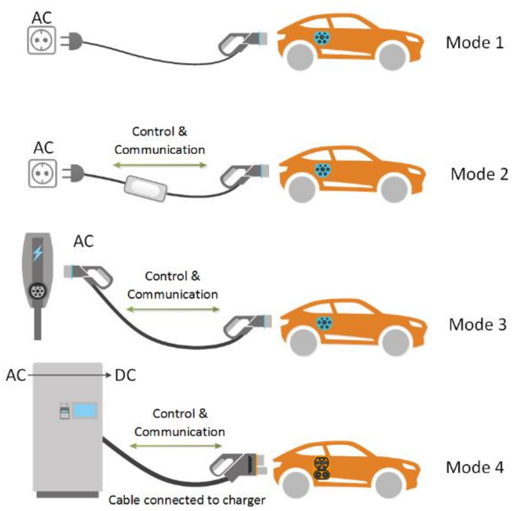


Figure 7: An illustration of each mode of electric charging (Deltrix Chargers, 2019)

In figure 7, mode 1 refers to charging from a standard power output with a simple extension cord. This method of charging does not provide users with shock protection against DC currents. Unlike mode 1 charging, mode 2 charging cables have built-in protection in the cables which protects against electric AC and DC currents. Mode 3 charging involves the use of a charging station, which also provides shock protection against AC and DC currents. At last, mode 4 is often referred to as 'DC fast-charge', due to the high power voltages (Deltrix Chargers, 2019). For electric equipment of construction works in the railway sector, mode 4 is required. These modes have mobile charging stations available on the market. This is very useful to situations in which charging plazas are meant to have a temporary character, which makes it easier to transfer them. AC charging is more time-consuming than DC charging due to the fact that an onboard charger needs to convert the alternating current. This is not necessary for DC, which can be plugged in directly to the battery system (*Interview Robert Daems (ABB)*, 2022).

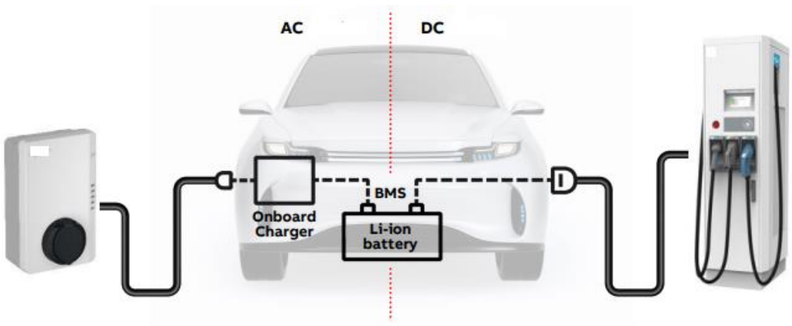


Figure 8: A schematic representation of AC and DC charging (Interview Robert Daems (ABB), 2022).

Charging stations provide the amount of power that the vehicle demands. For example, if a car demands 300 kW, but the charging station has a power capacity of 450 kW, the charging station will give out 300 kW in order to avoid overloading the vehicle or truck. On the other hand, if the vehicle or truck demands 450 kW, whereas the charging station can only provide 300 kW, the charging station will supply the vehicle with 300 kW. This will result in a longer period of charging to also avoid overloading the charging station (*EV Charging Management Software (CMS)*, 2022). As a charging plaza consists of one single grid connection, this means that there is one source of energy that supplies the charging plaza (NKL Nederland, 2019). All charging stations are connected to this source. In the distribution of energy are multiple options applicable. The software can distribute it equally among all connected charging stations or it can prioritize. However, this has to be saved to the settings in the software. Also, so-called *advanced energy services* can be added to the settings in the software. This service offers a very efficient and advanced tool to minimize costs and reduce the load on the entire grid. For example, the tool is connected to Wi-Fi to include weather forecasts into the process of charging. This means that the vehicle is going to be charged in an hour if the forecasts tells us that the sun will shine in an hour (*Interview Robert Daems (ABB)*, 2022).

3.4 Conclusion chapter 3

A charging plaza is considered to be the best option for ProRail to charge electric construction equipment from contractors. Therefore, the ins and outs are covered in this chapter. A charging plaza contains of two or more charging stations, which share the same connection to the grid. All over the country, there are now charging plazas being realized due to the fact that it is more cost-efficient, less time-consuming and increases system efficiency and security. In this chapter, the question '*What do charging plazas look like and what needs to be considered in designing charging plazas?*' was addressed. The way a charging plaza looks like is explained by means of a conceptual model and an illustration of a charging plaza for construction equipment. It contains battery storage, renewable sources, electric construction equipment and charging stations. Because of the fact that this thesis is about the integration of solutions on charging plazas, examples of requirement factors as well as assessment factors are given. In addition, a distinction is made. For all charging plazas, mode 4 charging stations is necessary due to the (high) power input and communication control which is necessary between present systems. Electric construction equipment demands a large number of energy which mode 4 is capable of.

4. Alternative energy solutions and their characteristics

In this chapter, an answer is given to RQ2: *What are potential alternative energy solutions for charging plazas and what are their characteristics?* In order to answer this question, desk research provided the foundation. During semi-structured interviews of RQ1, experts were also asked about potential alternative energy solutions that could be used for charging plazas of electric construction equipment. These solutions are proposed and discussed by means of a SWOT-analysis which provides insight into the characteristics of these alternative energy solutions. The end of this chapter determines what alternative energy solutions are included into the scenarios of charging plazas for ProRail. These charging plaza scenarios are used for a model in Excel in chapters 5 and 6.

4.1 Introduction to alternative energy solutions

Sustainability is a promissory movement, but the increase of renewable energy sources and the rise of electrification cannot always be processed properly by the electricity grid. This phenomenon is called *congestion* (Netbeheer Nederland, 2019). A widely used metaphor is that traffic jams should not occur on high voltage lines. In nine out of ten times there is no congestion on the grid, but as renewable energy sources are highly volatile, peaks in energy generation result in reaching the maximum capacity of transport of electricity on the grid (PAOTM, 2021). If this maximum has been reached, new projects are not connected to the grid to consume or inject electricity to the grid. In order to avoid congestion, the electricity grid must be enforced or extended. Besides enforcing or extending the grid, there are ways to peak shave load. This means that a consumer reduces power consumption to avoid a spike in consumption. This is possible by temporarily scaling down production, activating an on-site power generation system or relying on a battery (Liu et al., 2021). An increase in energy storage reserve capacity on the user side can increase the system stability.

For charging plazas it is important to match the right technologies with the environment. As a result of (potentially) insufficient grid capacity, it is crucial to find the right set of tools. The tools for generation, storage and usage of energy are known as *alternative energy solutions*. In table 4 below is an overview given of the addressed topics during interviews. The conducted interviews provided alternative energy solutions that could be used on charging plazas. From these interviews, their perspectives on the inclusion or exclusion of alternative energy solutions into charging plazas is given. This information is used for the SWOT-analysis in section 4.2. Only alternative energy solutions that are discussed with at least two interviewees are taken into account. For example, Jan van Rookhuijzen (2022) came up with the technology of formic acid, which is not considered. Because of the fact that the objective of ProRail has to be accomplished by 2030, only well-known and developed technologies are included. These are the following: solar energy, wind energy, battery storage, hydrogen, vehicle-to-load.

Table 4: An overview of addressed topics during the conducted interviews.

Interviewee	**Alternative energy solution**				
	Generation		**Storage**		**Both**
	Solar energy	Wind energy	Battery storage	Vehicle-to-Load	Hydrogen
Jan van Rookhuijzen			X	X	X
Roy Kat			X	X	X
Robert Daems			X	X	
Robbie Blok	X	X	X	X	
Daan Geldermans	X		X		X
Maarten Deutekom		X	X		
Anna Vissers	X				

4.2 SWOT-analysis of alternative energy solutions

In this paragraph, a SWOT-analysis is executed for each solution presented in the table above. The analysis is based on scientific literature and interviews with experts. The analysis consists of strengths, weaknesses, opportunities and threats of each solution.

Solution 1: Battery storage

Battery storage are devices that enable energy from renewables to be stored and then released when customers need power most (National Grid Group, 2022).

A. *Strengths:*

- It helps balance the energy system. It can absorb from or discharge electricity to the network at a fraction of a second's notice (Yao et al., 2016).
- It complements intermittent renewables. With the addition of energy storage, wind and solar energy become more akin to traditional "baseload" sources of energy (Addleshaw Goddard LLP, 2016).
- Battery storage avoids network reinforcement (*Interview Daan Geldermans (Skoon Energy)*, 2022). Some grid connections cannot cope with the extra demand placed on them and the usage of battery storage can help avoid or at least delay the need for expensive network reinforcement (ElaadNL, 2021). This is also the case for ProRail as grid connections are in abundance.
- Costs for battery storage has dropped rapidly. Since 2020 it has become competitive with more traditional sources of power and is rolled out on commercial scale (Yao et al., 2016).

B. Weaknesses:

- Battery storage is still expensive compared to other power generation/ grid balancing services at the moment. It is capital-extensive, requiring a large up-front cost (*Interview Robbie Blok (NKL)*, 2022).
- There still is technological uncertainty. Many batteries are still being developed and tested as there is risk that they do not perform as specified (*Interview Robert Daems (ABB)*, 2022).

C. Opportunities:

- All industry commentators seem to agree that electricity storage is due to take off in the next 5-10 years. Renewable energy and storage will go hand in hand (Addleshaw Goddard LLP, 2016).
- Time of use tariffs. This makes it possible for energy users to draw from the grid at cheap times and use stored energy at times of high demand and prices (*Interview Robbie Blok (NKL)*, 2022).
- It can be offered in combination with PV panels on top of it. This fills up the battery (*Interview Daan Geldermans (Skoon Energy)*, 2022) .

D. Threats:

- Because storage is so new, regulation has not caught up. It is classed as a form of generation and/or an end user. As a form of generation, a battery storage facility needs to be licensed and comply with Grid Codes (Addleshaw Goddard LLP, 2016).

During an interview with Jan van Rookhuijzen (2021), two options of battery storage systems came out: battery containers and interchangeable battery packs. Battery containers have the big advantage of large storage capacity. If it is connected to the grid, it can be filled at times during off-peak hours and serve as extra storage capacity during peak hours. However, its size makes it hard to transport on a frequent basis (*Interview Jan van Rookhuijzen (ElaadNL)*, 2022).
The big advantage of interchangeable battery packs is that it is easy to transport due to its relatively small size. When construction equipment is running low on battery, a new battery pack can take over and construction equipment can continue its work. If construction work is done for long distance projects and construction needs to take place in a short period of time, it is easier for construction equipment to change batteries instead of returning to a battery container (*Interview Jan van Rookhuijzen (ElaadNL)*, 2022).

Solution 2: Solar energy

The roof of solar carports is made out of solar panels, which harness power from the sun and turn it into electricity (Forbes, 2022).

A. *Strengths:*

- It is limitless as it originates from the sun. However, the contribution of solar energy to the global energy supply is still insignificant (Guangul & Chala, 2019a).
- Ease of usage/harvest. Solar panels can be installed anywhere. For instance, solar panels are now easily placed on rooftops or carports.
- It is environmentally friendly as it collects and stores energy to generate electricity.
- Less overall cost due to low running cost. In the long-run the cost benefit of using solar energy would be better than other sources of energy (Kabir et al., 2017).
- The solar carports provide shelter at times of bad weather (*Interview Anna Visser (GroenLeven)*, 2022)

B. *Weaknesses:*

- Availability of sun rays is only in day time. So solar panels can only convert solar energy into other forms of energy when there is sunlight.
- Solar panels are still inefficient. Nowadays, the average efficiency of a solar panel is approximately 22%. The thermodynamic efficiency limit states that solar energy will never reach 100% efficiency. However, the overall efficiency of solar panels are improving every year (World Water Reserve, 2021).
- Space required for PV panels. Due to its inefficiency more photovoltaic cells are needed to absorb enough energy for larger applications.
- High initial costs. Although installation of solar system brings immense benefits, the initial investment cost is expensive. Subsidy and tax exemptions are used by governments to help reduce the burden (Conserve Energy Future, 2015).

C. *Opportunities:*

- Cost reduction. Over the last few decades the cost of silicon photovoltaic cells has dropped dramatically from $76.67 in 1977 to $0.36 in 2014 (Peter Diamandis, 2014).
- Availability of subsidy and support. In most countries organizations have subsidy and income tax exemption schemes (Guangul & Chala, 2019a).

D. *Threats:*

- The disposal of solar panels, which contain unsafe components, such as lead, chromium and cadmium, but effort to minimize the adverse effect is very minimal (Barnes, 2017).
- It is trending toward more affordable options, but still is not widely available to most household (World Water Reserve, 2021).

Solution 3: Wind energy

Wind energy is used to produce electricity by converting the kinetic energy of air in motion into electricity. In wind turbines, wind rotates the rotor blades, which convert kinetic energy into rotational energy. Rotational energy is transferred by a shaft to the generator, thereby producing electrical energy (IRENA, 2021).

A. *Strengths:*

- Wind energy is a clean energy source (*Interview Maarten Deutekom (WES)*, 2022).
- Wind energy is a sustainable energy source with one of the highest efficiencies (Born to Engineer, 2017).
- Wind energy has cost certainty. No fuel is required for wind energy generation. Only maintenance costs need to be taken into account (World Water Reserve, 2021).

B. *Weaknesses:*

- The limitation in geographical location. Depending on the wind speed the feasibility of the investment varies from place to place (Guangul & Chala, 2019b).
- Fluctuation of wind. The turbine only generates energy if wind blows. This dependency makes it hard to rely on such sources fully.
- High initial investment. This is a result of high cost to erect the turbine to construct a strong foundation. Also transportation cost is significant due to the size of the blades and turbine (Guangul & Chala, 2019b).

C. *Opportunities:*

- Smaller wind turbines can generate electricity for up to 20 years. Also, their placement is easier as a result of reduction in size (World Water Reserve, 2021).
- Mobile wind turbines are a more flexible option for small capacity projects (*Interview Maarten Deutekom (WES)*, 2022).

D. *Threats:*

- It is devastating to wildlife. Birds and bats would die as a result of collisions with wind turbines.
- 85-90% of wind turbine structure is recyclable. Currently, there is a lack of technical standards and regulations for sustainable repurposing (Kieran Ruane et al., 2022).
- Noise and obstruction of sight has caused a low level of social acceptance (Knopper & Ollson, 2011).

Solution 4: Hydrogen

Hydrogen can be extracted from fossil fuels, biomass, from water, or from a mix of both. Natural gas is currently the primary source of hydrogen production. It is light, energy-dense and storable (IEA, 2019).

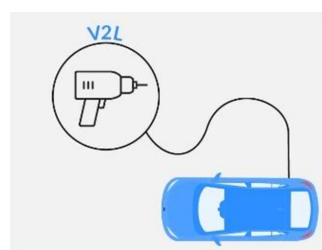
A. *Strengths:*
- Hydrogen has a relatively high energy density. Hydrogen has an energy density of 5.6 MJ per liter whereas lithium-ion batteries have an energy density of 2.63 MJ per liter (Gray et al., 2021).
- It is an efficient energy carrier. For long term projects or long distance transport, hydrogen storage is more effective than batteries (*Interview Roy Kat (BAM)*, 2022).

B. *Weaknesses:*
- The conversion of hydrogen. Conversion equipment is expensive and the process consumes an high amount of energy (Cole et al., 2017).

C. *Opportunities:*
- Heavy industry and long distance transport, such as marine or aviation sector, are industries most suitable to hydrogen due to high energy density (Gray et al., 2021).

D. *Threats:*
- Hydrogen is rather an energy carrier than an energy source. Competition with other renewable resources cannot be ignored. However, the technologies for electricity generation from renewable resources are more advanced and mature than those for hydrogen production (Ren et al., 2017).
- Unconfirmed market potential. In the past few years, hydrogen has been presented as the key to a green economy. However, cost and competition seem a big threat (Ren et al., 2017).

Solution 5: Vehicle-to-Load



Vehicle-to-Load is a feature available on battery electric vehicles that lets them use their stored energy to power external devices, such as electric construction equipment. Therefore, it is an option to serve as a solution for energy supplies (APTIV, 2022).

A. *Strengths:*
- It can provide storage backup for renewable energy sources due to its storage capability (Zhou et al., 2013).
- The storage function provides an incentive-pricing plan to motivate drivers to charge during off-peak hours. This can decrease dependency on central power plants in peak hours and lowers overall cost (Bibak & Tekiner-Moğulkoç, 2021).

B. *Weaknesses:*

- Only two car manufacturers produce the V2G/V2L function (*Interview Roy Kat (BAM)*, 2022).
- It requires an high initial investment. EVs have to be equipped with plug in connectors and metering equipment to measure the input and output power and sending the level of battery charging to operators (Bibak & Tekiner-Moğulkoç, 2021).

C. *Opportunities:*

- It is the most promising opportunity to adopt EV in power systems because of its specific features of feeding energy back to the grid or load (Zhou et al., 2013).
- The adoption of V2L needs governmental support. If they make it mandatory in rules and regulation to car manufacturers, a quick uptake is possible. An example is Japan (Interview Robbie Blok (NKL), 2022).

D. *Threats:*

- Stochastic and uncertain nature of EV's, such as departure/arrival times to charging plazas, battery sizes charger/discharger types, daily driven distances, etc. (Bibak & Tekiner-Moğulkoç, 2021).
- It requires a mutual flow of information, power and money between EVs owners, grid operators, telecommunication providers (*Interview Robert Daems (ABB)*, 2022).

Based on the results from the SWOT-analysis, the inclusion and exclusion of alternative energy solutions is made. It was decided to include three options because it is practically infeasible and difficult to recreate a scenario with all options in Excel.

Depending on a project, both solar energy and wind energy are included as these renewable sources can generate energy for supplies. Battery storage is crucial in balancing and managing load and to offer extra capacity to a charging plaza. As fluctuant renewable sources, such as solar and wind energy, are included, battery storage must offer stability to the charging plaza.

Both hydrogen and vehicle-to-load are excluded from the remainder of the project. Hydrogen is practically not feasible and too expensive. The production of hydrogen demands a lot of electricity because of the fact that it is still relatively inefficient. This electricity could better be used for charging a battery container or construction equipment. Vehicle-to-load is an immature technology. More rules and regulation, for example about ownership of energy and payments, is necessary for manufacturers to include the function to more vehicles. In short, solar energy, wind energy and battery storage are included in the proceedings of the project.

4.3 Conclusion chapter 4

In this chapter, first, an introduction is made to alternative energy solutions. Second, the way alternative energy solutions are selected to be analyzed is explained by means of a table. This table shows what interviews discussed certain alternative energy solutions. One of the criteria to the inclusion of a solution was that at least two interviews had to discuss it. Overall, most interviews led to the same proposal of alternative energy solutions. From this point, five alternative energy solutions were analyzed by a SWOT-analysis with the help of results from interviews and desk research. This had led to the following conclusions in regard to the inclusion and exclusion of alternative energy solutions in charging plaza scenarios:

- Inclusion of solar energy (PV carports)
- Inclusion of wind energy
- Inclusion of battery storage
- Exclusion of hydrogen
- Exclusion of vehicle-to-load

Battery storage is crucial in balancing and managing load and to offer extra capacity to the charging plaza. Solar and wind energy, are included, which is the reason why battery storage must offer stability. The renewables need to generate enough energy for charging the construction equipment, but have no certainty in generation due to the randomness of sunshine and wind speeds.

Both hydrogen and vehicle-to-load are excluded. Hydrogen is practically not feasible due to the restricted availability. Also, the production of hydrogen demands a lot of electricity which makes it too expensive. This electricity could better be used for charging battery containers or construction equipment. Vehicle-to-load is an immature technology. More rules and regulation, for example about ownership of energy, is necessary for manufacturers to manufacture the function to more vehicles.

5. Assumptions and scenarios

In this chapter, assumptions and scenarios are made and discussed. An answer is given to RQ3: *What are realistic charging plaza scenarios for ProRail and what assumptions do they contain?* As concluded in chapter 4, battery storage, solar energy and wind energy are included into the model of charging plazas. The assumptions are obtained from structured interviews with specialists in the type of field that the assumption concerns and desk research. In these (structured) interviews, a prepared list of questions was followed during the interview. Besides assumptions, a morphological analysis is done in order to develop charging plaza scenarios. This analysis consists of a morphological chart, a realization table and a combination table, see Appendix C. These tables are based on real life projects that are created in collaboration with experts from Movares. Based on the assumptions and scenarios made in this chapter, a model is built in Microsoft Excel in chapter 6.

5.1 Assumptions

A model, which is a simplification of the real world, requires data to be build. The in-depth analysis of this research project did not have access to assumptions to be build. The assumptions are in regard to choices in battery storage, grid capacity, charging station/demand, PV panels and wind turbines. Battery storage, PV panels, grid capacity and wind turbines are also the parameters of the morphological chart. These parameters, or building blocks, are inserted into an Excelsheet in order to recreate scenarios of charging plazas. From these Excelsheets, simulations were made to determine if the included building blocks are able to meet demand of the charging plaza scenario. These results are given in chapter 6.

Battery storage

In the selection of battery type for storage of energy produced by renewable energy sources it is essential to take into account the total costs (initial, installation, maintenance, disposal), the lifetime of batteries as well as their efficiency, safety, reliability and impact on the environment. Most frequently used batteries are lithium ion batteries. They have high efficiency, high energy density, long life cycle and the possibility of continuous discharge. Also, they are not made of toxic materials and are mostly used for small scale projects. Currently, the main drawback is the relatively high costs, which is decreasing over the years (Symeonidou et al., 2021). An overview of assumptions in battery storage is shown in the table below.

Table 5: An overview of the assumptions in battery storage.

Alternative energy solution	Assumption	Motivation
Battery storage	All battery storage options are made of lithium-ion	It is the most frequently used battery due to its high efficiency, high energy density, long life cycle and exclusion of toxic materials
	The battery can be fully discharged	No long-term effect is caused if battery discharges 100% continually

	The charge time of each battery option is 3 hours	The maximum charging time of lithium-ion batteries is approximately 3 hours

The dimensions in the morphological chart for battery storage are as follows: 0 kWh, 120 kWh, 350 kWh and 500 kWh. As shown in the figure below, the charge time of lithium batteries on average is around 3 hours, which is also the case for the 120 kW battery from RECO (RECO, 2022). This charge time of the battery is used for each battery capacity option. Also, the depth of discharge (DOD) is assumed to be 100%. It is stated that it is recommended to discharge down to 80% to maintain battery life, but 100% would not cause a long-term effect (RELiON, 2019).

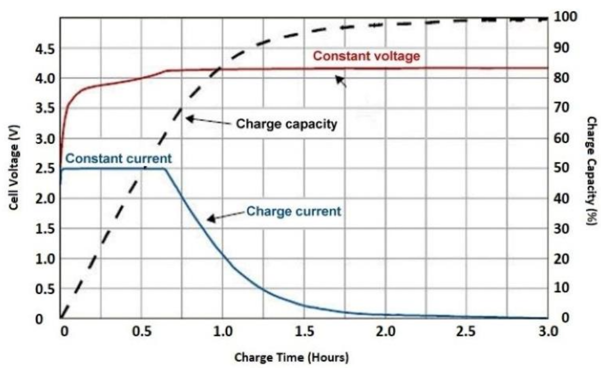


Figure 9: Charge curve of Lithium-ion cell (EVreporter, 2022).

Available grid capacity

The problem of today is getting a connection to the grid with sufficient capacity. Therefore, this parameter contains different percentages in capacity availability. The different percentages are the following: 0%, 50%, 75% and 100%. These percentages were chosen randomly in collaboration with colleagues from Movares. Grid capacity is dependent on the available capacity of the grid operator and will change over the upcoming years. However, if capacity is ensured, capacity starts with 50% and increases to 100% over the years. The required capacity or the permeability value determines the size of the connection:

- Small consumption: no more than 3x 80 A
- Large consumption: greater than 3x 80 A

Costs for temporary grid connections greater than 3x 80 A need to be requested by the grid operator. Therefore, the costs of grid connections are not included in the total costs of each scenario as this remains unknown.

Charging station

Construction equipment require high power voltage when charging. Therefore, charging stations with mode 4 (DC) have to be installed. In this case, a 120 kW DC charging station is used for the model. The formula that is used to calculate the charging time is as follows:

$$Charging\ time\ (min) = \frac{Battery\ capacity\ (kW)}{Charging\ velocity\ \left(\frac{kW}{\min}\right)}$$

This charging station can charge 120 kW per hour. This means that for equipment with a battery capacity of 240 kW and a charging station of 120 kW per 60 min, 120 minutes is needed to charge to full capacity. A charging period of an electric vehicle is used for the charging pattern of electric construction equipment. This has a specific pattern as can be seen in the figure below. The state of charge (SoC) does not go below 20%. For construction equipment with 240 kW capacity, this means that most demand can be 20%*240 kW= 192kW. A requirement is that the equipment needs to be 'fully' used.

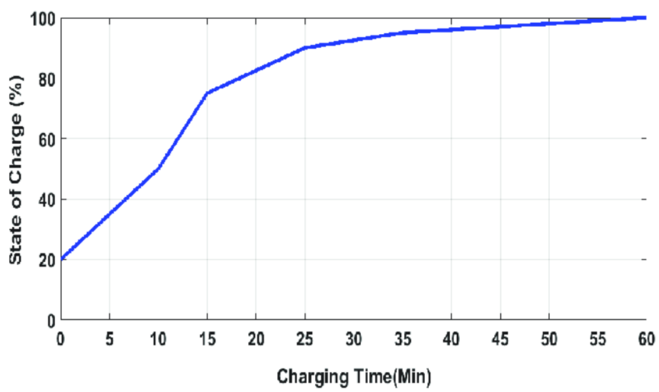


Figure 10: Characteristics of charging pattern of an electric vehicle (Asna et al., 2021).

A second characteristic is that the first 25 minutes of charging goes relatively rapid as it charges till an SoC of approximately 85%. The other 35 minutes are really time-consuming to maintain the quality of the battery. From 20% SoC till 100%, the trend line has a slope of 1,33. Therefore, the charging demand function over time is the following:

$$Demand\ charging\ station\ (t2) = demand\ (t1) * (0{,}67^{\frac{1}{amount\ of\ charging\ stations}})$$

, where

$$Demand\ (t1) = \ amount\ of\ charging\ stations * battery\ capacity * 80\%$$

All assumptions of charging stations and demand are shown in the table below.

Table 6: An overview of assumptions of charging stations and demand.

Artefact	**Assumption**	**Motivation**
Charging station	Each charging station has a capacity of 120 kW DC (mode 4)	For construction equipment a relatively high power output is necessary. This charging station has an above average capacity.
	Charging pattern of an electric vehicle is used	The e-krol contains four interchangeable battery packages of 60 kWh, which is similar to a medium sized electric vehicle

Charging demand	Each charging station is occupied by an e-krol of 240 kWh of charging demand	As of today, this is the highest charging demand of electric construction equipment.
	Charging demand is at its peak when employees go home and install construction equipment to the charging station, at 5 pm or 7 am (depends on scenario)	Once employees go home, construction equipment needs to be charged as it is used all day/night
	Charging demand is expected to be zero when employees go to work and offload construction equipment from the charging station, at 5 pm or 7am (depends on scenario)	All construction equipment is used once the employees get to work. After a full night/day of charging, it may be charged full
	Charging demand reduces over time if it is installed on a charging station between 5pm and 7 am	Demand reduces as construction equipment is being charged

Solar energy

Solar energy is used in the form of photovoltaics (PV). PV panels are easy to install and can generate a fair amount of energy. In most cases for a charging plaza, a solar carport is used. This means that construction equipment can charge and fill the area, whereas the carport provides shelter and can generate electricity due to the installment of PV panels. An overview of assumptions of solar energy is given in the table below.

Table 7: An overview of assumptions of solar energy.

Alternative energy solution	**Assumption**	**Motivation**
Solar energy	Monocrystalline PV panels	They are the most efficient PV panel, tend to last longer, but are expensive
	Azimuth of 180 degrees south	This is the most frequent azimuth on the Northern hemisphere (Dubey et al., 2013)
	Tilt of 35 degrees	This is the optimal tilt in the Netherlands (European Commission, 2022)
	400 Wp solar panels	Most residential solar panels have power output rating up to 400 Wp (Sunrun, 2019)
	Average generation capacity per year is 380 kWh	Each panel generates 1,04 kWh per day (= 380/365)

The total costs of one single 400 Wp PV panel in 2022 is between €350-€550 in the Netherlands. This includes taxes, installation and inverter (Zonnepanelen-expres, 2022). Because of the fact that this estimation includes taxes, the total costs of one PV panel equals €350. For each case, a multiplication is made from this assumption.

In the morphological chart, there are five different options for total capacity generated by PV panels. The options are as follows: no capacity, 2000 Wp, 4000 Wp, 8000 Wp and 16000 Wp. This has been chosen because one panel has a wattage of 400. Each solar panel covers an area of approximately 2 m^2 (Zonnepanelen 400 Wp, 2022). The smallest scenario, which is scenario 1, assumes that a charging plaza is able to cover at least 5 panels (approx. 10m^2).

Wind energy

There has been chosen to take the following capacities of wind turbines into consideration: 0, 10, 100, 350 and 500 kW. The option of no wind turbine is also possible due to the fact that a wind turbine is not flexible and easy to install. In the table below, an overview of assumptions of wind energy is given. This means that long-term projects have a higher chance for the inclusion of wind energy than short-term projects. This is because of the fact that permits have to be granted to install wind turbines. On the other hand, short-term projects (~ 5 years) can also install wind turbines due to current high energy tariffs. This results in positive business cases (*Interview Wind Energy Solutions*, 2022).

Table 8: An overview of assumptions of wind energy.

Alternative energy solution	Assumption	Motivation
Wind energy	Turbines with three blades and horizontal axis are considered	The most efficient wind turbines have three blades
	Full load hours per day of a wind turbine is 4,13 hours per day	An average of 1506 hours per year of full load hours (average annual production/ rated power)
	The full load hours start when charging of construction equipment starts	Wind energy is a less fluctuating source compared to solar energy
	High energy tariffs will remain the coming years	As of now, wind energy is deemed to have a positive business case for 5 year projects

Each wind turbine has horizontal axis and contains three blades as most turbines have three blades, which is the most efficient option (Energy.gov, n.d.). A modern wind turbine produces electricity 70-85% of the time, but it generates different outputs dependent on the wind speed. Over the course of a year, it generates about 30% of the theoretical maximum output (Sciencing, 2020). In addition, full load hours refers to the time for which a plant would have to be operated at nominal power in order to convert the same amount of electrical work as the plant has actually converted within a year (Energy Transition – The Wiki, 2022). As all included wind turbines have no higher tower than 50 meters, an average has been taken from the full load hours of wind turbines up to 50 meters. This provides us with an average of 1506 hours per year (4,13 hours per day) (CBS, 2022). Wind energy is a less fluctuating energy source in comparison with solar energy. Therefore, it is assumed that wind start its 'full load hours' when charging kicks off. So the wind starts blowing from 7 am or 5 pm till 4.13 hours have passed.

5.2 Scenarios

In this section, three scenarios are derived from morphological charts, realization tables and combination tables. The realization table and combination table are given in Appendix C. Each morphological chart consists of five dimensions as it contains five parameters. The parameters are as follows: project span, available grid capacity, battery storage capacity, PV panels capacity and wind turbine capacity. The options to the parameters are given by experts in solar carports, battery storage and wind turbines during interviews. There are 3125 combinations (5x5x5x5x5) possible, in which not all of them are practically feasible. As a result, three combinations are selected in collaboration with experts from Movares, see Appendix B7. Charging plazas are not used for construction equipment yet, which is why scenarios could choose any time period. The time periods are based on real life projects to make sure that a distinction in time and charging demand is grounded. Discussions on the input of each parameter happened to make the scenarios as realistic and likely as possible. The three scenarios are the following: a long-term project (~20 years), a five-year project and a six-month project. The aim of analyzing these three scenarios is to show to what extent alternative energy solutions can fulfil in demand of a respective charging plaza without or partially with grid capacity.

5.2.1 Scenario 1- A long-term project (~20 years)

An example of a permanent or long-term site is a so-called rail access point. This is a place in which construction equipment can be inserted to the railway system. A scenario has been created for a rail access point in the morphological chart below.

Table 9: Morphological chart of a long-term project.

Project span	Available grid capacity	Battery storage capacity	PV panels capacity	Wind turbine capacity
~ 1 week	No	No	No	No
~ 6 months	Yes but 25% of demand	50 kWh	2000 Wp	10 kW
~ 2 years	Yes but 50% of demand	120 kWh	4000 Wp	100 kW
~ 5 years	Yes but 75% of demand	350 kWh	8000 Wp	350 kW
long-term (~20 years)	Yes (100%)	500 kWh	16000 Wp	500 kW

In this scenario, there is no grid capacity available due to the fact that the rail access point is close to a substation. It is assumed that the connection to the substation is sufficiently adequate. Therefore, the charging station is connected to the substation. Such an access point is not a big area and contains one charging station with two guns. The charging station has a total power output of 120 kW, which can also be shared by two construction equipment at the same time (2x60 kW).

Two construction equipment (e.g. an e-krol) can be charged during the day (7 am-5pm) and must be available at night (5 pm- 7 am). Each e-krol has a battery capacity of 240 kWh.

Due to the fact that the first scenario is a long-term project, a wind turbine belongs to the possibilities. However, a fairly small amount of capacity is required for this charging plaza. Therefore, a relatively small turbine has been selected as well as a small amount of PV panels because it must fit a small sized location. In order to store enough energy from these volatile sources, a medium sized battery should offer enough capacity to store enough during peak hours of demand.

5.2.2 Scenario 2- A 5-year project

An example of a five-year project is Programma Hoogfrequent Spoor Amsterdam (PHS Amsterdam). A scenario has been recreated for PHS Amsterdam in the morphological chart below.

Table 10: Morphological chart of a five-year project.

Project span	Available grid capacity	Battery storage capacity	PV panels capacity	Wind turbine capacity
~ 1 week	No	No	No	No
~ 6 months	Yes but 25% of demand	50 kWh	2000 Wp	10 kW
~ 2 years	Yes but 50% of demand	120 kWh	4000 Wp	100 kW
~ 5 years	Yes but 75% of demand	350 kWh	8000 Wp	350 kW
long-term (>10 years)	Yes (100%)	500 kWh	16000 Wp	500 kW

A charging plaza for a five-year project is assumed to have the highest amount of charging demand among scenarios. In this case, it is expected to have 75% capacity available of all demand at the charging plaza. Such a charging plaza is relatively big and contains fifteen charging stations with each two guns. The total output of all charging stations added up is 1800 kW. This means that each gun can power 60 kW if all charging stations are occupied. Construction work is executed during the day, which means that equipment has to be charged at night.

Charging demand can be spread over 15 charging stations of 120 kW overnight from 5 pm until 7 am. However, 75% of demand is supplied by the grid, which has been subtracted from the charging demand. For a five yearlong project, in general, it is hard to install a wind turbine. Licenses and permission have to be granted in order to install a wind turbine. However, nowadays, this is usually being granted due to high energy tariffs. An e-krol, the construction equipment that is used as large standard charging equipment on the charging plaza, consists of four battery packs of 60 kWh each. However, an e-krol can be used with a single battery unit. After a night of charging, not all charging demand of all equipment can be met. This is not necessarily a big problem, since one battery can be used per construction equipment. At 7 pm, charging demand is around 152 kWh, which means that only As such a charging plaza is relatively big, there is enough space for a solar carport to install twenty PV panels and locate a 500 kWh battery.

5.2.3 Scenario 3- A 6-month project

An example of a six-month project is renewal of rail over a certain distance. A scenario is created for such a six-month project in the morphological chart below.

Table 11: Morphological chart of a six-month project.

Project span	Available grid capacity	Battery storage capacity	PV panels capacity	Wind turbine capacity
~ 1 week	No	No	No	No
~ 6 months	Yes but 25% of demand	50 kWh	2000 Wp	10 kW
~ 2 years	Yes but 50% of demand	120 kWh	4000 Wp	100 kW
~ 5 years	Yes but 75% of demand	350 kWh	8000 Wp	350 kW
long-term (>10 years)	Yes (100%)	500 kWh	16000 Wp	500 kW

A charging plaza for a six-month project is considered to be medium sized overall in these three scenarios. In this case, it is expected to have 50% grid capacity available of all demand at the charging plaza. 300 kW has to be supplied by alternative solutions in this scenario. Such a charging plaza contains five charging stations with each two guns. The total output of all charging stations added up is 600 kW, which means each gun has 60 kW of power. Construction work is executed during the day from 7 am till 5 pm. Therefore, the battery should be charged during the day which can help to satisfy charging demand at night. During the day, it can be possible that in total approximately one e-krol is charged by equipment that rest for an hour. The battery can be charged during the day by electricity generated from PV panels. In this case, 20 panels and a battery of 350 kW capacity must offer enough to satisfy 300 kW to the charging plaza.

5.3 Conclusion chapter 5

The sub question questions what scenarios of charging plazas are possible and what assumptions they contain. A morphological analysis, consisting of a morphological chart, a realization table and a combination table resulted in three scenarios. The parameters were discussed with experts in the field of solar carports, battery storage and wind turbines to create realistic options. This chapter sets up three types of charging plazas that differ in time span and charging demand: a six-month project with medium charging demand, a five-year project with high charging demand and a long-term project (~20 years) with small charging demand. These charging plaza types aimed to replicate real life projects to make it realistic. The three types resulted from a brainstorming session with experts from Movares, who have a great deal of experience in such projects. In relation to the main research question, this chapter identified the types of charging plazas that selected alternative energy solutions from chapter 4 are integrated into. In addition, made assumptions for relevant parameters are discussed. The foundation for the model in Excel is laid in this chapter and can now be worked and calculated with in chapter 6.

6. Result analysis of scenarios

In this chapter, results from the model in Excel are presented and discussed for each scenario that was created in chapter 5. An answer is given to the fourth sub question: *How do the charging plaza scenarios for ProRail fulfil in charging demand and what are their total costs?* The results are presented by means of a graph that shows whether energy supplies of alternative energy solutions are able to meet demand in the created scenarios. Also, linear programming is used to determine if a charging plaza is able to generate sufficient amount of power by finding the optimal solution to a given objective function. This method is briefly explained in Appendix E. For scenarios that are able to meet demand of the charging plaza in time, an indication is made of the total costs and the benefits for changing to charging plaza.

6.1 Result of scenario 1- A long-term project (~20 years)

The rail access point in scenario 1 has integrated a 120 kWh battery, 5 PV panels and a 100 kW wind turbine into the charging plaza. PV panels are not able to generate much of energy during the day. Approximately 5.2 kWh is generated by 5 PV panels which is around 1.35% of total charging demand of the charging plaza. This energy is captured by the 120 kWh battery during the day and at night. As most charging demand of the charging plaza has to be supplied by wind energy, it is relevant to determine if the proposed 100 kW wind turbine is sufficient. In the figure below, the result is given.

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$C$12	Daily power output (kWh)	0	378.7945205

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$A$12	Wind turbine capacity (kW)	0	91.8061089	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Total charging demand (kWh)	384.0	$B$14>=0	Not Binding	384.0
$B$15	Demand/supply	0.0	$B$15>=0	Binding	0.0
$B$9	Total charging demand (kWh)	384.0	$B$9<=$B$14	Binding	0
$C$12	Daily power output (kWh)	378.7945205	$C$12>=0	Not Binding	378.7945205
$A$12	Wind turbine (kW)	91.8061089	$A$12>=0	Not Binding	91.8061089

Figure 11: The linear programming function in Excel and its result for charging demand of scenario 1.

The figure above shows the results to the linear programming problem in the Solver function of Excel. The decision variable is the variable cell of wind turbine capacity. This variable is changed to the optimal solution according to the objective function and the constraints. The objective is to find the minimum daily power output for a wind turbine that supplies enough power to meet charging demand of the charging plaza. Besides, searching for the optimal solution, the program only considers according to constraints that determine a feasible region. The most important constraint is that total charging demand must equal or be lower than total capacity, otherwise there is a mismatch. The result shows that a wind turbine of 91 kW is able to meet charging demand, which means that the proposed 100 kW wind turbine is able to meet charging demand of scenario 1.

However, due to the fact that a 120 kWh battery system is present, the charging pattern of a charging station is not able to go in one way as the first 25 minutes demands a lot of energy. This is shown in the figure below.

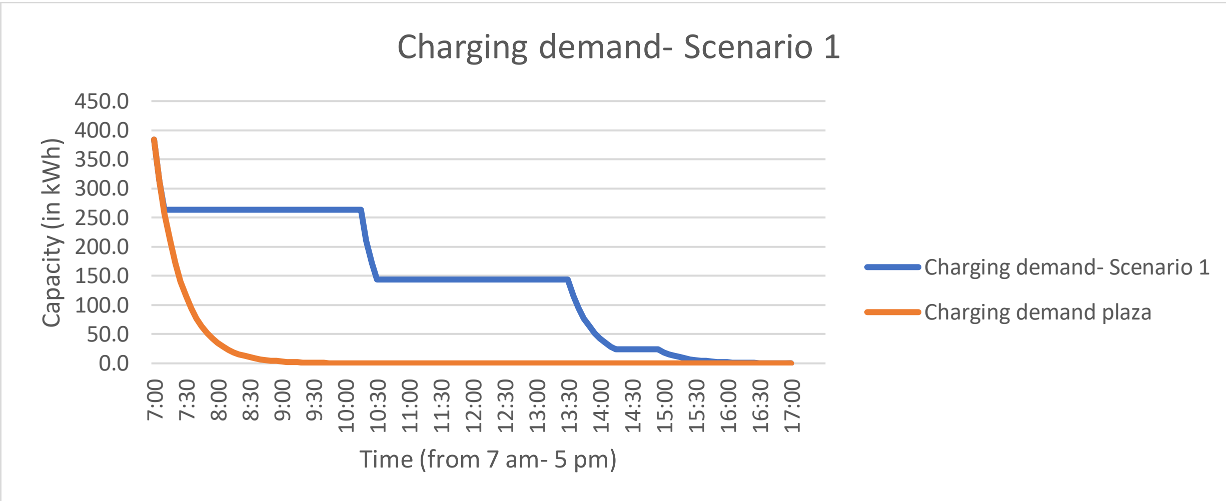


Figure 12: A graph showing the result of scenario 1. The orange line represents charging demand of scenario 1. The blue line shows how demand flows with the available alternative energy solutions being integrated on the plaza.

It is assumed that the wind blows when charging starts. However, if this would not be the case, a 400 kWh battery container is necessary to capture enough energy for the charging plaza during the rest of the day. As can be seen in the table below, a wind turbine of 100 kW is able to generate enough output per day. PV panels do not make a big difference and serve as an extra energy source to fill the battery but energy from the wind turbine makes the difference. In this scenario, charging of the two construction equipment is finished before 5 pm when construction workers get to work. For this scenario, only a difference could be made in battery capacity. In the figure above, there has been worked with the capacity of full load hours, which is likely to not happen every day. Therefore, a battery of 400 kWh would help to overcome this scenario to capture enough energy during working hours. More power can be stored, which results in charging demand (orange line in the figure above) to be met at any time.

From the interview with Maarten Deutekom (*Interview Wind Energy Solutions*, 2022) the information in the table below has been retrieved about costs of wind turbines. Also, the total costs of one single 400 Wp PV panel in 2022 is between €350-€550 in the Netherlands. This includes taxes, installation and inverter (Zonnepanelen-expres, 2022). Because of the fact that this estimation includes taxes, the total costs of one PV panel equals approximately €350. For each case, a multiplication is made from this assumption. For example, if 5 panels are considered, the total costs for the scenario equals 5*€350= €1,750. Lithium-ion batteries current cost range of LFP and NMC is on average around €345 per kWh. The report treats LFP and NMC as a single technology, because they both fall under the umbrella of 'lithium-ion' (Li-ion) batteries, and have similar cost and technical performance (CSIRO Energy, 2015). The article assumes maintenance costs on batteries of residential and medium scale (7 kWh<x<1,000 kWh) cost around €190 for every five years. The installation costs range from €6,000 to €13,000 (Solar reviews, 2022).

Table 12: Approximated total costs of scenario 1.

Alternative energy solution	**Capex (approx. in €)**	**Opex (regular preventive maintenance) (approx. in €)**	**Installation costs (incl. foundation works) (approx. in €)**	**Total costs (approx. in €)**
1x Wind turbine 100 kW	225,000	2,500	25,000	252,500
5x PV panel 400 Wp	-	-	-	1,750
120 kWh battery pack	41,464	760	6,681	48,909
375 kWh battery container	129,574	760	6,681	137,019

The table above shows the costs of each element within a created system of scenario 1. However, only one battery container should be included. Both options would suffice charging demand within the required period of time. However, a larger battery container can fulfil demand of the charging plaza in one go whereas the smaller option needs to charge it and eventually takes a longer period of time. Besides, on days of low velocity wind it is possible that the smaller battery is unable to fully charge itself. This might lead to uncharged construction equipment which would be disastrous to the project.

Therefore, a larger battery container is able to take out most of this uncertainty because total charging demand can be generated and stored during day and night. In the pie charts below, the contribution to total costs is shown for both a battery container of 120 kWh and 375 kWh. The installation costs and operation and maintenance costs are expected to be similar to both battery solutions as they belong to the same range. It is clear that a wind turbine is by far most expensive. However, it also generates, respectively, all energy required. A larger battery container increases the total costs by around 19%.

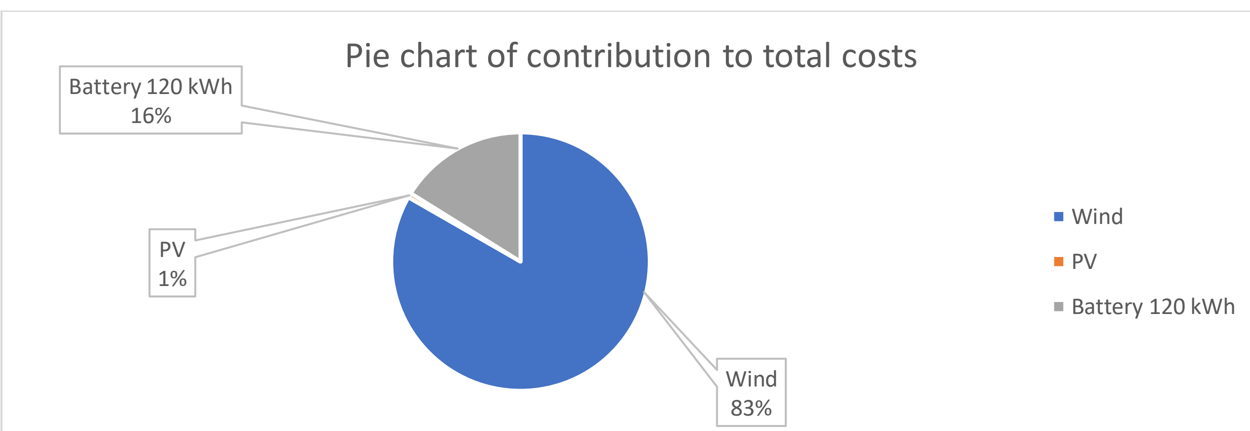


Figure 13: Pie chart of contributions to total costs of scenario 1 with a 120 kWh battery container.

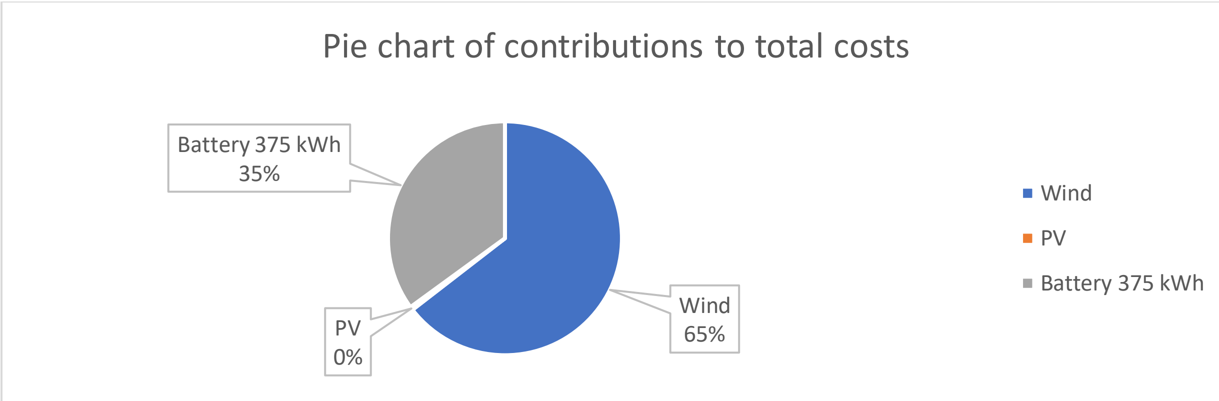


Figure 14: Pie chart of contributions to total costs of scenario 1 with a 375 kWh battery container.

To put these results into perspective with *former* construction process work, it is worth looking at the benefits of switching to a charging plaza. So in the past when rail work was executed, a krol consumed 15 litres of diesel per hour, in which the data is extrapolated to a distance of 100 metres (SGS Search Consultancy, 2021). In the model, an e-krol is taken into account that can last for eight hours without being charged. As no sources in literature point out a difference in efficiency of work in time, it is assumed that a krol consumes 120 litres in eight hours of similar work. When a krol consumes one litre of diesel, 3.468 kg of CO_2 is emitted into the atmosphere (CO2 emissiefactoren, 2023). Also, the costs for one litre of diesel are €1.83 on the 10th of February, 2023 (Brandstof-zoeker.nl, 2023).

To sum things up, an rough indication of benefits is made. In comparison to scenario 1, two krol vehicles need diesel to cooperate whereas in scenario 1, the energy is generated by renewable sources. The costs for diesel sum up to around €3.2 million (= €1.83*240 litres*365 days *20 years). In addition, around 6,000 tonnes of CO_2 is emitted over 20 years of construction work (= 3.468 kg* 240 litres* 365 days* 20 years). In scenario 1, the total costs were less than €450,000.

6.2 Results of scenario 2- A 5-year project

HPS, which has been replicated in scenario 2, is a very big project in Amsterdam that contains a lot of charging demand of electric construction equipment. In this scenario, a 350 kW wind turbine, 40 PV panels and a battery of 500 kWh is integrated into the charging plaza from the morphological chart in previous chapter. As elaborated on previously, 30 charging guns are occupied by construction equipment at night. It is known that PV panels do not generate large amount of energy to rely on (~ 0.7% of total charging demand in this scenario). Again, wind energy should fulfil in most charging demand of the charging plaza. Therefore, the Solver function has provided results to the linear programming problem of scenario 2. The objective in this scenario is to find the minimum amount of wind power that is needed so charging demand meets daily power output including applied grid capacity. The minimum amount of power of the wind turbine (kW) is the decision variable. The results are shown in the figure below. The most important constraint is that charging demand should be equal or lower to total generated capacity, which includes the alternative energy solutions and available grid capacity.

On a daily basis 1440 kWh is left to be supplied by alternative energy solutions. The final value for wind turbine capacity is 349 kW. This means that the proposed wind turbine of 350 kW is able to meet charging demand of the charging plaza in scenario 2.

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$I$16	Daily power output (kWh)	0	1440

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$G$16	Wind turbine capacity (kW)	0	349.0039841	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$16	Total charging demand (kWh)	5760.0	$B$16<=$B$15	Binding	0
$B$18	Demand/supply	0.0	$B$18<=0	Binding	0
$G$16	Wind turbine capacity (kWh)	349.0039841	$G$16>=0	Not Binding	349.0039841

Figure 15: The linear programming function in Excel and its result to scenario 2.

As PV panels do not make a big difference, a 350 kW wind turbine should be installed on this charging plaza. In addition to this, a 500 kWh battery and 40 PV panels resulted in the figure below which shows a timelapse of such a charging plaza.

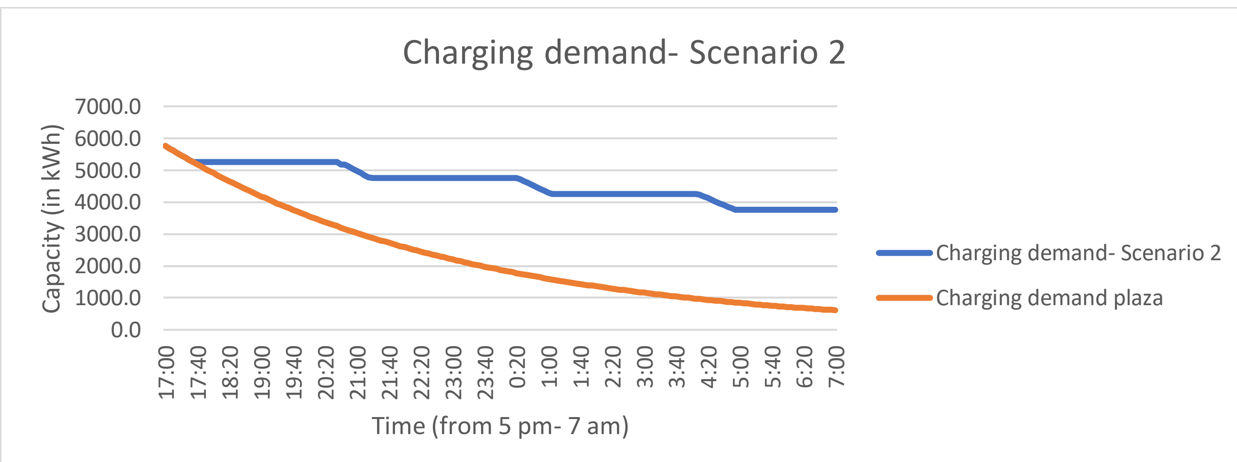


Figure 16: A graph showing the result of scenario 2.

In the figure above can be seen that capacity of alternative energy solutions do not meet charging demand during a night of charging. This means that the amount of demand cannot be supplied during this amount of time with the present charging stations and energy solutions. In this case, higher capacity charging stations are necessary to charge faster including higher voltages. However, ultra-high power charging stations, for example, could offer a solution as it is able to power around 360 kW. If two construction equipment are connected to one Terra 360 charging station, it can be divided into 2x 180 kW. This is thrice as much as the assumption in this model, but still insufficient. The charging time over night is 14 hours (e.g. from 5 pm until 7 am), whereas total demand equals 5,760 kWh.

This means that a charging station needs to supply 411.4 kW (=5,760/14) of power every hour. There are higher power charging stations under development. However, as shown previously, a 350 kW wind turbine should suffice total charging demand. As PV does not make a big difference in total supply capacity, it means that battery capacity should be raised to the amount of total charging demand. For example, a battery container of 2 MWh remain around 1,750 kWh (30% of total demand) after 14 hours. The biggest battery container in the area of 5,760 kWh demand is picked (a 5 MWh battery container) to make charging plaza meet as much demand as possible. Therefore, an analysis of total costs is included in the table below.

Table 13: Approximated total costs of scenario 2.

Alternative energy solution	**Capex (approx. in €)**	**Opex (regular preventive maintenance) (approx. in €)**	**Installation costs (incl. foundation works) (approx. in €)**	**Total costs (approx. in €)**
1x Wind turbine 350 kW	565,000	6,000	80,000	651,000
20x PV panel 400 Wp	-	-	-	7,000
5 MWh battery container	1,727,650	233,100	480,000	2,440,750

Based on the obtained information from Maarten Deutekom (2022), Opex costs for larger turbines round up to €6,000 per year and installation costs around €80,000. The capital costs for a wind turbine are on average 1.75 million dollars per MW of capacity installed (Windustry, n.d.). This means that a 350 kW installed wind turbine costs around €565,000. As mentioned in previous chapter, the estimation of total costs of a 400 Wp PV panel is around €350. This means that the total costs for 20 PV panels equals €7,000. According to CSIRO (2015), around €9.25 is paid for every kW of battery that requires maintenance every year. This sums up to €46,260 every year and eventually €233,100 every 5 years. Lithium-ion batteries current cost range of LFP and NMC is on average around €345. The report treats LFP and NMC as a single technology, because they both fall under the umbrella of 'Lithium-ion' (Li-ion) batteries, and have similar cost and technical performance (CSIRO Energy, 2015). In the figure below can be seen that battery storage accounts to nearly 80% of the total costs in scenario 2.

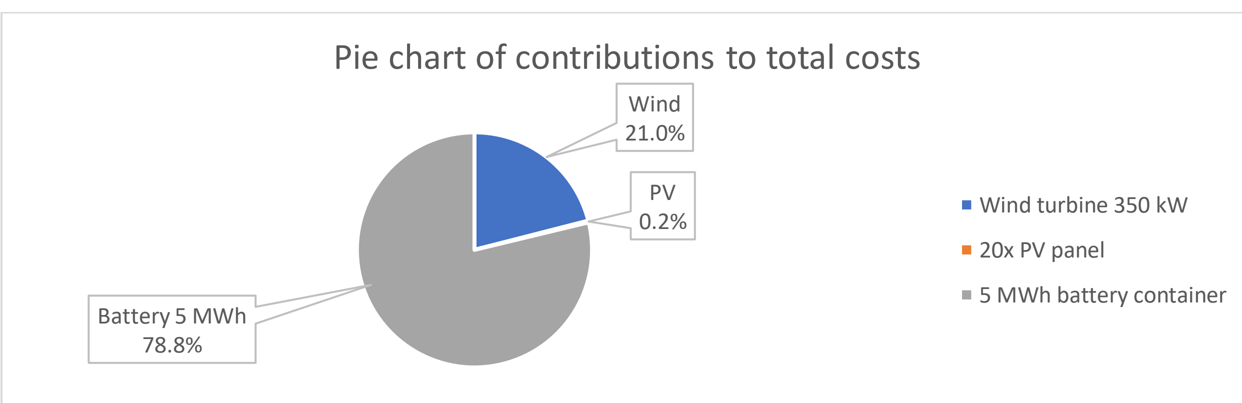


Figure 17: Pie chart of contributions to total costs of scenario 2 with a 5 MWh battery container.

Again, an indication of the benefits is made for making the transition to electric construction equipment. In old circumstances, as explained in chapter 3, thirty krol vehicles would need diesel instead of electricity as generated by renewable sources in scenario 2.. The costs for diesel sum up to around €12.0 million (= €1.83*3600 litres*365 days *5 years). In addition, around 22,784 tonnes of CO_2 is emitted over 20 years of construction work (= 3.468 kg* 3600 litres* 365 days* 5 years). In scenario 2, the total costs were less approximately €3.1 million.

6.3 Results of scenario 3- A 6-month project

A six-month project, as created in scenario 3, contains a 350 kWh battery pack, 20 PV panels and 50% of charging demand is captured by the grid. The 20 PV panels generate an amount of 1.08% of total charging demand. As it is a six-month project, 20 PV panels is already a relatively high amount to install. More PV panels do not make a big difference in the end as it is not close to generating the required amount of energy.

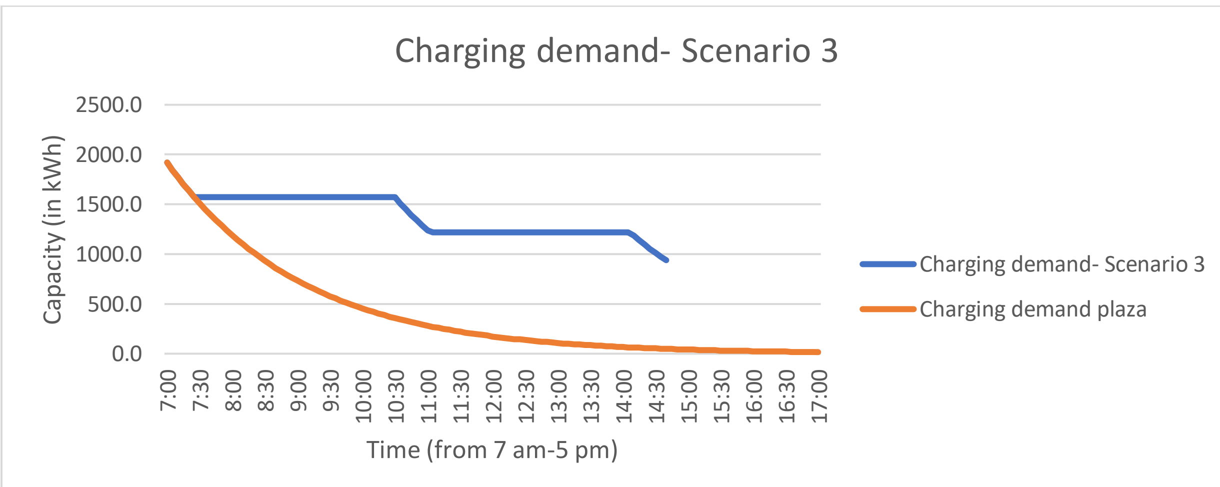


Figure 18: A graph showing the result of scenario 3.

As can be seen in the figure above, supply does not meet demand of the charging plaza. Wind turbines are not an option as it does not have a positive business case for only six months. However, mobile wind turbines can be an option, but they are only available in low capacities (<50 kWh) (*Interview Wind Energy Solutions*, 2022). This would not help this scenario as charging demand is too high. If PV generation has to fulfil charging demand in this scenario, it would mean that a lot of panels have to be installed, which is practically infeasible. Area limitations would be met in this regard. Therefore, this scenario could only be solved by an increase in available grid capacity. Alternative energy solutions cannot meet full demand of this charging plaza scenario. As this is not a solution to the scenario, no estimation of total costs are made.

6.4 Conclusion chapter 6

In chapter 6, the results of created scenarios of charging plazas with integrated alternative energy solutions are presented. The results are made with the help of Excel and show whether energy supplies of alternative energy solutions can fulfil in demand of each charging plaza scenario, created in chapter 5. For a long-term project (~20 years), it is clear that without the help of grid connection and only usage of battery storage, wind and solar sources, charging demand of present construction equipment is met in time. Also, an overview of total costs of this scenario is given. This scenario saves a large number of CO_2-emissions and costs as the plaza does not need diesel anymore.

For a five-year project, there exists a very high charging demand of all construction equipment. Wind and solar sources generate sufficient amount to meet charging demand in this scenario with made assumptions. However, in real life, wind and solar sources are more fluctuant which would lead to a less reliable outcome. Also for this case, an overview of total costs is given, which shows that battery storage is relatively more expensive due to the higher capacity that is necessary, compared to scenario 1. It is important to integrate a very large battery container onto the charging plaza, otherwise it is difficult to charge all equipment in time as smaller batteries spend a great deal of time charging themselves. Again, this scenario saves a large number of CO_2-emissions and costs as the plaza does not need diesel anymore.

For a six-month project, alternative energy solutions are not able to meet demand of the charging plaza any time without the help of a grid connection. This is due to the fact that wind energy cannot be integrated for such a short period of time. PV panels are not able to generate sufficient amount of energy, which leaves a mismatch.

7. Conclusion

This final chapter concludes this thesis report by determining whether the objective of this research has been fulfilled and provides the key findings from this study. The objective of this chapter is to provide an overview of results, their meaning in a broader context and recommendations for future research.
In this chapter, a recap is made of the proposed research questions and the corresponding findings for this study in section 7.1. Accordingly, the scientific contribution is set out in 7.2. Then, in 7.3 a reflection of the thesis project is made. The thesis report is concluded with suggestions for further research in section 7.4 and the link of the project to the master thesis program of CoSEM in 7.5.

7.1 Recap of research questions and findings

Throughout this thesis report, four sub questions are answers to obtain an answer to the main research question. The answers of the sub questions can be found at the end of each chapter in which a specific sub question has been discussed. In this study, alternative energy solutions are examined and analyzed to find out whether they can have a positive impact on charging plaza scenarios. The aim of the study is described as follows:

> *To gain understanding on the impact that alternative energy solutions could have on different types of charging plazas from ProRail for electric construction equipment.*

7.1.1. A charging plaza

The first sub question was proposed as – *What do charging plazas look like and what needs to be considered in designing charging plazas?* – in which is elaborated on charging plazas and its artefacts. The artefacts of a charging plaza discussed in this chapter are (electric) construction equipment and charging stations. An illustration of what a charging plaza looks like is shown as well as a conceptual model of a charging plaza. Such a system consists of battery storage, renewable sources, charging stations and electric construction equipment. Because of the fact that this thesis report discusses the integration of alternative energy solutions on a charging plaza, examples of requirement factors and assessment factors to design a charging plaza are presented.

A charging plaza consists of two or more charging stations, which share the same connection to the grid. This is the reason why charging plazas are considered to be more cost-efficient, less time-consuming and increases system efficiency and security than single charging stations. Examples of design requirements of a charging plaza have been listed in a table containing requirements such as local load balancing and safety of impulse currents on cables and the charging station. Likewise, factors to assess the application of charging plaza are listed. These lists have been drawn up to give an indication of factors that need to be taken into account. This has no correlation to a specific project or scenario.

The development of electrification of construction equipment is still ongoing and will continue to grow in the coming years. As heavy vehicle trucks are becoming electric, the prediction is made that all small, medium and partly heavy construction equipment will mostly become electric as well.

The highest charging demand of electric construction equipment up to now is an e-krol of 240 kWh. In the rest of the research, the e-krol is taken as the example of input to charging demand.

At last in this chapter, charging stations are explained. However, mode 4 charging stations is most suitable for charging plazas with construction equipment due to the high power output and communication control. This way, power output can be distributed among present equipment.

7.1.2. Alternative energy solutions

The second sub question was proposed as – *What are potential alternative energy solutions for charging plazas and what are their characteristics?* – in which different alternative energy solutions are proposed, analyzed and selected for the rest of the research project. Semi-structured interviews with experts in the field of charging plazas and alternative energy solutions put forward multiple options to consider for charging plazas. In order to answer this question, desk research and a SWOT-analysis is executed to provide insight into alternative energy solutions and their characteristics.

Battery storage cannot be ignored. Each and every scenario of charging plazas must contain battery storage to offer load management and to store extra grid capacity. The capacity of battery storage depends on the total charging demand of the charging plaza. Solar and wind energy are renewable energy sources that can generate energy for charging plazas. The idea for solar energy is to install PV panels on top of a carport, so-called solar carport. This offers energy generation and shelter for electric construction equipment, for example. Wind energy can be installed for projects that have positive business cases. Such a project must have enough charging demand, since wind energy is able to generate a lot of energy in a relatively short period of time, and time span to have return on investment.
Hydrogen and vehicle-to-load are not proposed as alternative energy solutions to take into account for charging plazas. Hydrogen is excluded as technological developments of construction equipment is expected to focus mostly on electrification as it has a far more efficient production process. In addition, vehicle-to-load is a relatively immature technology. It has potential as it can serve as a battery pack on wheels. But for now, it is not expected to play a big role in the coming years because of a lack of regulation and production.

7.1.3. Assumptions and scenarios

The third sub question was proposed as – *What are realistic charging plaza scenarios for ProRail and what assumptions do they contain?* – in which assumptions are made to create scenarios and build a model. The scenarios are drawn up from an estimation with experts from Movares. This resulted in three different scenarios based on three different time spans. As the time span differs, charging demand differs too.

This results in a variety in parameters, such as wind capacity, grid capacity, PV panels and battery capacity. The scenarios that are created are the following:

- Scenario 1: A long-term project (~20 years). This scenario receives grid connection as the rail access point is close to a substation. There is a battery storage capacity of 120 kWh, 2000 Wp of PV panels capacity is present as well as a wind turbine of 100 kW.
- Scenario 2: A 5-year project. This scenario receives a grid connection that fulfils in 75% of total charging demand of the charging plaza. Battery storage capacity of 500 kWh is present as well as 16.000 Wp of PV panels capacity and 350 kW of wind turbine capacity.
- Scenario 3: A 6-month project. This scenario receives a grid connection that meets total charging demand of the plaza up to 50%. There is no wind capacity available as permits and licenses cannot be granted due to the short period of time. Battery storage capacity of 350 kWh is present as well as 8.000 Wp of PV panels capacity.

Each artefact or element present in the charging plaza system contains assumptions in order to build the model in Excel. The list of assumptions are presented per artefact in chapter 5, which are the following: battery storage, solar energy, wind energy, charging stations and charging demand. All assumptions are listed in the table below.

7.1.4. Result analysis of scenarios

The fourth sub question was proposed as – *How do the charging plaza scenarios for ProRail fulfil in charging demand and what are their total costs?* – in which the results of created scenarios of charging plazas with included alternative energy solutions are presented. The results are made in Excel and show whether energy supplies of alternative energy solutions can fulfil in demand of each scenario.

For a long-term project (~20 years), it became clear that without the help of grid connection and usage of battery storage, wind and solar, charging demand of present construction equipment is met in time. Also, an overview of total costs of this scenario is given.
For a five-year project, there exists a high charging demand of all construction equipment. Wind and solar sources generate sufficient amount to meet charging demand in this scenario with made assumptions. However, in real life, wind and solar sources are more fluctuant, which would lead to a less reliable outcome. It is recommended to install a fairly large battery container, because it enables more equipment to be charged during the time period. Smaller battery containers cannot meet demand in the same period because they have to be charged more frequently. Also for this case, an overview of total costs is given, which shows that battery storage is relatively more expensive due to the higher capacity that is recommended, compared to scenario 1.
For a six-month project, alternative energy solutions are not able to meet demand of the charging plaza any time without the help of a grid connection. This is due to the fact that wind energy cannot be installed for such a short period of time, which makes it a negative business case. Only a solar carport is far from generating required amounts of energy.

7.1.5. Main conclusion

This study aims to provide an answer to the following main research question:

> *What impact could alternative energy solutions have on charging plazas for electric construction equipment from ProRail by 2030?*

An answer to this question is twofold; for short-term charging plaza projects (shorter than 5 years), alternative energy solutions cannot meet demand without the addition of sufficient grid capacity. PV panels do not generate an effectual amount of energy for such projects and wind energy is, in general, not an option as it does not have a positive business case.

Longer term projects (equal to or larger than 5 years) have shown that alternative energy solutions can be integrated successfully to charging plazas. With the help of battery storage, wind energy and solar energy, demand of charging plazas can be met. In these scenarios, wind energy was a key factor in generating required amount of energy supplies. Without wind energy, both scenarios would not have been able to fulfil in the need of the charging plaza because PV panels seemingly generate a smaller fraction of what is necessary in demand. In addition, it is preferable to have a battery as large as possible to store energy during the day and night. A smaller battery results in more charging periods and less time to charge equipment.

Following from these answers to the main research question, it can be concluded that the research objective is accomplished. An understanding is created of the impact of alternative energy solutions on different charging plaza scenarios.

7.2 Scientific contribution

In section 1.2.2, two identified scientific knowledge gaps were addressed. These knowledge gaps were as follows:

Knowledge gap 1: The understanding on what alternative energy solutions can be used to supply power for charging plazas for electric construction equipment;

Knowledge gap 2: The understanding of what scenarios of charging plazas for charging electric construction equipment.

The aim to fill both knowledge gaps would lead to an indication of the impact that alternative energy solutions could have on charging plazas in various different charging plaza scenarios. This is relevant because of the fact that grid capacity might not fulfill entire demand of a charging plaza at times of congestion. Alternative energy solutions can help out and generate or store electricity to fulfill this need. Therefore, it is very useful to gain understanding in the developments of construction equipment and alternative energy solutions. As of today, most charging plazas are realized for buses or electric vehicles. There is not much information on both charging plazas and electric construction equipment for rail purposes.

To begin with, knowledge gap 1 is answered by RQ2, which resulted in a SWOT-analysis of proposed alternative energy solutions that could be installed on charging plazas.From this analysis including interviews and desk research, wind energy, solar energy and battery storage were recommended as alternative energy solutions that could be integrated on charging plazas for charging electric construction equipment.

Second, examples of scenarios of charging plazas are created in chapter 5 to answer RQ3. The three scenarios differ in time span and in charging demand. The differences are based on real life examples to show a clear distinction in project size and time span. So is a long-term project of 20 years based on a rail access point with low charging demand, a five-year project of HPS Amsterdam contains very high demand and a six-month project has medium high demand.

7.3 Reflection

This section presents a reflection of this thesis on two aspects: qualitative research and research choices. First, a reflection is made on qualitative research is reflected. Second, there is reflected on the research choices.

7.3.1. Reflection on qualitative research

The research process is reflected upon four scientific quality criteria: credibility, dependability, confirmability and transferability (Stenfors et al., 2020).

I. Credibility

The first criterion 'Credibility' means that the research findings are trustworthy, plausible and align between theory, research question, data collection, analysis and results. This thesis collected data by conducting semi-structured and structured interviews, literature reviews and additional desk research. In total, eight interviewees of different organizations and departments are interviewed to ensure the inclusion of varietal perspectives as well as colleagues from Movares. An interview can create bias in the project as respondents' answers are used as input to research questions. If other people were interviewed, different answers would have been obtained. It is also possible that respondents do not give the full picture to a certain question. The number of interviewees is minimal to what is required. More interviews lead to different perspectives or opinions and higher reliability.

The question could be raised to what extent interviews have provided useful information. However, interviews with experts provided *realtime* information on developments in the Netherlands and in the construction sector or charging plaza industry. Most certainly, similar information could have been found in literature, but interviews have case/sector specific knowledge, which results in more accurate information. Also, literature can be about developments in China or USA, whereas this research project is focused on the Netherlands. The degree of anonymity can also influence results. The numbers and data used for building the model are based on assumptions only consisting of all sorts of averages. Averages give a reasonable indication but lack hard data. Also, the scenarios that are created, is made up with the help of examples and experience from experts.

II. Dependability

The second criterion 'Dependability' focuses on the question whether the research could be replicated in similar conditions. This means to what extent other researchers using the same research approach would come to the same research outcomes. The researcher should be able to follow the same procedural steps, albeit reaching different conclusions.
The research subject has developed over time during this thesis project. However, the creativity used during the project is not documented. Therefore, the reliability of the research approach is guaranteed as the steps that are taken during the research are clearly described and documented. This makes it able for other researchers to follow the same steps and replicate the research.

III. Confirmability

The third criterion 'Confirmability' focuses on the question whether there is a clear link between the data and the findings. The link is ensured by inserting a *conclusion* to each chapter. By doing this, each chapter is checked upon the integrality of providing an answer to the concerned sub question. Also, the search of information has been clearly documented. For interviews, all relevant information was summarized and put into the appendix. For assumptions, all relevant information was listed and put into the appendix. This way, all relevant information is clearly written down and easily accessible. This helps in the continuation of processing data. In chapter 6, the results of processed data are presented. In this section, both the approach and the results are explained and discussed. Therefore, the research findings are described through detailed descriptions.

IV. Transferability

The fourth criterion 'Transferability' represents the question whether the findings may be transferred to another setting, context or group. It is believed that the findings can be transferred to another setting, context or group. The finding that short-term projects with lots of charging demand cannot be fulfilled in supplies by alternative energy solutions is relevant to ProRail. However, congestion is a big problem throughout the whole country. Not only ProRail is in need of power for short-term projects, but more companies working on infrastructure or buildings do. Also, not only contractors working for ProRail are exposed to this problem, but the entire market. The fact that projects with a durance of more than five years can have a positive business case, might be relating to other infrastructural construction purposes other than rail.

7.3.2. Reflection on research choices

The second aspect that is reflected upon are the research choices that are made during the thesis project. Throughout the research process, several key choices are made that have influenced the outcome of this thesis. Each choice in the beginning phase have an impact on later choices or outcomes in the project. This section discusses the key research choices of this thesis.

I. The choice for including/excluding alternative energy solutions

The first key choice was about the inclusion/exclusion of alternative energy solutions in chapter 4. This chapter was meant to provide an overview of present alternative energy solutions that could make a contribution to the supplies of charging plazas. It seemed logical to set a focus on some of the alternative energy solutions to obtain a better grasp on their value. That is the reason for including only three options as well as the fact that more options make it very chaotic with all assumptions included. Also, hydrogen and vehicle-to-load do not have sophisticated data available that could be inserted into the model as not much information is available.

II. The choice for creating scenarios

As mentioned previously in the reflection, the research lacks hard data to be reliable and more credible. Therefore, the research was in the first place meant to include five scenarios developed by a research company. However, this research company was not able to develop these scenarios in time, which led to adjustments in the research approach. One of the adjustments was that the scenarios would be developed in collaboration with experts in the field through a brainstorming discussion and the help of an analysis in morphological charts, realization tables and combination tables. This analysis approach identifies any potential engineering scenarios of charging plazas. Afterall, this approach highlights the imagination and flexible footprint of the researcher in this work.

III. The choice for building each scenario in Microsoft Excel

The third key choice is for recreating each scenario in Microsoft Excel. It was decided to make assumptions first and process these data in order to visualize the contribution of alternative energy solutions to different scenarios of charging plazas. By visualizing data, results are better to understand and easier to verify. Microsoft Excel is a program that I am very confident with and like to use. The objective in this research to visualize to what extent supply and demand in different scenarios would meet each other is accomplished with the help of Excel.

7.4 Recommendations for future research

This section presents suggestions for future research that can use this research project as input.

One of the foremost suggestions for future research that would really be of added value is to include hard data. The scenarios that had been created are based on assumptions in one type of construction equipment (e-krol), and averages in generation of alternative energy solutions and charging demand. This could be made more specific. For example, a study could be made on designing a charging plaza on a specific location with certain types of construction equipment. If more data becomes available on capacity of different battery packs of construction equipment, obtained results would be more practical and closer to *real life.* If a specific location is set, a clear design could be made of the integration of alternative energy solutions. Now assumptions are not used as input but location-based data can be obtained.

This means that the amount of sun or wind can be used to calculate on the generation of energy on this location. Overall, it becomes a more hands-on project.

In addition, a study could be executed on the different types of charging plazas for construction equipment. It is known that a company is expected to develop these scenarios but such a study is necessary to continue developments in the realization of charging plazas.

Also, a study could be conducted on the developments of V2L or hydrogen. In this study, it is concluded that hydrogen and V2L are underdeveloped and need time to obtain a bigger role in the energy system. However, it is interesting to see what specific legal and technical developments should be made to come to this point. An investigation on privacy (ownership), financial and technical issues can offer an interesting study.

7.5 Link of this thesis project with the CoSEM Master's Program

The Complex Systems Engineering and Management (CoSEM) master's program focusses on the design of technological innovations in complex socio-technical environments. These environments consist of multi-actor and technological complexities. Besides technology, factors as regulations, logistics, behavioral change, financial incentives are taught on the energy system.

This thesis project concerns both the energy transition and infrastructure. These are two urgent themes that are of great importance in society and (academic) literature. I have been interested in the energy transition for some time, which is one of the reasons why I chose the CoSEM Master's Program and the Energy track. This thesis project is a CoSEM research because it concerns a multidisciplinary and complex issue, involving multiple factors and actors in a dynamic world. Especially the course SEN1161 Design Project has made me realize that I enjoy projects in which complex issues are discussed and need to be dissected, worked out and solved step by step. This course consisted of a group project in which the possibilities for TU Delft were investigated to install a geothermal source and heat surrounding residential areas with residual heat.

With this research project I would like to make a contribution to accelerating the transition of electric construction equipment. This research is relevant to ProRail, contractors and suppliers of alternative energy solutions.

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8. Appendices

8.1 Appendix A- Selected articles of the literature review

Table 14: An overview of the selected articles of the initial literature review.

Article/report (Author and year of publication)	**Specific aspect addressed, relevant to research topic**	**Domain**		
		Alternative energy solutions	**Charging infrastructure/ plazas**	**Construction equipment**

Bons et al., 2020	Impact of smart charging for consumers		X	
CE Delft, 2022	Emission-free construction sites ProRail		X	X
van Capellen et al., 2022	Charging with restricted grid capacity	X	X	
Donker et al., 2015	Renewable sources providing energy and flexibility	X		
ElaadNL, 2021	The development of electric construction sites in the Netherlands by 2035		X	X
J. Guldenaar, 2022	The electricity demand of mobile equipment at construction sites in 2030		X	X
NAL, 2022	Charging for logistics with limited grid capacity	X	X	
Netbeheer Nederland, 2019	The roadmap of charging infrastructure in the Netherlands		X	
ProRail, 2021	Inventory of the CO2-emissions of 2020		X	X
Rijkswaterstaat, 2019	Renewable energy carriers in mobility	X		
TNO, 2022	Mobile (railway) equipment			X
Universiteit van Wageningen, 2020	Producing maximum renewable energy without grid reinforcement	X		
Un-Noor et al., 2021	Feasiblity assessment of battery electric construction equipment			X
TenneT E-Top, 2020	Electrification and demand profile in 2030 of flex options	X		
Trahey et al., 2020	Energy storage emerging	X		

8.2 Appendix B- Interview transcripts

In this appendix, transcripts of the interviews are documented in the form of summaries. Since the interviewees were all in Dutch, the invitation e-mail and interviews were in Dutch. Therefore, brief translations have been made from both the invitation e-mail and interviews. After the interviews had been held, summaries of the interviews had been sent to the interviewees and they were being asked to verify or add (missing) information.

B.1- Interview invitation e-mail

Subject: request for interview about CHARGING PLAZAS/ (ELECTRIC) CONSTRUCTION EQUIPMENT / ALTERNATIVE ENERGY SOLUTIONS

Dear mr./mrs. NAME,

My name is Sander Baltes, graduate intern at Movares and student at the Technical University of Delft. My research project is about the potential contribution of alternative energy solutions to charging plazas in order to make a transition to zero-emission construction equipment and avoid grid congestion. In this phase of my research, I am searching for specific information about CHARGING PLAZAS/ (ELECTRIC) CONSTRUCTION EQUIPMENT / ALTERNATIVE ENERGY SOLUTIONS. I am reaching out to you to ask for an interview as I came across your name with the help of a COLLEAGUE/WEBSITE/ARTICLE. It won't take longer than one hour and can be done both online or offline, whatever your preference may be. I hope to have finished the interview by DATE.

I hope to hear from you soon!

Kind regards,
Sander Baltes

B.2- Interview Rob de Jeu (ProRail)

Interviewee: Rob de Jeu
Function: Expert energy supply
Company: ProRail
Date: 6-10-2022

Summary:

This interview was arranged concerning a different project at Movares that has overlap with my project. ProRail is working on emission-free construction sites by 2030. In doing this, charging infrastructure is required. Movares was asked by ProRail to conduct research on the technical and organizational aspects of realising charging infrastructure. Rob de Jeu is responsible for the availability of high and low voltage supply systems.

Reliability:

It is very important to design an energy management system: When does which charging station obtain a certain amount of power? It should not be a problem to connect a charging plaza to the traction network, but energy supplies should be prioritized. The trains should not be bothered. Their energy supplies should be secured and the leftovers of capacity can be used for other purposes, for instance, a charging plaza. If an error occurs, not the entire network should shut down. Everything that is connected can in emergency cases result in less reliable or trustworthy system. If a charging plaza is designed selectively, it should not have much influence on this reliability issue. It will probably be of value to raise the margin for security setting from 10% to 20%. Also, it should not be a problem to connect charging stations to 400 V grid connection with rectifiers.

Safety:

There are some concerns about the grounding if a charging plaza is placed next to other rail installations. There is a chance that traction current is going back to the substation via your ground (stray currents). We prefer not to use earth leakage circuit breakers, but in some cases have to do so. Before setting up a charging plaza, a good look at the grounding must be taken into account. If a crane has to be charged, cables will be all over the charging plaza. According to Rob, this should not form a big problem. In general, safety should not be an issue in realising charging plazas. It just has to be taken into account and dealt with.

Organizational/ judicial:

Responsibilities: Who is responsible for a charging plaza? The constructor? Charging station company? A clear distinction should be made in responsibility within the supply chain of energy.

B.3- Interview Jan van Rookhuijzen (ElaadNL)

Interviewee:	Jan van Rookhuijzen
Function:	Technical advisor of logistic charging infrastructure
Company:	ElaadNL
Date:	27-10-2022

Summary:

Jan van Rookhuizen made an Outlook in 2021 about the electrification of building. This Outlook showed that in 2030 a relatively small percentage (approximately 12%) of construction equipment would be electric. They divided all equipment into three groups: small, medium and large.

Objective ProRail:

ProRail is a fairly small player in the construction sector. All clients from the Dutch government are going to set up zero-emission tenders to 2030. For example, Rijkswaterstaat set the target to have zero-emission fleet of busses by 2030. Each newly purchased bus had to be electric from 2025 onwards, but now approximately 30% of buses is already electrically driven. So these targets really stimulate and fasten developments within sectors. Therefore, the curve will probably lie much higher than illustrated in the figure above and ProRail could be able to reach their objective in 2030. In addition, the crises in the Netherlands about nitrogen will also fasten the transition as large (public) parties will demand zero-emission from their contractors.

As of now, there are no obstacles in the transition to zero-emission construction equipment but time. The biggest challenge is how to obtain energy at the construction site. There are multiple ways in doing this but they are all more complex than diesel. I can imagine that they have a lot of construction work that has to be finished within a certain amount of time. For example, last weekend they worked in between Haarlem and Amsterdam. So for a weekend, a lot of electricity will be demanded for a short period of time. That is a big challenge to the grid operator and probably for ProRail and contractors. Nowadays, grid congestion slows down the proceedings of projects. On the map of Netbeheer Nederland this is shown. First, the capacity issue needs to be fixed before they will give out capacity within a critical region. A large grid connection also demands that it will be used for a certain period. This won't be provided if the project lasts for a week.

Grid operators are not allowed to prioritize. First come, first serve. People do have an opinion about this but that doesn't change a thing. The request for a grid connection depends on the capacity that is asked for. If sufficient capacity is available, it usually takes around 18 weeks. Nowadays, it is harder to make this period of time as a result of delays in supply of transformers, for example.

Insufficient grid capacity:

In the construction sector work can be so diverse. For example, building a new neighbourhood. In this case, the connection will also be used after construction work has been completed. Now it is important to have sufficient amount of grid capacity before construction work begins. In this situation, a battery container can help out in the beginning of the project.

A different case is a long distance project. I cannot imagine equipment returning back to a charging plaza for kilometres after a day of work. Then local options will be evaluated. For example, farmers sometimes offer their capacity to construction equipment. Usually a combinations of options is used. Battery containers is also a valid option. If 400 kW is available, but 600 kW is required. Then 200 kW can be obtained from battery containers or other options. This should be taken into account beforehand.

Hydrogen and fuel cell:

Hydrogen is still very uncertain. For example in Nieuwegein, there was a need of a very large grid connection or two tube trailers of hydrogen. However, a hydrogen station is filled with one single tube trailer. In the best outcome, all of the available hydrogen would be for us. If someone would get there before us, we wouldn't have enough hydrogen. Therefore, the choice is a large grid connection. On the short term, hydrogen is not practically feasible.
Besides, if the energy consumption is not 'high", there is no single reason for the usage of hydrogen. Hydrogen has a very inefficient production process and is, of course, way more expensive compared to electricity. It will take a very long time until green hydrogen is available in big numbers. If it gets available, heavy industry will be first to take it. It would be unacceptable if equipment could be supplied with hydrogen if Tata Steel Ijmuiden is not making a transition.

Future equipment will be produced with an electric engine for sure. But I can imagine them installing an electric engine in combination with a fuel cell to offer a solution to insufficient grid capacity locations. The location determines the solution. An advantage of an interchangeable battery pack is that there are multiple. The one that is not installed on the equipment will be charged.
An advantage of a battery container on construction site (charging plaza) is it offers a lot of flexibility. During the day it can be charged fully with either grid capacity or solar/wind energy. At night it can charge construction equipment.

Safety issues:

There are no numerous safety issues. It still is a machine and can have it errors at times. However, I do witness that people can hear more of their surroundings as a result of less noise from electric equipment. In the past, nothing was hearable but diesel engines. All the installations should be idiot-proof.

Alternative solutions:

Formic acid is a very immature technology. But everything is small scale yet. For now, if it works, it works and the choice is cheapest. But in the construction sector, a combination of options is most preferred. In neighbourhoods, at night there is a lot of capacity left for usage. Currently, a project has started for requests for a time period. So if you only have demand at night, this can be distributed and a connection can be given. In the Netherlands there is a lot of grid congestion according to Netbeheer Nederland, but in theory this can be solved by better management of load and capacity.

A charging plaza can be a good solution for ProRail. However, it is important to get a full picture of construction equipment to determine their charging profiles. What kind of equipment do we have? How many? What is their charging demand? And when do they charge?

Costs:

I have no idea about costs of construction equipment but most of it is expensive. Emission-free Network

Infrastructure (ENI) is a consortium. There is plenty of knowledge over there. Doosan too, Korean company, is looking to convert their equipment too electric as well as BAM. There is a lot possible technically speaking to convert it, but the problem is high valuation. From the government, there are plenty of subsidies. If you invest in sustainable products or processes, there is usually a subsidy or regulation to lower investment. If work goes via a tender, there is room to ask for emission-free construction equipment or lowest emissions during the process. It is the way to go forward. Besides, it is too easily said that return on investment is high enough. This is the case for private electric vehicles or so, but construction equipment need grid connection, which has big influence on the total cost of ownership. However, on the construction project itself, it might reduce the total emission by 1-2%.

V2L and V2G:

Both V2G and V2L are very immature and under development. In this sector, the question that arises is the contribution. Buses and trucks can also have this function but they need to drive as much as possible to gain back its investment. Sometimes it might serve as an extra battery package but then software needs to regulate it optimally, so that it can still drive away. V2L has restricted charging power and won't charge heavy equipment fast. Second question is if ProRail wants electric vehicles to be present on their charging plazas. What needs to be charged and how much capacity is necessary?

B.4- Interview Roy Kat (BAM)

Interviewee: Roy Kat
Function: Team manager of electric vehicle desk
Company: BAM Energie & Water
Date: 27-10-2022

Summary:

His department tries to help in the electrification of the entire fleet on national scale. Currently they focus on private and lease electric vehicles. In the coming years, trucks and buses will be considered. We help to set up the installation of charging stations and its maintenance and repair services.

Objective ProRail:

He thinks that ProRail serves the task to fulfil an exemplary role to the rest of the sector. Therefore, it is very important to have set the objective of zero-emission construction sites by 2030. As ProRail have set this target, BAM's objectives align to it. There is no fixed solution yet as there are many different options available. Another important factor is the developments from grid operators. Can they keep up with electrification and start of new projects? Also, it is crucial to not delineate ourselves to electrification only. As mentioned, there is no official solution yet and many sufficient ideas might develop in upcoming years. If clients demand objectives to tender projects, it stimulates to move and fulfill these objectives. So if ProRail demands emission-free construction equipment, we should push and try to make this happen.

There are subsidies available for parties that invest in new emission-free innovations. However, I have heard that these subsidies do not always apply to listed companies (on the stock market).

Conversion to electric construction equipment:

BAM is already actively investigating options to convert construction equipment running on diesel engines to electric engines. We try to contribute to this transition, for example, by the introduction of the first electric krol. Certain technological developments is partly our responsibility as we have knowledge on our own needs and desires of construction equipment. The power capacity, the type of battery storage system, the working hours are factors that should be known before we bring it to manufacturers.

Insufficient grid capacity:

As of today, shortage on grid capacity is not very often the case. However, this will be the case soon. Battery storage is of big importance in this situation due to the fact that most equipment is used during the day and charged at night. If battery storage is part of your system, it provides a lot of flexibility. Only grid capacity makes it hard to balance load demand and load supply. You should be over the moon if you obtain sufficient grid capacity. To receive a connection to the grid is not hard yet.

The biggest challenge right now is to get enough grid capacity from this connection. In a lot of cases, there is insufficient grid capacity after getting a connection. This is a limitation.

On long distance projects a battery system might seem insufficient. However, I do believe that charging plazas are still the solution to this. In these cases, it is crucial to think outside the box. The only thing that should be taken into account is the application of interchangeable battery packs. This means that you don't have to move battery containers all the way each time you move along. You have to change the empty battery pack for a new one and bring it on location. Besides, mobile battery containers always contain the spatial problem. An interchangeable battery pack is small and easy to insert within the system.

Criteria for a charging plaza:

Criteria that I can think of that are of importance to engineering charging plazas is the time schedule. How long will the project endure and for how long will the location be occupied? Everything should be safely designed but that should not offer a problem. Also, grid capacity, charging demand, charging profiles are important.

Hydrogen:
Hydrogen is a frequently named solution in this sector. But I don't think it will serve a big role in this case. The reduction in price and the increase in size of batteries show hopeful developments on this side. Besides, batteries for short term storage is way more efficient as hydrogen is expensive to produce and costs a lot of energy. In this sector, less solution contain a role for hydrogen. However, long distance transport, like marine or aviation, will benefit from the inclusion of hydrogen as their fuel. If you have peak demand during the day and you also need to produce hydrogen in these hours to be able to charge overnight, there won't be an equilibrium in demand and supply.

V2G and V2L:
V2G is not applied to charging plazas that I have realized. This is due to the fact that V2G is applicable by two car dealers. It is not made mandatory in rules and regulation to car manufacturers yet, so you are not able to obtain data for AC charging. This is possible to DC charging.
If this is solved, it will be applied throughout the country as it can serve as a mobile battery that can also drive. If vehicles contain this function, a charging plaza might have quite some power capacity available.

B.5- Interview Robert Daems (ABB)

Interviewee: Robert Daems
Function: Sales Specialist Electric Vehicle Charging Infrastructures
Company: ABB
Date: 8-11-2022

Summary:
In the first weeks of my internship at Movares, I was given the opportunity to attend a sales meeting at ABB with colleague Arie-Peter Hijkoop. During this sales meeting, Robert Daems made the expertise of ABB clear which includes charging stations and battery containers. After this meeting, I had an interview with Robert Daems to be able to understand the full picture for this research project.

Charging stations:
Mode 1 refers to charging from a standard power output with a simple extension cord. This method of

charging does not provide users with shock protection against DC currents. Unlike mode 1 charging, mode 2 charging cables have built-in protection in the cables which protects against electric AC and DC currents. Mode 3 charging involves the use of a charging station, which also provides shock protection against AC and DC currents. At last, mode 4 is often referred to as 'DC fast-charge', due to the high power voltages. For electric equipment of construction works in the railway sector, mode 3 and 4 will be necessary. These modes have mobile charging stations available on the market. This is very useful to situations in which charging plazas are meant to have a temporary character, which makes it easier to transfer them. AC charging is more time-consuming than DC charging due to the fact that an onboard charger needs to convert the alternating current. This is not necessary for a direct current, which can be plugged in directly to the battery system. The grid has an alternative current of 400 Volts. The DC charging station consists of a rectifier that is able to turn 400 V AC from the grid into direct current.

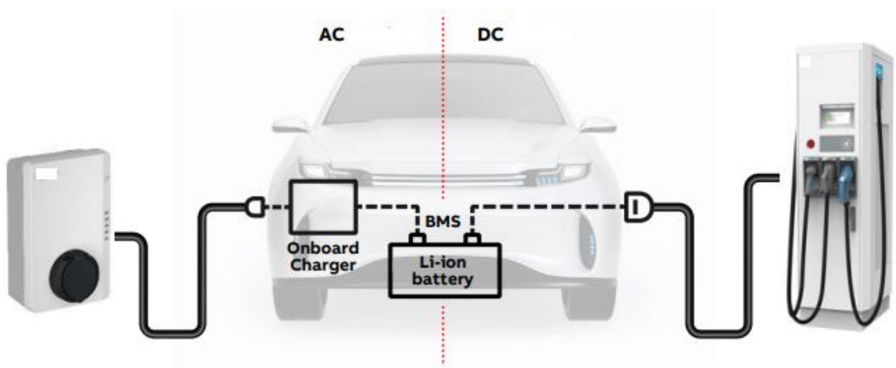

Figure 7: A schematic representation of AC and DC charging.

Charging stations provide the amount of power that the vehicle demands. For example, if a car demands 300 kW, but the charging station has a power capacity of 450 kW, the charging station will give out 300 kW in order to avoid overloading the vehicle or truck.

On the other hand, if the vehicle or truck demands 450 kW, whereas the charging station can only provide 300 kW, the charging station will supply the vehicle with 300 kW. This will result in a longer period of charging to also avoid overloading the charging station.

Advanced energy systems:

Their charging stations include advanced energy services which is an automatic way of applying charging strategies. These advanced energy services contribute to load management. Load management is a very important factor to not exceed limits of both the grid and the charging stations. He showed this by providing two diagrams. One diagram shows the results without the use of management software and the other diagram shows the influence of management software to the grid. The case is about a charging plaza concerning 10 buses, 10 chargers, a 300 kWh battery each and a maximum of 100 kW charging.

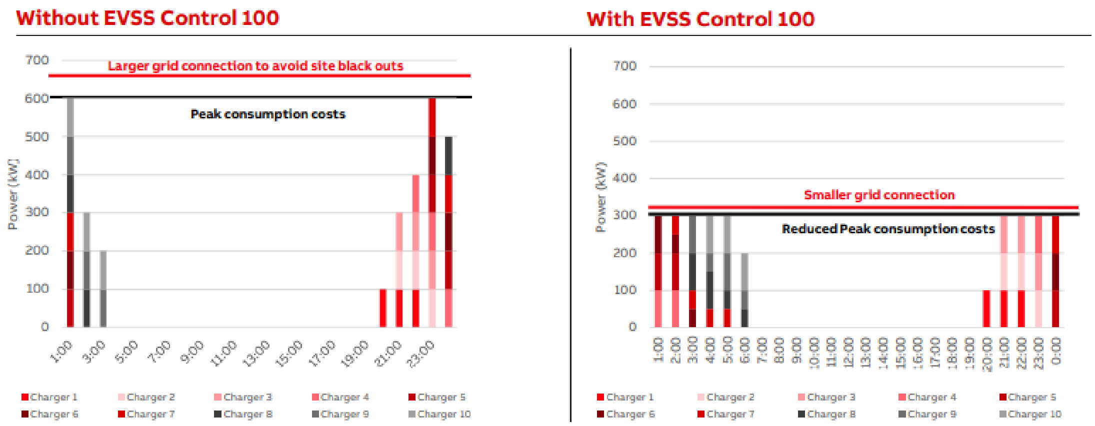

Figure 19: The influence of software to manage load in a case for a charging plaza.

The management software system results in a reduction of costs (both CAPEX and OPEX) and faster project implementation due to the fact that the connection to the grid is stable. The load management software is part of the so-called advanced energy services. This takes into account a lot of key factors, such as weather forecast, predictive load profiles, fleet schedules and energy prices/trading.

V2L/ V2G:
It is still very immature. It needs to be included into standards to fasten developments. For example, in Japan it is mandatory to make use of a CHAdeMO charging station if you want to charge. This is due to the fact that Japan had lots of difficulty in energy supplies after the earthquake in 2011. CHAdeMO, a Japanese car manufacturer, designed a charging system that is able to return electricity to the grid. However, this has not become the standard for car manufacturers in designing new models. Questions arise in the introduction of bidirectional charging: Who is the owner of energy within the battery? The owner of the car? The car manufacturer? The energy company? So the technology is ready, but the market is not. Whenever the market is ready, new car models will include bidirectional charging.

B.6- Interview Robbie Blok (NKL Nederland)

Interviewee: Robbie Blok
Function: Project manager of charging plazas
Company: NKL Nederland
Date: 9-11-2022

Summary:

Since 2017 he has been focusing on charging infrastructure for electric vehicles. In 2009 the first charging station was installed in the Netherlands. Afterwards, multiple questions arose that concerned market parties, grid operator and governmental institutions. None of these parties had the expertise to solve these questions. Therefore, NKL was established in 2014 as a foundation and became independent in 2015. They always focused on fastening the influence of charging infrastructure and making it cheaper for consumers. They are working hard on targets set by the government to have 1,5 million electric vehicles and 1.7 million charging stations by 2030. They deliver reports on requirements for charging infrastructure/plaza/station and guidelines on different topics.

Charging plazas:

Charging plazas have multiple advantages:

- There is a higher charge availability. The chance that there is a free spot on a place where you need to charge your vehicle is way higher.
- Especially for bigger charging plazas, the costs for charging infrastructure decreases. It is similar to a bath tube: at first, a charging station is not very expensive, some charging stations become more expensive until you reach enough charging stations that make it not expensive again. This is due to the fact that once you scale up the amount of charging stations, there is a need for a bigger grid connection. To begin with, there is a 3x25 connection but once more charging stations are installed, it becomes 3x50.
- It can be used as a local energy grid. If you have PV panels and battery storage on the location, it becomes easier to manage load.

Biggest challenge for a charging plaza:

The choice for dimensions of the charging plaza is the biggest challenge. What size and how scalable do I want to make the charging plaza? You can start off with 6 points but in short term an increase is expected. This can be taken into account in the request for a grid connection. A different question if ProRail wants to manage the charging plaza themselves. An advantage is that you have full control over the system. On the other hand, it is not their core business. Without the expertise, it can be hard to innovate in this system. This can be executed by a third party with more experience in doing this.

Insufficient grid capacity:

In Haarlemmermeer, a charging plaza had a shortage on grid capacity. In addition, they added batteries to the seats that were present on location. In this way, the charging plaza is able to deal with a shortage on grid capacity and higher energy demand.

Alternative energy solutions:

Alternative energy solutions that are available are PV panels on carports. This provides vehicles with shelter and generates more energy for the charging plaza. Everything that is being generated on location will benefit the charging plaza and reduces the amount that is needed from the grid. It can be injected back into the grid or used by construction equipment. Around 20-25% is supplied by our PV panels on our charging plazas. So it is able to deal with smaller grid capacity connection.

There can also be made use of smart charging and load balancing. Instead of one gun providing equipment with 11 kW may divide it over two devices of 7 kW each. There is excellent software available that is able to manage and balance energy load within a system. They are able to distribute it equally or prioritize among the charging stations.

Hydrogen or electrification?

Everything will become electric. In the coming years, there will be an insufficient amount of hydrogen to supply heavy industry or equipment. Last week I attended World of E-mobility. Over there, I was able to witness interchangeable battery packs of 400 kW. I had a conversation with people from Scania, for example, and they argued that it is impossible to get hydrogen at places where charging infrastructure is possible. Deserted place might be attractive to hydrogen due to very large distances. But in the Netherlands, it would be inefficient to make big losses in electricity to produce hydrogen. ProRail is always located near rail infrastructure which would mean that energy supply is not far away. Small and medium equipment will also be connected to electric charging infrastructure. If heavy trucks are becoming electric with these immense batteries, it is likely that heavy construction equipment can become also electric. This won't differ much in my perception. Hydrogen, both the technology and its infrastructure is not available yet. First, heavy industry wants to make a move to hydrogen but this won't be the case for road transport. We just don't have the volume to start off such projects. In over ten years it may be the case. And both electric and hydrogen make use of a fuel cell, so the principle is similar. It is not a combustion engine. So if hydrogen becomes emerging, it will be easy to make a transition within five years from a battery pack to an hydrogen pack.

Wind energy:

Wind turbines are not located on a charging plaza yet due to the fact that it generates so much power within a short amount of time. Smaller wind turbines are possible and will be similar to PV panels or carports. Is there enough capacity available? If not, solar and wind energy are options to lower capacity needs.

V2L and V2G:

V2L and V2G are still not frequently used technologies. Hyandai and Nissan have car models that are able to charge bidirectionally. There is an increase in usage and charging plazas can handle it.
I don't think it is an interesting option for ProRail. For offices with electric vehicles it is an attractive option because they can be charged at low price levels and serve as an extensive battery when necessary. They can play with using it as battery or as car. ProRail has structured time slots of construction work so the advantage of low price levels is not consistent. Also, the amount that a car can return to load won't help much for charging their construction equipment.

B.7- Brainstorm session with experts from Movares

Attendants	Function
Bart de Vet	Consultant energy systems and EMC
Sjaak den Breeje	Advisor rail energy

Teun Kleijburg	Sr. Advisor (traction) energy systems
Florian Simonsen	Advisor energy transition

Company: Movares
Date: 10-11-2022

Summary:

I had started interviews and literature research after the kick-off meeting. However, at some point I questioned the relevancy of this research project. It became clear from interviews with experts in the field of charging plazas that hydrogen and V2L/V2G are not developed technologies yet. Charging plazas are designed for electric vehicles/equipment. In addition, the tendency of most construction equipment is to become electric too. Hydrogen seems to be a very expensive fuel due to the high energy loss in the production process. As trucks and other heavy vehicles have developed to become electric, experts expect most construction equipment to become electric too.

The market of V2L/ V2G is underdeveloped. This innovation needs rules and regulation for its usage concerning shared data between users, grid operator and suppliers of electric vehicles and charging stations. In addition, more car manufacturers need to fabricate the option of bidirectional charging to make it more common. As a result, hydrogen and V2G/V2L would be left out of the analysis of the contribution of alternative energy solutions to charging plazas.

This would mean that I was going to focus an analysis on interchangeable battery packs or battery containers. Both have much in common which would not be of added value to Movares nor my thesis project. Therefore, I made the decision to gather experts around and discuss the continuation of my project. Bart de Vet and Teun Kleijburg are very experienced specialists with much expertise in energy supply and rail infrastructure. Beforehand, I had thought of directions for the subject to head into which could be validated by the experts. This led to a very smooth discussion about the continuation of my project.
In addition, the scenarios and some of their assumptions were made in collaboration with Sjaak den Breeje and Florian Simonsen. They know about the situation of the three types of project, which led to a discussion about the input of the morphological chart and realization table. The parameters were set based on likeliness and examples in real life.

B.8- Brainstorming session with Daan Geldermans (Skoon Energy)

Interviewee: Daan Geldermans
Function: Co-founder
Company: Skoon Energy
Date: 24-11-2022

Summary:

Daan Geldermans is an acquaintance of mine and co-founder of the company Skoon Energy. They came up with the idea to make it possible for vessels to sail electrically with the help of big interchangeable battery containers. In order to make this successful on a large scale, they found out that these batteries had to be standardized so that they could be used in many other applications in addition to ships. Mobile batteries have now shown to be a proven alternative to diesel generators on construction sites, events, and other applicational sites. Skoon Energy has now launched a platform on which batteries and other alternatives can easily be rented.

During this period of time, I was wondering what direction I could go with my thesis project, see previous brainstorming session with experts from Movares. Due to the fact that Daan Geldermans is an acquaintance of mine and an expert on battery storage and PV panels, I reached out to him to discuss my thesis project. This brainstorming session was in relation to the application of batteries. He told me that his platform offers batteries in combination with PV panels installed on top of the battery. This way, easy (but small amount of) generation of energy is possible and already installed. Also, he told me that battery storage should always be available in cases in which renewable sources take care of the generation of energy. Batteries can serve an important role in storing energy in times of lots of wind or sunshine. Also they offer load management which is useful in a closed system as a charging plaza.

Besides these insights in batteries, we had a discussion about assumptions that could be made on battery storage. He told me that lithium-ion batteries is the most frequently used battery type on the market, especially for smaller scale projects. They are charged within 1-3 hours and have a long lifetime which makes it a good business on such platforms as Skoon Energy.

B.9- Interview Maarten Deutekom (Wind energy solutions)

Interviewee: Maarten Deutekom
Function: Project Developer
Company: Wind energy solutions
Date: 5-12-2022

Summary:

Durance of projects to install wind turbine(s)
A wind turbine can be installed for a 5 yearlong project. However, this is dependent on regulation per municipality. The minimum durance of a project including wind turbine(s) depends on the business case and the location. Current energy tariffs make it very feasible business cases for wind turbines for 5 yearlong projects. However, more common is a project of 20 years as the lifetime of most wind turbines approximates 20 years.

Mobile wind turbines

Mobile wind turbines do exist. However, they are only available for power capacity up to 5 kW. The smallest wind turbine capacity has 50 kW for which no mobile applications are available.

Efficiency of wind turbines

The higher the wind turbine is, the bigger the rotor diameter usually is. This leads to a higher efficiency. Smaller wind turbines below a 50 kW power capacity are less profitable, unless energy tariffs allow it. Wind and production predictions are based on long-term period averages.

Batteries and wind turbines

A wind turbine can be installed at an off-grid location. However, there will be a need of another source of energy that can store or use the energy. Usually, leftover energy will be injected to the grid at times of low demand. So in this respect, batteries are useful to have for charging plazas.

Batteries in combination with a wind turbine is in development. Lithium-ion batteries are most common, often as containers, and its capacity is often matched with the maximum power capacity of wind turbines and/or PV panels and demand (or gap in generation).
Wind turbines generate much more steadily and much less during peak hours like PV panels. This is a big difference for having a battery for wind turbines or PV panels. However, if there exists a standard demand and there is a need to supply energy at times of no wind or sun, the inclusion of a battery is a must-have.

Costs of wind turbines

Table 15: An overview of costs for different types of wind turbines.

Wind turbine (kW)	Capex (approx. in €)	Opex (regular preventive maintenance) (approx. in €)	Installation costs (incl. foundation works) (approx. in €)	Total costs (approx. in €)
10	55.000	2.500	25.000	82.500
100	225.000	2.500	25.000	252.500
250	492.000	6.000	80.000	578.000

B.10- Interview Anna Visser (GroenLeven)

Interviewee: Anna Visser
Function: Manager Sales Coordination
Company: GroenLeven
Date: 6-12-2022

Summary:

The type of solar panel and its construction are coordinated and aligned to each other. This has to do with certain components that must be custom-made for each type of construction. In principle, any panel can be used, but the construction must be adapted accordingly. To prevent delivery problems, we determine at an early stage which construction and type of panel will be used.
The number of solar panels depend on the wishes of the customer and the type of parking space concerned. Cost-wise, a double carport is more cost-efficient that a single carport. Have a look at the figure below for a double carport.

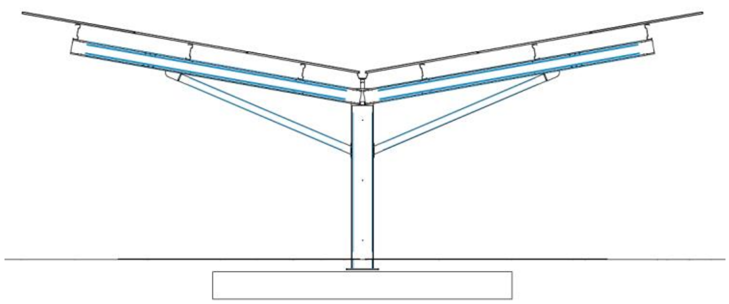

Figure 20: A schematic figure of a double carport.

The companies we often do business with already have a large-scale consumption connection (larger than 3x250A). It is not necessary for 50 parking spaces. A 3x80A will be sufficient for smaller parking spaces. Also, the solar carports that are being sold, are mostly in combination with battery storage. This ensures that the system is less dependent on grid capacity.

Battery storage is useful to increase system efficiency and management of load balancing. Software of today is able to regulate it and optimize flow of energy.

However, there are five big obstacles:

1) The biggest one is to realise a feasible business case. As of yet, the construction, restricted scale and aesthetic demand make a lot of projects unfeasible.
2) Missing nearby infrastructure or nearby energy consumers.
3) Solar carports influence the urban perspective. This causes tumult in a lot of communities which is a reason why solar carports are not incorporated in projects as a potential energy source.
4) Due to solar carports, parking spaces are less flexible to be used for markets or event purposes. Flexible or mobile solar carports would offer a solution, but there are no examples to this yet.
5) Adjustments in the destinations plan leads to higher costs, risks and problems in time. Developers of solar carports will not move towards a solar carport if a destination plan must be adjusted.

On the other hand, solar carports have opportunities:

1) They can lower energy consumption and costs of companies or institutions
2) They offer shelter in all sorts of weather conditions
3) Feasible business cases in combination with charging stations

8.3 Appendix C- Realization tables and combination tables

The created scenarios in the morphological charts in chapter 5.2 contain uncertainties that must be taken into account. In a realization table, these uncertainties are presented. According to the time span and charging demand of the scenario, the uncertainties are selected. This has been done in collaboration with experts from Movares. In the combination table, a score is given to the parameters and uncertainties. Each scenario and their uncertainties are given scores in a combination table. This provides to what extent the scenario has lived up to the uncertainties. The appendix has been split up into the created scenarios: long-term project, five-year project and six-month project.

C.1- A long-term project (~20 years)

Market prices of both lithium and batteries will remain the same over a long-term project. As economy tells us, after its highs in inflation, time will bring us in a recession to its lows. So over a long-term period the market price will remain stable. As most rail access points are already located, it is assumed to be possible to install a charging station and alternative energy solutions at this site. Due to the fact that it is a long-term project, a permit can be granted to install a wind turbine on this site. Also, the past few years, weather conditions have improved for PV panels and wind turbines. There are more days of sunshine, which helps to fill the battery.

Table 16: Realization table of a long-term project.

	Grid capacity	Weather conditions	Market price battery/panels/ turbine	Market price materials	Spatial availability	Permission for wind
Insufficient	Not enough capacity	Not enough sun or wind	Increase	Increase	Desired location	Not allowed
Sufficient	50% available	Good amount of sun and wind	Stable	Stable	Location with available space	Allowed
Proficient	At least 50% available	More than enough sun and wind	Decrease	Decrease	Not enough space to realize concept	Allowed

As the scenario has been created and its uncertainties are given. This is based on the combination table shown below. Scores are given based on the scenario.

Table 17: Combination table of a long-term project (influence on each parameter is rated by means of a positive (+), negative (-) or no influence (0) score.

	Project span	Available grid capacity	Battery storage capacity	PV panels capacity	Wind turbine capacity
Grid capacity	+	-	0	0	0
Weather conditions	+	0	+	+	+
Market price battery/panels/ turbine	0	0	0	0	0
Market price materials	0	0	0	0	0
Spatial availability	+	0	+	+	+
Permission for wind	+	0	0	0	+

C.2- A 5-year project

The morphological chart that resulted in the second scenario also led to the realization table below. As inflation has occurred the past year, prices are expected to increase in the coming years too. Also, an interview with Maarten Deutekom (2022) made it clear that permission for wind energy can be granted these days for 5 year projects due to high energy tariffs. Therefore, it is "allowed". Both the scenario parameters and uncertainties are rated in table 20 below.

Table 18: Realization table of a 5 year project.

	Grid capacity	Weather conditions	Market price battery/panels/ turbine	Market price materials	Spatial availability	Permission for wind
Insufficient	Not enough capacity	Not enough sun or wind	Increase	Increase	Desired location	Not allowed
Sufficient	75% available	Good amount of sun and wind	Stable	Stable	Location with available space	Allowed
Proficient	At least 75% available	More than enough sun and wind	Decrease	Decrease	Not enough space to realize concept	Allowed

Table 19: Combination table of a 5 year project (influence on each parameter is rated by means of a positive (+), negative (-) or no influence (0) score.

	Project span	Available grid capacity	Battery storage capacity	PV panels capacity	Wind turbine capacity
Grid capacity	-	+	0	0	0
Weather conditions	+	0		+	+
Market price battery/panels/ turbine	-	0	-	-	-
Market price materials	-	0	-	-	-
Spatial availability	0	0	+	+	+
Permission for wind	-	0	0	0	-

C.3- A 6 month project

The morphological chart that resulted in the third scenario also led to the realization table below. Similar to a 5 year project is it expected that prices of materials will increase the coming year as inflation occurred the past year. Besides, wind energy cannot be installed due to the fact that 6 months do not make a positive business case. The costs are too high for such projects and no return on investment can be made. Both the scenario parameters and uncertainties are rated in table 22 below.

Table 20: Realization table of a 6 month project.

	Grid capacity	Weather conditions	Market price battery/panels/ turbine	Market price materials	Spatial availability	Permission for wind
Insufficient	Not enough capacity	Not enough sun or wind	Increase	Increase	Desired location	Not allowed
Sufficient	50% available	Good amount of sun and wind	Stable	Stable	Location with available space	Allowed
Proficient	At least 50% available	More than enough sun and wind	Decrease	Decrease	Not enough space to realize concept	Allowed

Table 21: Combination table of a 6 month project (influence on each parameter is rated by means of a positive (+), negative (-) or no influence (0) score.

	Project span	Available grid capacity	Battery storage capacity	PV panels capacity	Wind turbine capacity
Grid capacity	-	-	+	+	-
Weather conditions		0	+	+	-
Market price battery/panels/ turbine	-	0	-	-	-
Market price materials	-	0	-	-	-
Spatial availability	0	0	-	-	-
Permission for wind	-	0	0	0	-

8.4 Appendix D- Assumptions model

Some assumptions had to be made for the creation of the model. As most of the assumptions have been written down in the report, some assumptions are given more context.

D.1- Assumptions wind energy

As there are multiple types of wind turbines, a specific type of turbine had to be chosen to start the creation of the model. Since charging plazas will be onshore, an onshore type of wind turbine had to be picked. There are multiple sizes, but most importantly the rotor diameter makes the distinction. An overview of specifications for each wind turbine is given in the table below.

Table 22: An overview of specifications for each wind turbine.

	Rotor diameter d (in m)	Rotor radius r (in m)	Cross-sectional area of wind/ A (in m^2)	Estimated annual output (in kWh)	Average wind speed (m/s)
10 kW turbine (Renewable On-Grid & Off-Grid	9,8	4,5	75,4	~ 15.000	5,0

Energy Systems, n.d.)					
100 kW turbine (Wind Energy Solutions, n.d.)	17,9	8,95	254	~ 150.000	7,0
350 kW turbine (Wind turbine models, n.d.)	33,4	16,7	876	~ 525.000	7,0
500 kW turbine (Aeronautic wind, n.d.)	47,0	23,5	1735	~ 750.000	7,5

The formula that is used to calculate power output (in Joule) by a wind turbine is as follows:

$$P(J) = 0{,}5 * \rho\ * A * v^3,$$

taking into account that V_{wind} is the average velocity of wind (in m/s), ρ (rho) is the air density (in kg/m^3) and A is the cross-sectional area of wind (in m^2). A modern wind turbine produces electricity 70-85% of the time, but it generates different outputs dependent on the wind speed. Over the course of a year, it will generate about 30% of the theoretical maximum output (Sciencing, 2020).

In addition, full load hours refers to the time for which a plant would have to be operated at nominal power in order to convert the same amount of electrical work as the plant has actually converted within a year (Energy Transition – The Wiki, 2022). As all included wind turbines have no higher tower than 50 meters, an average has been taken from the full load hours of wind turbines up to 50 meters. This provides us with an average of 1506 hours per year (4,13 hours per day) (CBS, 2022). Wind energy is a less fluctuating energy source in comparison with solar energy. Therefore, it is assumed that wind start 'their full load hours' when charging kicks off. So the wind starts blowing from 7 am or 5 pm till 4.13 hours have passed. Nowadays, high energy tariffs have made 5 year projects a positive business case for including wind turbines. Therefore, it is assumed that the high energy tariffs will remain for the upcoming years.

D.2- Assumptions PV carport

In order to maximize panel output, the panel should be as close to perpendicular to the sunrays as possible, which allows it to capture most solar energy possible at a given time. Most solar panels are fixed, which means that the location of PV panels need to be chosen carefully. For fixed panels, there are two factors to consider:

1) Azimuth:
   The compass direction that the panel faces. Typically, 0° is due north, 90° is east, 180° is south and 270° is west. As can be seen in the figure below, the most frequent azimuth on the Northern hemisphere is 180 south. This will be the case in each scenario.

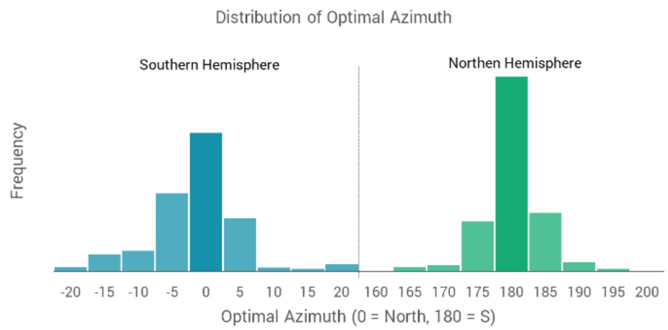

Figure 21: The distribution of optimal azimuth per hemisphere (Dubey et al., 2013).

2) Tilt:
The angle above the horizon to which the panel is *tilted*. According to the PV-GIS website from the European Commission, the optimal tilt in the Netherlands is an angle of 35 degrees (European Commission, 2022).

A solar panel outputs DC electricity. This means that the electricity flows in one direction. For households, AC electricity is used, which requires an inverter to convert DC to AC. However, load of the charging plaza will require DC which means that no inverter is necessary. There are three types of solar panels: polycrystalline, monocrystalline and thin-film. The power output of these PV panels is dependent on the quality and efficiency of the solar cells themselves (Deege Solar, 2022).

- Monocrystalline PV:
  These are the most developed type of solar panels. They are made of a single crystal silicon solar cell. As the cells are composed of a single crystal, they have a higher power output. Also, they tend to last longer, have higher efficiencies and are more expensive.
- Polycrystalline PV:
  They are referred to as the multi-crystalline panels, which are less efficient but more affordable. Due to the fact that there are more crystals in each cell, there is less freedom for the electrons to move, which results in lower efficiency.
- Thin-film PV:
  They tend to have lower efficiencies and power capacities compared to crystalline panels. They require a lot more roof space to generate a large amount of solar energy. They also tend to degrade more quickly resulting in shortest warranties.

Table 23: A table showing differences in PV panel in regard to efficiency, environmental impact and affordability (Greentech Renewables, 2010).

	Efficiency	Environment	Affordability
Monocrystalline	16-23%		
Polycrystalline	15-19%		
Thin-film sillicon	8-12%		

As can be seen in the table above, crystalline is the better option in comparison with thin-film. The choice in crystalline depends on the budget. The price of crystalline modules have sharply decreased and the

price gap is narrowing(Greentech Renewables, 2010). Therefore, the choice has been made to go with monocrystalline PV panels because of the higher efficient panels.
The output power of each PV system (P_{pv}) at time *t* can be obtained from the solar radiation formula (Maleki & Askarzadeh, 2014):

$$P(pv) = I(t) * A * \eta(pv)$$

where I is the solar radiation, A denotes the PV area and η(pv) is the overall efficiency of PV panels and DC/DC converter. If the number of PV systems is N_{pv} , the overall produced power is $P_{pv}(t) = N_{pv} * p_{pv}(t)$. It is assumed that 1 kiloWattage (kWp) of capacity generates around 950 kiloWatt hours (kWh) per year. A 400 Wp solar panel generates 380 kWh per year (0,95 kWh*400 Wp= 380 kWh). This also means that there is an estimated amount of full load hours of solar energy of 950 hours per year. This amount equals 2,60 hours per day. As can be seen in the figure below, in all seasons most sunshine is irradiated between 13:00 and 16:00. As this is before charging demand occurs, solar energy needs to be captured. This results in no hourly inclusion of PV energy as it will be provided from battery storage.

D.3- Assumptions battery storage

- All battery storage options are made of lithium ion. It is the most frequently used battery due to its high efficiency, high energy density, long life cycle and exclusion of toxic materials
- The charge time of each battery option is 3 hours. This is because the maximum charging time of lithium-ion batteries is approximately 3 hours.
- The battery can be fully discharged. This is because no long-term effect is caused if battery discharges 100% continually. However, it is recommended to discharge up to 80% to maintain longer lifetime of the battery.

D.4- Assumptions charging station and demand

- Each charging station has a capacity of 120 kW DC.
- Charging pattern of an electric vehicle is used. This means that the first 25 minutes go very rapidly until it reaches a state of charge of 85%. The other 35 minutes are spent to charge fully. However, the slope of 1,33 has been taken into account.
- For a rail access point, each charging station is expected to be occupied by an e-krol. They contain batteries of 240 kWh in total each.
- Charging demand is at its peak when employees go home and install construction equipment to the charging station, at 5 pm or 7 am (depends on scenario).
- Charging demand is expected to be zero when employees go to work and offload construction equipment from the charging station, at 5 pm or 7am (depends on scenario).
- Charging demand reduces over time if it is installed on a charging station between 5pm and 7 am.

8.5 Appendix E- Linear programming

In this section, an introduction to linear programming is given. Linear programming (LP) is a method used to mathematically find an optimal solution to a problem. The optimal solution can be a maximum or minimum. Various fields of study use this method of optimization. While it is widely used in operations research in business and economics, it has a proven track record in engineering. It is often applied in modeling optimization problems in planning, routing, scheduling and design. Also, it is often used in energy management as it is now. I found out about this method in the course of Engineering Optimization and Integrating Renewables in Electricity Markets (SEN1511). A linear programming problem consists of an objective function, decision variables and constraints, which are explained. Also, an example is given.

Objective function

The objective function is a function that defines some quantity that should be minimized or maximized. The arguments of the objective function are the same variables that are used in the constraints. For a linear programming problem, the objective function should be linear (*Linear Programming | Brilliant Math & Science Wiki*, n.d.). In general, the objective function of a business project is to minimize costs of the entire project, for example. In this thesis, the minimum solution is found for the capacity of a wind turbine to know if installed capacity would be enough to fulfil in demand of the charging plaza scenario.

Decision variables

The decision variables are the unknown quantities that are expected to be estimated as an output of the linear programming problem solution. It affects the quantity being optimized. The objective of solving a linear programming problem is to find a set of decision variables that will produce the optimal output (Educative, 2023)
In this thesis, the only decision variable was the wind turbine capacity (kW) that would determine the generation of the charging plaza. This was a result of the fact that PV panels do not generate enough energy to supply the charging plaza. Wind energy generates the lion share and should have enough capacity.

Constraints

A constraint is an inequality that defines how the values of variables in a problem are limited. In order for linear programming techniques to work, all constraints should be linear inequalities (*Linear Programming | Brilliant Math & Science Wiki*, n.d.). "Common sense" constraints that should be written. If it is not possible to produce less than 0, this is also written as: $x>0$.

In this thesis, the constraints were:

- Total charging demand >= 0
- Demand/supply >= 0

- Total charging demand <= Total capacity (generated)
- Daily power output (kWh) >= 0
- Wind turbine (kW) >= 0

Example of linear programming

In solving a Linear programming problem, the simplex method is used for problems with two or more decision variables. However, the Solver function in Excel is useful in solving such problems too.

Decision variables:
X1 = number of PS4 units produced
X2 = number of Game units produced

Objective function:
Max Z = 40X1 + 30X2

Constraints:
X1 + X2 <=12
2X1 + X2 <= 16
X1>= 0, X2 >= 0

After presenting this problem, the method brings us an optimal set of numbers in which X1 and X2 have the maximum output to 40X1 + 30X2 with the constraints taken into account.