Investigation of the potential for PV energy supply to reach net energy neutrality in the railway infrastructure by 2030

A case study of ProRail in the Netherlands

Master thesis – Energy Science

Niek Bouw - 6135625

niekbouw23@hotmail.com

Supervisors Utrecht University: W.H.J. Graus & I. Kluts

Second reader: dr. R. Harmsen

Supervisor Movares: Dhr. P. Versteeg

Master thesis – 30 ECTS

29th of July 2022

Table of Contents

List of Figures

List of Tables

Acknowledgements

First of all, I would like to thank my two supervisors from Utrecht University Wina Crijns-Graus and Ingeborg Kluts. Their continuous involvement and guidance in the research process, critical feedback, and flexible availability to make appointments certainly increased the quality of this master thesis.

Secondly, special thanks to my second reader Robert Harmsen. With the advice and feedback points received at the early stages of this research, I was guided in the right direction and able to improve the foundation for the execution of this study.

Lastly, I am also thankful for the guidance and input from Movares. Many thanks to my supervisor Pieter Versteeg who, although his experience was not in this research field, did make sure that I spoke to the right people and could finalize my master thesis with the data collection problems faced in the research process. In addition, I would like to thank Sjaak ten Breeje, who provided me with important input regarding the energy provision of the railway infrastructure.

Executive summary

As of today, more organisations act on their Corporate Environmental Responsibility (CER) and acknowledge their contributions to environmental impacts. ProRail, responsible for the Dutch railway network, is one of these organisations and set clear sustainability goals as a result. One of these goals is to reach energy neutrality in 2030. To reach this goal, renewable energy on ProRail assets is needed to ensure the energy demand is met annually. As a result, this study investigated the potential of solar photovoltaic (PV) energy and the implementation within the ProRail infrastructure to contribute to this goal.

The perspective of the 2030 energy demand of ProRail was investigated with scenario creation. Two frozen technology scenarios were created which showed increases in the energy demand due to the expected rise in train passengers. In addition, an energy efficiency scenario was constructed that contained proposed energy efficiency improvements that significantly contribute to a 22% reduction in energy consumption. Despite this demand reduction, the analysed energy efficiency measures were not sufficient to reach a 30% reduction in the energy demand compared to 2015 levels. ProRail pursued this goal from 2015 onwards with yearly 2% energy efficiency improvements. As a result of this finding, additional energy efficiency improvements need to be explored and implemented.

Furthermore, the technical and techno-economic potential for solar photovoltaic technology installations on ProRail assets was analysed. This analysis was performed through ArcGIS software. The technical analysis showed limited potential for the roofs of buildings and platforms, as it could only provide 26% of the energy consumption of ProRail in the most favourable energy efficiency demand scenario. On the other hand, the open fields owned by ProRail have a technical potential to

cover 100% of the energy demand and facilitate additional energy for other consumption sources such as trains. However, it was also found that the uncertainty of this finding indicates that detailed further research is necessary to retrieve results with higher accuracy. The techno-economic potential showed that 37% of the PV installations had a positive NPV value. Despite this relatively low percentage, the overall positive Net Present Value (NPV) for all the investigated PV installation locations of the rooftops was positive. This indicates that 37% of the surfaces with positive NPVs outweigh the negative values and relatively high financial attractivity is reached. The range of Levelized Cost of Electricity (LCOE) values found for all the PV locations is quite comparable with the general outlook of the LCOE of solar PV in 2030. In addition, the LCOE range was cheaper than all fossil-fuel technologies indicating financial attractiveness and competitiveness.

A SWOT analysis was performed and found that the implementation of PV is troubled by the electricity network administrator role of ProRail, as they are unable to generate electricity for other organisations that use the overhead electricity line of the railway network. The availability of subsidies and research projects could be used effectively to investigate new opportunities for PV implementation. Furthermore, an increased number of trains will contain an electricity meter on board. As a result, railway transport operators like NS measure their electricity use and could enter their own individual contracts. ProRail, responsible for the railway infrastructure and overhead electricity lines, is left with the energy losses in the cables that is not included in the energy contracts and administrated as ProRail energy use. Consequently, the energy demand almost doubles in 2030. This indicates that a fast implementation process of PV is required and energy efficiency improvements are crucial to reach energy neutrality by 2030.

1. Introduction

1.1 Context

Global warming is one of the most urgent matters in the world, as it endangers mankind to a large extent (IPCC, 2018). Anthropogenic emissions, greenhouse gases emitted by humans, are largely responsible for this (IPCC, 2018). One of the anthropogenic sources of emissions is the combustion of fossil fuels, which is causing approximately 80% of greenhouse emissions (EPA, 2020; EIA, 2021). Reducing the current fossil fuel-based generation and consumption of energy by increasing energy supply from renewable sources, and increasing energy efficiency, are therefore critical to reduce these greenhouse emissions (EEA, 2017).

Action is necessary from corporate organisations and governments to reduce greenhouse emissions. The concept of Corporate Environmental Responsibility (CER) refers to this duty of reducing negative environmental impacts by companies and organisations (DesJardins, 1998). As a result, each organisation and sector must take responsibility to make sure to contribute to this. One of these sectors that also has this duty is the railway sector. In the Netherlands, the company that is managing the national railway network infrastructure is ProRail. They are responsible for the construction, renewal and maintenance of the railway network, including train stations and traffic control (ProRail, n.d.-c). Looking at their energy use and CO_2 emissions, the total scope 1 and 2 energy use and emissions are 569 TJ and 5,413 tonnes of CO_2 in 2020 respectively (ProRail, 2021b). This is equal to the energy usage of approximately 11,500 Dutch households (CBS et al., 2021). This energy use is divided into four categories: offices, infrastructure, train stations and mobility. The energy consumption consists of 81% electricity, 13% natural gas, 3% heat from district heating sources, and 3% petrol and diesel (ProRail, 2021b). Because of the large share of electricity and the purchase of renewable electricity from wind farms, the emissions based on the reported energy use are 5,413 tons, as zero emissions are taken into consideration for wind electricity use in line with the reporting standards (ProRail, 2021b). Moreover, ProRail has upstream and downstream CO_2 emissions caused by manufacturers, suppliers and contractors, also referred to as Scope 3 emissions. These emissions are estimated to be approximately 300,000 tons of CO_2 in 2020, which substantially increases their environmental impact (Aardenburg & Drok, 2021). This mainly consists of the energy consumption of trains and contractors, and the production of several materials such as rails, turnouts, and railway sleepers (Aardenburg & Drok, 2021).

ProRail has acknowledged its contribution to these environmental impacts and set several sustainability goals to decrease its impact. One of these goals is to become energy neutral in 2030 for their own practices and activities. This means that ProRail wants to supply its energy consumption with renewable sources on its own assets on a yearly basis (Bouwmeester et al., 2018). Consequently, this goal is focused on scope 1 and 2 energy use and emissions of ProRail. To meet this goal, generation from renewable energy sources must be increased to meet this scope 1 and 2 energy demand in 2030.

1.2 Knowledge gap and relevance

Previous literature has already studied energy-related subjects within the railway sector. Novel measures and systems focused on renewable energy generation specifically, have been investigated and studied for this sector. Integration of vertical axis wind turbines close to the railway in Spain has been studied to harvest more wind energy due to aerodynamic benefits (Asensio et al., 2018). Ning et al. (2021) investigated the development of a railway renewable energy system with PV panels (RPIS) in a traction-storage-information integrated station (TSIIS) in China. Another study researched the energy management of the railway network in Poland, with a focus on energy efficiency measures (Kuzior & Staszek, 2021). In terms of energy neutrality, research has been done on the railway network of China (Paul, 2021), but this lacked an in-depth analysis. In addition, the focus of this and other studies has been mainly on other countries, which means that a study specifically for the Netherlands is missing.

As of today, the Dutch railway network controls 7,051 km of rails, 398 stations, and 9,892 ha owned area (ProRail, 2022e). With these assets, there is a large potential for renewable energy generation, especially the integration of solar panels with the availability of rooftops and open fields. This potential could be used to reach energy neutrality by 2030 and provide the energy demand of scope 1 and 2 activities. Moreover, there could be significant potential that is large enough to provide some energy for scope 3 activities and reduce this impact simultaneously. This would extend the Corporate Environmental Responsibility of ProRail beyond its energy neutrality goal of 2030 and also focus on scope 3 energy use and emissions. A study investigating the potential of renewable energy supply could therefore provide significant societal relevance.

ProRail did investigate its energy use and CO_2 emissions and constructed an energy efficiency and emission-saving strategy (ProRail et al., 2017; ProRail, 2018). These strategy documents provide concrete points of action that are or will be taken to reduce energy use and emissions. As these two documents provide useful information already, it must be noted that the focus of these documents is until 2020. Although long-term interventions are mentioned, it only covers energy reduction and efficiency measures on minor aspects lacking a clear strategy. It also lacks focus on the integration of different renewable sources for energy generation, as it only mentions that there is potential for renewable energy supply in 2030, but a clear foundation and numbers are missing. Moreover, as shown before, scientific literature on renewable energy topics for the railway sector of the Netherlands is non-existent. Research on the railway network done in other countries does provide some useful examples, but a study on the railway network of the Netherlands is required to investigate the technical and economic potential for renewable energy generation.

In addition, the Dutch railway network is a unique and interesting case. The distance travelled by train is significantly above average in the Netherlands (Ministry of Transport, Public Works and Water Management, 2010). Moreover, as the Netherlands is a relatively densely populated country, the railway network is of high density as well. This study could therefore provide significant scientific relevance in developing a methodological approach on the potential of renewable energy within dense railway networks. Novel information and insights related to the technical and economic aspects of renewable energy generation in these networks could be identified. Similar cases or countries with dense networks could use this study to retrieve relevant information on how the potential of renewable energy could be identified and how this could be implemented.

1.3 Research aim & questions

Given these observations, it is clear that there is a knowledge gap that needs to be fulfilled. This research, therefore, aims to investigate the renewable energy generation possibilities for ProRail to reach its 2030 energy neutrality goal for scope 1 and 2 energy use. In particular, this study focuses on solar energy and the implementation of photovoltaics technology.

Due to a large number of available rooftops and open fields, it is clear that the potential of this form of renewable energy is most suitable. In addition, based on communication with ProRail, it was demonstrated that the implementation of other forms of renewable energy was difficult within the railway infrastructure and facing boundaries in the near future. As a result, the scope was delimitated to solar energy to carry out a detailed analysis and left out other forms of renewable energy such as wind or biomass. The main research question is therefore formulated as follows:

Main research question
"What is the potential of solar photovoltaics technology that could be deployed by ProRail to reach net energy neutrality by 2030 and how could this be implemented within the owned infrastructure of ProRail?"

To structure the research and answer the main research question, three sub-questions are formulated:

1. What is the energy demand of ProRail in the current situation, two frozen technology 2030 scenarios and an energy efficient 2030 scenario?
2. What is the technical and techno-economic potential for solar PV technology on ProRail assets?
3. Which challenges and opportunities regarding the implementation of PV technology could be identified and how could ProRail and relevant stakeholders play a role in this?

1.4 Research structure

This research report is structured as follows. First of all, Chapter 2 discusses the concepts, methodology and results of the first sub-question that is focused on the energy demand scenarios, phase I of this study. Secondly, Chapter 3 focuses on the concepts, methodology and results of phase II which is both the technical and techno-economic potential of PV technology on ProRail assets, whereas Chapter 4 does this for the challenges and opportunities for the implementation of PV, also referred to phase III. In addition, Chapter 5 is the discussion that thoroughly interpretates the results and provides theoretical implications, discusses some constraints and limitations and mentions suggestions for further research. Finally, a conclusion is given in Chapter 6, which comes back to the main research and sub-questions and provides recommendations. At the end of the report, an Appendix could be found that provides some more detailed and additional information that is referred to in the report.

Figure 1 below shows the research framework that is used in this study. This could be used as guidance to read through this research report. The dashed polygon is the boundary for the scope 1 and 2 energy use and therefore also the scope of this research. The corresponding concepts, methodologies and frames are discussed in detail in the following chapters of this study.

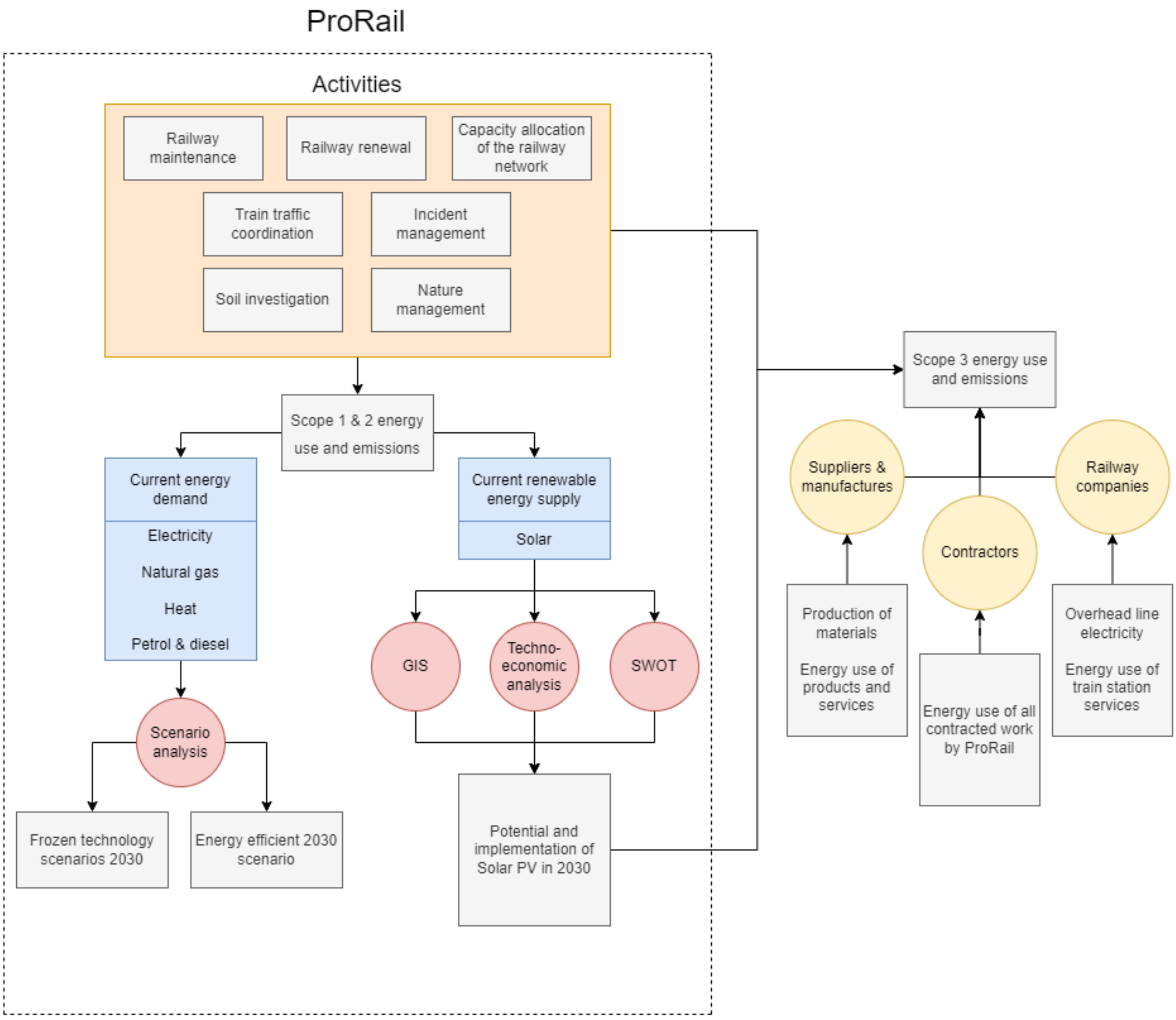

Figure 1: Research framework

2. Phase I: Energy demand scenarios

2.1 Energy use of ProRail

2.1.1 Delimitation of activities

To reach energy neutrality for scope 1 and 2 activities of ProRail, it is important to specify the activities of ProRail. In the Netherlands, there are one large and some small railway transport operators that are responsible for all passenger trains and the travel of the passengers. The largest one is the Nederlandse Spoorwegen (NS), which makes use of the railway network managed by ProRail. Other operators are Arriva, Connexxion and Keolis (ProRail, 2021c). Additionally to passenger transport, there is also freight transport. This is managed by around twenty railway freight transport operators (ProRail, n.d.-b). ProRail classifies its activities into seven main categories. These are described in Table 1 below.

Table 1: Categories of ProRail activities (ProRail, n.d.-d)

Activity	Details
Maintenance of the railway network	This contains all the activities that are needed to maintain the quality of the railway network. This includes construction and operation activities, but also inspection of the rails, stations, switches and ballasts.
Renewal of the railway network	The renewal of all rails, switches and train stations that is for example needed to replace outdated parts or to increase the capacity.
Allocation of the capacity	The allocation and planning of all passenger and freight trains on the railway network. The distribution of this is realized with the support of a planning system.
Coordination of the train traffic	With an operational control centre (OCCR) located in Utrecht, ProRail is responsible to deal with malfunctions and failures on the rails.
Incident management	Their incident unit (ICB) deals with incidents on the railway and makes sure the railway could be back in operation as soon as possible
Soil investigation	ProRail execute its own soil investigation in some projects for archaeological purposes
Nature management	ProRail is responsible for the nature management of soil next to the railway. They connect nature reserves and make sure nature is conserved.

It must be noted that NS is the owner of the passenger services within stations such as shops, restaurants and bicycle storage (Ministerie van IenW, 2021), whereas ProRail is responsible for the construction, maintenance and management of these train stations and platforms (Ministerie van IenW, 2014).

2.1.2 Delimitation of energy use

In addition to the scope of the activities that fall within the responsibilities of ProRail, it must be defined which energy usage of these activities fall within the scope of this research. As already mentioned, this study focused on scope 1 and scope 2 energy usage and emissions. This is also referred to as direct energy content, which is the energy used or purchased by the organisation directly (Pick & Becker, 1975). This means that scope 3 energy use and emissions, energy used in all contracted work and by suppliers, manufacturers and railway transport operators related to the activity categories discussed above, is not considered. This also means that at train stations, where NS is responsible for all passenger services, the energy usage of these services such as the heating and lighting of shops and restaurants is outside the scope. On the other hand, the energy use of the station itself, for example general station lighting, escalators and elevators, is of ProRail and within the scope. Moreover, the electricity of the overhead line is the energy used by railway companies and thus is not within the scope of this research. However, it must be noted that a small margin of the electricity is not used by the trains, but for e.g. lighting poles next to the rails, and ventilation for other facility buildings. This falls under the authorization of ProRail and is therefore energy use that falls within the scope.

2.1.3 Energy neutrality

The goal of ProRail is to reach energy neutrality in 2030. Energy neutrality has various definitions in scientific literature. First of all, energy neutrality is defined as self-sufficiency, which means that the ratio between the locally generated energy and the total energy demand is 100% (Ciocia et al., 2021). This does mean that all generated energy is directly used and thus matches the load profiles. This is also referred to as 'zero energy', which is mostly applied to buildings where at the strictest level all the required energy is met by local renewable energy sources (Torcellini et al., 2006). However, energy neutrality could also be defined as **net** energy neutrality. This means that a site, building or overall organisation produces at least as much energy as it uses on an annual basis from renewable sources, also referred to as **net** zero (site) energy (Derkenbaeva et al., 2022; Torcellini et al., 2006). This definition is also applied in the energy neutrality goal of ProRail, where the aim is to provide all required final energy of scope 1 and 2 activities from renewable energy on their assets on an annual basis.

2.1.4 Energy demand

The sources of the scope 1 and 2 energy demand of ProRail are classified into four main categories: offices, infrastructure, stations, and mobility (ProRail, 2021b). The energy that is necessary for offices consists of space heating and electricity for e.g. control centres systems. The infrastructure category is the energy used for all infrastructural installations and buildings such as bridge keeper houses and electricity substations. The energy demand of train stations consists of lighting, escalators and elevators. The energy use of mobility is all the energy used for business travel by rental and lease cars, planes and trains. To reach energy neutrality, it is essential to lower the energy demand as much as possible.

In order to construct and estimate the energy demand of ProRail in 2030 in three scenarios, it is important to visualize the current energy demand for these four demand categories and the different energy carriers. This data was collected in the data collection process, described in 2.3.1 Data collection.

2.1.5 Energy efficiency

An important concept for the scenario creation of the energy demand in 2030 is *energy efficiency*. Simply put, *energy efficiency* is using less energy to get the same output as before (Energy Star, n.d.). Currently, inefficiencies are causing the energy demand to be unnecessarily high, and energy efficiency could decrease this. ProRail has acknowledged the importance of energy efficiency and has set a goal to reach 2% energy efficiency improvements per year from 2015 onwards until 2030 (ProRail, 2022a). This results in a reduction in the energy demand of ProRail by 30% when the activity level remains equal. One practical example of energy efficiency that ProRail is working on is switching to larger voltages on the overhead line, from 1.5 kV to 3 kV, which is much more efficient because of reduced transmission and distribution losses (Movares, 2022). Although a small portion of the electricity is energy use of ProRail and most of the electricity is for the trains and falls within the energy use of NS, it is still a perfect example of energy efficiency measures executed by ProRail and specifically applied in the railway network. This study identified and explored other energy efficiency measures, focussed on the four energy demand categories. This was used as input in the description for the energy efficient 2030 scenario discussed in 2.3.4 Energy efficiency scenario.

2.1.6 Energy supply

The supply of energy could originate from both non-renewable and renewable sources. Non-renewable sources are e.g. fossil fuels and nuclear energy, whereas renewable sources are energy from replenishable sources. Currently, ProRail already produces some renewable energy on its assets. In 2021, ProRail generated 1.5 GWh of electricity by solar panels on stations and other rooftops (ProRail, 2022b), which is only 1.2% of the total electricity demand. The rest of the supplied energy is bought from external energy cooperatives. This energy is green, meaning that it is 100% renewable from wind energy and gas is generated by biomass (ProRail, 2021a). To reach the energy neutrality goal in 2030, all energy must be supplied and generated on ProRail assets by renewable sources. These sources include sunlight, wind, tidal, wave, biomass and geothermal. For ProRail, tidal and wave energy is not relevant, as this is not possible within the boundaries of the organisation and therefore not taken into consideration in this study. Geothermal energy may also be difficult to investigate due to the spreading of ProRail assets. In addition, the large share of electricity in the energy demand means that the potential contribution of geothermal heat is limited. The usage of geothermal electricity could be beneficial, however, this requires a lot of space and deep and expensive drilling (Kayebi, 2019). Solar, wind and biomass are therefore the potential sources of renewable energy that could be considered. However, this study had a clear focus on solar energy. Not only was this decided due to time constraints, but also the implementation difficulties that ProRail faces with wind and biomass concluded after communication with ProRail.

This is explained in more detail in 5.1.2 Phase II, where the capability of PV energy to meet the energy demand in 2030 is discussed. Available space for solar energy includes all the area, buildings and other constructions such as sound barriers that are owned by ProRail.

2.2 Energy demand scenarios

As the first sub-question already indicates, this study focused on the creation of three scenarios for the energy demand of ProRail in 2030. Scenarios are known as descriptions of possible futures based on events, activities and perspectives of the past and present (Lelah et al., 2014). They are mainly used to guide and improve the quality of the decision-making progress, but also to manage transitions in the future (Lelah et al., 2014). Notten et al. (2003) have developed a detailed scenario typology based on an extensive review of a varied number of sources. The constructed typology has three overarching themes, also referred to as the three key aspects of scenario creation, with corresponding scenario characteristics. After a reviewal of these characteristics, guidance questions were formulated by the researcher to clarify the characteristics. This is reported in Table 2 below (Notten et al., 2003).

Table 2: Scenario typology (Notten et al., 2003)

Overarching theme		**Scenario characteristics**	**Guidance question**
Theme A: Project goal *exploration vs decision support*	1.	Inclusion of norms: descriptive vs normative	Is the scenario an exploration of a **possible** (descriptive) future or a **preferable** (normative) future?
	2.	Vantage point: forecasting vs backcasting	Is the scenario an **exploratory forecast** or **anticipatory backcast** for the future?
	3.	Subject: issue-based, area-based, institution-based	Is the scenario analysing a **societal issue** such as the future of crime, a **geographical area** such as New York, or an **organisation/sector** such as Shell?
	4.	Time scale: long term vs short term	Is the scenario addressing a scale of **3-10 years** (short term) or **more than 25 years** (long term)?
	5.	Spatial scale: global/supranational vs national/local	Is the scenario focussing a global, national, sub-national, regional or local area?
Theme B: Process design *intuitive vs formal*	6.	Data: qualitative vs quantitative	Is the scenario based on quantitative data, qualitative data or a combination of both?
	7.	Method of data collection: participatory vs desk research	Is the collected data based on **individual conversations with experts** or **scientific journals**?
	8.	Resources: extensive vs limited	Are the resources (money, time, manpower) invested in this project extensive or limited?
	9.	Institutional conditions: open vs constrained	To what extent is the scenario analysis given a large room for manoeuvring?
Theme C: Scenario content *complex vs simple*	10.	Temporal nature: chain vs snapshot	Is the scenario **developmental and path descriptive** (chain - film) or **end-state oriented** (snapshot – photo)

	11.	Variables: heterogeneous vs homogenous	To what extent are the scenarios addressing many types and numbers of variables?
	12.	Dynamics: peripheral vs trend	Is the scenario extrapolating from **existing trends** (trend) or **including unlikely and extreme events** (peripheral)?
	13.	Level of deviation: alternative vs conventional	Is the scenario describing multiple scenarios that **differ significantly** or are **relatively equal and based on present trends**?
	14.	Level of integration: high vs low	To what extent is the scenario interdisciplinary with many scales and domains included?

This typology is used to formulate the scenario creation for the energy demand of ProRail. In 2.3 Methodology phase I: Energy demand scenarios, the details of how this typology is applied to the scenario creation are discussed. In the context of energy, scenarios are mostly used to analyse future energy developments for a specific geographical or sectoral coverage (Paltsev, 2017). This is mainly to construct future outlooks of the total energy system, which includes concepts like primary energy supply by source. An example is a report of the World Energy Council (2013), which constructed scenarios for energy futures in 2050 for the whole world. These scenarios are usually constructed in modelling tools designed for energy systems like HOMER, EnergyPlan, PLEXOS and many more (Ringkjøb et al., 2018). Contrary to the usual scenario creation for energy systems, this research had a different approach based on several aspects. First of all, this study focussed on the energy demand only, which means there is a small focus within the energy system. Secondly, the scenario creation is not using modelling software but is based on rough estimates of the current energy data and possible qualitative energy efficiency measures. Thirdly, the creation of the scenarios is for one organisation only, which means that a usual larger scope on one country or continent was not included.

2.3 Methodology phase I: Energy demand scenarios

The first phase of the research focused on the current energy demand situation of ProRail and a projection of this demand in 2030. Insight into this energy demand provides a significant foundation for the other research phases. First of all, two frozen technology scenarios were constructed. These two scenarios took the increased train capacity and the resulting increase in energy demand into account. This is mainly to give insight into the effect of the expected increase in passengers in 2030. The energy efficiency scenario describes a scenario that could be realised after the yearly energy efficiency percentages of 2% and additional energy efficiency improvements for particular sources of energy demand. These improvements focused on each of the four categories described in 2.1.4 Energy demand. This scenario creation enabled to address energy efficiency improvements that could be of significant relevance to the energy neutrality goal of 2030. This was based on desk research and semi-structured interviews. The semi-structured interview method was chosen and used to enable reciprocity and allow space for follow-up questions (Kallio et al., 2016).

The theory behind scenario creation was discussed in 2.2 Energy demand scenarios. The scenario typology constructed by Notten et al. (2003) described in Table 2 is suited to act as a foundation to indicate how the scenarios of the energy demand were shaped. The scenarios are explorative, intuitive, and simple. The different scenario characteristics are deliberately mentioned on an individual basis and explained in Table 3 below. This shows how the scenario typology was applied to the scenario creation of this study.

Table 3: Scenario characteristics of the scenario creation for this research (based on Notten et al., 2003)

Overarching theme	Scenario characteristic	Explanation
Theme A: Project goal *exploration*	I. Descriptive	The study investigated three possible scenarios of the energy demand of ProRail in 2030, independent of any preferences.
	II. Forecasting	The three scenarios were exploratory forecasts for the future of ProRail's energy use based on present data.
	III. Institution-based	The scenario creation was for one organization only, ProRail in this case.
	IV. Short term	The three scenarios were created for 2030, which means that the focus is short term.
	V. National	The three scenarios were focused on ProRail, which is operating on a national level.
Theme B: Process design *intuitive*	VI. Qualitative & Quantitative	The scenarios are based on a combination of qualitative and quantitative data. Qualitative measures created a storyline, whereas quantitative data was used to estimate the energy demand in 2030.
	VII. Participatory & Desk research	The data was collected from individual conversations with ProRail and Movares experts, which was focused on retrieving quantitative data and expected developments in the energy demand in the future. Desk research was focused on additional quantitative data and qualitative measures.
	VIII. Limited	The resources were quite limited, as the research was executed by one researcher only in a limited period.

	IX. Open	The scenario analysis was bounded within the energy use of ProRail, but different measures were introduced to investigate its effects on the energy demand in 2030.
Theme C: Scenario content *simple*	X. Snapshot	The three scenarios were developed and presented as a snapshot of the 2030 energy demand, which means it is end-state oriented.
	XI. Homogenous	As the three scenarios were focused on energy data only, there are not many types of variables included.
	XII. Trend	The three scenarios were created based on existing data on energy demand and information. The scenarios are therefore not including unlikely or extreme events.
	XIII. Conventional	The three scenarios were based on present trends, which means they are closely related.
	XIV. Low	The scenario creation was only focused on the energy demand of ProRail, which means that only one domain and scale is included.

The next section discusses the data collection and general details that were used in the scenario creation process. In addition, the three scenarios are discussed in two separate sections and it is explained how the collected data was analysed and used to construct all three scenarios.

2.3.1 Data collection

Quantitative and qualitative data on the current energy demand of all ProRail activities was collected through semi-structured interviews and desk research. The interviews were held with Movares and ProRail employees to acquire qualitative data about the energy demand and strategy for energy efficiency improvements in the future. A list of the conducted interviews is included in Appendix III: Conducted interviews. The desk research collected quantitative data from online available documents and sources of ProRail on the current energy demand. The focus of this data retrieval was to acquire the most recent data available. Unfortunately, the most recent data available on a detailed level was from 2015. Quantitative data on the energy use was collected from 2020, however, this was not specified per energy demand category and further detailed energy sources within these categories.

For the creation of the energy efficiency scenario, additional qualitative and quantitative data was collected. This was retrieved from a desk research and focused on energy efficiency measures for the four demand categories (see 2.1.4 Energy demand) and their estimated quantitative energy reduction. In addition, the semi-structured interviews that were conducted with personnel of ProRail and Movares from sustainability and energy groups were used. Their expertise and knowledge provided additional insights into the expected changes in energy demand in the period up to 2030. In addition, these conversations were useful to investigate whether ProRail is up to speed with the 2% energy demand reduction per year.

2.3.2 Data analysis

Three energy balances of the demand side were created for the three scenarios similar to the one used in the energy efficiency strategy document of ProRail in 2017 and provided in Appendix I: Energy demand of ProRail in 2015 (ProRail, 2017). Table 4 below is a summary table, with the current energy demand of ProRail for the four demand categories and energy sources of electricity, natural gas, heat, or transport fuels.

Table 4: Total energy demand of ProRail in the four demand categories for the different energy carriers in GWh (ProRail, 2021b; ProRail et al., 2017)

	Electricity	Natural gas	Heat	Transport fuels (diesel/petrol)	Total	Unit	Year
Stations	54.66	3.80	0.54	0	59.00	GWh	2015
Infrastructure	73.59	28.44	0	0	102.02	GWh	2015
Offices	7.50	2.60	4.33	0	14.44	GWh	2015
Mobility	0	0	0	4.85	4.85	GWh	2020
Total	135.75	34.84	4.87	4.85	180.30	GWh	

Table 4 shows that the numbers of the energy demand for mobility are from 2020, whereas the other three categories only have data on this detail level for 2015. Although this may concern the validity of the data, the energy usage has not changed to a large extent. This is confirmed by a recent publicly disclosed document of ProRail, the CO_2 and energy savings plan 2021-2025 (ProRail, 2022a). In this document, the overall energy usage over the period from 2015 to 2020 is displayed in a bar chart. It shows that the total energy demand of ProRail in 2020 is slightly lower than in 2015. However, the influence of Covid-19 in that year may have decreased the energy consumption by some extent as simply fewer trains were travelling. In addition, the 2020 data was not available on the same detail level. As a result, 2020 data was not suited to be used for this research and therefore not collected and analysed further. When comparing the total energy demand in 2015 with 2019, the most recent year with no influence of Covid-19, the bar chart shows relatively equal values. The collected 2015 data is therefore suited to be used as a benchmark for the current situation and the scenario creation. Based on Table 4 and Table 26 in Appendix I: Energy demand of ProRail in 2015, two frozen technology scenarios and an energy efficient 2030 scenario were created.

2.3.3 Frozen technology scenarios

Two frozen technology scenarios were created for the year 2030. These scenarios are mostly used to visualize the energy demand that will occur due to an increase in passengers in 2030. ProRail expects an increase of 30% in passengers in 2030, which means they aim to increase the capacity of the infrastructure to enable more trains in the future (ProRail, 2019). This would have an impact on the energy use of ProRail. However, ProRail does expect that until 2030, the increased capacity could be managed within the current infrastructure, which means that substantial increases in energy use are not likely (ProRail, 2019). Given this fact, and the uncertainty regarding the influence of this increased number of passengers on the energy demand, two frozen technologies were created.

The first scenario assumes a 10% increase in energy use due to this expected increase in train capacity, whereas the second scenario assumes a 20% increase. As a result, there is a range visualized for the energy demand in 2030 when there are no energy efficiency improvements implemented until 2030. It must be noted that both the 10% and 20% increase is applied to all four categories, as the increased number of passenger influence them all. However, there is one exception, which is the station lighting and travel information. This is highly independent of the number of passengers and thus assumed to be the same as the 2015 values.

2.3.4 Energy efficiency scenario

The energy efficiency scenario is created to visualize the energy demand of ProRail in 2030 with yearly energy efficiency improvements percentages and additional energy efficiency improvements for particular energy sources on top. From 2015 onwards, ProRail has set the goal to reduce its energy demand by 2%, eventually reaching a 30% reduction in 2030 compared to 2015 data (ProRail, 2021b). It was therefore assumed that this target of 30% reduction of energy consumption is reached in 2030, and implemented in this energy efficiency scenario. In addition to this general energy efficiency improvement percentage, several other measures that reduce the energy consumption were implemented in this scenario. These measures replace the standard 30% energy efficiency for the accompanied applications, as they are better estimates for the potential energy reduction. Finally, to create a realistic scenario, it was also assumed that the energy demand increases because of the expected increase in train capacity. It was decided to use a value of 15% for this increase in energy demand, the mean value between 10 and 20%, which are the values used for the two frozen technology scenarios. The methodology of the calculations for the additional energy efficiency measures is discussed for each category specifically below.

2.3.4.1 Stations

For the stations category, the energy efficiency improvement that is implemented is to replace all lighting used in stations with LED lights. ProRail has already acknowledged this and started to implement LED at all stations. As the available data is from 2015, it must be determined to what extent LED was already implemented at that time to be able to implement the effect of this measurement on the scenario. ProRail acknowledged on the 9^{th} of December in 2016 that only twelve stations had LED lights implemented (ProRail, 2016). This means that this is only a small fraction of the total of 398 stations that ProRail possesses. As a result, it was assumed that no LED was implemented in the year 2015 as of yet. The actual energy savings of this measurement were hard to find out, as there are very few studies available on this specific topic in this particular sector. ProRail claims that implementing LED lights on all stations reduces the energy consumption by 50% (ProRail, 2016). However, the International Union of Railways (UIC) estimates the energy consumption reduction to be 28% (UIC, 2016). Both these estimations include smart control systems to dim the lighting when no one is around.

Without further additional information, it was therefore assumed that the energy consumption is reduced by 39% for this scenario, in the middle of both estimations. This percentage replaces the assumed 30% energy efficiency improvement for station lighting.

Regarding the other sources of this category, there was no sufficient knowledge and information available to implement energy efficiency improvements and estimate their reduction potential. These sources include travel info, elevators, escalators and other unspecified sources and use around 58% of the total energy demand for the Station demand category. These sources use the energy efficiency improvement percentage of 30%.

2.3.4.2 Offices

For the office category, one measurement is implemented for this scenario. It is assumed that in 2030, all offices of ProRail have an A label for their energy use. This means that the insulation of these buildings is improved and e.g. heat pumps are installed. It is mainly aimed to indicate the energy reduction potential when this rather extreme measurement is implemented. To estimate this potential, specific data on the office buildings was collected. The current energy labels of the buildings were collected through EP-Online, a database with information about energy labels and indicators for non-residential buildings (Rijksoverheid, n.d.). The surfaces of the buildings, which is the total surface of the building taking multiple floors into account, were collected from the online BAG register (Kadaster, n.d.). With this information and the energy data from the table in Appendix I: Energy demand of ProRail in 2015, the current electricity and heating use (in kWh/m^2) was estimated. It was assumed that 6% of the heat is used for tap water, which means that 94% of the 2015 value was used to estimate the current heating use in kWh/m^2 (Gerbens-Leenes, 2016). For the incidents unit and regional offices, the total heating use as reported on the 2015 energy balance, was divided by the sum of all individual surfaces.

To calculate the heating reduction potential for when all buildings were improved from their current energy label to label A, The NTA 8800 was used. This is a calculating method for energy performances of buildings that started on the first of January 2021 (Innax, n.d.). This method has specified the total yearly heating use of each label per m^2. The NTA 8800 includes five energy labels with label A, ranging from A to A++++. As this method was introduced last year, it was assumed that the highest A labels with the lowest energy usage apply to new construction houses. Therefore, it was assumed that the A+ label would be the highest label possible within the current offices of ProRail. As a result, the value of label A+, which is 90 kWh/m^2, is used for the heating use reduction calculations to investigate the largest energy reductions possible. Using the surfaces of the offices and the calculated current heating use, the absolute heating use reduction was estimated in Table 5 below. The absolute heating use reduction was subtracted from the 2015 heating use.

Table 5: Input data for the heating use reduction for ProRail offices

Office	Surface (m^2)	Current energy label	Current electricity use (kWh/m^2)	Current heating use (kWh/m^2)	A label heating use reduction (MWh)
Adm. Helfrichlaan	10300	A	674	77	0
De Inktpot	30500	A	182	66	0
Tulpenburg	7225	G	308	146	405
Incidents units	2514	A, B & E	221	210	302
Regional offices	16672	A & D	200	124	570

For the electricity use, the 30% reduction as energy efficiency improvement percentage was used, as the electricity use is not dependent on the energy labels but dependent on behavioural or other energy efficiency measures (Majcen et al., 2017).

2.3.4.3 Infrastructure

For the infrastructure category, the same methodology of the LED lights for stations was applied for the lighting emplacements source of energy demand, which accounts for around 5% of the total infrastructure energy demand. As there are no LED lights implemented, it is assumed that also a reduction of 39% is realized by replacing all old lights with LED (G.O. Monnikhof, personal communication, 2022).

In addition, this scenario takes a measure into account for the railroad turnouts. This is completely phasing out gas-fired railroad turnouts and switching to electrical ones. As a result, natural gas is not needed for this heating process and this could be generated by sustainable electricity sources. Regarding both heating processes, 1000W/meter of rail is used for gas-fired turnouts, whereas 330W/meter of rail is needed for electrical ones (Szychta et al., 2012). With the available data on the number of turnouts from ProRail and their average heating distance, it may be possible to determine the energy savings (ProRail, 2022e; Voestalpine, n.d.). However, literature on the difference in time span that both types of turnouts need to operate to heat the same length of the rail, was not available. These operating times are necessary to calculate the energy use of both turnouts from the power consumption data. As a result, the actual difference in energy use was not able to be reproduced. Consequently, it was assumed that a 17% energy reduction is reached when switching from gas to electricity. This was based on the Switzerland case, where 63% of the gas-powered turnouts were switched to electrical units, which saved 7 GWh from the total of 65 GWh energy use per year (Zasiadko, 2019). Moreover, ProRail also mentioned that the energy savings from switching gas-fired to electrical turnouts are relatively low, contrary to the realized CO_2 savings (G.O. Monnikhof, personal communication, 2022). This internal expertise and the Switzerland case was therefore sufficient to use 17% as a valid energy reduction percentage for this measurement.

Finally, for the VL-posts (verkeersleiding post) source in this category, which is approximately 13% of the total infrastructure energy demand, the same methodology used for the office electricity and heating reduction was applied. VL-posts are also office buildings used by ProRail and control the train traffic nearby, but do not fall within the office demand category. This means that the same energy reduction potential could be indicated when improving their energy label. The total heating use reported in Table 26 in Appendix I: Energy demand of ProRail in 2015 was divided by the sum of all eleven VL-posts surfaces. Table 6 below specifies the current electricity and heating use, as well as the absolute heating reduction for the sum of all VL-posts used as input data.

Table 6: Input data for the heating use reduction for ProRail VL-posts

VL post	Total surface (m^2)	Current energy label	Current electricity use (kWh/m^2)	Current heating use (kWh/m^2)	A label heating use reduction (MWh)
All VL posts	20120	A - C - D - E - F - G	564	109	383

2.3.4.4 Mobility

For this final demand category, one measure is implemented in the energy efficiency scenario. It was assumed that all energy use in the mobility sector is from cars. As the mobility data was not included in the retrieved 2015 data, it was added to the energy balance of 2015 in Appendix I: Energy demand of ProRail in 2015 . With this assumption, the measure to replace all diesel and petrol lease and rental cars from ProRail with electric cars in 2030 was estimated. It was chosen to implement this measure to visualize the potential savings that could be reached, also with the government of the Netherlands deciding that in 2030 100% of the car sales must be electric (RVO, 2021). To calculate the potential energy savings, data from a TNO report is used which investigated the real-world fuel consumption and electricity consumption of cars over the years (TNO, 2022). Data on the average electricity and fuel used per 100 km is retrieved to support the calculations. Including all charging losses, 20.1kWh per 100 km is used for average Dutch electric cars. With the retrieved petrol and diesel specific fuel consumption of 6.6l/100km and 6.1l/100 km in 2020 and the total litres of fuel used in 2020 by ProRail, the number of kilometres driven was calculated. Multiplying this with the 20.1kWh/100 km factor finds the energy consumption of all the kilometres driven in 2030, which is thus assumed to be equal to the 2015 number. As a result, based on these values the final energy consumption for the mobility category is reduced by 65%.

2.4 Results Phase I: Energy demand scenarios

Figure 2 & Figure 3 below show the two frozen technology and energy efficiency scenarios of the 2030 energy demand of ProRail compared to the current energy demand. Figure 2 shows the energy demand of each scenario sorted by energy carrier, whereas Figure 3 shows the energy demand sorted by demand category. It is shown in both figures that the two frozen technology scenarios show a gradual increase in energy demand. The energy efficiency scenario shows a clear significant reduction in energy demand of 39 GWh, which is a decrease of 22% compared to the current situation. To realise a 30% reduction of the total energy demand in the energy efficiency scenario, a much smaller increase of 4% due to increased train capacities is required. One interesting observation is that the natural gas usage is reduced significantly, which is caused by phasing out natural-gas fired railroad turnouts and improving the energy labels of both the offices and VL-posts. As a result, the electricity for turnout heating is increased by approximately 10 GWh in the infrastructure demand category. Despite this increase, there is still a small decrease of 7.7 GWh of electricity demand due to the general 30% energy efficiency improvements and/or additional measures, as shown in Figure 2.

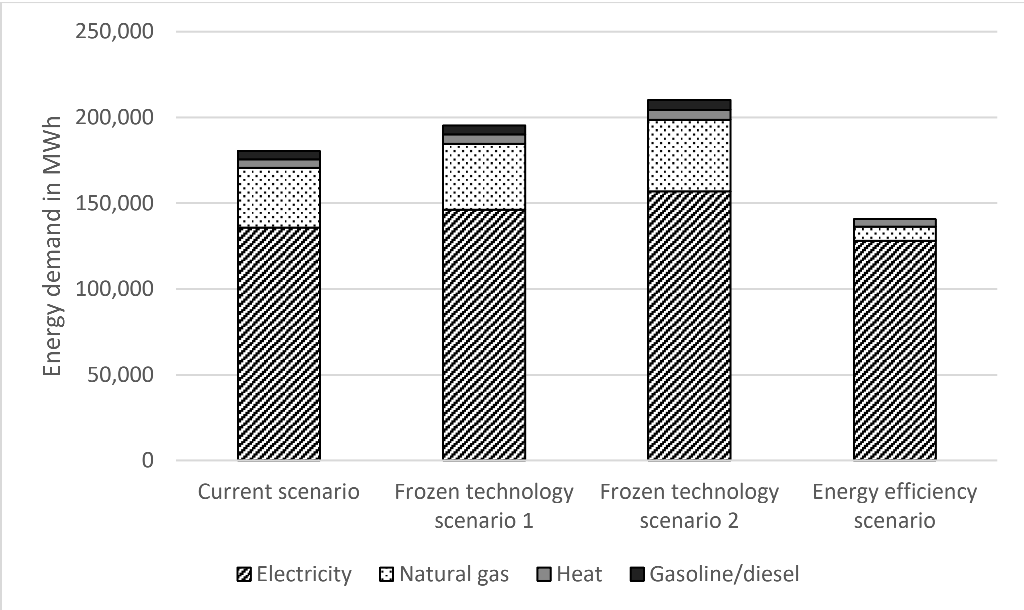

Figure 2: Comparison of energy demand sorted by energy carrier

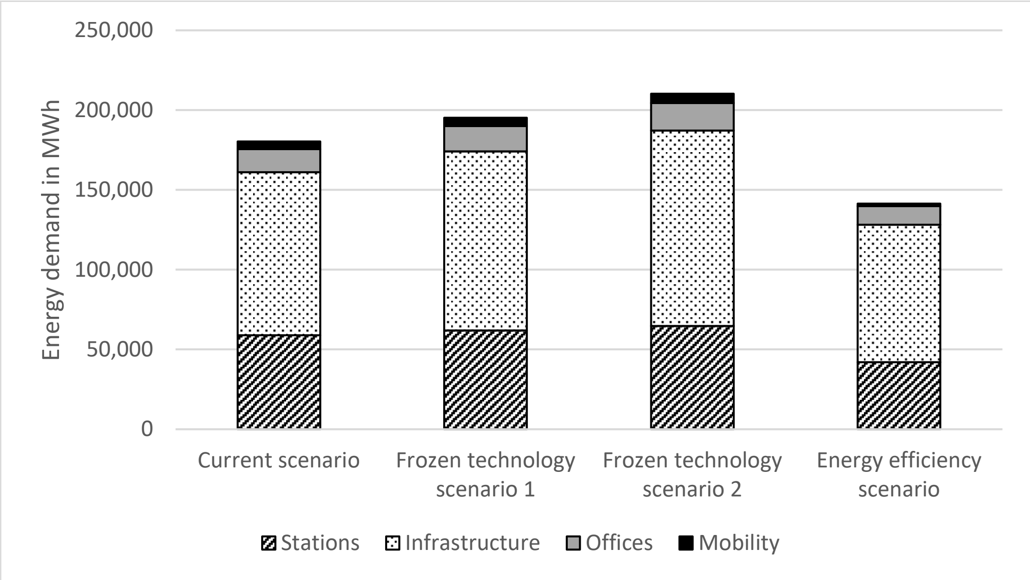

Figure 3: Comparison of energy demand sorted by demand category

Table 7, Table 8 & Table 9 below show the energy demand for each energy carrier and demand category separately for all three scenarios. A more detailed version of the energy demand for the scenarios is provided in Appendix II: Detailed energy demand scenarios. Some additional context on the results of the energy efficiency improvements of the energy efficiency scenario is given for the four demand categories.

Table 7: Frozen technology scenario 1

Category	Electricity	Natural gas	Heat	Gasoline/diesel	Total	Unit
Stations	57,097	4,179	588	0	61,864	MWh
Infrastructure	80,947	31,279	0	0	112,227	MWh
Offices	8,251	2,864	4,767	0	15,882	MWh
Mobility	0	0	0	5,330	5,330	MWh
Total	144,045	37,541	4,059	5,330	195,302	MWh

Table 8: Frozen technology scenario 2

Category	Electricity	Natural gas	Heat	Gasoline/diesel	Total	Unit
Stations	59,531	4,559	642	0	64,731	MWh
Infrastructure	88,306	34,123	0	0	122,429	MWh
Offices	9,002	3,124	5,200	0	17,326	MWh
Mobility	0	0	0	5,814	5,814	MWh
Total	156,839	41,806	5,848	5,814	210,300	MWh

Table 9: Energy efficiency scenario

Category	Electricity	Natural gas	Heat	Gasoline/diesel	Total	Unit
Stations	38,561	3,058	430	0	42,050	MWh

Infrastructure	83,469	3,471	0	0	86,047	MWh
Offices	6,039	1,746	3,928	0	11,712	MWh
Mobility	1,614	0	0	1,614	1,614	MWh
Total	128,069	8,275	4,358	0	141,423	MWh

Stations
Looking at this demand category, it can be seen that the measure of replacing all station lights with LED lights and the 30% energy efficiency percentage for other sources of demand, reduces the energy demand by 17 GWh (29%) in the energy efficient scenario compared to the current situation. 50% of this 17 GWh is reduced by the implementation of LED lights, which shows that this relatively simple measure is important to reduce energy consumption in this category. The natural gas and heat consumption is equal in both scenarios, as the measure for the energy efficient scenario is only affecting electricity consumption.

Infrastructure
The effect of the railroad turnouts measure is that the electricity demand in this category increases by 24 GWh, an increase of 621% compared to the current situation, whereas the natural gas usage is reduced significantly by 25 GWh (88%). In combination with the implementation of LED lights for the emplacements, the 30% energy reduction in the electricity use of sources within this category, and the increased train capacity of 15%, the electricity use increases by 9.9 GWh. As a result of the calculations for the energy savings for the VL-posts, it can be seen that the natural gas usage is reduced by 17% for this source of energy demand.

Offices
For this demand category, there is a 33% reduction in natural gas consumption due to the energy performance of the office buildings to label A+. The district heating demand reduction is, compared to the natural gas reduction, relatively less with 9.4%. This mainly has due to do with the Inktpot and Adm. Helfrich offices, as they already have energy label A+ and use heat from the district heating network in Utrecht instead of natural gas, which means that there is no reduction of heat consumption realized.

Mobility
For this last category, it immediately strikes out that the implementation of electrical cars reduces the energy consumption for this category by a large amount. With a 100% car park of electrical cars, there is an energy use of 1,614 MWh, which is a reduction of 64% and substantially lower compared to the 4,845 MWh of the current energy demand.

To conclude these observations for the energy efficiency scenario, with an estimated total decrease in the energy demand of 22% compared to the current energy demand, it potentially falls short to realise a reduction of 30% in 2030 compared to 2015.

In addition, to realise this 30% energy demand reduction, a 4% increase in energy demand due to increased train capacities is required instead of 15%. Even though the energy consumption increase due to an increased number of passengers is very uncertain in terms of magnitude, it seems realistic to assume that a 4% increase in energy demand due to an expected 30% increase in passengers is highly unlikely. As a result, to realise a 30% reduction in energy demand in 2030, even more radical energy efficiency improvements are necessary.

3. Phase II: Technical & techno-economic potential

3.1 Photovoltaic technology

Solar energy is one example of a renewable and sustainable source of energy. With its daily irradiance on the earth's surface, it has a large potential to supply us with free energy that could be used for all sorts of practices. With an average power density of 168 W/m^2, the theoretical power that could be extracted is about 21,940 TW on a global level (de Castro et al., 2013). This number could significantly contribute to supply enough electricity for the global population. Of course, there are many other limiting factors, technical as well as economic, social and political ones, that decrease this potential. Still, all countries realize that this large potential exists. As a result, the number of installed solar panels is growing each year, as shown in Figure 4 (IEA, 2022).

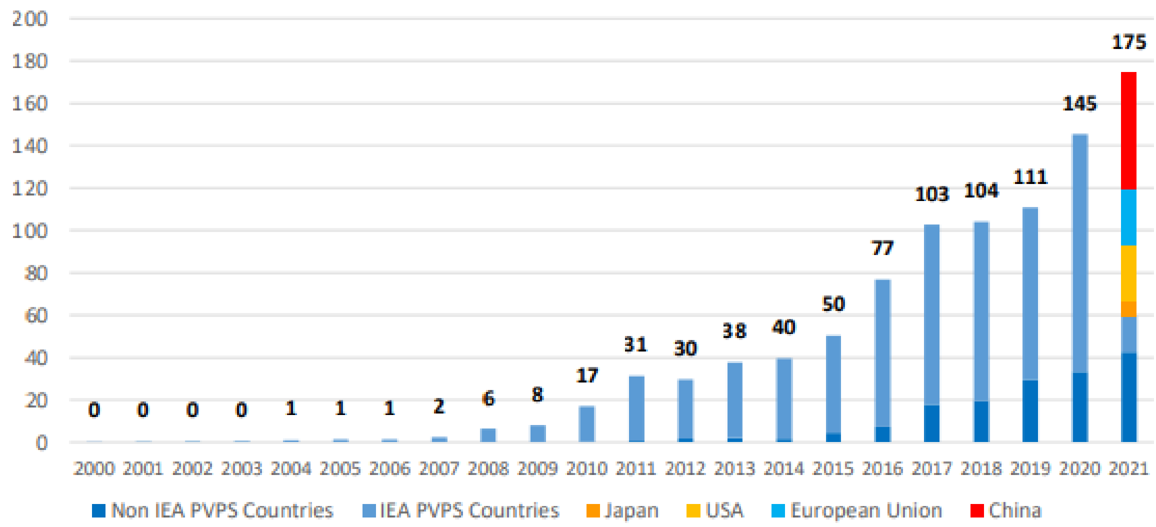

Figure 4: The yearly installed capacities in GWp of PV installations over time (IEA, 2022)

In order for ProRail to fulfil this technical potential as much as possible as well, it is crucial to use their available area to extract this energy and generate electricity. This research investigates this technical potential on the available surfaces and areas that ProRail possesses. With their assets, they could not only contribute to their own energy neutrality goal, but also to the global energy transition that is necessary to combat climate change.

3.1.1 Solar radiation & power

The solar radiation that reaches the surface of the earth is affected and influenced by many factors. The two factors with the largest influence are the location and time of the year. The sun is shining more in the summer in Spain than in the winter in Iceland, which means that more radiation is reached and could be used here. Next to these two factors, there are also many other effects from the atmosphere that influence the radiation. This includes clouds and pollution, but also general absorption, scattering and reflecting of radiation due to small particles in the atmosphere (Honsberg & Bowden, 2015).

These effects cause the radiation to take three different forms: direct, diffuse, and reflected radiation. Direct radiation is the radiation that directly reaches the earth's surface in a straight line. Diffuse radiation is caused by scattering processes, where radiation is scattered in the atmosphere causing the radiation to reach the earth from many different angles. Reflected radiation is sunlight that is reaching the earth by reflecting on several objects on the ground such as buildings and roads. This is also illustrated in Figure 5 below.

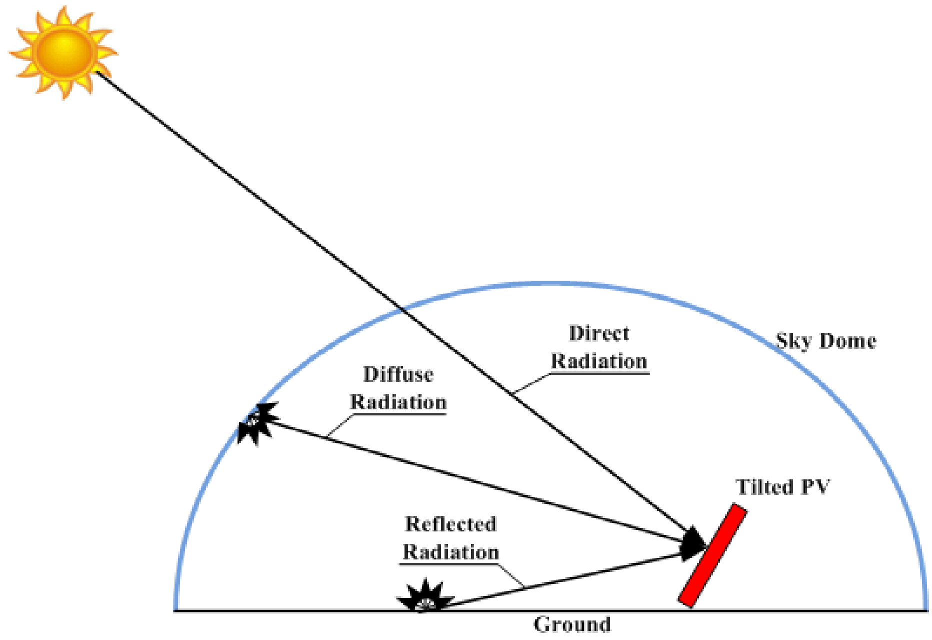

Figure 5: Direct, Diffuse and Reflected Radiation (Al-Shamma'a, 2013)

For PV panels, only direct and diffused radiation is important. Reflected radiation is usually difficult to capture and therefore mostly ignored. The total of the direct and diffuse radiation that reaches the earth's surface is referred to as Global Horizontal Irradiation (GHI), which is expressed in W/m^2 or Wh/m^2. This is also the indicator used in the calculations of the technical potential for this study. To convert this solar energy in the form of radiation into electricity, PV technology is used. This technology is optimized over the years by different companies and research institutions, causing different PV panels with different performances to co-exist. In order to compare them, they are tested under standard test conditions (STC). This takes the solar radiation, solar spectrum, and temperature into account, which is 1000W/m^2, 1.5 AM and 25 °C respectively. The power output under these conditions is referred to as watts peak (Wp). This value illustrates the standard performance that a panel can deliver in terms of output. For the output of the PV panel, the STC efficiency of the panel is also important. This value determines to what degree solar energy is converted into electricity output. The STC efficiency is different for each PV panel type.

However, in real-life, conditions are deviating from STC conditions, which means the actual output is lower or higher than the standard output. To calculate the power output of a PV panel, the following formula is identified and could be used (Umar & Wamuziri, 2016):

$$E = A * r * H * PR \tag{1}$$

Where

$E = Annual\ average\ power\ output\ PV\ panel\ [W]$
$A = Surface\ of\ PV\ panel\ [m^2]$
$r = STC\ efficiency\ of\ PV\ panel\ [\%]$
$H = Annual\ average\ solar\ irradiation\ based\ on\ orientation\ and\ tilt\ [\frac{W}{m^2}]$
$PR = Performance\ ratio\ based\ on\ de-rating\ factors\ and\ albedo$

The formula could be changed by using the solar irradiation in kWh/m^2, which means the energy output of the PV panel is calculated in kWh. The formula also shows that four types of factors play a role in the calculation of real-life PV panel output, which are dependent on the placement details of the PV panels. These are summed up and explained below:

1. Orientation (or Azimuth)
2. Tilt angle of the PV panel
3. Albedo (ground reflectance)
4. De-rating factors

Orientation is the direction in which the PV panels are faced. This direction determines how much irradiation is captured. The most optimal direction is South, as the most irradiation is captured in that case. However, other rooftops facing a bit more East or West do not have high reductions in electricity production and are still suited for the placement of PV panels.

The tilt angle of the PV panel is the second factor that strongly influences the electricity output. This optimum angle is determined by adding 15 degrees to your latitude during the winter and subtracting 15 degrees in summer. This means for a latitude of 52° in the Netherlands, this is 77° in the winter and 37° in the summer. However, it is estimated that the best tilt angle for the Netherlands is a bit lower at 34°, as this captures the yearly differences in the path and angle of the sun (Jacobsen & Jadhav, 2018). However, in practical terms, it is not wise to aim for the tilt angle of 34° in open fields or flat roofs. This is because, with a high tilt, there is a larger area of shadow, which means fewer rows of solar panels could be placed on the same area. As a result, PV panel installations on these surfaces often use a tilt of around 15°. A tool that combines both the tilt and orientation is the table of Hespul (IvoSolar, n.d.). This table summarizes all possible orientations and tilts and the accompanying performance loss factor. With this table, the specific performance loss factor of the PV panels with different orientations and tilts could be identified.

Thirdly, the ground reflectance or albedo is a factor that influences the output of the PV panel. This is the reflection of solar radiation from objects, reflected radiation, that bounces on the PV panel. Although this has a relatively small effect, it could positively influence the yield of the panel. Moreover, other de-rating factors influence the real-life performance of a PV panel. These could be environmental factors such as temperature, shading and dirt on the PV panels themselves. There are also technical factors, which are losses that occur due to the degradation of the PV panels over the years, inverter efficiencies and other technical losses in the system.

To take these factors into account, a de-rating factor is used in the estimation of PV panel output. For the Netherlands, common values for this de-rating factor that are used in similar recent studies are in the range of 80-84% (Tanesab et al., 2017; Idoko et al., 2018).

Finally, when the actual power output is estimated based on these discussed factors, energy in the form of electricity could be generated. The difference between the two is that power is the energy rate over time measured in Watts (W), whereas energy is the causation of motion or work and measured in Joules (J) or Watthours (Wh). To estimate the technical potential of PV on ProRail assets, it is important to estimate the energy production based on the calculated power output. As a result, it becomes known whether it is possible to cover the energy demand of ProRail in 2030. A common factor that is used to calculate this energy generation from power output is the capacity factor. This is defined by the EIA (n.d.) as "The ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period". In other words, the number of hours per year that the power output unit is operating at full capacity. This factor is usually expressed in a percentage or ratio. Each power generation technology has its own capacity factor based on fuel or weather characteristics. For solar energy, a capacity factor of 8% was estimated for the Netherlands in 2019 (IRENA, 2021a). However, this study did not use this capacity factor because the collected GHI irradiation data was in kWh/m^2. This means that the energy production could be calculated directly, and a capacity factor was not needed.

3.1.2 Technologies & ProRail applications

To capture the solar radiation and convert it into power, photovoltaic technology is required. PV technology has gone through decades of developments and energy efficiency improvements. The National Renewable Energy Laboratory (NREL) follows this development over the years and constructed a figure with the highest confirmed PV cell efficiencies of the different types. This is displayed in Figure 6 below.

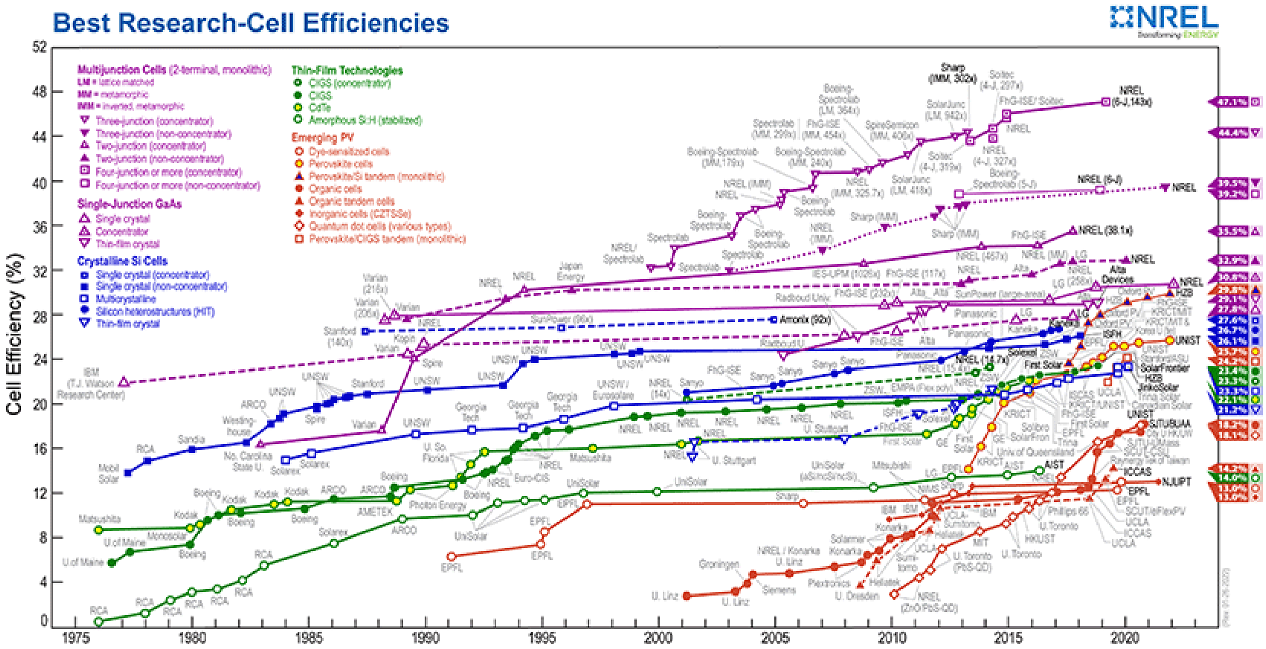

Figure 6: PV cell efficiencies per panel type for the period of 1975-2022 (NREL, 2022)

The different types of PV panels and technologies displayed in this figure could be classified into three generations (Zhang et al., 2018). These are described below, where also the applications for ProRail are discussed simultaneously.

First generation

The first generation PV panels are from crystalline silicon (c-Si), the purple and blue names and lines in Figure 6. This is the most dominant technology and is associated with the highest energy efficiencies. These panels are mostly constructed with monocrystalline silicon (m-Si) or polycrystalline silicon (p-Si) (Reddy et al., 2020). First generation panels are currently widely adopted on the rooftop of households or other buildings. This application is also referred to as Building Applied/Attached PV (BAPV). Another application that is also suitable for first generation panels is Building Integrated PV (BIPV), where solar panels are integrated into a building and form a wall, window or roof (Reddy et al., 2020). The BAPV application is most useful for ProRail located on the rooftop of buildings and open fields. However, it must be mentioned that BAPV is not possible on particular buildings, where the material is not strong enough to hold the weight of the first generation PV panels (J. Maltha, personal communication, 2022). This mostly applies to the train platform roofs. A different and lighter type of PV panel is therefore required to make use of these surfaces.

Second generation

The second generation of PV technology is known as thin films. The material of these panels is much lighter and more flexible, which means that a supporting construction is not necessary (Zhang et al., 2018). Thin-film technology often requires fewer materials and is more simple compared to the first generation panels.

However, their efficiencies are much lower, as shown by the green lines in Figure 6. The most common materials used in this generation are amorphous silicon, CdTe and CIGS (Reddy et al., 2020). As these thin films are lighter than first generation panels, they are perfectly suited for BIPV. This means that for ProRail, these thin films could be used for 'weak' rooftops, such as the station platform and bicycle storage roofs. This will enable ProRail to generate electricity from solar energy on these surfaces.

Third generation

The third generation of PV technology is all emerging technologies currently explored in laboratories and universities. These developments are focused on using new materials to increase the efficiencies of thin-film panels. As Figure 6 shows with the red/orange lines, they recently started developing these panels, which means they are not economically viable and useful in the short term. These panels are therefore not considered and used in this study.

3.1.3 Geographical information system (GIS)

To investigate the technical potential of renewable energy supply options, a geographic information system (GIS) is used. GIS is a system where a map with location data is integrated with other descriptive and location-driven data (Esri, n.d.-b). This tool is used in several fields such as emergency planning, resource management, and land allocation (Chang, 2016). For this study, information about all areas and buildings of ProRail could be easily accessed through this GIS software. The specific GIS program that was used is ArcGIS Pro version 2.9 (Esri, n.d.-a).

3.1.4 Technical analysis

The first part of phase II is focused on the computation of the technical potential of the PV installations. As the concept of "technical" could be interpreted in different ways, it is necessary to clarify the definition of this term and to determine the scope of this analysis. In literature, diverse types of potentials exist, mostly used for biomass and bioenergy (Dyjakon & Garcia-Galindo, 2019). However, these potentials are applied to other forms of renewable energy as well (Grassi et al., 2015). These potentials are generally classified as follows (Dyjakon & Garcia-Galindo, 2019):

- Theoretical potential: The maximum available amount of energy available within the physical limits.
- Technical potential: The fraction of the theoretical potential that is available taking the technical possibilities and boundaries into account.
- Economic potential: The share of the technical potential that has financial attractivity.
- Implementation potential: The share of the economic potential that could be implemented based on other factors, such as socio-economic factors or practical limitations. Sometimes an additional category is added, which tackles the relevant sustainability criteria that potentially decrease the available potential.

The technical potential analysis does focus on the definition of the 'technical potential' provided above. The study estimates to what extent the first and second generation panels with different technologies capture the theoretical available potential of solar energy on the surfaces. The economic potential is investigated in the techno-economic analysis, the second part of this phase. Finally, the implementation potential is not quantitatively estimated, but limiting factors based on the operating environment of ProRail are assessed in Phase III.

3.1.5 Techno-economic analysis

The second part of this phase is to compute the techno-economic potential of the PV installations at the collected available surfaces. A techno-economic analysis or assessment is commonly used to evaluate the economic feasibility of new products or services (UTC, 2022). Especially technologies in the chemical, bioprocess and energy industries are analysed with a techno-economic analysis. This analysis takes the costs, benefits, risks and timeframes of the technologies into consideration in several indicators. This study evaluates two indicators, the Net Present Value (NPV) and Levelized Cost of Electricity (LCOE). The NPV indicator shows the current value of all the expected cash flows in the future (Abdelhady, 2021). With a positive NPV, there is an attractive investment as these cash flows are positively related to the initial investment (Abdelhady, 2021). The NPV indicator is therefore a useful tool to analyse the economic viability of the investment of several locations for PV installations. The LCOE indicator calculates the present average costs of the generation of energy during the lifetime of the technology (Ouyang & Lin, 2014). This indicator is usually used to compare the different energy generation technologies to pinpoint the difference in costs (Ouyang & Lin, 2014). Estimating this indicator for PV electricity generation could therefore compare these costs with fossil-fuelled or other forms of renewable electricity generation.

3.2 Methodology Phase II

The research methodology of the second phase focused on the technical and techno-economical potential of the PV technology on ProRail assets. The technical potential is the electricity that could be produced on ProRail assets to meet their expected energy demand in 2030. The techno-economical potential estimates the economic viability of the PV installations.

3.2.1 Technical Potential

3.2.1.1 Data collection

Data was collected on PV panel characteristics for both the first and second generation panels. Part of this was collected through internal contacts and information from Movares and ProRail. The power output under STC conditions, STC efficiency of the panels, and the surfaces of the panels with and without additional constructions were retrieved from here. Additional information and input data were acquired through desk research. This was data on the de-rating loss factor, the ratio between PV panel area and roof/ground area for different types of surfaces, the table of Hespul with performance loss factors due to orientation and tilt, and formulas to calculate the electrical power output. In addition to this, geographical data was retrieved. This geographical data contained all the surfaces and areas available for the installation of PV panels. This was retrieved through the ArcGIS software. Maps and layers of ProRail were collected through online ArcGIS servers and could be accessed through the internship organisation (ProRail, 2022c; ProRail, 2022d). These servers provided several folders and services with information and data about ProRail assets. Within these folders and services, layers could be inserted into the map of the Netherlands on the ArcGIS software. This enabled a visualization of the data with all the surfaces for ProRail owned locations with rooftops and open fields. In addition, geographical solar radiation was retrieved from the Netherlands on a yearly basis. This was GHI data in kWh/m^2 from the Global Solar Atlas database in total annual values (Global Solar Atlas, n.d.).

3.2.1.2 Data analysis

With the collected ArcGIS servers, the geographical data on ProRail assets could be analysed. For this research, three specific map and feature servers were used. These are provided and discussed in Table 10 below.

Table 10: Used map & feature servers from ProRail ArcGIS database

Map & Feature Server	Usage
Cadastral (Kadastraal)	This server consisted of a property map (Eigendomskaart) that pinpoints which area is owned and managed by which stakeholder (ProRail, NS or other third parties). This layer was mostly used to identify the open fields owned by ProRail.
Engineering structures and buildings (Kunstwerken_gebouwen)	This server consisted of two maps with all buildings within and around the railway network (Bouwwerk: radius spoor & Gebouw: binnen station). These two maps identified all buildings with

	rooftops that could potentially be used for PV electricity production.
Transfer	This server contained one map that identified all different types of surfaces and structures within the train stations. The surface class part of this dataset that was relevant for this research is the platform roofs (perronoverkappingen), as potentially PV panels could be placed here.

As mentioned in Table 10, both the Transfer and Engineering structures and building server consisted of potential rooftops that could be used for PV installations and electricity production. In order to use one layer instead of two separate ones, the tool "Merge" was used in ArcGIS. This resulted in one layer with all buildings and platform roofs that could be used for the calculations. This means that the map "Bouwwerk: radius spoor" "Transfer" and "Gebouw: binnen station" were merged into one layer. It was made sure that all buildings with ProRail as the administrator (Beheerder) or as BGT source holder (BGT Bronhouder) was selected with the "Select by Attributes" function.

The retrieved GHI irradiation data, a map with yearly average GHI values, was inserted into the ArcGIS project. It must be noted that one important altercation to this data was necessary. The file contained raster data, which means that other tools needed for the calculations could not be used. As a result, the ArcGIS tool "Raster to Point" was used, where the data was converted to point features. After all this data preparation in the ArcGIS software, one final tool was used. To find the GHI values for each surface, the tool "Spatial Join" was applied. This tool joins attributes from one feature map to another based on their spatial relationship. This means that a new joined map feature was created for each surface and building with their original area in squared metres, but also the closest GHI point and accompanying value. As a result, all data could be retrieved and a dataset of all available surfaces from these three ArcGIS layers with their associated surface in m^2 and irradiance in kWh/m^2 was created. The total collected number of surfaces from the merged three layers was 1338 surfaces and was reduced to 691 suitable surfaces. Non-suitable surfaces were removed or decreased in size when the roofs were facing north, when roof(part)s were not suitable for PV installations due to roof characteristics, or the surfaces of the roofs were too small (<10 m^2).

To calculate the potential of PV on roof or open field surface *x*, the following formula was used, taking the tilt, orientation, ground reflectance, and other de-rating factors such as shading or dirt into consideration (based on Umar & Wamuziri, 2016):

$$E_{PV} = G_T * A_S * \eta_{nom} * P_{PV} * f_{PV} * f_s \qquad (2)$$

Where

$E_{PV} = electricity\ output\ PV\ surface\ x\ [kWh]$

$G_T = Total\ annual\ irradation\ for\ horizontal\ surface\ x\ [\frac{kWh}{m^2}]$

$A_s = Area\ of\ roof\ or\ open\ field\ surface\ x\ [m^2]$

$\eta_{nom} = nominal\ efficiency\ of\ PV\ panel\ including\ inverter\ efficiency$ [%]
$P_{PV} = performance\ loss\ factor\ based\ on\ orientation\ and\ tilt\ of\ surface\ x$ [%]
$f_{PV} = the\ PV\ derating\ factor$ [%]
$f_s = ratio\ of\ panel\ surface\ per\ roof\ or\ open\ field\ surface$ [%]

The total annual irradiation and area of all the surfaces were extracted from the ArcGIS project. By using the irradiation in kWh/m^2, it was possible to estimate the performance loss factor for each surface based on the orientation and tilt. The performance loss factor for each surface was estimated by going through the map of the Netherlands on ArcGIS and estimating the orientation of the rooftops. The tilt of each surface was estimated by looking up the location on Google Maps and a rough estimation of the angle of the surface was made. For open fields and flat roofs, a tilt value of 13° was used for BAPV applications, as this was applied by ProRail and Movares in previous case studies. As the retrieved GHI data is for surfaces with a tilt of 0°, the performance loss factor of each surface was calculated with help of the table of Hespul. This was done with the following formula:

$$P_{PV} = \frac{P_{PV,h}}{P_{PV,tilt=0}} \tag{3}$$

Where
$P_{PV} = final\ performance\ loss\ factor$
$P_{PV,h} = performance\ loss\ factor\ identified\ by\ table\ of\ Hespul\ for\ roof\ surface\ x$
$P_{PV,tilt=0} = performance\ loss\ factor\ for\ tilt = 0, which\ is\ a\ value\ of\ 0.87\ for\ all\ surfaces$

This method is much more accurate than using a general capacity factor in combination with irradiation in W/m^2. Moreover, the application of each surface, BAPV or film, was estimated based on the description in 3.1.2 Technologies & ProRail applications. This was relevant for the used nominal efficiency, but also for the ratio of the panel surface per roof surface in combination with the tilt of panels. The nominal efficiency of the BAPV panel is 19.3% and 10% for the film panel. Additionally, an inverter efficiency of 98% was assumed and multiplied by the nominal efficiency of each panel (Fraunhofer, 2022).

In addition, for the ratio of panel surface per roof/open field surface, different ratios were used for the different types of surfaces (van Hooff et al., 2021). The ratios for the different areas and BAPV and film applications are shown in Table 11 below.

Table 11: Ratio of PV panel surface area per roof or open field surface area (Van Hooff et al., 2021)

Surface	BAPV	Film
Normal tilted roof	1	1
Flat surface roof	0.5	1
Flat surface open field	0.65	n/a

Finally, a value of 82% was used for the derating factor, the mean value of the estimated range of 80-84% used or found in the mentioned studies (Tanesab et al., 2017; Idoko et al., 2018).
For open fields, the property map of the Cadastral server was used. This study only used the areas with full ownership of ProRail. These areas were selected with the "Select by Attributes" function. Within these areas, open fields were identified that could be used for PV panel installations. To find a total potential area that was suitable for PV installations of the railway network, samples were taken. Ten random parts of the railway network in the Netherlands with relatively similar lengths were thoroughly analysed and available surfaces were collected, with their accompanying coordinates. These surfaces were carefully selected by taking into consideration the accessibility of the railway track for e.g. maintenance work and the presence of nature in the open field. When the area contained large quantities of trees or bushes judged by the aerial photo of ArcGIS, the area was omitted. The following railway track parts were analysed and shown in Table 12.

Table 12: Ten samples of track parts of ProRail railway network for available open fields for PV installations

Track part	**Location**	**Total length (km)**
Track part I	Boxtel - Eindhoven Strijp	18.07
Track part II	Zevenbergen - Dordrecht Zuid	19.12
Track part III	Leeuwarden Camminghaburen - Buitenpost	21.33
Track part IV	Heerhugowaard - Hoorn	21.51
Track part V	Almelo - Oldenzaal	24.01
Track part VI	Barnveld Noord - Ede-Wageningen	18.56
Track part VII	Blerick - Swalmen	19.40
Track part VIII	Utrecht Overvecht - Bussum-Zuid	18.61
Track part IX	Voorschoten - Hillegrom	22.81
Track part X	Beilen - Meppel	34.01

The mean intensity in m^2/km was used and multiplied by the total length of the railway network, which is 7,052 km. This area was then inserted in the discussed formula (2). The average GHI for all building surfaces was used for the open fields, as it was assumed that this average GHI is also representative of areas close to the railway track. This also accounted for the average performance loss factor based on orientation and tilt. The ratio PV panel area/surface area for BAPV and open field from Table 11 was used, as well as the 19.3% BAPV panel efficiency and 98% inverter efficiency.

3.2.2 Techno-economic potential

3.2.2.1 Data collection

For the calculations of the techno-economic potential, quantitative data was collected. This data retrieval focused on the benefits and costs of PV technology. This consisted of investment, operation and maintenance, and other costs, but also economic benefits related to the generation of renewable energy. These benefits are dependent on the expected electricity price in 2030. All this data was retrieved from the literature, but also from internal sources of Movares. Similar case studies that were already executed, used estimated investment costs for the different capacities of PV installations and the two applications of BAPV and film panels. These values were therefore retrieved and also used in the analysis of the data.

3.2.2.2 Data analysis

To estimate the techno-economic potential of the implementation of PV technology, two techno-economic indicators were analysed. First of all, the indicator that was calculated for each location suitable for PV implementation is the Net Present Value (NPV). It must be noted that the estimation of this indicator was only executed for the surfaces of the building and platform roofs, and not for the open fields. This is because the size of the surfaces and their electricity generation values were not known for the open fields, as this potential was estimated with ten railway track samples. As a result, it was only possible to estimate this indicator for the building and platform roofs. The formula of the NPV that was used is as follows (Blok & Nieuwlaar, 2020):

$$NPV = -I + \frac{B - C}{\alpha} \tag{4}$$

$$\alpha = \frac{r}{1-(1+r)^{-L}} \tag{5}$$

Where

$I = investment$ [€]

$B = the\ benefits\ of\ the\ investment$ [€]

$C = the\ costs\ of\ the\ investment$ [€]

$\alpha = capital\ recovery\ factor$

$r = discount\ rate$

$L = lifetime\ of\ the\ project\ or\ decpreciation\ period$

The investment costs were retrieved from internal Movares sources and divided into two sources. First of all, the investment for the PV system was estimated for four different capacity size ranges for both PV applications. It was assumed that the costs of the system, inverters and necessary structural components are included in these values. This source of investment costs is therefore referred to as hardware investment costs. Table 13 below shows these estimated investment costs for the different sizes that were used for the data analysis.

Table 13: Investment costs for the PV systems of the two applications

Installed PV capacity (kW)	BAPV	Film	Unit
0-32	900	684	€/kW
32-100	700	532	€/kW
100-1000	650	494	€/kW
1000+	600	456	€/kW

In addition to the investment costs for the systems, there are investment costs for the connection of the PV systems with electricity lines to the grid. Although it is unclear whether this is an investment made by ProRail, it was still included to visualize the influence of these investment costs and the difference between a private and social perspective NPV. This investment is unique for each location, as these costs are dependent on the distance between the system and the closest transformation station. These distances are unknown for all collected surfaces in the technical potential calculations. As a result, the installation costs of the electricity lines, which consist of the actual cables and labour costs, are based on the capacity of each surface to compute more accurate estimations. The value used for the total costs of labour and electricity cables is assumed 401.8 €/kW (NREL, 2017). This number is used by the NREL study for a large range of capacities from 10 kW to 2 MW, where most of the collected ProRail surface capacities fall into. Despite an expected scaling effect for these costs, the same value is used for all surfaces based on this methodology of the NREL study.

For the benefits, a value of 115 €/MWh was assumed for the electricity price (Braat et al., 2021). Given the uncertainty for the electricity price, also with the current high energy prices, it was decided to perform a sensitivity analysis on this parameter. This is discussed in 5.2.1 Sensitivity analysis. Since there are no fuel costs for PV panels, the only included costs are yearly O&M costs for the panels. The value used for these costs was 18 €/kW and multiplied by the capacity of each surface (IRENA, 2021b). The used discount rate is 5%, a value used in other LCOE calculations for renewable energy by IRENA for OECD countries in 2020 (IRENA, 2021b). Finally, the lifetime of the PV panels was assumed to be 25 years and used in the calculations (Sodhi et al., 2022).

In addition, the second techno-economic indicator that was estimated is the LCOE. These LCOE estimations were focused on the overall PV electricity generation to compare it with other technologies, but also on specific locations to compare them individually. Similar to the NPV indicator, the LCOE was only calculated for the PV installations on building and platform roofs. The LCOE is calculated with and without the electricity cable investment costs to be able to compare them both with other technologies, as these costs are often not included in LCOE estimations. The formula of LCOE that was used is as follows (Blok & Nieuwlaar, 2020):

$$LCOE = \frac{\alpha * I + OM + F}{E} \tag{6}$$

Where
$\alpha = capital\ recovery\ factor$
$I = investment$ [€]
$OM = annual\ costs\ for\ operation\ and\ maintenance$ [€]
$F = annual\ fuel\ costs$ [€]
$E = \ annual\ electricity\ production$ [kWh]

For the calculation of the LCOE for PV, fuel costs are left out of the equation since this does not apply to this technology. It must be noted that this indicator is thus calculated for the year 2030 and assumes constant annual electricity production and operation & maintenance costs.

3.2.3 Case studies

In addition to the technical and techno-economic analysis for PV installations of all the collected locations, some additional case studies were investigated. These case studies are a few specific locations of ProRail assets that were analysed on a more detailed level. Differences in the technical and techno-economic results were investigated and the factors that cause these differences were explored. This shows how the results were actually calculated and also contributes to a better understanding of the estimated overall results. The selection of the cases was based on clearly noticeable differences in either the technical or techno-economic potential. The following locations were analysed and are discussed:

- Station Zoetermeer
- Station Almelo
- Station Alkmaar

3.3 Results Phase II

This section discusses the results of the second phase of this research. First of all, the results of the technical potential of PV implementation on ProRail assets are displayed. Secondly, the techno-economical potential results are shown on the two indicators mentioned in the methodology.

3.3.1 Results Technical potential

3.3.1.1 Buildings

Table 14 below shows a random sample taken from all the collected surfaces of roofs from buildings or platforms. The code of each rooftop, the location of the track part, GHI and area were retrieved from the ArcGIS data. The orientation, tilt and panel type were estimated based on the explained methodology and thus were manually included. Based on the estimated orientation and tilt, the Hespul factor was determined. This example table shows that this is greater than 1 for all surfaces. This is because the collected GHI irradiation data is for flat surfaces with a tilt of 0°. As a result, all surfaces with a more optimal tilt experience higher irradiation, which means a factor larger than 1 is applied in the calculations. This table is included in the results section to show what the collected dataset looked like and how it was used to calculate the overall technical potential of PV technology.

Table 14: Random sample of collected surfaces used in the technical potential calculations

Code	Track part location of surface	GHI (kWh/m2)	Area (m2)	Orientation (azimuth)	Tilt	Panel type	Hespul factor
6948	Ressen = Bemmel - Zevenaar	1047.17	76.41	170	13	BAPV	1.09
6950	Breda - Lage Zwaluwe	1052.29	65.76	150	13	BAPV	1.09
6952	Amersfoort Bokkeduinen	1021.97	128.19	230	25	BAPV	1.10
6953	Amersfoort Bokkeduinen	1021.24	13.71	150	30	BAPV	1.13
6954	Amersfoort	1021.60	42.67	190	13	BAPV	1.09
6956	Dordrecht	1055.21	77.75	210	13	BAPV	1.09
6962	Den Haag HS	1087.71	72.00	150	13	BAPV	1.09
6964	Den Haag HS	1087.71	133.32	150	13	BAPV	1.09
6967	Geldermalsen - Dordrecht	1059.96	38.23	180	13	BAPV	1.10
6971	Weesp Aansl. - Lelystad Industrieterrein	1058.49	26.66	110	13	BAPV	1.05
6972	Weesp Aansl. - Lelystad Industrieterrein	1057.03	67.67	150	13	BAPV	1.09
6974	Groningen	1004.07	172.59	260	13	BAPV	1.05
6975	Geldermalsen - Dordrecht	1059.59	60.71	170	13	BAPV	1.09
6976	Geldermalsen - Dordrecht	1060.69	15.85	160	13	BAPV	1.09

3.3.1.2 Open fields

Table 15 below shows the ten samples of the track parts that were analysed for the estimation of the technical potential of open fields owned by ProRail. The locations of these track parts show that the samples were taken from all over the Netherlands, increasing the reliability. The track parts were chosen between two train stations and it was aimed to choose tracks with relatively similar lengths. As Table 15 shows, the average length of the track parts is around 22 km, with only one small outlier of 34.01 km for track part X.

Additionally, the total areas for each track part show that there is a large deviation in terms of availability. Track part II has the largest available area with 40,577 m^2, whereas track part IX only has 1,355 m^2 available. In the final row of the table, the mean value of the intensity (available surface in m^2 per km of rails) of the ten samples is shown. This value was used to extrapolate this with the total length of rails in the Netherlands of 7,051 km to calculate the total available surface for PV implementation.

Table 15: Open field surfaces of the sampled ten track parts of ProRail

Track part	**Location**	**Total area (m^2)**	**Total length (km)**	**Intensity (m^2/km)**
Track part I	Boxtel - Eindhoven Strijp	27,544	18.07	1,524
Track part II	Zevenbergen - Dordrecht Zuid	40,577	19.12	2,122
Track part III	Leeuwarden Camminghaburen - Buitenpost	3,308	21.33	155.07
Track part IV	Heerhugowaard - Hoorn	29,098	21.51	1,353
Track part V	Almelo - Oldenzaal	10,717	24.01	446.35
Track part VI	Barnveld Noord - Ede-Wageningen	2,450	18.56	132.00
Track part VII	Blerick - Swalmen	4,216	19.4	217.29
Track part VIII	Utrecht Overvecht - Bussum-Zuid	2,022	18.61	108.63
Track part IX	Voorschoten - Hillegom	1,355	22.81	59.40
Track part X	Beilen - Meppel	3,495	34.01	102.76
Mean		13,476	21.74	622.08

3.3.1.3 Final results

Table 16 below shows the estimated technical potential of PV electricity production on an annual basis. The results are divided into results for the buildings, with BAPV and film applications, and open fields. It is clearly visible that the potential of the open fields is much larger than the technical potential of the roofs of buildings and platforms. For the buildings, it could be seen that the available surface and the electricity production are highest for the BAPV. However, with the large availability of platform roofs, and their large individual areas, films are also responsible for significant production of electricity of 9.41 GWh. The difference in electricity production in kWh/m^2 of both applications is therefore also not so large. Without the contribution of the open fields, ProRail is far to meet the energy demand of 2030 as discussed in Chapter 2. When only the PV on buildings is used, 26.4%, 19.1 % and 17.8% of the frozen technology 1, frozen technology 2 and energy efficiency scenario demand is met. The open fields are therefore crucial to increase the technical potential for PV implementation significantly.

Table 16: Estimated technical potential of solar electricity production

Surface	**Total PV panel surface (km^2)**	**Electricity production (GWh)**	**Electricity production (kWh/m^2)**
Buildings	0.34	37.47	97.93
1. BAPV	0.24	28.06	98.87
2. Film	0.10	9.41	92.25
Open fields	4.38	499.61	113.17
Total	4.71	536.96	105.49

3.3.2 Results Techno-economic potential

The overall results of the techno-economic analysis input values are shown in Table 17. The total results are also split up into the two different applications for ProRail to visualize the differences. To install PV panels on each selected surface, a total investment of 42 million euros is necessary. In return, almost 4.3 million euros in yearly benefits are received, with yearly O&M costs of almost three-quarters of one million euros. Table 18 shows the results of the two indicators, with two columns for the LCOE with and without cable and installation investment costs included. The overall NPV is positive, which confirms that the investment is financially attractive for all the surfaces combined. The LCOE for the films is 0.01 €/kWh lower compared to the total average LCOE of 0.11 €/kWh for both LCOE estimations. This is caused by the relatively higher investment costs per kW for BAPV panels as seen in Table 13. Although the electricity generation is higher for the BAPV panels, this does generally not compensate for the increase in investment costs. As a result, both LCOEs for the electricity of these panels are 0.02 €/kWh higher compared to the films. In addition, because films often occupy a relatively large area of platform roofs, hardware investment costs are also smaller as shown in Table 17. Moreover, the range of the LCOE estimations for both panels show that there is a large overlap. This indicates that even though the average LCOE is higher for BAPV, it does not mean all surfaces with BAPV have a higher LCOE value compared to film panels or the other way around. Individual factors are therefore important to estimate the financial attractivity for each surface. This is also shown in the case studies.

Table 17: Overall techno-economic potential input results for all selected building surfaces

	Hardware investment	Cable & installation investment	Benefits	O&M Costs	Capital recovery factor
Total	€ 25,865,051	€ 16,333,800	€ 4,295,983	€ 731,728	0.071
BAPV	€ 20,871,821	€ 12,290,474	€ 3,213,179	€ 550,594	0.071
Film	€ 4,993,229	€ 4,043,326	€ 1,082,804	€ 181,135	0.071

Table 18: Overall techno-economic potential results of the two indicators for all selected building surfaces

	Total NPV	Average and range of LCOE with cable investment costs (€/KWh)	Average and range of LCOE without cable investment costs (€/KWh)
Total	€ 8,035,557	0.11 (0.08-0.13)	0.08 (0.05-0.10)
BAPV	€ 4,364,038	0.12 (0.09-0.13)	0.09 (0.06-0.10)
Film	€ 3,671,519	0.10 (0.08-0.12)	0.07 (0.05-0.09)

In addition, to compare the costs of the generated electricity from PV installations on ProRail assets, Figure 7 below is constructed. This figure shows the range of LCOE with the lowest and highest calculated values of LCOE in the dataset. A distinction has been made by including the LCOE with and without cable installation costs. These costs are usually not included in the LCOE calculations, which means it is only fair to compare the LCOE without these costs with the LCOE of other technologies. The expected LCOEs of PV and other electricity generation technologies in 2030 estimated by Fraunhofer ISE are also shown in Figure 7. The calculated LCOE for PV by Fraunhofer ISE shows a lower range compared to the LCOE with cables and only a small overlap.

However, the LCOE without cables almost completely overlaps and is only slightly higher compared to the Fraunhofer range for PV. Compared to the other renewable energy technologies, the LCOE of bioenergy is higher, whereas the LCOE of onshore wind is comparable but also a bit lower, especially compared to the LCOE with the cable costs. For the fossil-fuel electricity generation options, the range of LCOE is quite similar to the Combined Cycle Gas Turbine (CCGT) and lignite/coal. Compared to the normal Gas Turbine (GT), the LCOE range with and without cable costs is significantly lower for all PV installations. It must be mentioned that the recent trends of large increases in gas and coal prices significantly alter the estimations of these LCOE values made in 2021. As a result, these estimations for 2030 may not be accurate and could turn out to be much higher. This means that the estimated ranges for both LCOEs of PV for ProRail are definitely lower compared to these fossil-fuel technologies.

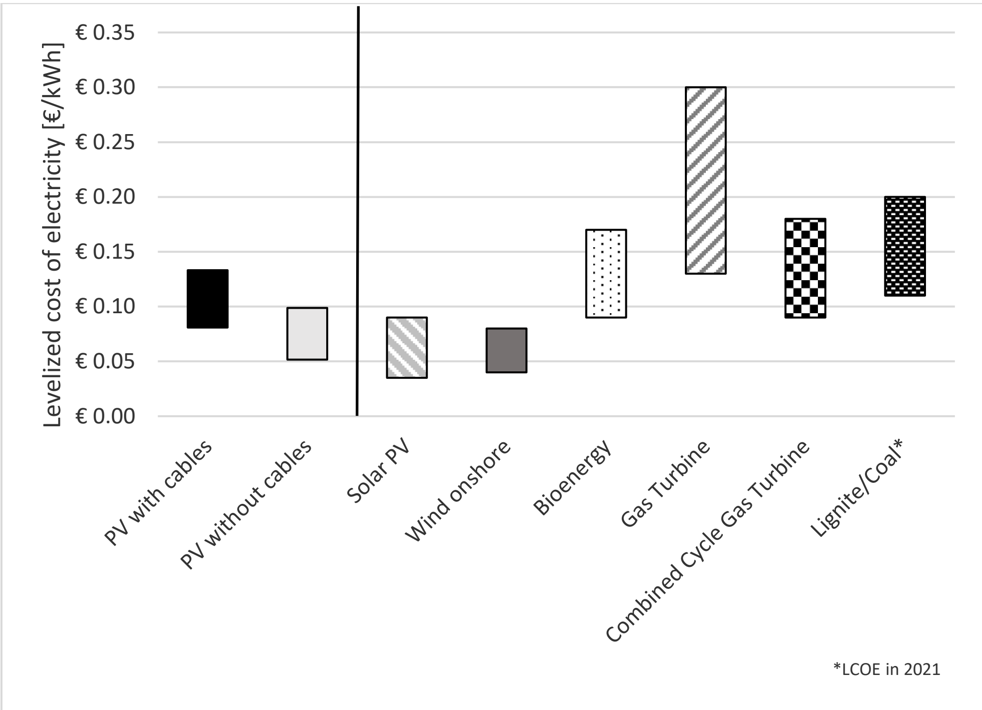

Figure 7: Calculated levelized cost of electricity of solar PV compared with other electricity generation technologies (based on Fraunhofer ISE, 2021)

An important note to the range of LCOE for PV, the high LCOE values are mostly found for surfaces with nonoptimal orientations or with relatively low areas. This means that for the large surfaces with optimal orientations, the LCOE is in the lower range and cheaper compared to fossil fuel options. Moreover, the LCOE values for these electricity generation technologies are also for large capacity sizes of Megawatts. The capacity sizes for the PV installations range from a few kW to a maximum of 1.3 MW. This means that the LCOE of these other technologies also has favourable scale advantages. Furthermore, the calculations of the Fraunhofer institute use a lifetime of 30 years for PV, which means the range of LCOE would be slightly higher and almost completely overlapping with both LCOE calculated values for ProRail PV.

3.3.3 Energy neutrality

Figure 8 visualizes the technical potential of PV for the buildings and open fields compared with the energy demand of the three constructed scenarios. This shows to what extent the energy neutrality goal could be reached solely with the implementation of PV energy. As can be seen, the technical potential of 37.47 GWh of the total buildings falls short and only produces 19.1%, 17.8% and 26.4% of the energy demand of the frozen technology 1, frozen technology 2 and energy efficiency scenarios, respectively. Fortunately, the potential for PV implementation in the open fields is much larger and could easily cover the energy demand on an annual basis. However, as will be explained in 4.3 Results Phase III, the practical usage of these open fields is difficult compared to the buildings. Although the potential for open fields is relatively high, several limitations could potentially decrease the technical potential and a smaller implementation potential is realized. The social and environmental adaptability of the panels, and also legal obstruction, which will be discussed in 4. Phase III: Implementation, are potential factors that determine the implementation potential of PV panels in these open fields. In addition to this, the result of the carried out sample analysis for the open fields and resulting extrapolation process could be perceived as uncertain, as a relatively small part of the railway track is analysed. As a result, the implementation potential for this surface type could be different and much lower or higher compared with the current value. In 5.2.1 Sensitivity analysis, a sensitivity analysis is carried out on the intensity value shown in Table 15 to visualize the impact on the technical potential of the open fields.

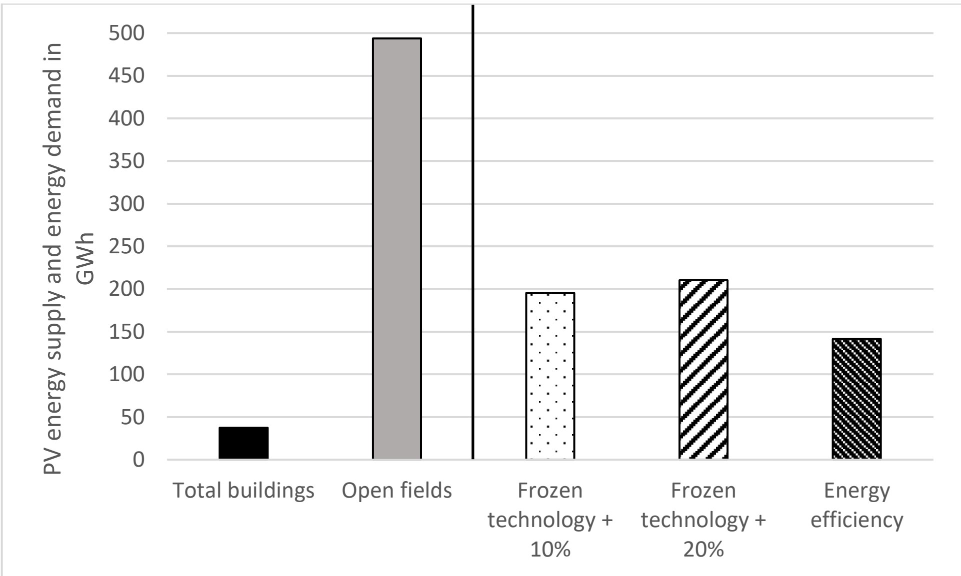

Figure 8: Potential of PV energy coverage of the constructed energy demand scenarios for 2030

3.3.4 Case studies

This final section shows some case studies of particular locations of the railway network in the Netherlands. These case studies act as examples to show how this analysis was executed and final results were calculated.

3.3.4.1 Station Zoetermeer

Figure 9 below shows the train station of Zoetermeer in the ArcGIS software. Both the "Bouwwerk & transfer" and "Gebouw" layer are visualized. The surfaces outlined with a blue line are selected based on the methodology process and are the only ones applicable for solar panels in this study. It is visible that four surfaces are outlined. However, the small building on the right of the train station was removed from the retrieved dataset, as the surface was deemed too small to install PV panels.

Figure 9: Aerial photo of Station Zoetermeer in ArcGIS with the inserted layers

Table 19 below shows the retrieved and inserted parameters, and the calculated electricity production in MWh and kWh/m^2. The orientation was estimated based on the compass and with their flat surfaces, a tilt of 13° was applied. For these rooftops, it was assumed that BAPV could be used, as they seemed strong enough to hold the weight of these panels from this aerial photo and additional Google pictures. With these surfaces relatively close to each other, the GHI, orientation, and Hespul factor as a result of the same tilt, are equal. Consequently, the calculated electricity production per m^2 based on these parameters is, therefore, the same for the three surfaces.

Table 19: Technical potential estimation of rooftops station Zoetermeer

Code	GHI (kWh/m^2)	Area (m^2)	Orientation (azimuth)	Tilt	Panel type	Hespul factor	Electricity production (MWh)	Electricity production (Kwh/m^2)
1724029	1067.63	237.01	190	13	BAPV	1.09	21.43	90.40

1724153	1067.99	728.06	190	13	BAPV	1.09	65.84	90.44
1724154	1067.63	221.57	190	13	BAPV	1.09	20.03	90.40

Table 20 below shows the techno-economic potential of the three rooftop surfaces of station Zoetermeer. It is visible that the surface with the largest surface on the left (1724153) has a positive NPV and the lowest LCOE of €0.10/kWh. Compared to the other two surfaces (1724029 & 1724154) with a negative NPV, it is only financially attractive to invest and install PV panels on this surface. The negative NPV for the two smaller surfaces is mainly caused by the hardware investment costs. These costs are only 2.5 times larger for the large surface (1724153) compared to the two smaller surfaces, whereas the electricity production is more than 3 times larger. As a result, the lower investment is more easily returned with also relatively higher benefits in the future.

Table 20: Techno-economic potential estimation of rooftops station Zoetermeer

Code	**Capacity (kW)**	**Hardware investment**	**Cable & installation investment**	**Benefits**	**O&M Costs**	**NPV**	**LCOE (€/kWh)**
1724029	22.98	€ 20,685	€ 9,235	€ 2,464	€ 414	-€ 1,021	€ 0.12
1724153	70.60	€ 49,420	€ 28,367	€ 7,572	€ 1,271	€ 11,020	€ 0.10
1724154	21.49	€ 19,337	€ 8,633	€ 2,304	€ 387	-€ 954	€ 0.12

3.3.4.2 Station Almelo

Figure 10 shows the train station of Almelo in the ArcGIS software and the eligible outlined surfaces. Three surfaces were included in the technical and techno-economic potential estimations. The small building right of the pink surface on the other side of the tracks was excluded as this surface was deemed too small for PV installations. In addition, on both sides of the large platform roof, a narrow extended roof was attached. However, these two surfaces were too narrow for PV panels, which means only the wide middle part of this roof was included (1724092). Based on the pictures of this large platform rooftop, it was assumed that the roof has enough carrying capacity for the heavier BAPV panels. The other two included surfaces are the green building at the top (1712808) and the pink surface below (1642385).

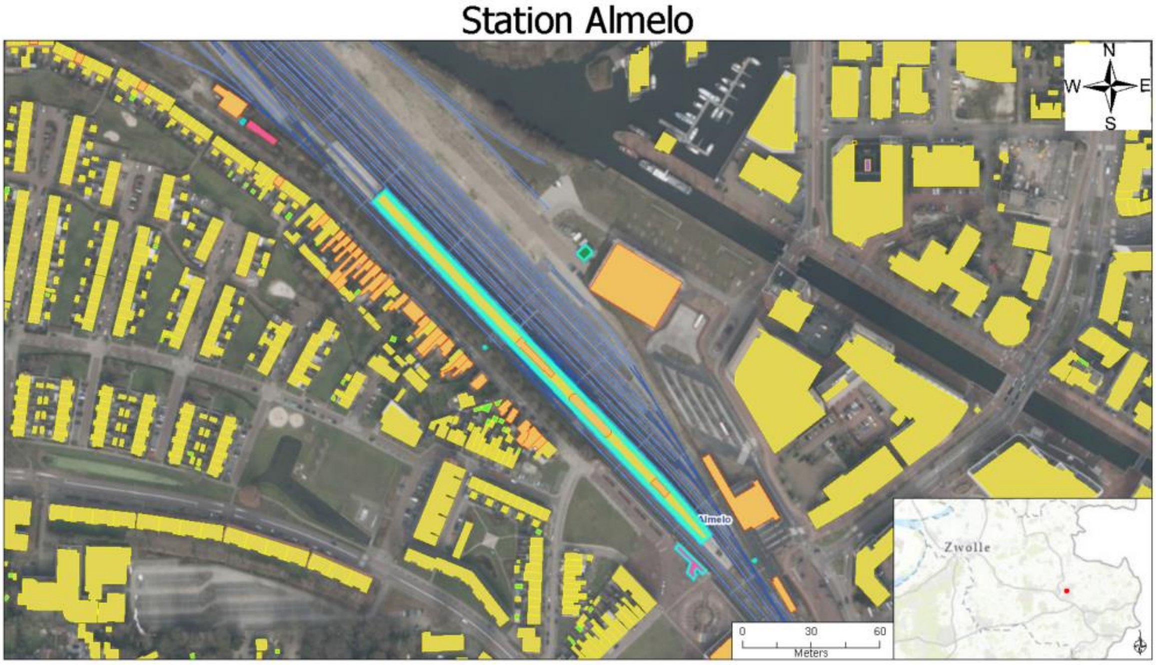

Figure 10: Aerial photo of Station Almelo in ArcGIS with the inserted layers

The technical potential of the three surfaces is shown in Table 21. The orientation, tilt and GHI irradiation are the same for all three surfaces. However, although the tilt is the same, the two surfaces of the smaller buildings are flat, whereas the large rooftop of the train platform is not and has a small tilt of 15 degrees. As a result, the PV panel/rooftop area ratio of 0.5, identified in Table 11, is used for these two surfaces. This results in a larger electricity production per m^2 for the large platform roof. In addition, it must be noted that the total area of the platform roof is 3,018 m^2 and was reduced to 1,418 m^2. This is because half of the roof is faced to the north and some small appliances are located here.

Table 21: Technical potential estimation of rooftops station Almelo

Code	GHI (kWh/m^2)	Area (m^2)	Orientation (azimuth)	Tilt	Panel type	Hespul factor	Electricity production (MWh)	Electricity production (kWh/m^2)
1724092	1028.91	1,418	220	15	BAPV	1.08	244.51	176.42
1712808	1028.91	67.62	220	13	BAPV	1.08	5.83	86.21
1642385	1028.91	76.80	220	13	BAPV	1.08	6.62	86.21

The estimation of the techno-economic potential for the surfaces is displayed in Table 22. The two smaller surfaces do not have a positive NPV and a higher LCOE compared to the large platform rooftop. The NPV for the larger pink surface (1642385) with more capacity and electricity generation, is lower. This is because the increase in investment costs for both the hardware and cables of this surface of €1,158 could not be covered over the technological lifetime of 25 years, as the additional benefits of €90 are too low.

The positive NPV of the platform roof is mainly caused by the scaling advantages of the investment costs for the large installations, due to a relatively lower increase in the hardware investment compared to the increase in production and benefits.

Table 22: Techno-economic potential estimation of rooftops station Almelo

Code	Capacity (kW)	Hardware investment	Cable & installation investment	Benefits	O&M Costs	NPV	LCOE (€/kWh)
1724092	275.03	€ 178,773	€ 110,509	€ 28,119	€ 4,950	€ 37,254	0.10
1712808	6.56	€ 5,902	€ 2,635	€ 670	€ 118	-€ 751.13	0.12
1642385	7.45	€ 6,703	€ 2,992	€ 761	€ 134	-€ 853.10	0.12

3.3.4.3 Station Alkmaar

The Alkmaar train station and its surroundings are depicted in Figure 11. Six surfaces were included in the potential estimations: the large purple building over the platform roofs, two platform roofs left and right of the purple surface, and the smaller purple surface at the top right. The narrow yellow surface just above the orange surface was removed from the dataset, as it was subject to a high degree of shading. The two most north yellow platform roofs (1724142 & 1724116) were assumed to not have enough carrying capacity for BAPV panels, and films were assumed instead.

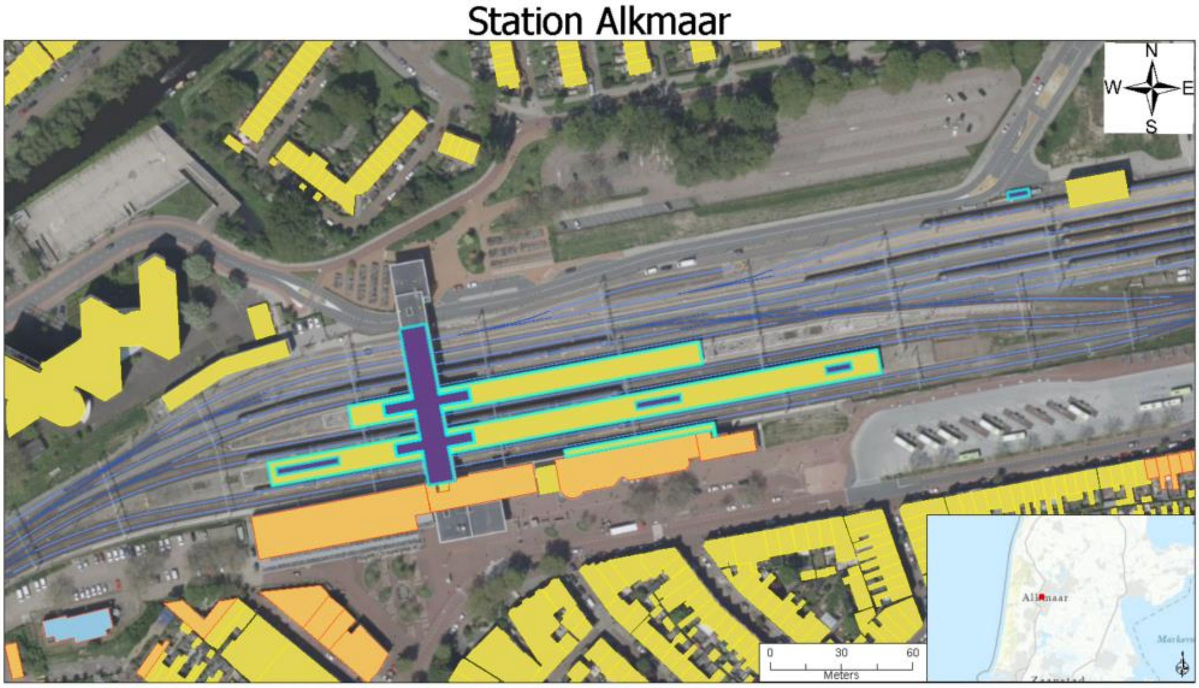

Figure 11: Aerial photo of Station Alkmaar in ArcGIS with the inserted layers

Table 23 shows the retrieved data and technical potential of the six selected surfaces. The areas of the four yellow platform roof surfaces were all reduced by just over 50%, as one side of the platform roof is facing north and some shading is experienced close to the purple building. The area of the purple building was also reduced by 130 m^2 due to the presence of some structural objects and windows. The two platform roofs at the bottom with BAPV panels have a much higher electricity production compared to the other two platform roofs with films.

Although the purple building has almost a similar size to the largest platform roof (1724119), the electricity production is almost 100 MWh lower. This is because this building has a less optimal orientation and a lower PV panel surface as this roof is flat. The panels on the purple surface are not able to be faced to the same orientation of 170° due to the placement of the structural objects and windows.

Table 23: Technical potential estimation of rooftops station Alkmaar

Code	**GHI (kWh/m²)**	**Area (m²)**	**Orientation (azimuth)**	**Tilt**	**Panel type**	**Hespul factor**	**Electricity production (MWh)**	**Electricity production (Kwh/m²)**
1724119	1079.31	928.87	170	30	BAPV	1.14	176.94	190.49
1724127	1079.31	300.10	170	30	BAPV	1.14	57.16	190.49
1724142	1079.31	438.69	170	30	Film	1.14	43.30	98.70
1724116	1079.31	93.82	170	30	Film	1.14	9.26	98.70
7207	1077.85	25.39	170	13	BAPV	1.09	2.40	94.58
7208	1079.31	860.02	250	13	BAPV	1.06	78.88	91.72

Furthermore, Table 24 contains the results of the techno-economic potential calculations for the six rooftops. All the calculated NPV values are positive, with the highest value for the 1724119 building, the largest platform roof. This also results in the lowest LCOE, together with the largest platform roof with film panels. The low LCOE for this roof with films is mainly caused by the relatively lower hardware investment costs. This also accounts for its relatively larger NPV, which is €4,321 more than the smaller platform roof with BAPV panels left from the purple building. In addition, an interesting observation is that, although the size of the rooftop of the purple building on the top right (7207) is relatively small, the NPV is still positive and an average LCOE is reached. This is caused by the south orientation of the surface, which results in a relatively large production of electricity.

Table 24: Techno-economic potential estimation of rooftops on Alkmaar

Code	**Capacity (kW)**	**Hardware investment**	**Cable & installation investment**	**Benefits**	**O&M Costs**	**NPV**	**LCOE (€/KWh)**
1724119	180.14	€ 117,094	€ 72,382	€ 20,348	€ 3,243	€ 51,601	€ 0.09
1724127	58.20	€ 40,740	€ 23,385	€ 6,574	€ 1,048	€ 13,761	€ 0.10
1724142	43.87	€ 23,338	€ 17,627	€ 4,979	€ 790	€ 18,082	€ 0.09
1724116	9.38	€ 6,567	€ 3,770	€ 1,065	€ 169	€ 2,291	€ 0.10
7207	2.54	€ 1,737	€ 1,020	€ 276	€ 46	€ 491	€ 0.10
7208	86.00	€ 45,753	€ 34,555	€ 9,071	€ 1,548	€ 25,722	€ 0.09

4. Phase III: Implementation

4.1 SWOT analysis

In the third sub-question of this research, the implementation of PV installations is investigated. A suitable tool to carry out this analysis is the strength, weakness, opportunity and threat (SWOT) analysis tool. The SWOT analysis is initially used to evaluate the organizational strategy and business opportunities in internal and external environments (Leigh, 2009). However, this tool could also be used to evaluate innovative measures and solutions that could potentially be valuable to the organisation, also specifically for renewable energy sources (Aydin, 2014). The first step is to identify all the relevant stakeholders included in both internal and external environments (Leigh, 2009). The second step is to identify the SWOTs (Leigh, 2009). The following definitions for these four factors are given by Capon and Disbury (2003):

1. Strength: an internal competence, valuable resource, or attribute that an organisation can use to exploit opportunities in the external environment
2. Weakness: an internal lack of a competence, resource, or attribute that an organisation requires to perform in the external environment
3. Opportunity: an external possibility that an organisation can pursue or exploit to gain benefit
4. Threat: an external factor that has the potential to reduce an organisation's performance

These definitions are constructed for general business strategies and are thus on an organizational level. However, as already mentioned, these strengths, weaknesses, opportunities and threats could also be identified for a RES technology, not for the whole organisation. Guangul & Chala (2019) identify and discuss a general SWOT analysis for solar energy as a renewable source. Table 25 summarizes the common strengths, weaknesses, opportunities and threats of this renewable form of energy.

Table 25: General SWOT analysis of solar energy (based on Guangul & Chala, 2019)

SWOT aspect	Description	Context
Strengths	Limitless	Solar energy is the largest source of unlimited free energy available that could be harvested.
	Less costly	Lower costs of electricity generation in the long run.
	Versatile	Different forms of utilization for industrial and residential purposes.
	Ease of usage	Solar panels could be installed on every surface under favourable conditions.
Weaknesses	Dependency on the sun	Solar power is only available in day-time and when the sun shines. This creates an interrupted form of power supply and additional backup systems are necessary.

	Inefficiency	The conversion efficiency is relatively low compared to other conversion systems.
	Required space	Lots of space is required to generate solar energy, which could be challenging for dense areas.
Opportunities	Business opportunities	This innovation could open up new business opportunities for large solar PV installations for all kinds of organisations.
	Subsidy and support availabilities	Incentives are available in most countries to stimulate and support the installation of PV panels.
	Cost reduction	The production of PV panels develops quickly and costs are largely reduced over the past decades.
Threats	Health risks	The disposal of solar panels could be damaging to the environment and humans due to the usage of hazardous components
	Carbon footprint	The production of PV panels is dependent on energy-intensive processes that cause CO_2 emissions
	Fossil fuel acquaintance	The current dependency on fossil fuels for several processes and technologies could form a barrier to solar energy usage

This table shows common SWOT aspects for solar energy in general. However, this does not consider any organizational context. The internal and external environment of organisations could significantly differ from each other. These structural, hierarchical, and cultural aspects are important for the implementation and realization of solar energy in the daily practices of the organisations, in addition to the general SWOT aspects. A SWOT analysis for solar energy in the internal and external environment tailored to ProRail is therefore necessary to be constructed to identify these aspects. The first step of the SWOT methodology is to identify all relevant stakeholders. Important for this is that both the internal and external environment of this organisation with relevant actors and partners that are involved in the implementation of solar energy are mentioned. The relevant external stakeholders for ProRail are mapped in Figure 12.

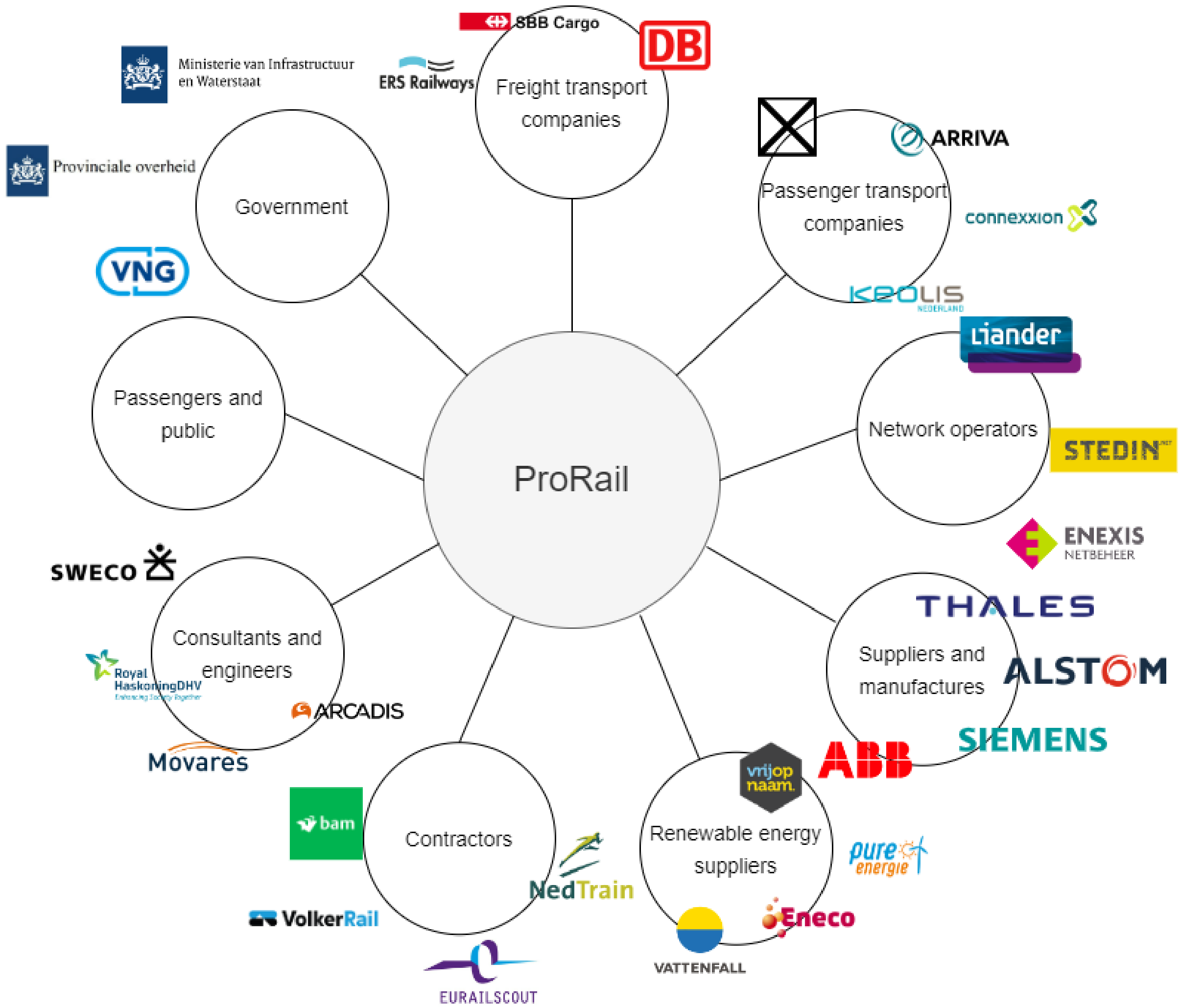

Figure 12: External environment of ProRail

As Figure 12 shows, many different actors are involved in the practices and supply chain of ProRail. The relationship between each actor and organization could potentially influence the implementation of solar energy on ProRail assets. This stakeholder visualization is therefore an important starting point for the investigation of SWOT analysis aspects that apply to the implementation of PV. The second step of the SWOT methodology is to identify the SWOTs within this environment. The methodology of this analysis is provided in the next section. After the methodology description, the results of the SWOT analysis are discussed.

4.2 Methodology Phase III

This section describes the methodology of the last phase of this research, which is the implementation of PV on ProRail assets. The chosen methodology for this is the SWOT analysis, as previously discussed. In addition to the general SWOT of solar energy, this methodology focuses on the creation of a SWOT analysis in the context of the internal and external ProRail environment.

4.2.1 Data collection

Qualitative data was collected during this phase by conducting semi-structured interviews. These interviews focused on retrieving qualitative data regarding strengths, weaknesses, opportunities, and threats for the implementation of PV technology. As the employees of ProRail and Movares are familiar with the internal and external environments of ProRail, they are capable to identify these four elements of the SWOT analysis in more detail. A list of the interviewees could be found in Appendix III: Conducted interviews. Moreover, additional desk research was executed that focussed on the general strengths, weaknesses, opportunities, and threats that appear with the implementation and investments of PV technology in an organisation. This desk research also collected articles and news about ProRail related to the PV technology topic. This provided additional information about the current implementation and usage of PV by ProRail.

4.2.2 Data analysis

As previously mentioned, the retrieved data was analysed through a SWOT analysis. The theory, elements and steps of this tool were followed accordingly. The strengths, weaknesses, opportunities, and threats were identified for the PV technology in the external and internal environment of ProRail. The SWOT aspects were identified individually by the researcher and not together with internal experts. However, this identification process was based on an analysis of the retrieved information from these experts. Some elements of the SWOT analysis are specific to the buildings or open fields, but this is mentioned in the description of the SWOT element it belongs to.

4.3 Results Phase III

Figure 13 below shows the SWOT analysis of PV technology implementation in the environmental context of ProRail. The content of the four SWOTs is written down in concise form to show the subject of each SWOT aspect. The individual strengths, weaknesses, opportunities and threats are explained in more detail below the figure.

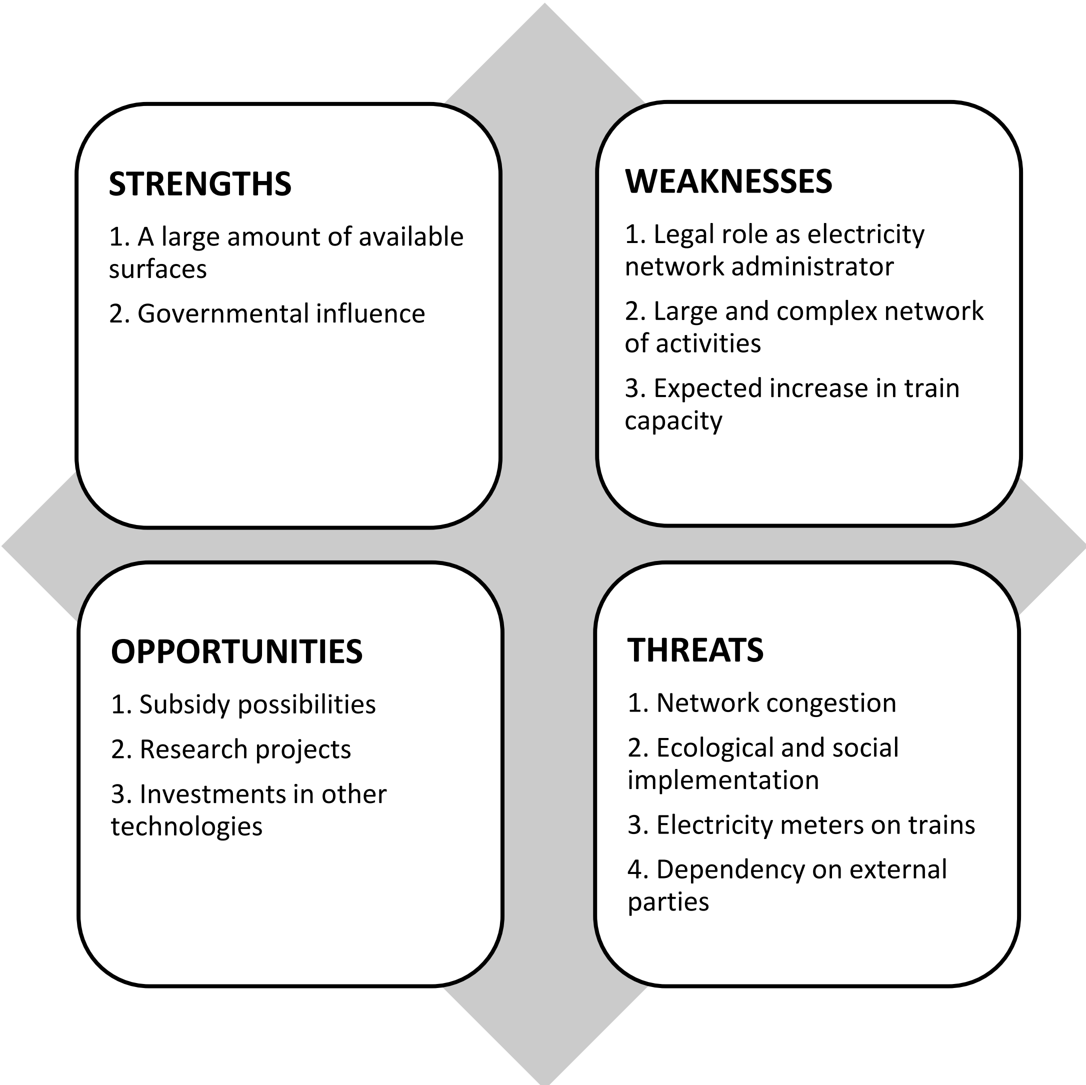

Figure 13: SWOT analysis of ProRail related to PV technology implementation

4.3.1 Strengths

1. **Large amount of available surfaces**

The first strength of ProRail regarding PV implementation is the large amount of available surfaces that they possess. This includes both buildings with rooftops, as well as open fields scattered around the whole country. The total available area of 34 hectares of rooftops found in phase II of this research supports this.

In addition, ProRail owns around 10,000 hectares of area in the Netherlands, where the technical potential investigation of Phase II showed that 438 hectares of this are available for PV panel installations. By owning these surfaces, ProRail is able to make decisions on them relatively quickly and speed up the installations of PV. It must be noted that there is a difference in the usage possibilities for ProRail between the building and open field surfaces. This is caused by the legal status of ProRail as an electricity network administrator. This is explained further in the first weakness point.

2. **Governmental influence**

Secondly, another strength for PV implementation is the governmental influence and support that ProRail has. As of the 1st of January 2021, ProRail is an independent administrative body (Dutch abbreviation: zbo). This means that they officially execute a governmental task, but they do not submit to the minister of Environment & Housing. However, the government is still responsible for the policies and the supervision of the executed work by ProRail. As a result, the government has some influence on the creation of the policies, also regarding the implementation of renewable energy in the form of PV panels. The support of the government could therefore realize supporting policies, funding or other measures that potentially speed up PV installations on ProRail assets. A recently started research project on PV panels on sound barriers is for example funded by the RVO, a governmental organization (ProRail, 2022f). This direct contact with the government could be perceived as a strength for ProRail.

4.3.2 Weaknesses

1. **Legal role as electricity network administrator**

The first weakness of ProRail in relation to PV implementation is the legal role of electricity network administrator. All the overhead lines that provide the electricity, also referred to as traction energy supply network (TEV), is an electricity grid that is owned and managed by ProRail. According to the law “independent net management (Dutch abbreviation: WON)”, network operators like ProRail are prohibited to perform any other activity other than managing the electricity and gas grid. As a result, ProRail is unable to generate electricity for any other organization but themselves. This means that generating electricity for railway transport operators like NS to supply the trains with electricity is not possible. This means that PV installations on open fields or buildings connected to this electricity grid are not able to be used by other organizations except ProRail. On the other hand, ProRail is able to rent out these surfaces to external renewable energy organizations or suppliers to install PV installations to obey this law. Unfortunately, this energy is not available to ProRail and the railway infrastructure but to others, as these installations are connected to the general electricity grid. In addition, this weakness limits ProRail to take action on their own. Fortunately, this legal role is not a problem for the PV installations close to railway stations, as these are not connected to their electricity grid with the overhead lines. This problem is therefore only applicable to the open fields and buildings far away from the stations close to the railway track.

2. Large and complex network of activities

Secondly, ProRail operates on a national basis with responsibilities for a lot of activities related to the railway network. On the one hand, this provides ProRail with a lot of available surfaces to install and use PV installations directly. This is also perceived as a strength, as discussed before. On the other hand, it means that electricity is needed in a huge geographical area and for different activities, appliances and technologies. Although the energy neutrality goal of 2030 is focused to become energy neutral on an annual basis, it does trouble the step of providing electricity with solar PV in the future on an hourly basis. With the activities spread out all over the country and with a lot of different hourly deviations in the electricity use of appliances, it means that PV panels must be nearby. This could be relevant in the future, as the energy transition strategy could focus on the decentralization of energy supply. This means that PV installations relatively close to the electricity consumption source are necessary. Furthermore, the large and complex area of operation does mean that a large internal team, but also a large number of different external partners, are necessary to realize PV installations in the different areas. For example, municipalities must be consulted and technical partners such as energy organizations that only operate in that particular area must be found.

3. Expected increase in train capacity

Finally, the last weakness is the expected increase in train capacity towards 2030. As already mentioned in 2.3.3 Frozen technology scenarios, the number of passengers is expected to increase by 30% in 2030 (ProRail, 2019). This development of people using public transport like trains instead of cars is much better for the environment, as it reduces CO_2 emissions. This switch is therefore in general preferred for environmental purposes. However, for ProRail, the expected increase in trains causes an increase in energy demand. The two frozen technology scenarios estimated a 10% and 20% increase in energy demand. This means that additional PV capacities are required to meet this energy demand in the future compared to the lower current energy demand. This makes it harder for ProRail to meet the energy neutrality goal and install enough PV panels in time. In addition, the increase in train capacity also potentially causes an expansion of the rails and the accompanying equipment and appliances. This also means that PV panels may be necessary at these new locations in the future to realize energy neutrality on an hourly basis.

4.3.3 Opportunities

1. Subsidies & research projects

The first opportunity for ProRail is the availability and usage of subsidies and research projects for PV installations. Recently, ProRail started a research project NEWRAIL with a subsidy from RVO to investigate the technical and financial potential of PV panels on sound walls (ProRail, 2022f). This is executed by a partnership with a graduate school in The Hague and TNO. These partnerships in the form of research projects together with additional financing could increase the PV energy potential and eventually the implementation. The extraction of new subsidies and research projects could be important, as it could substantially contribute to the implementation of PV energy in the future.

2. **Investments in other technologies**

Moreover, the second opportunity for ProRail is potential investments in other technologies related to solar PV technology. The expected increase of PV panels in the coming years for ProRail means that more renewable electricity is going to be used by ProRail (ProRail, 2022f). This means that for example storage technologies such as batteries are also more attractive and necessary. Attractivity increases as batteries are useful when simultaneously used with PV panels and excess electricity could be stored during daytime. The necessity increases because using batteries in combination with PV creates the opportunity to reach energy neutrality on an hourly basis instead of an annual one. This reduces the usage of fossil-fuelled electricity when the sun is not shining because less backup power is necessary to provide an assured baseload of electricity.

4.3.4 Threats

1. **Network congestion**

The first threat for the implementation of PV panels is grid network congestion. Electricity grid operators in the Netherlands report that grid congestion occurs in more areas in the Netherlands (Bellini, 2021). The capacity map of the electricity grid for new connected solar installations or other large renewable energy supply systems, show highly congested grids in most parts of the provinces Drenthe, Friesland, Overijssel, Flevoland, and some areas in Brabant, Limburg, Zeeland and Gelderland (Netbeheer Nederland, 2022). The national scale of this problem causes severe problems and potentially hinders PV implementation on ProRail assets throughout the whole country. This is especially problematic for the PV installations on buildings and platform roofs that are not connected to the ProRail TEV network with the overhead lines. Serious attention must be paid to the grid congestion problems at these suitable locations of PV.

2. **Ecological and social implementation**

Secondly, the implementation of PV has to consider other important factors. Ecological factors such as the preservation of biodiversity, increasing climate adaptation and generally improving natural areas are focus points that ProRail is aiming for (ProRail, n.d.-a). These factors may sometimes conflict with the interest of growing the number of PV installations for a renewable energy supply. The decision to use an area for nature or energy generation purposes is constantly considered. When it is decided to install PV panels, it must not hinder the ecological purpose of this area. In addition to the ecological factors, social factors may play a role in the PV implementation. The perception of the public in the form of passengers but also residents living close to the railway track may influence the PV implementation to some extent. As a result, there could be a growing concern that passengers dislike the view of PV panels next to the railway network when travelling and this travel experience is damaged when this implementation is not well managed. Because of this concern, a detailed manual is constructed with clear and strict instructions for the integration of PV panels at stations (ProRail, 2020). Although this manual provides clearance on the implementation of PV, it may also trouble and complicates it in the future when more installations are required to meet the energy neutrality goal.

3. Electricity meters on trains

The third threat is a general trend that is happening in the railway sector related to electricity use. The number of trains that contain an electricity meter that solely measures the electricity use of the train is increasing (S. ten Breeje, personal communication, 2022). As a result, the current structure and regulations regarding the purchase of electricity may change in the coming years. Currently, there are yearly contracts for the electricity of the overhead lines that include the electricity for all railway transport operators and ProRail. However, with an increasing number of train electricity meters, it is possible to measure the individual electricity use of the trains. As a result, railway transport operators like NS could purchase from their individually chosen electricity provider for the electricity use of their trains. This change in electricity contracts means that the electricity loss within the overhead line is for the energy bill of ProRail, which results in an energy demand increase of approximately 140 GWh per year (S. ten Breeje, personal communication, 2022). Consequently, more PV capacity is necessary to increase electricity production and meet this energy demand for the energy neutrality goal in 2030. On the other hand, this does mean that a much larger part of the total overhead line electricity is for ProRail. As a result, ProRail could independently install PV panels and generate electricity for their own energy demand instead of passenger companies and connect them to the TEV overhead line grid. Obviously, this is only possible when the electricity network administrator role does not prohibit ProRail to execute this. This indicates that specific changes for ProRail regarding these legislations are necessary.

4. Dependency on external parties

Finally, the last threat regarding the PV implementation for ProRail is the dependency on external energy organizations and suppliers for PV in open fields. As already mentioned in 4.3.2 Weaknesses ProRail is legally an electricity network administrator. This network entails the entire grid of the overhead line system for the trains. As a result, ProRail is unable to execute any other activity, such as generating electricity for other organizations that use this electricity grid. This entails that, especially for open fields, ProRail needs to rent out the area to external parties that use this area to generate electricity with PV installations. Recently, ProRail rented out almost 12.5 hectares to an energy company “Vrijopnaam” to install PV panels (ProRail, 2022g). Fortunately, stations are not connected to this grid, which enables ProRail to install PV on their roofs directly. However, this role as electricity administrator does limit the direct implementation of PV and increases dependency on others.

5. Discussion

5.1 Interpretation and implications

This study found results based on a scientific approach and methodology. It is important to interpret these results to pinpoint relevant implications to the existing theory and literature concerning this topic. This section discusses these implications for the three different phases of this research.

5.1.1 Phase I

The first phase of this research focused on the energy demand scenarios for ProRail in 2030. The retrieved values of the total energy demand for the two frozen technology scenarios showed that an increase due to an increase in passengers in 2030 is apparent. The energy efficiency scenario made clear that despite this train capacity increase, energy efficiency measures could significantly reduce the energy demand by almost 40 GWh compared to the current situation with a 180 GWh energy demand. With relatively easy measures such as the implementation of LED lighting for stations and emplacement locations and the usage of electrical cars, significant reductions are realized. In addition, the phase-out of natural gas for the usage of turnout heating, but also a reduction due to improved insulation and energy labels, reduces the total demand for natural gas by 76%. Simultaneously, the removal of natural gas eases the implementation and usage of PV electricity, as PV energy facilitates electricity usage and not natural gas. All in all, the results of phase I prove that energy efficiency is key to reducing the energy demand and facilitating the transition to energy neutrality in 2030 as just less PV energy is needed.

On the other hand, it must be noted that one important external factor influences the energy demand of ProRail in 2030. As already mentioned in 4.3.4 Threats, an increase in electricity meters within trains is expected, which means the actual electricity consumption for each train is measured and tracked. Compared to the current situation where the electricity use of ProRail and all passenger train companies are lumped together and bought from one energy supplier in the same contract, this is quite different (S. ten Breeje, personal communication, 2022). As a result, the passenger transport companies will now choose their own electricity supplier, and ProRail is responsible for the electricity losses that occur within the overhead line. This means that a substantial increase in electricity demand of 140 GWh is expected (S. ten Breeje, personal communication, 2022). This means that the energy demand increases to 335 GWh, 350 GWh, and 281 GWh for the frozen technology 1, frozen technology 2 and energy efficiency scenario, respectively. However, it must be noted that the demand increase of 140 GWh is with current voltages of 1.5 kW. These losses could be reduced by an increase in this voltage to 3 kW. Although this is just a structural and administration change, it does change the scope 1 and 2 energy use for ProRail and influences the achievement of energy neutrality goal ambitions in 2030.

Additionally, this also shows that the focus on the energy demand of ProRail has its limitations, and the scope of the whole railway network including the railway transport operators may be more appropriate. When this 140 GWh increase in energy demand does happen in 2030, the energy neutrality goal could still be reached with the estimated technical and techno-economic potentials, but the final implementation potential is not clear and could be reduced significantly. This is also shown in the sensitivity analysis for the technical potential of open fields in 5.2.1 Sensitivity analysis. Changing the narrative towards the whole railway network sector, including the energy use of the train companies, and adjusting the goals to this system could increase the accuracy and feasibility of these goals. The current energy neutrality goal of 2030 may not be reached, but when the scope is widened to the energy use of the trains and set to 2035 or 2040, it is more likely that the goal is achieved. Especially with the inclusion of all the railway network actors, the collaboration increases, and thoughtful agreements could be made and new goals focused on the sustainable energy transition could be set. This could be more beneficial and reduces the fragmentation of the railway sector regarding their actions related to sustainability issues. Simultaneously, this contributes to the bigger picture, as the complete railway infrastructure includes a much larger energy demand and is not bounded to the ProRail demand sources. However, the downsides of expanding the system boundaries could be increased complexities and the stakeholders feeling less ownership due to shared responsibility. It is therefore important that one organisation, which could be ProRail, is focused on the energy transition and delegate clear actions to the other railway network actors. It could also be beneficial to appoint a dedicated group or commission with the necessary hierarchical power to focus on the energy transition in the railway sector, which means that there is always clear ownership and a sense of responsibility.

5.1.2 Phase II

The results of the technical potential analysis indicated that the potential of the rooftops of buildings and platforms ProRail owns is 37 GWh and only covers 19.1%, 17.8% and 26.4% of the energy demand for the frozen technology 1, frozen technology 2 and energy efficiency scenarios, respectively. When the energy demand for these three scenarios increases with 140 GWh (see 5.1.1 Phase I), these percentages drop to 11.1%, 10.7% and 13.3%. This clearly shows that the technical potential of these surfaces alone is not sufficient to meet the energy demand on an annual basis to reach net energy neutrality. The open fields are therefore crucial to make sure enough PV installations are implemented to support this goal, as their estimated technical potential is 500 GWh. For dense railway networks such as the Netherlands, it is much more difficult to use these open fields for PV installations as the total available surface is just smaller and other interests or possessions from other parties could conflict more easily. Reaching energy neutrality for these railway networks with PV energy may therefore be perceived as more challenging, but not impossible with the available surface that is more than sufficient to meet the energy demand in this case.

In addition, there are also two other potential renewable sources of energy that could be deployed by ProRail to increase the feasibility of the energy neutrality goal, which are wind and biomass.

However, it was found during this research that these sources were hard to utilize. The implementation of wind is hard, as large horizontal axis turbines are difficult to integrate next to the rail infrastructure and civilization nearby. ProRail experienced that the opposition against these turbines is due to the caused noise and horizon pollution (G.O. Monnikhof, personal communication, 2022). ProRail also investigated the option to use vertical axis turbines, which are much smaller in size than the usual HAWT turbines. However, it turned out that it did not significantly contribute to the increase in energy supply (G.O. Monnikhof, personal communication, 2022). ProRail is therefore not committed to integrating these turbines. The same applies to the usage of biomass. In theory, biomass could be a viable option to be used to generate energy for ProRail activities. Only 50% of the owned 10,000 hectares contains railway tracks, the other half contains a lot of nature with trees and plants (ProRail, n.d.-a). Nature management, which is also one of ProRail activity categories, could potentially collect waste wood that could be used for energy generation purposes. However, the usage of biomass for this purpose is proven to be difficult due to several reasons. First of all, an external party has researched the usage of biomass for several purposes and concluded that using the biomass for bio-based materials was better (G.O. Monnikhof, personal communication, 2022). Secondly, the current nature management is focused on the ecological function to enhance biodiversity. This means that most waste wood is left behind to enhance this function. As a result, nature management has to change completely, with also additional required expenses and permits to collect the wood instead of leaving it (G.O. Monnikhof, personal communication, 2022). Thirdly, the stream of collected biomass is not constant over time and therefore difficult to monitor. It is therefore difficult to find third-party energy companies to deliver the biomass to and use it for energy generation purposes. As a result, it is uncertain to what extent these two forms of renewable energy could be deployed next to PV energy. This indicates the importance of PV energy and the necessity of exploiting the technical potential as much as possible to reach the 2030 goal.

The overall techno-economic potential results show a positive NPV for both the BAPV and film panels. Despite the lower output for the film panels, the total NPV is quite comparable with the NPV for BAPV, mainly caused by the lower investment costs and the relatively larger surfaces of platform roofs, where the films are applicable. This supports the implementation of second generation panels, which are thus not obstructed by financial aspects. Moreover, an interesting observation in the dataset, which is also shown by the case studies, is that the size of the surface does not necessarily determine the financial viability of the PV installation. Surface 7207 for the station of Alkmaar is only 25.4 m^2 but does have a positive NPV. This surface has the most optimal orientation and tilt, resulting in a positive NPV despite the relatively small available area. On the other hand, surfaces 1712808 and 1642385 do have larger areas of 67.6 and 76.8 m^2 but have negative NPVs. This is caused by their flat roof, with thus less area covered with PV panels, and a less optimal orientation and tilt. Orientation and tilt are therefore crucial parameters in the financial attractivity of the PV installations for the available surfaces.

The calculated average LCOE values for the BAPV surfaces are 0.02 €/kWh higher than for the surfaces with film panels. This shows that although the electricity production of the BAPV panels is higher, the costs per unit of electricity are higher and higher investments are needed. The comparison of the calculated LCOE with the other electricity generation options shown in Figure 7 visualizes a clear view of the compatibility of solar PV on ProRail assets. The fact that the LCOE for ProRail PV without the cables installation costs for sizes up to 1.3 MW is almost similar to the Solar PV LCOE of Fraunhofer ISE, shows that the results are comparable with other estimations for 2030. Additionally, the fact that the LCOE ranges of the fossil-fuelled electricity generation options are higher compared to the estimated LCOE of this study, means the implementation of PV is not only beneficial for the environment, but also for the reduction of costs. Especially with the high fossil fuel prices that have been rising recently. This result, therefore, proves that the implementation of PV must be rapidly diffused in the railway network to take advantage of this economic benefit next to the environmental one.

5.1.3 Phase III

The SWOT analysis of phase III uncovered important aspects for the implementation of PV in the context of ProRail and the Dutch railway network. The most important strength is the large availability of surfaces with ownership rights, which could be classified as crucial for the energy neutrality ambitions of railway networks in general. Furthermore, the large number of stakeholders operating in the external environment of ProRail causes significant opportunities, but also threats regarding the facilitation of PV installations. The availability of subsidies and research projects, which is mostly attracted through the governmental influence in ProRail, does provide important tools to investigate PV implementation possibilities and speed up the diffusion of the panels throughout the whole railway network. This could potentially discover new opportunities, such as the recently started tests of small PV panels between the rails in Germany shown in Figure 14 below (Seijlhouwer, 2022).

Figure 14: Tests of small PV panels in between the rails by Deutsche Bahn & Bankset Energy in Germany (Seijlhouwer, 2022)

On the other hand, the identified threats need to be dealt with accordingly. Especially the dependency on external parties for open fields, because of the legal role as a network administrator, troubles the diffusion of PV panels. The generated energy on these fields does technically contribute to the energy neutrality goal of 2030, as these fields are still assets of ProRail. However, to make sure the complete railway infrastructure including the power consumption of trains is using renewable energy in the near future, it is not favourable when the generated PV energy is not available for railway network activities. In addition, when a decentralized energy supply is necessary in the future, PV energy must be installed locally to provide renewable energy on an hourly basis. Therefore, it would be easier when the electricity network administrator role is not determinative and the focus is on the complete railway network, including the energy use of train companies. This simplifies the playing field for ProRail and smoothens the transition towards renewable PV energy, as fewer third parties have to be involved.

5.2 Limitations and future research

This research aimed to carry out a scientific analysis as detailed and complete as possible. However, there are still some limitations of this research that could be pinpointed. This section discusses some of these points. Based on these limitations, future research possibilities are suggested.

First of all, there was no access or availability of information regarding the energy usage of some sources of energy demand. A share of the energy demand for all four categories fell into the category of 'overig', which consisted of all the energy with smaller sources that were not mentioned or discussed in the retrieved data. In addition, information on the energy demand and energy efficiency improvements for escalators, elevators, tunnels, bridges and train security systems was not available for this research. As a result, specific energy improvement measures were not assessed or explored, because the data for this was missing. A literature review on this data came up with little and only general information and because of the boundaries and scope of ProRail that influence the energy demand and profile of these sources, this data was not accurate. Unfortunately, this resulted in fewer energy efficiency improvements included in the energy efficiency scenario and therefore a less accurate scenario for the year 2030. Further research on these sources of energy demand could therefore be beneficial to get insight into the specific energy efficiency improvements within the railway infrastructure. On the other hand, with the yearly 2% energy efficiency improvement that ProRail aims for, it was possible to estimate and visualize the energy demand for these sources.

Moreover, the second limitation of this study is the uncertainty about the increase in energy demand from the expected 30% increase in train passengers in 2030. For the two frozen technology scenarios, 10% and 20% were assumed, whereas 15% was used for the energy efficiency scenario. Although the 10% and 20% already provided some range for the potential energy demand increase, it is still unknown how this train capacity increase influences the energy demand in the near future and whether the estimated values are experienced in reality.

In addition, the 15% for the energy efficiency scenario is only one value, which makes the final energy demand of this scenario debatable. Without an energy demand increase from the increased number of passengers, 18 GWh (13%) is reduced to a final demand of 123 GWh. On the other hand, a 30% energy demand increase results in a total energy consumption of 155 GWh, a 9.9% increase. This shows that the final energy demand of this scenario is somewhere in this substantial 32 GWh range. Despite the estimation of 141 MWh energy demand for the energy efficiency scenario, a decline or incline within this range must be seriously taken into consideration.

Moreover, not all surfaces possessed by ProRail were included in the estimation of the technical potential of PV. The calculations used ProRail layers with buildings and open fields included in the ArcGIS software, but it became clear that these layers did not include all of them. First of all, sound barriers were not included as a surface, but solely with lines and points. This made the usage of these surfaces difficult as area values were not available. Manually measuring the surfaces of these sound barriers would be inefficient as also the height factor was missing. Fortunately, ProRail is investigating the possibility of using sound barriers for PV panels with the NEWRAIL project and could use the outcome of this research project to gain insight into the technical and techno-economic potential of these surfaces. In addition, some specific surface types were not included in every location. Bicycle storage roofs next to stations were only included in the layers for some locations, but most of them were omitted in the source data. It was unclear whether this was due to the incompleteness of the map or ProRail did not have full responsibility and ownership over these roofs. These missing surfaces could substantially increase the technical potential of PV panels on ProRail assets estimated by this study. In addition, future research must be executed for the techno-economic potential of open fields, which is not included in this study. This will gain insight into the economic viability of these open fields, and to what extent the estimated technical potential of this study is decreased by these economic factors.

Furthermore, it could be argued that the estimation of the tilt and panel type for each surface is a small limitation of this research. The estimation of tilt was based on an investigation of Google pictures, as hard data on the tilt of these surfaces was not available. In addition, the usage of the first generation or film panels was assessed by the visual appearance of the surface based on the aerial photo and Google pictures as well. No data was available on the strength of the roof and the weight/m^2 it could hold. As a result, it could be possible that some surfaces were not suitable for BAPV but for films, or the other way around. This means that the technical potential could potentially change due to the incorrect estimation of the available panel type. However, the research aimed to be a bit conservative, which means that when in serious doubt, the film application was chosen to not overestimate the potential.

5.2.1 Sensitivity analysis

In addition to the general limitations of the executed research, it is wise to carry out a sensitivity analysis for some particular input values to investigate the effects on the overall results.

This is in particular relevant for values with high uncertainty. These values could potentially decrease the reliability of the research, as the results are not reproduced by new studies or witnessed in real-life conditions in the future. For this study, a sensitivity analysis was carried out for the calculated intensity of available open field area per km rails and the electricity price for the techno-economic benefits estimations.

Figure 15 shows the sensitivity analysis of the intensity, the available surface in m^2 for each km of railway track. The range used for the analysis is from 50 to 2,122 m^2/km. This was based on the lowest intensity found for track part IX of 59.40 m^2/km and the highest intensity of 2,122 m^2/km found for track part II shown in Table 15. The graph visualizes a clear linear correlation between the intensity and the resulting total electricity production for the open field surfaces. The change in total electricity production is substantial, as there is an average increase of 0.8 GWh when only 1 m^2/km is added to the intensity value. Although this value of 0.8 GWh seems small, it is already 0.57% of the energy demand in the energy efficiency scenario. This shows the highly sensitive nature of the intensity value on the calculated electricity production. Taking this into consideration, it is not apparent that 500 GWh is the actual technical potential, as the ten investigated samples are only a small fraction of the railway network. The average intensity could therefore significantly be changed when the complete railway network is analysed. The question remains whether the average intensity could increase or decrease when the total railway network is investigated. Based on the collected samples in Table 15, it is clear that most track parts have a lower intensity compared to the mean value of 622.08 m^2/km. This average value is mainly found because of the three outliers with high intensities compared to the other seven track parts. As a result, the median intensity value is depicted in Figure 15. This shows a much lower value for the technical potential of open fields of 150 GWh, which is just enough to provide the energy demand of the energy efficiency scenario. In addition, given the dense nature of the railway network in the Netherlands, a decrease in the intensity is expected earlier, with a lower technical potential as a result. This is also supported by a top-down view of the technical potential. As already mentioned in 5.1.2 Phase II, 50% of the 10,000 hectares owned by ProRail is not containing any rails. Following our estimation of the average intensity value, 438 hectares are available for the open fields. This means that roughly 10% of the available area could be used for PV installations, which seems reasonable. Following these observations and the sensitivity analysis, it is most likely that the resulting electricity production on open fields is somewhere between the average and median value.

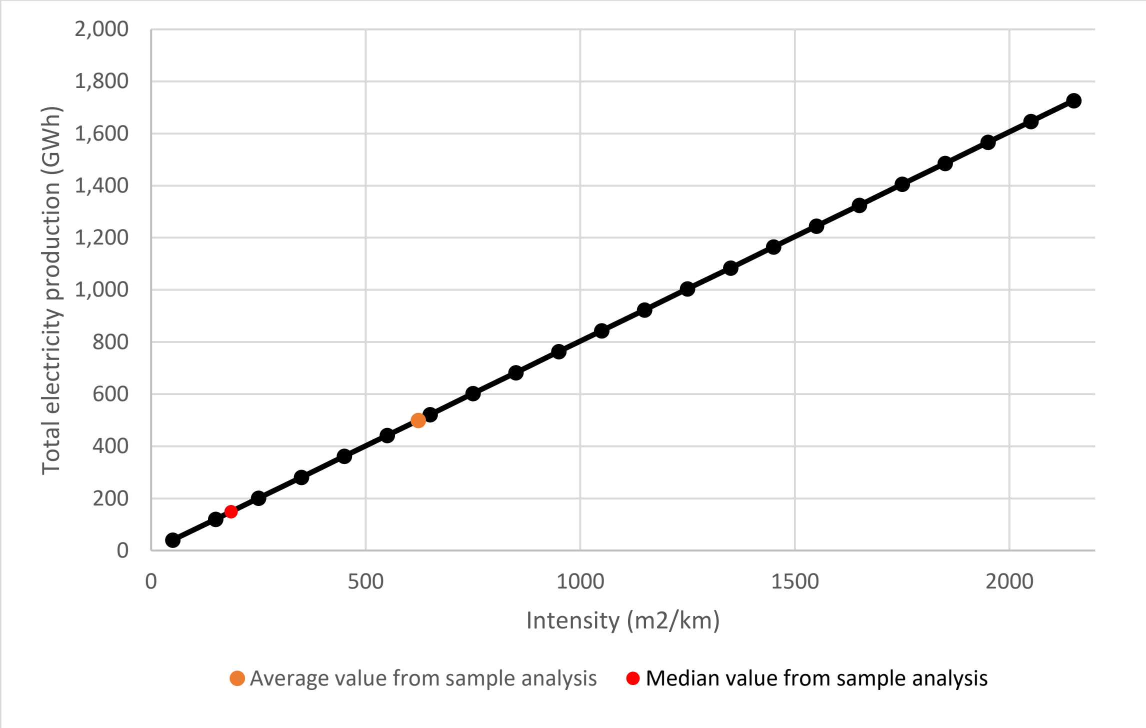

Figure 15: Sensitivity analysis of the intensity input value on the technical potential estimation of open fields

Figure 16 visualizes a sensitivity analysis of the electricity price on the total NPV value of all the collected surfaces. The range of the analysis is between the prices of 20 €/MWh and 540 €/MWh. The lowest value of 20 was chosen based on a report from the TU Delft focused on electricity prices of 2030 which estimated prices around this value (Afman et al., 2017). The price of 540 €/MWh as the highest value was chosen to visualize the current electricity prices and their effect on the NPV. The graph shows a linear relationship between the electricity price and the resulting NPV. An interesting result is the break-even point, an NPV of 0, which occurs with an electricity price of 100 €/MWh. Electricity prices below this value cause a total NPV to be negative. However, when the current electricity prices of around 500 €/MWh are still there in 2030, there is an extremely large increase in the NPV of the PV installations. Moreover, it must be mentioned that this is only the total NPV value and not for each location. Even though the total NPV is negative with an electricity price below 100 €/MWh, there are still locations that have positive NPVs. However, although it is currently not likely that the overall NPV turns negative for the locations in 2030 with these low electricity prices, the price must be closely monitored over time to visualize its impact on the benefits and NPV of the PV installations.

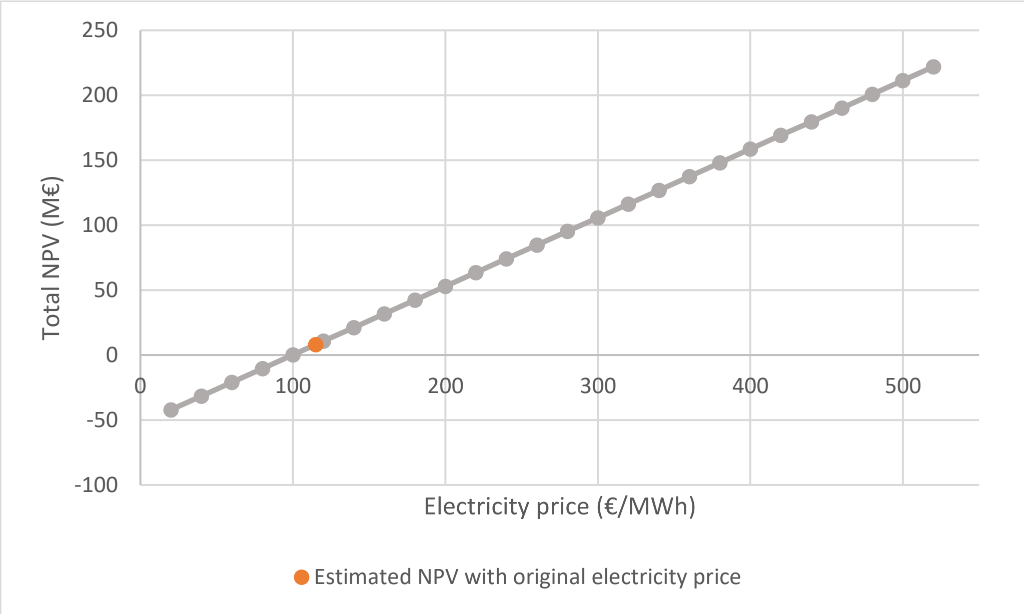

Figure 16: Sensitivity analysis of the electricity price on the total NPV of all selected locations for PV installations

In addition to the influence of the electricity price on the techno-economic potential of the locations, the costs of the PV panels potentially impact the two indicators. The learning curves of both first and second generation panels indicate cost reductions in previous years (Elshurafa et al., 2018). It is expected this trend continues for both panel generations and cost reductions of maximum 200 €/kW are realized (Chen et al., 2018). As a consequence, the NPV of the locations increases and becomes positive for more PV installations. Moreover, the LCOE decreases and its competitiveness against fossil fuel technologies improve. It is therefore also important to consider these cost reductions towards 2030 and beyond to monitor the NPV and LCOE values for the potential locations for PV panels.

6. Conclusion

To combat the endangering problems of climate change, an energy transition towards renewable energy usage and emission reductions are necessary. To realise this, Corporate Environmental Responsibility and organisations acknowledging their environmental impacts is becoming more crucial. Fortunately, ProRail has taken this responsibility and set an energy neutrality goal in 2030 on an annual basis. To realise this goal, energy generation from renewable sources within the Dutch railway network is necessary. Currently, scientific research on the Dutch railway network regarding the renewable energy topic is missing and the potential of PV along the railway infrastructure is not estimated with scientific methods. As a result, this study has aimed to answer the following research question: "What is the potential of solar photovoltaics technology that could be deployed by ProRail to reach net energy neutrality by 2030 and how could this be implemented within the owned infrastructure of ProRail?".

To investigate the requisite potential of PV energy supply, three different scenarios were created to estimate the energy demand in 2030. Whereas the two frozen technology scenarios warn for increases in the energy demand of 15 and 30 GWh compared to the current situation, the energy efficiency scenario showed that an energy demand reduction of 39 GWh could be realised. However, despite the decrease in energy consumption, a 30% reduction of the energy consumption as a result of the yearly 2% energy efficiency improvement is not met, and additional energy efficiency measures are necessary.

Following the energy demand scenarios, the technical and techno-economic potential of locations for PV installations throughout the whole railway network was analysed. The ArcGIS software was used to retrieve the available surfaces and the required parameters for the calculations. The results showed that the technical potential of rooftops of buildings and platforms is too small to meet the energy demand in 2030, as these roofs could only provide 26.4%. On the other hand, the open fields have a technical potential of 500 GWh, which is more than enough to cover the energy demand of the scenarios. However, the performed sensitivity analysis and the dense nature of the Dutch railway network unveiled that this potential could be significantly reduced. As a result of these observations, the energy demand could likely be covered completely, and between 0 and a maximum of 359 GWh is available for the energy consumption of trains depending on the energy demand of the 2030 scenarios.

The techno-economic results of the building and platform surfaces showed an overall positive NPV. The range of identified LCOE values corresponds to general estimations of LCOE for solar PV in 2030, especially for the estimated LCOEs without cable installation costs included. Compared to the fossil-fuel options, the LCOE was cheaper, even including the cable installation costs, which proved that the implementation of PV also brings financial benefits.

The implementation of PV within the infrastructure of ProRail was investigated by performing a SWOT analysis. This analysis was based on semi-structured interviews and a small desk research. The main results identified that subsidies and research projects could be used by ProRail as an organisation with close governmental bonds, especially as their assets provide a large number of available surfaces for PV implementation. On the other hand, their dependency on external organisations for open field PV installations due to their role as an electricity network administrator, and the ecological and social limiting factors, may hinder the fast implementation process. In addition, the risk of a substantial increase in the energy demand due to more train electricity meters troubles the feasibility of energy neutrality in 2030. Meanwhile, this expected development could incentivize and be perceived as an opportunity to reduce energy losses in the cables by increasing voltages. In return, energy demand is reduced and energy neutrality could be reached more easily.

6.1 Recommendations

Based on the outcomes of this study, several recommendations are constructed. These could be used as focus points by ProRail, policymakers or other stakeholders involved to make sure the energy neutrality goal in 2030 is realised with the help of PV implementation.

It is suggested to focus on additional energy efficiency improvements to reduce the energy consumption of ProRail. The scenario creation showed that with the proposed energy efficiency improvements, the assumed 2% yearly energy efficiency improvements, and increased train capacities, a 30% energy reduction for 2030 compared to the 2015 situation is not met. It is therefore of crucial importance that additional energy efficiency measures for other energy sources are investigated and executed.

Furthermore, a detailed analysis of the technical and techno-economic potential of the open fields is needed. The performed sensitivity analysis on the intensity value found by the sample analysis showed that the technical potential estimation could change severely. With a techno-economic analysis also missing for these surfaces, it is crucial to investigate both these potentials to get insight into the actual potential of open fields and to what extent the energy demand could be covered by PV on all assets.

Moreover, it is recommended to start implementing PV installations on most locations as soon as possible. As the techno-potential analysis indicated, the range of LCOE estimations for the roof surfaces is lower than all the fossil-fuel technologies to generate electricity. As a result, it is financially attractive to invest in these installations, besides the well-known environmental benefits. It would be wise to monitor the electricity price and hardware investment costs, as it was shown and discussed that both have a significant influence on the NPV and LCOE values of the suitable locations for PV rooftops.

Finally, policymakers must consider facilitating PV implementation in different ways. The legal role of ProRail as electricity network administrator troubles the usage of open fields for the implementation of PV, as third-party energy organisations are needed to hire these fields and invest in these installations. As this generated electricity is also used by others instead of ProRail, decentralized renewable energy supply to facilitate energy neutrality on an hourly basis comes at a risk, as less electricity is available for the railway infrastructure. Being able to omit this legal obstruction so ProRail could generate electricity for the overhead line electricity is beneficial for ProRail to speed up and simplify the implementation process of PV. Permitted cooperation with NS as the largest railway transport operator could for example be a different way to run interference for this problem faced by the railway infrastructure.

7. References

Aardenburg, C., & Drok, W. (2021, September). Rapport Dominantieanalyse ProRail 2021. Retrieved from https://www.prorail.nl/siteassets/homepage/toekomst/duurzaamheid/documenten/dominantie-analyse-2021---bh8722-rapport-dominantieanalyse-scope-3-co2-emissies-eindversie.pdf

Abdelhady, S. (2021). Performance and cost evaluation of solar dish power plant: sensitivity analysis of levelized cost of electricity (LCOE) and net present value (NPV). Renewable Energy, 168, 332–342. https://doi.org/10.1016/j.renene.2020.12.074

Afman, M., Hers, S., & Scholten, T. (2017, January). Energy and electricity price scenarios 2020–2023-2030. CE Delft. https://cedelft.eu/wp-content/uploads/sites/2/2021/04/CE_Delft_3H58_Energy_and_electricity_price_scenarios_DEF.pdf

Al-Shamma'a, A. A. A. (2013). *ANALYSIS AND SIMULATION OF HYBRID RENEWABLE POWER SYSTEMS FOR RURAL ELECTRIFICATION IN KSA* (Doctoral dissertation, Faculty of Engineering Electrical Engineering Department

Asensio, F. J., San Martín, J. I., Zamora, I., Onederra, O., Saldaña, G., & Eguía, P. (2018, October). A system approach to harnessing wind energy in a railway infrastructure. In IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society (pp. 1646-1651).

Aydin, B. (2014, March). SWOT analysis of renewable energy. In *2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE)* (pp. 1-7). IEEE

Bellini, E. (2021, December 14). Netherlands updates grid congestion map. Pv Magazine International. Retrieved June 25, 2022, from https://www.pv-magazine.com/2021/12/14/netherlands-updates-grid-congestion-map/

Blok, K., & Nieuwlaar, E. (2020). Introduction to energy analysis. Routledge. Chapter 11

Bouwmeester, A., Morren, P., Monnikhof, G. O., & Diks, J. (2018, March). Zaaien om te oogsten Inspiratiebijeenkomst duurzaamheid. Retrieved from https://www.railcenter.nl/wp-content/uploads/2018/04/InnoRail-DZH-Ans-Bouwmeester-Patrick-Morren-Gerald-Olde-Monnikhof-en-Jeff-Diks.pdf

Braat, M., Tsafarakis, O., Lampropoulos, I., Besseling, J., & van Sark, W. G. J. H. M. (2021). Cost-Effective Increase of Photovoltaic Electricity Feed-In on Congested Transmission Lines: A Case Study of The Netherlands. Energies, 14(10), 2868. https://doi.org/10.3390/en14102868

Capon, C., and Disbury, A. (2003). Understanding organisational context: Inside and outside organisations. London: Financial Times/Prentice-Hall

CBS, Hoebergen, A., van Polen, S., & van Middelkoop, M. (2021, February 19). Lagere energierekening, effecten van lagere prijzen en energiebesparing. Retrieved March 30, 2022, from https://www.cbs.nl/nl-nl/longread/rapportages/2021/lagere-energierekening-effecten-van-lagere-prijzen-en-energiebesparing?onepage=true#c-2--Daling-gemiddelde-energierekening-door-lagere-prijzen-en-verbruik

Chang, K. T. (2016). Geographic information system. *International Encyclopedia of Geography: People, the Earth, Environment and Technology: People, the Earth, Environment and Technology*, 1-9

Chen, Y., Altermatt, P. P., Chen, D., Zhang, X., Xu, G., Yang, Y., ... & Verlinden, P. J. (2018). From laboratory to production: learning models of efficiency and manufacturing cost of industrial crystalline silicon and thin-film photovoltaic technologies. IEEE Journal of Photovoltaics, 8(6), 1531-1538

Ciocia, A., Amato, A., di Leo, P., Fichera, S., Malgaroli, G., Spertino, F., & Tzanova, S. (2021). Self-Consumption and Self-Sufficiency in Photovoltaic Systems: Effect of Grid Limitation and Storage Installation. Energies, 14(6), 1591. https://doi.org/10.3390/en14061591

de Castro, C., Mediavilla, M., Miguel, L. J., & Frechoso, F. (2013). Global solar electric potential: A review of their technical and sustainable limits. Renewable and Sustainable Energy Reviews, 28, 824–835. https://doi.org/10.1016/j.rser.2013.08.040

Derkenbaeva, E., Vega, S. H., Hofstede, G. J., & Van Leeuwen, E. (2022). Positive energy districts: Mainstreaming energy transition in urban areas. *Renewable and Sustainable Energy Reviews*, *153*, 111782

DesJardins, J. (1998). Corporate environmental responsibility. *Journal of business ethics*, *17*(8), 825-838

Dyjakon, A., & García-Galindo, D. (2019). Implementing agricultural pruning to energy in Europe: Technical, economic and implementation potentials. *Energies*, *12*(8), 1513

EEA. (2017, August 29). *Energy and climate change*. Retrieved February 25, 2022, from https://www.eea.europa.eu/signals/signals-2017/articles/energy-and-climate-change

EIA. (2021, May 21). Where greenhouse gases come from - U.S. Energy Information Administration (EIA). Retrieved March 10, 2022, from https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php#:%7E:text=Fossil%20fuel%20combustion%20(burning)%20for,U.S.%20anthropogenic%20CO2%20emissions.

Elshurafa, A. M., Albardi, S. R., Bigerna, S., & Bollino, C. A. (2018). Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations. Journal of Cleaner Production, 196, 122–134. https://doi.org/10.1016/j.jclepro.2018.06.016

Energy Star. (n.d.). What is Energy Efficiency? Retrieved March 4, 2022, from https://www.energystar.gov/about/about_energy_efficiency

EPA. (2020, March). *Report on the Environment - Greenhouse Gases*. Retrieved February 25, 2022, from https://www.epa.gov/report-environment/greenhouse-gases

Esri. (n.d.-a). About ArcGIS Pro—ArcGIS Pro | Documentation. ArcGIS Pro. Retrieved July 7, 2022, from https://pro.arcgis.com/en/pro-app/2.8/get-started/get-started.htm

Esri. (n.d.-b). What is GIS? | Geographic Information System Mapping Technology. Retrieved March 22, 2022, from https://www.esri.com/en-us/what-is-gis/overview#:%7E:text=A%20geographic%20information%20system%20(GIS,what%20things%20are%20like%20there).

Fraunhofer ISE. (2021, June). Levelized cost of electricity: renewable energy technologies. https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.htm

Fraunhofer ISE. (2022, February). PHOTOVOLTAICS REPORT. *https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf*

Gerbens-Leenes, P. (2016). Energy for freshwater supply, use and disposal in the Netherlands: a case study of Dutch households. International Journal of Water Resources Development, 32(3), 398–411. https://doi.org/10.1080/07900627.2015.1127216

Global Solar Atlas. (n.d.). The World Bank Group. Retrieved April 22, 2022, from https://globalsolaratlas.info/download/netherlands

Grassi, S., Veronesi, F., Schenkel, R., Peier, C., Neukom, J., Volkwein, S., ... & Hurni, L. (2015, June). Mapping of the global wind energy potential using open source GIS data. In Proceedings of the 2nd International Conference on Energy and Environment (ICEE 2015): Bringing Together Engineering and Economics, Guimarães, Portugal (pp. 18-19)

Guangul, F. M., & Chala, G. T. (2019). Solar energy as renewable energy source: SWOT analysis. In *2019 4th MEC international conference on big data and smart city (ICBDSC)* (pp. 1-5).

Honsberg, C. & Bowden, S. (2015). *PVEducation*. Available at: http://pveducation.org/

van Hooff, W., Kuijers, T., Quax, R., & Witte, J. (2021, March). Ruimtelijk potentieel van zonnestroom in Nederland. TKI Urban Energy. https://www.topsectorenergie.nl/sites/default/files/uploads/Urban%20energy/publicaties/Ruimtelijk%20potentieel%20van%20zonnestroom%20in%20Nederland.pdf

Idoko, L., Anaya-Lara, O., & McDonald, A. (2018). Enhancing PV modules efficiency and power output using multi-concept cooling technique. Energy Reports, 4, 357–369. https://doi.org/10.1016/j.egyr.2018.05.004

IEA. (2022, May). Snapshot of Global PV Markets 2022. https://iea-pvps.org/wp-content/uploads/2022/04/IEA_PVPS_Snapshot_2022-vF.pdf

INNAX. *(n.d.). NTA8800 | INNAX Kennisbank. Retrieved May 26, 2022, from https://www.innax.nl/kennisbank/woningkwaliteit-op-orde/nta8800-voor-woningen*

IPCC. (2018). Global Warming of 1.5°C. *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

IRENA. (2021a). Energy profile Netherlands. https://www.irena.org/IRENADocuments/Statistical_Profiles/Europe/Netherlands_Europe_RE_SP.pdf

IRENA. (2021b). Renewable power generation costs in 2020. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

IvoSolar. (n.d.). IvoSolar - Opbrengst berekenen zonnepanelen. Retrieved July 1, 2022, from http://ivosolar.com/Zonnepaneel-systemen/Opbrengst-berekenen-zonnepanelen/

Jacobson, M. Z., & Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. Solar Energy, 169, 55–66. https://doi.org/10.1016/j.solener.2018.04.030

Kadaster. (n.d.). Basisregistratie Adressen en Gebouwen (BAG). BAGviewer Kadaster. Retrieved May 29, 2022, from https://bagviewer.kadaster.nl/lvbag/bag-viewer/index.html#?geometry.x=160000&geometry.y=455000&zoomlevel=0

Kallio, H., Pietilä, A. M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. Journal of advanced nursing, 72(12), 2954-2965

Kuzior, A., & Staszek, M. (2021). Energy Management in the Railway Industry: A Case Study of Rail Freight Carrier in Poland. Energies, 14(21), 6875. https://doi.org/10.3390/en14216875

Leigh, D. (2009). SWOT analysis. *Handbook of Improving Performance in the Workplace: Volumes 1-3*, 115-140

Lelah, A., Boucher, X., Moreau, V., & Zwolinski, P. (2014). Scenarios as a Tool for Transition towards Sustainable PSS. Procedia CIRP, 16, 122–127. https://doi.org/10.1016/j.procir.2014.01.015

Majcen, D., Itard, L., & Visscher, H. (2013). Energy labels in Dutch dwellings – their actual energy consumption and implications for reduction targets.

Ministerie van Infrastructuur en Waterstaat (IenW). (2014, December). Beheerconcessie 2015–2025. Rijksoverheid. Retrieved from https://www.rijksoverheid.nl/onderwerpen/openbaar-vervoer/documenten/rapporten/2014/12/15/bijlage-2-beheerconcessie-2015-2025

Ministerie van Infrastructuur en Waterstaat. (2021, April 7). Voorzieningen op stations. Retrieved March 1, 2022, from https://www.rijksoverheid.nl/onderwerpen/openbaar-vervoer/comfortabel-reizen/voorzieningen-stations

Ministry of Transport, Public Works and Water Management. (2010, June). Public transport in the Netherlands. Retrieved from https://www.emta.com/IMG/pdf/brochure.pdf

Movares. (2022, February 22). Landelijke Netanalyse tractie Energievoorziening. Retrieved March 4, 2022, from https://movares.nl/projecten/landelijke-netanalyse-tractie-energievoorziening/

Netbeheer Nederland. (2022, June 23). Capaciteitskaart invoeding elektriciteitsnet. Retrieved June 25, 2022, from https://capaciteitskaart.netbeheernederland.nl/

Ning, F., Ji, L., Ma, J., Jia, L., & Yu, Z. (2021). Research and analysis of a flexible integrated development model of railway system and photovoltaic in China. Renewable Energy, 175, 853-867

NREL. (2017, September). U.S. Solar Photovoltaic System Cost Benchmark. https://www.nrel.gov/docs/fy17osti/68925.pdf

NREL. (2022). Best Research-Cell Efficiency Chart. Photovoltaic Research | NREL. Retrieved June 3, 2022, from https://www.nrel.gov/pv/cell-efficiency.html

Ouyang, X., & Lin, B. (2014). Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China. Energy Policy, 70, 64–73. https://doi.org/10.1016/j.enpol.2014.03.030

Paltsev, S. (2017). Energy scenarios: the value and limits of scenario analysis. *Wiley Interdisciplinary Reviews: Energy and Environment*, *6*(4), e242

Paul, J. (2021). Study of Energy Neutrality in Kochi Metro Rail, India (master thesis)

Pick, H., & Becker, P. (1975). Direct and indirect uses of energy and materials in engineering and construction. Applied Energy, 1(1), 31–51. https://doi.org/10.1016/0306-2619(75)90022-7

ProRail. (n.d.-a). Natuur. Retrieved June 23, 2022, from https://www.prorail.nl/toekomst/duurzaamheid/natuur#:%7E:text=ProRail%20bezit%20zo%27n%2010.000,het%20vergroten%20van%20de%20biodiversiteit.

ProRail. (n.d.-b). Onze klanten. Retrieved March 3, 2022, from https://www.prorail.nl/samenwerken/vervoerders/onze-klanten

ProRail. (n.d.-c). Over ons. Retrieved February 25, 2022, from https://www.prorail.nl/over-ons

ProRail. (n.d.-d). Wat wij doen. Retrieved March 1, 2022, from https://www.prorail.nl/over-ons/wat-doet-prorail

ProRail. (2016, December 9). Duurzame ledverlichting op 400 stations. Retrieved May 26, 2022, from https://www.prorail.nl/nieuws/duurzame-ledverlichting-op-400-stations

ProRail, Luiten, T., Monnikhof, G. O., & Schipper, R. (2017, May). Energie-efficiency plan 2017–2020. Retrieved from https://www.prorail.nl/siteassets/homepage/toekomst/documenten/energie-efficiency-plan-2017-2020.pdf

ProRail. (2018, January). CO2-Besparingsplan 2018–2020, met doorkijk naar 2030. Retrieved from https://www.prorail.nl/siteassets/homepage/toekomst/duurzaamheid/co2-prestatieladder---co2-besparingsplan--2018-2020.pdf

ProRail (2019, March 26). Meer en snellere treinen. Retrieved May 25, 2022, from https://www.prorail.nl/nieuws/meer-en-snellere-treinen

ProRail. (2020). Handboek Zonnepanelen Stations. https://issuu.com/bureauspoorbouwmeester/docs/20161122-def-prorail_richtlijn_este

ProRail. (2021a, June 21). Hard op weg naar nog meer CO2-reductie. Retrieved March 22, 2022, from https://www.prorail.nl/nieuws/hard-op-weg-naar-nog-meer-co2-reductie

ProRail. (2021b, November). ProRail CO2 emissie inventaris 2020. Retrieved from https://www.prorail.nl/siteassets/homepage/toekomst/duurzaamheid/documenten/co2-emissie-inventaris-2020-09-11-2021-15-09.pdf

ProRail. (2021c, December 12). Reizigersvervoerders & concessies [Map]. Retrieved from https://maps.prorail.nl/portal/sharing/rest/content/items/7dd2721751574306af80f8cc42000f92/data?token=

ProRail. (2022a, May). *CO2- en Energiebesparingsplan 2021–2025.*

ProRail. (2022b, March 21). Duurzaamheid | ProRail Reports. Retrieved March 22, 2022, from https://prestaties.prorail.nl/duurzaamheid/cDU208_Duurzaamheid.aspx

ProRail. (2022c). *Folder: /*. ArcGIS REST Services Directory. Retrieved April 20, 2022, from https://mapservices.prorail.nl/arcgis/rest/

ProRail. (2022d). *Folder: /*. ArcGIS REST Services Directory. Retrieved April 20, 2022, from https://maps.prorail.nl/arcgis/rest/services

ProRail. (2022e). Kerncijfers | ProRail Reports. Retrieved March 31, 2022, from https://prestaties.prorail.nl/kerncijfers/cDU209_Kerncijfers.aspx

ProRail. (2022f, February 2). Ruim tweeduizend zonnepanelen op stations. Retrieved June 24, 2022, from https://www.prorail.nl/nieuws/tweeduizend-zonnepanelen-op-stations

ProRail. (2022g, June 3). Zonneparken op grond van ProRail. Retrieved July 7, 2022, from https://www.prorail.nl/nieuws/zonneparken-op-grond-van-prorail#:%7E:text=ProRail%20verhuurt%20bijna%2012%2C5,komende%20periode%20twee%20zonneparken%20bouwen.

Reddy, P., Gupta, M. V. N., Nundy, S., Karthick, A., & Ghosh, A. (2020). Status of BIPV and BAPV system for less energy-hungry building in India—a review. *Applied Sciences*, *10*(7), 2337

Rijksoverheid. (n.d.). *EP-Online*. EP-Online. https://www.ep-online.nl/

Ringkjøb, H. K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renewable and Sustainable Energy Reviews, 96, 440–459. https://doi.org/10.1016/j.rser.2018.08.002

RVO. (2021, December). Electric Vehicles Statistics in the Netherlands. https://www.rvo.nl/sites/default/files/2021/12/electric-vehicles-statistics-in-the-netherlands.pdf

Seijlhouwer, M. (2022, July 12). Zonnepanelen op de treinrails. Change Inc. Retrieved July 19, 2022, from https://www.change.inc/mobiliteit/zonnepanelen-op-de-treinrails-38619

Sodhi, M., Banaszek, L., Magee, C., & Rivero-Hudec, M. (2022). Economic Lifetimes of Solar Panels. Procedia CIRP, 105, 782–787. https://doi.org/10.1016/j.procir.2022.02.130

Szychta, E., Szychta, L., Luft, M., & Kirag, K. (2012). Application of 3D Simulation Methods to the Process of Induction Heating of Rail Turnouts. Infrastructure Design, Signalling and Security in Railway. https://doi.org/10.5772/36917

Tanesab, J., Parlevliet, D., Whale, J., & Urmee, T. (2017). Seasonal effect of dust on the degradation of PV modules performance deployed in different climate areas. Renewable Energy, 111, 105–115. https://doi.org/10.1016/j.renene.2017.03.091

TNO. (2022, March). Real-world fuel consumption and electricity consumption of passenger cars and light commercial vehicles - 2021. https://www.tno.nl/en/focus-areas/traffic-transport/roadmaps/sustainable-traffic-and-transport/sustainable-mobility-and-logistics/improving-air-quality-by-monitoring-real-world-emissions/overview-of-reports-of-actual-fuel-consumption-by-passenger-cars/

Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). *Zero energy buildings: a critical look at the definition* (No. NREL/CP-550-39833). National Renewable Energy Lab.(NREL), Golden, CO (United States)

UIC. (2016, December). TECHNOLOGIES AND POTENTIAL DEVELOPMENTS FOR ENERGY EFFICIENCY AND CO2 REDUCTIONS IN RAIL SYSTEMS. https://uic.org/IMG/pdf/_27_technologies_and_potential_developments_for_energy_efficiency_and_co2_reductions_in_rail_systems._uic_in_colaboration.pdf

Umar, T., & Wamuziri, S. (2016). Briefing: Conventional, wind and solar energy resources in Oman. *Proceedings of the institution of civil engineers-energy*, *169*(4), 143-147

UTC. (2022). Techno-Economic Analysis | Research Contracts and Innovation. University of Cape Town. Retrieved July 13, 2022, from http://www.rci.uct.ac.za/rcips/fundinnov/tea

Voestalpine. (n.d.). Heavy rail - voestalpine Turnout Technology Netherlands B.V. Retrieved May 26, 2022, from https://www.voestalpine.com/turnout-technology-netherlands/nl/portfolio/wissels/heavy-rail-00001/

World Energy Council. (2013). World Energy Scenarios: Composing energy futures to 2050. https://www.worldenergy.org/assets/downloads/World-Energy-Scenarios_Composing-energy-futures-to-2050_Executive-summary.pdf

Zasiadko, M. (2019, December 4). Five railway hacks to survive winter. RailTech. Retrieved May 26, 2022, from https://www.railtech.com/infrastructure/2019/12/04/five-railway-hacks-to-survive-winter/?gdpr=accept

Zhang, T., Wang, M., & Yang, H. (2018). A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. Energies, 11(11), 3157. https://doi.org/10.3390/en11113157

8. Appendix

Appendix I: Energy demand of ProRail in 2015

Table 26: Energy demand of ProRail in 2015 displayed for each demand category and source (ProRail et al., 2017)

Description	**Category**	**Details**	**Electricity**	**Natural gas**	**Heat**	**Total**	**Unit**
Total			135,753	34,838	4,868	180,304	MWh
Stations		Total	54,663	3,799	535	58,997	MWh
	Lighting	Station hall	1,662	0	0	1,662	MWh
		Lighting platform	13,330	0	0	13,330	MWh
		Lighting waiting rooms	1,263	0	0	1,263	MWh
		Lighting bicycle storage	5,493	0	0	5,493	MWh
		Lighting traverses	247	0	0	247	MWh
		Lighting tunnels	3,102	0	0	3,102	MWh
	Travel info	Departure information	5,212	0	0	5,212	MWh
		CTA/Info+	18	0	0	18	MWh
	Escalators/ele vators	Elevators	2,722	0	0	2,722	MWh
		Escalators	5,798	0	0	5,798	MWh
	Other	Other stations	15,817	3,799	535	20,151	MWh
Infrastructure		Total	73,588	28,436	0	102,024	MWh
	Rail systems	Turnouts heating	3,862	24,517	0	28,379	MWh
		Lighting emplacements	4,863	0	0	4,863	MWh
		Tunnels	7,325	0	0	7,325	MWh
		Bridges	1,182	0	0	1,182	MWh
	Traffic guidance (VL)	VL-posts	11,343	2,194	0	13,537	MWh
	Train security	TEV fed installations	23,759	0	0	23,759	MWh
		Crossroads from facility	2,000	0	0	2,000	MWh
		Keyrail	7,165	514	0	7,679	MWh
	Other	Other Infrastructure	12,089	1,211	0	13,300	MWh
Offices		Total	7,501	2,603	4,333	14,438	MWh
		De Inktpot	2,264	0	2,111	4,375	MWh
		Tulpenburg	907	51	1,111	2,069	MWh
		Adm. Helfrich	2,812	0	833	3,645	MWh
		Regional offices	1,320	1,901	278	3,499	MWh
		Accidents unit	198	651	0	849	MWh
Transport	Car	Diesel/petrol	0	0	0	4,845	MWh

Appendix II: Detailed energy demand scenarios

Table 27: Detailed frozen technology scenario 1

Description	Category	Details	Electricity	Natural gas	Heat	Total	Unit
Total			147,078	37,541	4,055	194,003	MWh
Stations		Total	60,130	4,179	588	64,897	MWh
	Lighting	Station hall	1,662	0	0	1,662	MWh
		Lighting platform	13,330	0	0	13,330	MWh
		Lighting waiting rooms	1,263	0	0	1,263	MWh
		Lighting bicycle storage	5,493	0	0	5,943	MWh
		Lighting traverses	247	0	0	247	MWh
		Lighting tunnels	3,102	0	0	3,102	MWh
	Travel info	Departure information	5,212	0	0	5,212	MWh
		CTA/Info+	18	0	0	18	MWh
	Escalators/elevators	Elevators	2,995	0	0	2,995	MWh
		Escalators	6,378	0	0	6,378	MWh
	Other	Other stations	17,399	4,179	588	22,166	MWh
Infrastructure		Total	80,947	31,279	0	112,227	MWh
	Rail systems	Turnouts heating	4,249	26,968	0	31,217	MWh
		Lighting emplacements	5,350	0	0	5,350	MWh
		Tunnels	8,057	0	0	8,057	MWh
		Bridges	1,300	0	0	1,300	MWh
	Traffic guidance (VL)	VL-posts	12,477	2,414	0	14,891	MWh
	Train security	TEV fed installations	26,135	0	0	26,135	MWh
		Crossroads from facility	2,200	0	0	2,200	MWh
		Keyrail	7,882	565	0	8,447	MWh
	Other	Other Infrastructure	13,298	1,332	0	14,630	MWh
Offices		Total	6,001	2,083	3,467	11,550	MWh
		De Inktpot	2,490	0	2,322	4,813	MWh
		Tulpenburg	998	57	1,222	2,276	MWh
		Adm. Helfrich	3,093	0	917	4,010	MWh
		Regional offices	1,452	2,092	306	3,849	MWh
		Accidents unit	218	716	0	934	MWh
Transport	Car	Electricity	0	0	0	5,330	MWh

Table 28: Detailed frozen technology scenario 2

Description	Category	Details	Electricity	Natural gas	Heat	Total	Unit
Total			162,904	41,806	5,848	216,365	MWh
Stations		Total	65,596	4,559	642	70,796	MWh
	Lighting	Station hall	1,662	0	0	1,662	MWh
		Lighting platform	13,330	0	0	13,330	MWh
		Lighting waiting rooms	1,263	0	0	1,263	MWh
		Lighting bicycle storage	5,493	0	0	5,493	MWh
		Lighting traverses	247	0	0	247	MWh
		Lighting tunnels	3,102	0	0	3,102	MWh
	Travel info	Departure information	5,212	0	0	5,212	MWh
		CTA/Info+	18	0	0	18	MWh
	Escalators/elevators	Elevators	3,267	0	0	3,267	MWh
		Escalators	6,957	0	0	6,957	MWh
	Other	Other stations	18,980	4,559	642	24,181	MWh
Infrastructure		Total	88,306	34,123	0	122,429	MWh
	Rail systems	Turnouts heating	4,635	29,420	0	34,055	MWh
		Lighting emplacements	5,836	0	0	5,836	MWh
		Tunnels	8,790	0	0	8,790	MWh
		Bridges	1,418	0	0	1,418	MWh
	Traffic guidance (VL)	VL-posts	13,612	2,633	0	16,245	MWh
	Train security	TEV fed installations	28,511	0	0	28,511	MWh
		Crossroads from facility	2,400	0	0	2,400	MWh
		Keyrail	8,598	617	0	9,215	MWh
	Other	Other Infrastructure	14,507	1,453	0	15,960	MWh
Offices		Total	9,002	3,124	5,200	17,326	MWh
		De Inktpot	2,717	0	2,533	5,250	MWh
		Tulpenburg	1,088	62	1,333	2,483	MWh
		Adm. Helfrich	3,374	0	1,000	4,374	MWh
		Regional offices	1,584	2,282	333	4,199	MWh
		Accidents unit	238	781	0	1,019	MWh
Transport	Car	Electricity	0	0	0	5,814	MWh

Table 29: Detailed energy efficiency scenario

Description	Category	Details	Electricity	Natural gas	Heat	Total	Unit
Total			128,069	8,275	4,358	141,423	MWh
Stations		Total	38,561	3,058	430	42,050	MWh
	Lightning	Station hall	1,014	0	0	1,014	MWh
		Lighting platform	8,131	0	0	8,131	MWh
		Lighting waiting rooms	771	0	0	771	MWh
		Lighting bicycle storage	3,350	0	0	3,350	MWh
		Lighting traverses	151	0	0	151	MWh
		Lighting tunnels	1,892	0	0	1,892	MWh
	Travel info	Departure information	3,649	0	0	3,649	MWh
		CTA/Info+	12	0	0	12	MWh
	Escalators/elevators	Elevators	2,192	0	0	2,192	MWh
		Escalators	4,667	0	0	4,667	MWh
	Other	Other stations	12,733	3,058	430	16,221	MWh
Infrastructure		Total	83,469	3,471	0	86,047	MWh
	Rail systems	Turnouts heating	27,843	0	0	27,843	MWh
		Lighting emplacements	3,412	0	0	3,412	MWh
		Tunnels	5,896	0	0	5,127	MWh
		Bridges	951	0	0	827	MWh
	Traffic guidance (VL)	VL-posts	9,131	2,082	0	11,214	MWh
	Train security	TEV fed installations	19,126	0	0	19,126	MWh
		Crossroads from facility	1,610	0	0	1,610	MWh
		Keyrail	5,768	414	0	6,182	MWh
	Other	Other Infrastructure	9,732	975	0	10,707	MWh
Offices		Total	6,039	1,746	3,928	11,712	MWh
		De Inktpot	1,822	0	2,111	3,934	MWh
		Tulpenburg	730	0	706	1,436	MWh
		Adm. Helfrich	2,264	0	833	3,097	MWh
		Regional offices	1,063	1,332	278	2,672	MWh
		Accidents unit	160	414	0	574	MWh
Transport	Car	Electricity	1,614	0	0	1,614	MWh

Appendix III: Conducted interviews

Table 30: Interviewed contacts of Movares of ProRail

Movares			
Name	**Function**	**Date interview**	**Topic**
Mieke van Eerten	Sustainability Advisor	22-02-2022	General information about sustainability implementation in Movares and ProRail activities
Sjaak ten Breeje	Project manager Energy	03-03-2022 14-04-2022	03-03-2022: Information about energy neutrality goal. Problems of ProRail around energy-related topics. 14-04-2022: Data collection strategy with ProRail contacts and data availability.
Herman Sibbel	Account manager Energy	18-03-2022	ProRail's ambitions and projects focused on energy and the energy neutrality goal.
Jorinde Guldenaar	Consultant Energy Transition	19-05-2022	Project on solar energy potential for a case study, data availability and methodology.
ProRail			
Name	**Function**	**Date interview**	**Topic**
Jorien Maltha	Program manager Sustainability - Stations	09-05-2022	ProRail activities on technical potential estimations of renewable energy generation on Station assets.
Gerald Olde Monnikhof	Program manager Sustainability	16-05-2022	ProRail's strategy on energy demand reduction and renewable supply to reach the energy neutrality goal of 2030.

Appendix IV: Details ArcGIS methodology

Table 31: All collected open field surfaces for the ten sampled track parts

Track part I: Boxtel-Eindhoven Strijp (18.07 km)		
Field	**Area (m^2)**	**Coordinates**
Samenvoeging spoor Boxtel	1,991.18	5.3124990°E 51.5896264°N
Grond onder spoor Boxtel station	697.87	5.3156418°E 51.5876450°N
Tussen spoor na Boxtel station	715.88	5.3238125°E 51.5822549°N
Grond na afslag spoor na Boxtel	7,177.71	5.3314377°E 51.5741521°N
Grond na afslag spoor na Boxtel	4,403.68	5.3329332°E 51.5721611°N
Grond bij bruggen na Boxtel	7,733.01	5.3378755°E 51.5677409°N
Grond bij rotonde na station Best	1,379.99	5.3960762°E 51.5040270°N
Grond bij rotonde na station Best	3,444.94	5.3967606°E 51.5024920°N
Track part II: Dordrecht-Dordrecht Zuid (19.12 km)		
Field	**Area (m^2)**	**Coordinates**
Middenberm tussen spoor bij station Lage Zwaluwe	2,400	4.664552°E, 51.688225°N
Terrein zuidelijk van station Lage Zwaluwe	1,659	4.666250°E, 51.686939°N
In het veld naast gebouw	157	4.670824°E, 51.679661°N
Op een veld op het talud	1,160	4.672634°E, 51.678718°N
In het veld	254	4.687210°E, 51.655650°N
In de berm tussen de sporen plus een talud	943	4.686829°E, 51.655817°N
In het veld naast gebouw	347	4.670729°E, 51.679899°N
In het veld dichtbij viaduct	451	4.666360°E, 51.685647°N
Perceel emplacement station Lage-Zwaluwe	814	4.663474°E, 51.689866°N
Perceel bij emplacement station Lage-Zwaluwe	449	4.665441°E, 51.688278°N
In het grasveld naast station Zevenbergen	1,158	4.610266°E, 51.641024°N
Op veld naast spoor boven Station Lage Zwaluwe	1,639	4.658786°E, 51.696745°N
In het veld	2,058	4.656616°E, 51.702009°N
In het veld	2,777	4.656162°E, 51.701870°N
In de overhoek	1,269	4.651570°E, 51.708190°N
Twee velden langs het spoor	2,412	4.649817°E, 51.710784°N
Twee velden zuidelijk van de brug	6,824	4.647814°E, 51.713696°N
Twee velden noordelijk van de brug	8,460	4.640068°E, 51.725337°N
Veld noordelijk van de brug	2,823	4.637561°E, 51.729058°N
In het veld richting Dordrecht	2,523	4.642761°E, 51.750975°N
Track part III: Leeuwarden Camminghaburen-Buitenpost (21.33 km)		
Field	**Area (m^2)**	**Coordinates**
Grond na de Westereen	1,036.25	6.0622382°E 53.2516038°N
Grond bij station Hurdegaryp	463.4	5.9332883°E 53.2197255°N
Grond rechts naast Leeuwarden-Camminghaburen	1,223.25	5.8726719°E 53.2068106°N
Grond boven spoor Leeuwarden-Camminghaburen	584.7	5.8471369°E 53.2038029°N
Track part IV: Heerhugowaard-Hoorn (21.51 km)		
Field	**Area (m^2)**	**Coordinates**
Uiteenloping spoor na Heerhugowaard	8,446.95	4.8339557°E 52.6759924°N
Grond tussen kassen richting Schagen	3,818.37	4.8408964°E 52.7045654°N
Grond bij flauwe bocht naar rechts rechterkant	910.88	4.8425071°E 52.7127559°N
Grond bij flauwe bocht naar rechts linkerkant	7,132.80	4.8427214°E 52.7149850°N
Grond bij brug naar Schagen	1,076.40	4.8438175°E 52.7201433°N
Grond onder spoor naar Opdam	1,504.49	4.8489065°E 52.6802671°N
Lange strook boven spoor naar Opdam	5953.41	4.8719931°E 52.6799790°N
Grond bij samenkomen spoor hoek	254.79	5.0361160°E 52.6461847°N
Track part V: Almelo-Oldenzaal (24.01 km)		

Field	Area (m^2)	Coordinates
Grond richting Hengelo	849.55	6.6886432°E 52.3314991°N
Grond bij station Hengelo	322.31	6.8032419°E 52.2612110°N
Grond tussen spoor na station Hengelo	231.54	6.8066958°E 52.2590193°N
Grond tussen Hengelo en Oldenzaal	9,313.58	6.8563953°E 52.2829508°N
Track part VI: Barneveld Noord - Ede Wageningen (18.56 km)		
Field	**Area (m^2)**	**Coordinates**
Stuk grond boven Barneveld Noord	1,824.79	5.5973475°E 52.1629259°N
Stuk grond tussen Barneveld Noord & Centrum	625.21	5.5960059°E 52.1554048°N
Track part VII: Blerick - Swalmen (19.40 km)		
Field	**Area (m^2)**	**Coordinates**
Grond na brug tussen Blerick & Venlo	410.55	6.1640599°E 51.3691685°N
Grond onder spoor Venlo	2,456.05	6.1728330°E 51.3630440°N
Grond na station Venlo links van het spoor	894.65	6.1768339°E 51.3597367°N
Grond tussen station Tegelen & Reuver	454.26	6.1127903°E 51.3135843°N
Track part VIII: Utrecht Overvecht - Bussum-Zuid (18.61 km)		
Field	**Area (m^2)**	**Coordinates**
Grond tussen spoor na Utrecht Overvecht	386.7	5.1424862°E 52.1168014°N
Grond tussen spoor en snelweg onder Hollandsche Rading	1,085.43	5.1700255°E 52.1627826°N
Grond tussen splitsing spoor bij station Hilversum	549.51	5.1857487°E 52.2233049°N
Track part IX: Voorschoten - Hillegrom (22.81 km)		
Field	**Area (m^2)**	**Coordinates**
Grond bij splitsing na Leiden Centraal	342.83	4.4931864°E 52.2015143°N
Grond tussen spoor naast perron Hillegrom	718.44	4.5646196°E 52.3025120°N
Grond onder perron Hillegrom zonder bomen	293.68	4.5654967°E 52.3029827°N
Track part X: Beilen - Meppel (34.01 km)		
Field	**Area (m^2)**	**Coordinates**
Grond boven spoor na station Hoogeveen	189.6	6.4759221°E 52.7364191°N
Grond onder spoor na station Hoogeveen	168.38	6.4762596°E 52.7363280°N
Grond rechts naast spoor tussen Hoogeveen & Beilen	1,876.32	6.5078444°E 52.8168596°N
Grond rechts naast spoor onder Beilen	660.78	6.5203756°E 52.8514639°N
Grond boven spoor tussen Hoogeveen & Meppel	599.91	6.3996544°E 52.7175360°N