Multi-criteria analysis of the Energy wall

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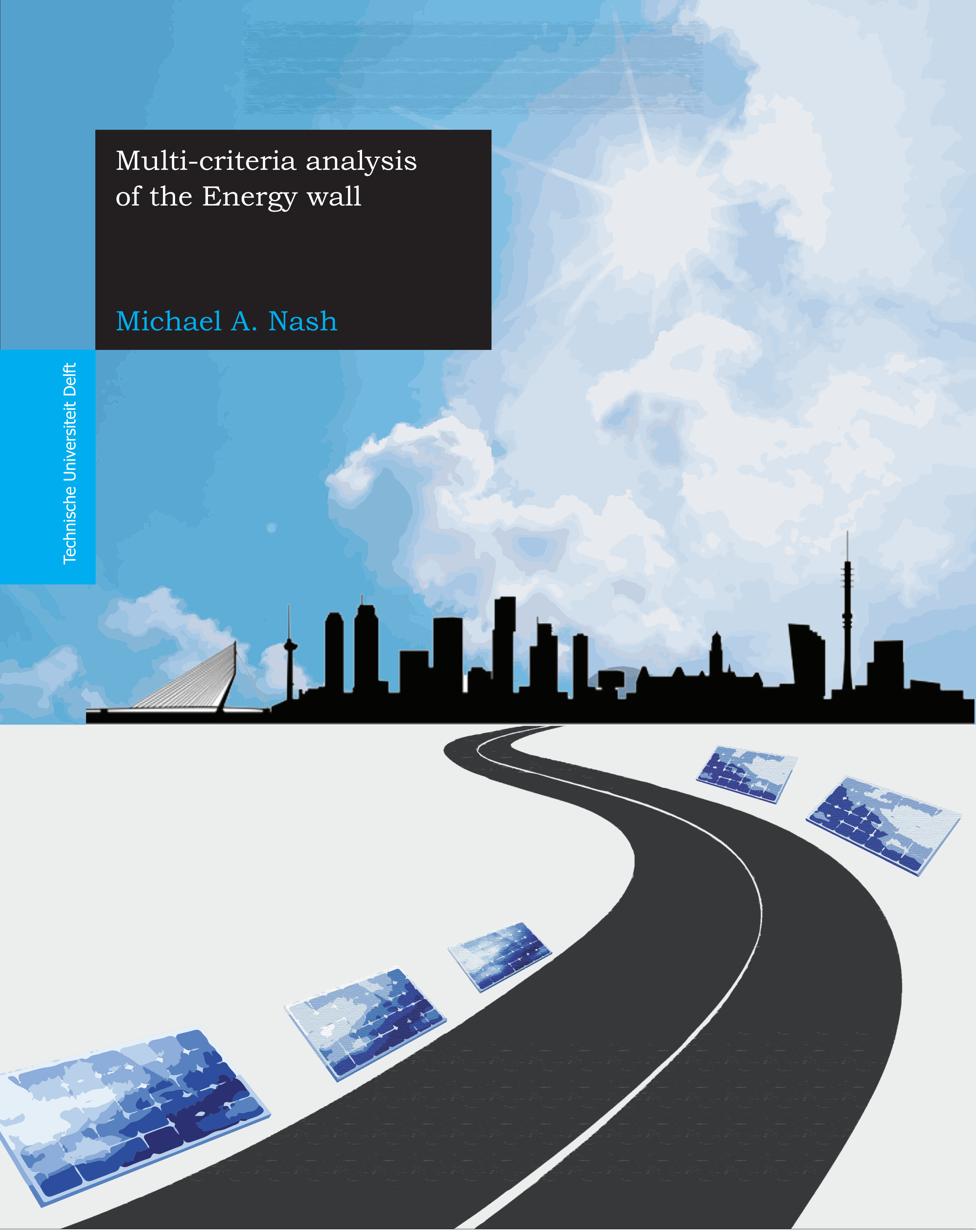

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Challenge the future

Multi-criteria analysis of the Energy wall

Feasibility of the deployment of solar noise barriers around the Rotterdam ring road

by

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In fulfilment of the requirements for a
Masters of Science
in Sustainable Energy Technology

Faculty of Electrical Engineering Mathematics & Computer Science
Technische Universiteit Delft
Delft, Netherlands
July 2018

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Abstract

The rapid growth of the PV industry has meant that prices have been falling steeply, making them more accessible for a wider range of applications. The combined use of noise barriers as energy generating facilities, usually coined as PVNBs has been occurring since the late 80's. It has not realised wide spread implementation, remaining mostly in the research domain. These structures are predominantly built in urban areas with high populations and energy consumption. In an attempt to shine light on the economic potential of these projects, an engineering design study has been carried out. By focusing on the retrofitting of current infrastructure it is hoped to stimulate investment for Energy wall projects.

The initial concept was coined as the Energy wall, which differed from PVNBs in that it consisted of a hybrid wind and solar system. However, in this thesis the focus remains on the solar aspect but the name Energy wall remains. An initial investigation of the infrastructure in the Netherlands was carried out using GIS, to determine what lengths of suitable noise barriers are currently available for conversion. A dataset gained from the Rijkswaterstaat, part of the Dutch ministry of infrastructure and the environment, was the base of this analysis. Calculations were made to add relevant attributes for determining the infrastructures suitability for conversion considering nearby spatially relevant data. The output of this, was used to develop a model that would perform a multi-criteria analysis, exploring PV types, configurations and PV systems costs. The focus was around the Rotterdam ring road to allow the methodology to be developed but with the hopes that the same process could be applied to a nationwide or multinational level. System costs were implemented based on interviews and research, which allowed for comparisons to be made and costs of energy to be found. A stakeholder analysis was also used to find the relevant parties for different system sizes, from here subsidies could be applied.

The model offers a guide for pricing of major components, highlighting critical parameters that could affect the success of the project. The main methodology for system comparisons is the LCOE. The application of subsidies can make project much more attractive to cooperation's or nearby companies for tax refunds or self-consumption. While on a large scale, economies of scale make the project competitive with conventional PV systems. Installations of this scale are rarely seen in the built environment and could have a major contribution to grid balancing.

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Acknowledgements

The submission of this thesis marks the end of a big chapter in my life, my Master's degree in Sustainable Energy Technology has thrown me lots of challenges. I have gained many skills along the road in a friendly international environment that I believe will give me the tools to make a difference in this world.

If I had to go back and do it all again, I would change very little, mostly having fewer bicycle crashes.

It has been a long journey and I wouldn't be here without many people. Firstly, I would like to thank my daily supervisor Nikolaos Chrysochoidis-Antsos for his guidance and support throughout, I wish you all the best in your future marriage and good luck for the completion of your PhD. To Prof. dr. Ad van Wijk I would like to thank you for your constructive comments in shaping this thesis, your knowledge of the industry is truly insightful.

I would like to thank my family for whom I would not be presenting this thesis without, their motivation and support were unwavering.

To all the friends from around the world, made during my time in Delft, we had many fun times together that I will not forget. To my housemates that made my house into a home, thanks for the amazing food, company and escape from the day.

To Minnie de Jong, thanks for showing me the facilities at TU/e and discussing the projects, it was very useful to me and I want to wish you luck in the completion of the Solar Highways project. To the other Interviewees, your input was vital in keeping the thesis as up to date as possible in the fast-moving world of Solar energy, thank you.

Michael A. Nash
July 2018

List of Abbreviations

AHN	Actueel Hoogtebestand Nederland
BIPV	Building Integrated Photovoltaics
BNEF	Bloomberg New Energy Finance
BOS	Balance Of System
CBS	Centraal Bureau voor de Statistiek
CF	Capacity Factor
DBFM	Design, Build, Finance and Maintain
DEM	Digital Elevation Model
DG	Distributed Generation
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
EEG	Renewable Energy Act
EIA	Energy Investment Allowance
EV	Electric Vehicle
GHI	Global Horizontal Irradiance
GIS	Geographical Information System
HAWT	Horizontal Axis Wind Turbine
HOMER	Hybrid Optimisation Model for Multiple Energy Resources
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
KIA	Small scale Investment Allowance
KNMI	Royal Netherlands Meteorological Institute
LCOE	Levelised Cost Of Energy
LIDAR	Light Detection and Ranging
LIFE	Financial Investment For the Environment
LSC	Luminescent Solar Concentrators
MIA	Environment Investment Allowance
MIP	Minimum Import Tax
MLPE	Module Level Power Electronics
MPP(T)	Maximum Power Point (Tracker)
NAP	Normaal Amsterdams Peil
NB	Noise Barrier
NPV	Net Present Value
NREL	National Research Energy Laboratory
PF	Power Factor
PPA	Power Purchase Agreement

PVNB	Photovoltaic Noise Barrier
RGO	Regional Grid Operator
RWS	Rijkswaterstaat
SDE+	Stimulation of Sustainable Energy Production
STC	Standard Test Conditions
VAMIL	Random Depreciation of Environmental Investments
VAWT	Vertical Axis Wind Turbine

1

Introduction

The world has become aware of its need to reduce its CO2 emissions so that the world of the future is a cleaner and healthier one than we inherited. This has resulted in the steep increase in the amount of renewable energy we see installed today, this has had a self-stimulating effect in that this has resulted in year on year price reductions. Some countries around the world are now seeing the price of energy from renewables reaching or surpassing the price of energy from the grid. This is pushing the traditional, polluting methods of electricity production aside.

Proposals such as the Paris climate accord in which most of the world agreed to collectively to curb CO2 emissions are reinforcing this commitment. Each country pledged to do what they could which has seen the Netherlands promising a 20% reduction of greenhouse gas emissions by 2020 and 30% by 2030.

Of course there is a need to curtail current levels of consumption through more efficient technologies but a better synchronisation of the large consumers and their energy supply is also needed. The urban environment is where over 50% of the worlds population lives, consuming around 75% of global primary energy, therefore making them also large CO2 emitters [1] [2].

To meet all these targets, a more localised approach is needed, provinces and cities are in the best position to self-design proposals, based on their knowledge to take advantage of their specific environment to exploit any opportunities that they find.

The Netherlands is not afraid of its commitment to renewable energy, installing 853MW in 2017 [3], however, this only accounts for 7% of the countries renewables as of March 2018 [4]. To continue with this rapid growth in renewables, new areas in which to install the energy technology are needed.

A great difficulty attributed to the generation of large amounts of renewable energy is the required land area, which, in cities is far more difficult/expensive to come by. To address the large demand for energy in the urban environment, out of the box ideas must be implemented.

The transportation network in the Netherlands is vital and is also one of the largest energy consuming sectors [4]. There has been a growing trend towards EV (Electric Vehicles) which will see a reduction in the need for fossil fuels, coupled with the fact that petrol and diesel vehicles will be banned from 2030 [5]. but should ideally be replaced with renewably generated electricity. This makes the transportation sector a large net-consumer of energy which occupies a large amount of land.

1.1 Motivation for Research

This paper looks at the the integration of renewables in the urban environment; namely the Energy wall along highways. This is a NB (Noise Barrier) that doubles as a energy generation wall through the mounting of solar panels and/or micro wind turbines. With the aim of diversifying the functionality of the transportation network, while increasing its sustainability.

Already with the technology available to us today many of the worlds energy needs can be met, we see huge wind farms in the sea, & solar PV plants in the dessert. They are located here because of the higher yield, usually built at large-scale to bring the cost down. To reduce the cost of urban renewable development, other cost opportunities must be realised.

If cheap energy can be produced close to the city where it is to be consumed, a more sustainable city will emerge. There needs to be agreement from many different parties, with support from land and building owners, support from nearby residents and the backing of the local government.

There is an increasing share of DG (Distributed Generation) on the electricity grid currently, with this comes much more complex requirements of the electrical network. The centralised model of a large power plant is becoming redundant and a more sophisticated grid is required that can adequately monitor and control the myriad of renewables needed.

The recent slow down in solar implementation in China is the solar market is becoming flooded with cheaper PV, continuing to fall in price at a rapid rate, this makes their implementation increasingly attractive [6].

1.2 Research Questions

Several areas of research will be the focus of this study which have been formatted into several key questions that should be answered to determine the feasibility of the Energy wall.

1. What design advantages/opportunities can be realised from implementing the Energy wall system in the urban environment?

2. What is the potential of the Energy wall in the Netherlands, based on the current infrastructure?
3. Can specific cost opportunities be found from mounting renewables on noise barrier, and what are they?
4. What technology and in which topology should be implemented on the Energy wall to realise the best design?
5. Can a model be developed to give a wider understanding of the critical design parameters of the Energy wall?
6. Can an implemented Energy wall in the field represent a return on investment, and who might these investors be?
7. What price and quantity of energy can the Energy wall achieve and how does this deviate across NBs and local infrastructure?

1.3 Report Structure

The report presents the reader with an overview of the picture at a country wide level while eventually looking at the Rotterdam ring area to give focus and present final system proposals as developed by a model.

Chapter 2 introduces the Energy wall further, giving an overview of similar projects in Europe and the motivation behind the idea. Discussing who is backing the project and exploring the differences and opportunities between conventional renewables and those that would be implemented on the Energy wall.

Chapter 3 explores the utilisation of GIS to analyse the infrastructure of NBs in the Netherlands, exploring which attributes were included in the Rijkswaterstaat dataset and which had to added through be calculation or derivation. From these statistics, the suitability of the infrastructure for Energy wall conversion can be found. From here focus is placed on the Rotterdam ring road to compare it to the country wide picture. Different designs are explored alongside nearby energy consumption based on land use data. Finally presenting a methodology to estimate the energy potential of the Energy wall, discussing any complications that arose.

Chapter 4 looks at who the Energy wall may be financially interesting to and which subsidies are present to make investments more attractive for specific demographics. The benefits of the subsidies are presented along with the constraints of each.

Chapter 5 looks at the technology that it is possible to mount onto the noise barrier to successfully convert it into an Energy wall. These are presented along with some of the most critical theory that would determine the systems feasibility in this environment. The range of solar panels that were considered in the model are presented, along with all other components required to harness the power from the PV panels.

Chapter 6 presents the six case study sites based on the output of the GIS analysis, from which a model was developed to identify the critical criteria to the Energy walls feasibility. At each site a meteorological analysis was carried out, then a design strategy implemented With the priority to design the system with the best financial output. Component sizing is calculated and differences from conventional systems are discussed as found, assumptions and design choices are clearly expressed and justified. With a final look at the expected losses at each site before a final energy potential can be found.

Chapter 7 explores costs associated with PV systems and presents those implemented in the model which is based on research. This is despite the lack on specific cost breakdowns for the Netherlands and PVNB. Additional social benefits are discussed that are more difficult to quantify in monetary terms, but could give added value to the project if considered. While finally the economic variables & calculations that will be used to determine the profitability are introduced.

Chapter 8 analyses the results from the developed model, comparing the performance of different implemented technology & configurations as introduced in chapter 5. The final cost of the produced energy is found so that the systems can be compared on common grounds. The most advantageous systems are then presented in greater detail, where an analysis of the energy output, system cost and the benefit to different stakeholders can be found, considering the relevant subsidies.

Chapter 9 concludes the findings, highlighting key design decisions and recommendations for future work in the field.

2

Energy wall concept

The Energy wall is an innovative concept that brings together the prospect of harnessing local energy resources within the urban environment, while simultaneously reducing noise pollution for nearby civilians. By utilising NBs to mount wind turbines and solar panels upon, energy production can be realised close to the consumer, reducing losses from transmission and overall system costs.

By harvesting energy in urban environments the Energy wall aims to either feed the energy into the local electricity grid to directly power nearby loads or store for later usage. This is in line with the growth of distributed generation that has been experienced. When these projects are built in an urban environment they are usually on a small scale, such as on residential or commercial rooftops. This is due to a lack of space in urban areas, the Energy wall tackles this by utilising areas that are not available for other developments. Coupled with the fact that there is a lack of available land for solar parks in the Netherlands, which is causing land prices to increase [7]. Figure 2.0.1 shows an artists impression of the project, with a solar PV face while on the top of the NB are ducted wind turbines.

It should be ensured that any alterations or future designs do not compromise the noise reduction capabilities of the NB. For this reason sound absorbing NBs should not be converted because PV panels reflective nature. It will be explored as to how the utilisation of a NB differs from conventional ground or roof-mounted PV arrays.

Figure 2.0.1: Artists impression of the Energy wall, a hybrid solar-wind energy generation facility

2.1 MOTIVATION FOR CARBON NEUTRAL HIGHWAYS

The province of Zuid-Holland has the motivation to make the N470 highway an energy generating road through the implementation of innovative projects, these are presented on the *N470 Geeft Energie* website. This is a road that passes adjacent to the TU Delft campus which makes it a good location for a test site of the Energy wall, which, as of April 2018 had its first wind turbine installed.

The Delft N470 NB is located on the intersection between the N470 & A13, its potential conversion was studied closely in [8]. This is one of the many projects that the Netherlands is using to meet its European targets of reducing CO2 emissions. While the country looks to use its current infrastructure in a more sustainable way.

Further along the N470 highway in Pijnacker-Nootdorp is a solar noise barrier or PVNB (Photovoltaic Noise Barrier), stretching 480m in length and 2.5m high. This project focused on the integration of PV cells in the noise reflecting glass, the resulting system is said to generate 25$\frac{kWh}{m^2}$ annually.

2.2 SIMILAR PROJECTS IN EUROPE

PVNB are not new to Europe and have been studied since the 80's but they have not seen widespread deployment. With reducing PV system costs the motivation to generate energy renewably in urban areas is growing.

The first PVNB was installed along the A13 in Switzerland in 1989 [9], since then many more PVNBs have been built, incorporating a range of technology through innovation.

In 1998 a PVNB was installed on the A9 Highway near Ouderkerk aan de Amstel, Netherlands, in which 220kW of AC PV panels were installed on top of the NB, testing two types of inverter. It is believed that this project is no longer operational but is still in place performing its primary role of noise mitigation. The recommendations from this project were to carry out an annual cleaning regime and that monitoring should remain for the life of the project [10].

One of the most relevant projects that is currently under construction is the Solar highways project near Uden, Netherlands. The design consists of bifacial integrated PV cells inside the reflective glass, taking advantage of the east/west facing NB. The project received a grant of €1.4M from the European commission under its LIFE (Financial Instrument for the Environment) fund. The PVNB is expected to generate energy to power 40 households and be up and operational by the end of 2018. The project is in collaboration with SEAC (Solar Energy Application Centre), ECN (Energy research Centre Netherlands) and RWS (Rijkswaterstaat) - The Dutch Ministry of Infrastructure and the Environment.

The SONOB project is an experimental setup testing LSC (Luminescent Solar Concentrators), built in 's-Hertogenbosch, Netherlands, to investigate the effects of shading, orientation and the performance of LSC PVNBs. The study also evaluates the effect of graffiti on system performance which appears commonly on NBs to determine the effect on energy production.

2.3 Cost Reduction Opportunities

Costs are critical to the validity of renewables, the Energy wall project is no different, it is competing with already well established technologies. Therefore, it is imperative that savings are found wherever possible, such as utilising the already in place structure.

High dependence is placed on RWS to determine the cost of the land as they own all the highways and the thin strip of land alongside, on which the NBs are located. Cost sharing opportunities are likely to present themselves if the PV was installed or integrated at the same time as the NB was erected.

2.3.1 Decreasing PV System Cost Trends

The picture is constantly changing in the world of PV costs, since October 2017, the MIP (Minimum Import Tax) on Chinese solar panels is being lifted, this will result in even cheaper hardware being available on the Dutch market, [11] claims of module prices as low as €0.18/Wp.

This seemingly monotonic decline in PV module price is expected to continue with BNEF (Bloomberg New Energy Finance) predicting a 34% decline in the price of multi-crystalline modules by the end of 2018 to $0.24/Wp [12].

2.3.2 Cost Comparison of Similar Projects

A comparison is made between different types of NBs, with and without PV panels, exploring monofacial, bifacial and thin-film transparent. The project finds that a low cost concrete barrier with monofacial PV, thanks to the offset from a high energy yield becomes the best financial option to take [13].

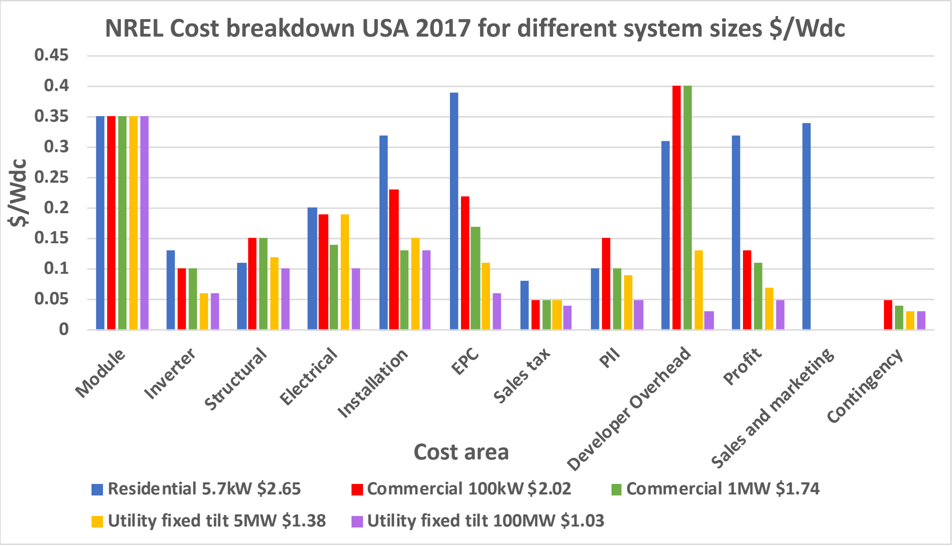


Figure 2.3.1: NREL cost breakdown for different PV system sizes [14]

2.3.3 ECONOMIES OF SCALE

When purchasing in bulk the price per unit is likely to be reduced, the same applies to large engineering projects. Much larger project incurring costs from the transportation of hardware, resources and labour will see lower overall costs.

Figure 2.3.1 shows NRELs cost breakdown for 2017 of different scales of system, with smaller projects being subject to much larger costs in some areas that larger projects don't have to consider such as sales and marketing. It should be noted that the displayed prices are from the USA, where prices were far higher than in Europe.

This however led to the decision to analyse different system sizes to explore cost opportunities that arise.

2.3.4 MODULAR DESIGN STRATEGIES

When designing modularly, savings can be made in installation time due to less work required on site, but this gives the design less flexibility. This may be possible with known dimensions and similarities between NBs. This is especially important when working next to highways to improve the safety of the workforce and reduces disruption of the roads.

2.3.5 Reduction in mounting structures

Through the utilisation of the currently installed NB, a lower cost for mounting structure should be realised. This will not be true if extra mechanical components are required to safely mount the additional technology to the NB, however, this itself will depend on the type of PV and NB. Savings with respect to the Energy wall vs a conventional roof-top or ground mount system are expected to present themselves.

2.4 Summary

The concept of the Energy wall has been introduced, explaining how it further utilises land near highways that was previously redundant apart from its noise mitigating abilities. It has been shown that this is an active area of research, where many PVNB projects have been completed in Europe. As of yet, widespread implementation has not been seen, despite some of the cost opportunities that were discussed. The combination of decreasing PV module price, economies of scale and pre-manufactured modular designs, may result in a much more attractive investment. To find these some more comprehensive research and design is needed.

3

GIS Noise Barrier Infrastructure Study

GIS (Geographical Information System) is a tool that allows for the analysis of spatial or geographic data, such as infrastructure, natural environment & demographics. GIS is used to assess the NB infrastructure to find the most advantageous sites for Energy wall conversion.

This chapter will aim to determine the potential for the Energy wall in the Netherlands by developing a methodology using the software, QGIS.

Data from RWS allowed for an analysis to be carried out on the Dutch NB infrastructure. From this, statistics could be drawn up and correlations between measured and calculated data could be found, to determine the suitability of the Energy wall in the Netherlands. Firstly, by looking at the defining attributes that make up the dataset of different types of NBs in the Netherlands. From this it is determined which attributes of NBs have the highest influence on the performance.

With analysis can be used to see how the Energy wall will integrate and interact with its surroundings.

The Netherlands holds an extensive infrastructure of NBs, the dataset being used was attained in October 2017. There were 6,138 NB segments, consisted of 1,071km of NBs, this number is likely to have increased by now. A **Segment** is defined as a length of a NB in which none of the attributes change along its length for the provided dataset. An **Entity** is defined as a continuous length of NB which can consist of many segments where attributes such as height & material etc, can change.

To bring more focus to the analysis, it was decided to base the study on a smaller geographical area with a high density of NBs and a motivation for urban sustainable integration. For this reason, the Rotterdam ring with its 62.5km of NBs that encircles the city was selected, in this way, a national and local level could be analysed and compared.

3.1 Noise Barrier Attributes

It was essential to find out how many NBs were suitable for conversion and how many were not. this judgement was based on literature, investigating how and why NBs work to identify the key attributes that would effect the performance on qualitative grounds.

3.1.1 Noise Barrier Size

The original dataset did not contain the height of the NBs, which is important to find the usable area on which solar panels can be mounted. The original dataset did include a Z-coordinate with reference to the NAP (National Amsterdam Peil/level), a vertical datum.

The technique involved subtracting the Z-coordinate from the ground elevation data, where the difference would be the height of barrier. The ground elevation data was attained from Lidar (Light detection and ranging) data. For the Netherlands this comes under the name of AHN (Actueel Hoogtebestand Nederland/ Actual Height Netherlands), consisting of three versions. AHN1 is outdated and of a too low resolution; 2004 measurements and 25m resolution. AHN 2 & 3 are of a greater resolution, consequently the entire dataset is made up of 1300 files of over 500MB each. This meant that the whole dataset was not able to be loaded on the available PC.

It was decided at this point to focus on the Rotterdam ring and use twelve 5km by 6.25km blocks from AHN2 to find the specific height of barriers which contained 470 NB segments. This meant that a country wide study couldn't be carried out. A method in [15] encountered this problem and used a shape file of state owned land 'Staatseigendommen' to clip the data to only the useful area; as all NBs are on state owned land. This was not used because of a failed reference to the source. The resulting distribution of NB heights for the Rotterdam ring can be found in figure 3.1.1.

It was found that for the Rotterdam ring the average height was around 5m, however problems occurred with this methodology. Cases when NBs were located on bridges, their Z-Coordinate was very high with reference to the NAP, but the base of the NB was not necessarily located at ground level. NBs going underneath roads found that the ground elevation was greater than the Z-Coordinate of the NB. These cases resulted in large or negative NB heights, however these occurred only for a few cases so were manually changed based on observation.

3.1.2 Noise Barrier Material

Depending on the specific requirements of the system (reflective or absorptive), space availability and finances, the materials used for construction can vary greatly. The original dataset consisted of a pri-

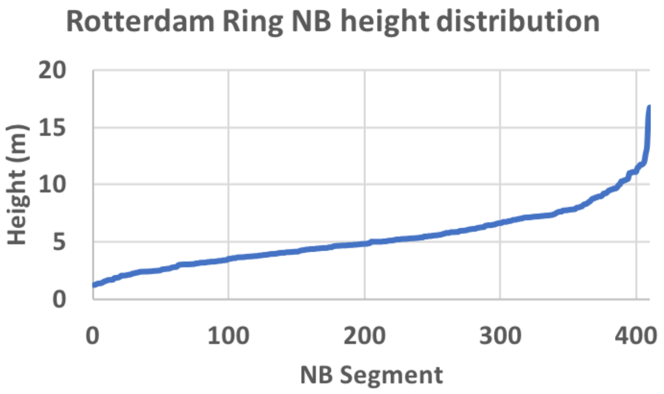


Figure 3.1.1: Height of NBs around the Rotterdam ring road that are of a suitable material for Energy wall conversion

mary and secondary material (if used), the length of NBs based on primary material are shown in figure 3.1.2.

Based on literature it was decided that the following materials would be excluded from the dataset due to their lack of suitability with the Energy wall conversion: Earth embankments, Wood & Timber, Stone Gabions and Vegetative. The reasons for exclusion varies from instability, susceptibility to damage or graffiti and being organic based, which could cause shading or the decay of the barrier itself if converted. Another material was specified as unknown/remaining, for lack of certainty these were also excluded. After their exclusion, 410 segments remained, which left a total of 48.7km of NBs, or 78%.

It can be seen from figure 3.1.2 that for the Rotterdam ring a greater proportion of the NBs are suitable for Energy wall conversion than the country wide, mainly due to the decline in the use of earth embankments. This could be a result of their much larger footprint as space is harder to find in a city environment.

3.1.3 ORIENTATION

Another attribute not included in the original dataset was orientation, this was calculated by finding the gradient between the first and last XY coordinates of each NB line segment by applying equation 3.1.

$$(atan((xat(-1) - xat(0))/(yat(-1) - yat(0)))) \times 180/3.14159 + 90 \tag{3.1}$$

It was found that for the Netherlands each degree of orientation on average consisted of 6000m of

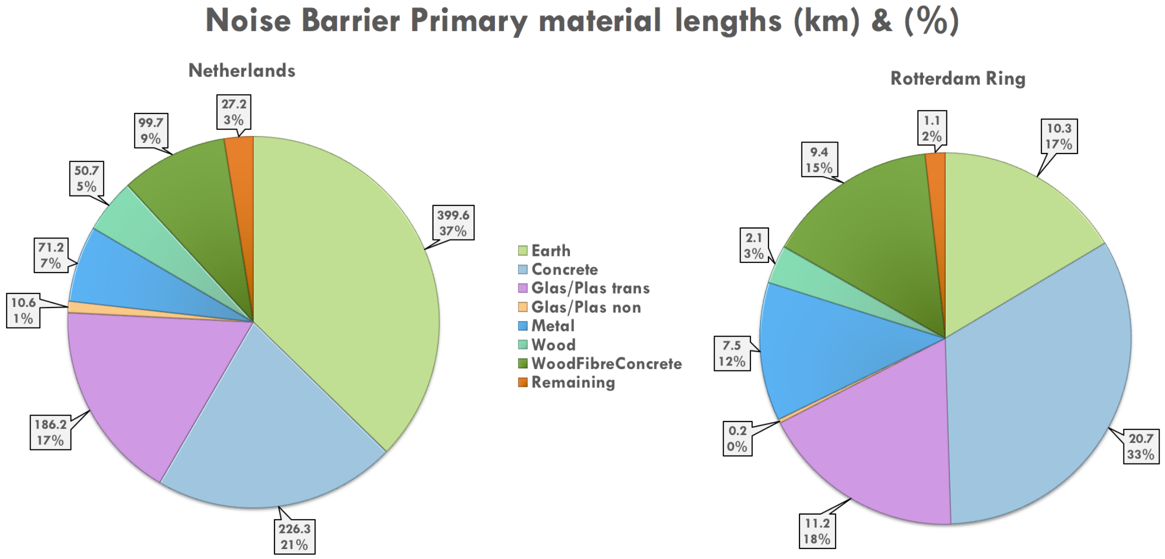


Figure 3.1.2: Material statistics for the Netherlands & Rotterdam ring (km, %), unsuitable materials accounting for 45% and 22% respectively

NB infrastructure, while for the Rotterdam ring was much closer to 400m. However, the rectangular shape of the Rotterdam ring resulted in a less homogeneous distribution of orientations compared to the country wide analysis with high densities at 20°, 80°& 170°. Where **0°** & **180°** are **East/West** direction NBs, the distributions can be seen in figure 3.1.3. A single orientation was taken per barrier segment while in reality the orientation would change along the length.

3.1.4 TILT ANGLE & DIRECTION

Determining which angle PV panels will be mounted on and whether that will be on the road or back-side are important characteristics to determine. This is because it effects the yield, safety of installation and shading from vehicles or vegetation.

Figure 3.1.4 shows the tilt directions for the Netherlands and Rotterdam ring 99% & 98% of the NBs either have no tilt or lean back, showing that it is very rare to have forwards leaning NBs.

To find the direction of the face a vector layer was added to each NB object which detected intersections with the road vector layer, in this way it could be found which side of the road the NB was on. This allowed for the direction of tilt and angle to estimate solar potential; a 20°backwards tilt facing south would receive very different amounts of irradiance than a north facing one. Some cases due to curved roads indicated an intersection in two directions, for example the south and the west this meant

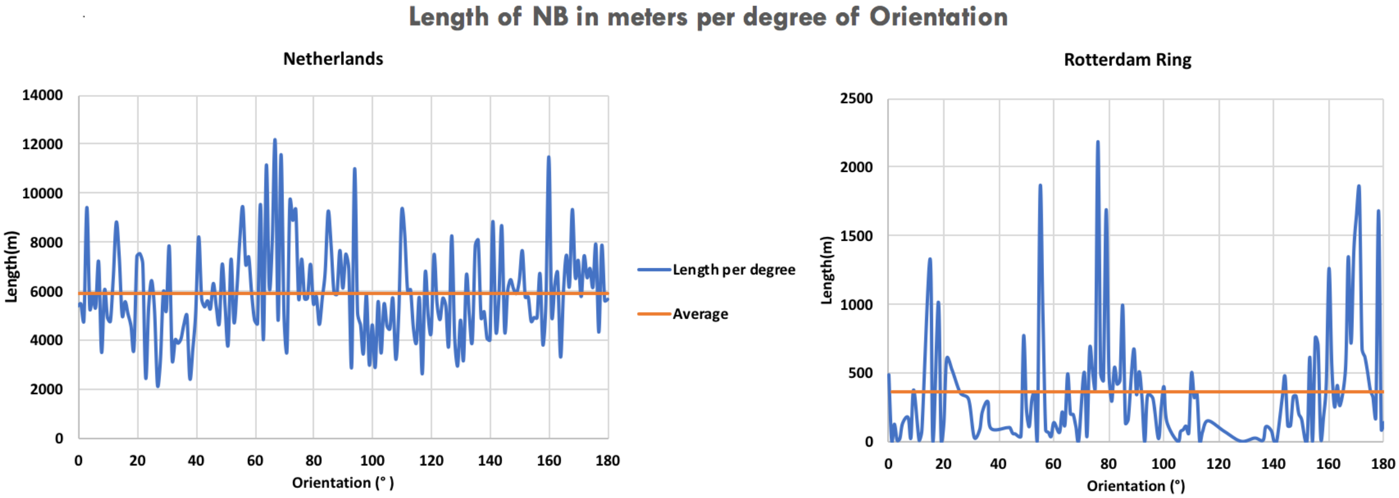


Figure 3.1.3: Length in meters per degree of orientation for the Netherlands and Rotterdam Ring respectively, with orange indicating the average

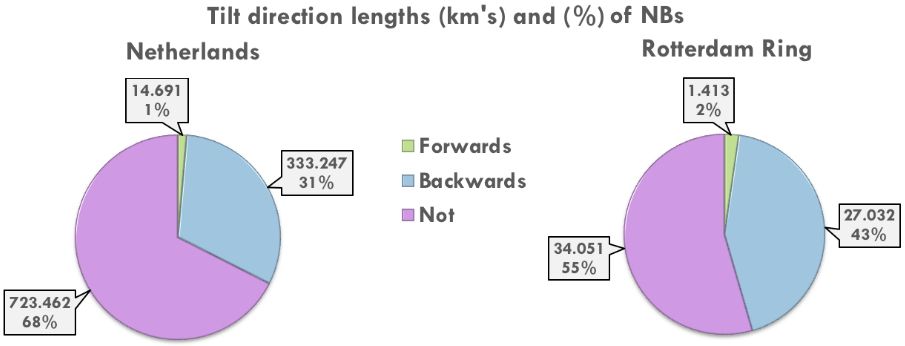


Figure 3.1.4: Pie charts showing the tilt direction of NBs in relation to the road where forwards is leaning towards the road for the Netherlands and Rotterdam ring respectively

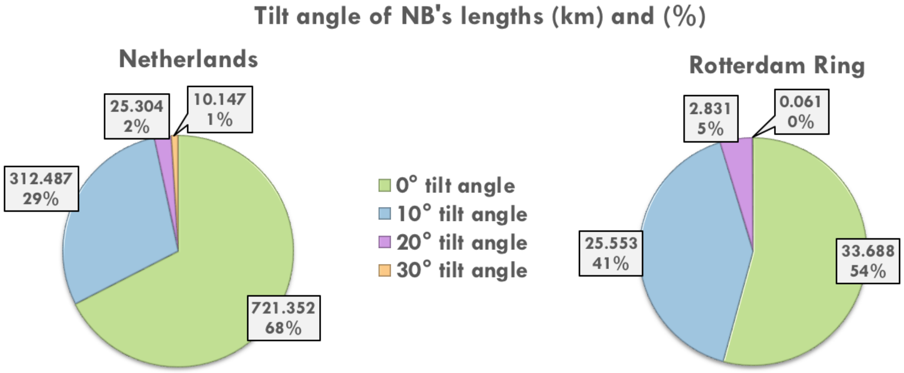


Figure 3.1.5: Pie charts showing the tilt angle of NBs where 0°is vertical, an inherited attribute from Rijkswaterstaat for the Netherlands and Rotterdam ring respectively

that the road was to the south west of the object. However, in extreme cases where the NBs was on a centre divide, all four cardinal directions resulted in an intersection. These had to be manually altered, which meant that this method could not be applied nationwide.

Figure 3.1.4 shows that larger tilt angles are deployed less frequently than 0°or 10°NB, where for the Netherlands only 3% of the NBs had a tilt greater than 10 °while for Rotterdam it was 5%. Solar PV in the Netherlands has an optimum tilt angle of around 55°from vertical for solar PV to achieve a maximum annual yield, therefore a significant reduction in performance is expected if flat mounted [16].

3.2 The Rotterdam Ring Investigation

To determine the Energy walls suitability for the nearby electrical infrastructure and loads, greater detail is required. The Rotterdam ring was selected because it offers a wide range of NBs in a relatively small geographical area. The city is also one of the most populous cities in the Netherlands and a huge hub for international trade.

3.2.1 Electrical Infrastructure

NBs are predominately located near residential areas as shown in figure 3.2.1, they are the most susceptible to disturbance from the highways which could even affect their health. This inherently meant that the NBs are located near/adjacent to electrical loads. With a focus on Rotterdam the RGO (Regional

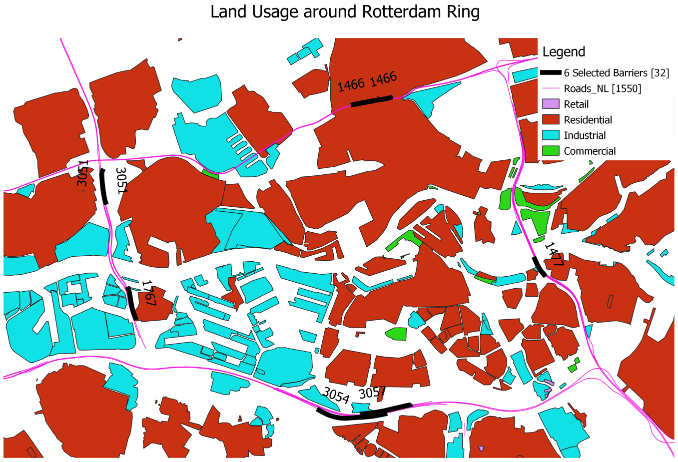


Figure 3.2.1: Land use data from CBS (Centraal Bureau voor de Statistiek)

Grid Operator) is Stedin, therefor data of the low voltage cabling and medium voltage transformers was used from Stedins open source data.

Electrical loads were the focus of this project because of their dominance as an energy carrier in the urban environment which would allow for high compatibility and direct use of the Energy wall. An electrical system can connect to a well-established network such as the one in Rotterdam. Alternatively converting the energy to heat to feed heating district could be another option as heat pumps become more used.

A grid-connected system allows for the minimal viable system to be produced, when autonomy is added the energy storage components become a major contributor to the overall system cost. In an urban environment with a well-developed grid, autonomy is less essential.

The open source data from Stedin allowed the distance to nearest grid connection point to be found, by running a nearest neighbour analysis with the NNJoin plugin, the results can be found in figure 3.2.2. It shows that for all 410 segments around the Rotterdam ring the distance ranged from 21.9m to 485m with an average of 175m. It should be noted that this distance is derived from the shortest path between the two objects, when installing cabling objects are likely to block a direct path so this could further increase the distance.

3.2.2 POTENTIAL LOAD MATCHING

When a grid-tied system is implemented there is a lack of storage, it is therefore ideal for the system to generate energy when it is to be consumed. This is a major problem currently with connecting

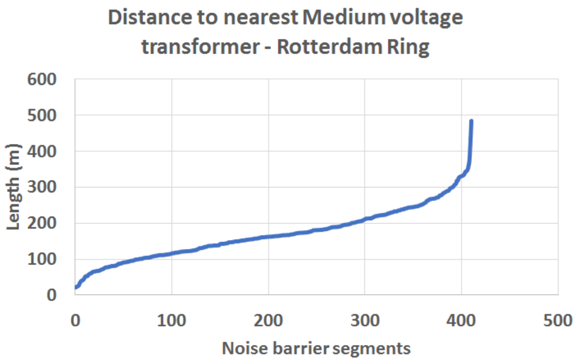


Figure 3.2.2: Ascending distances to transformers for all suitable material NBs around the Rotterdam ring

renewables to the grid; they destabilise the grid because of their intermittency. Solar having a large increase in production for the summer when for colder countries it is likely that their consumption will peak in winter. The Netherlands has a strong dependence on natural gas for space heating [17], but as this is gradually electrified the electricity demand is set to increase in the winter months especially.

A greater need for electrification is desired because of a reduction in CO2 emissions when the electricity is generated renewably. For the Netherlands, which is very dependent on gas, the move away from gas will be extremely difficult, despite some safety concerns with extraction, causing earthquakes in Groningen [18]. Intraday fluctuations put strain on the grid, resulting in the controllable energy sources needing to be activated, which usually emit CO2. These intraday fluctuations can be seen in the spot price for electricity, for example, on the day of writing, the cost of electricity was 78% more at 11am than it was at 4am [19].

Areas with a higher demand can be prioritised to locate production sources like the Energy wall near. These could be areas with high densities of residents or industrial areas with large consumption, however energy sources located in and around these areas are likely to have a greater impact in supporting the grid. Different sectors exhibit different energy usage trends throughout the day and week, loads that match the generation would benefit most from its direct usage.

By correlating land use and energy consumption data it was possible to find average energy consumption by land use type for the Netherlands as shown in table 3.2.1. This can then be used to identify how much of the annual demand can be satisfied by the Energy wall while making the quantity of energy easier to understand for civilians.

Table 3.2.1: Average energy consumption in kWh by land type for the area around Rotterdam

Type	Average Annual Energy Consumption (KWh)
Residential	3,264
Commercial	7,773
Retail	8,651
Industrial	10,054

3.3 NOISE BARRIER ENERGY POTENTIAL METHODOLOGY

The methodology aims at classifying NBs based on energy potential from solar PV & micro-wind turbines. This is to aid in locating NBs that would yield the greatest potential if converted.

3.3.1 SOLAR

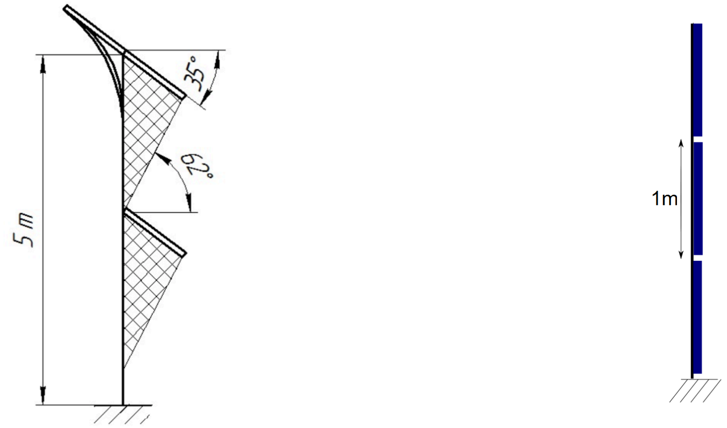
Orientation had one of the largest effects on potential, where PV would usually be mounted on the most southerly side.

Using the available area from the length and height of the barriers, the number of PV panels that it is possible to fit on the NB can be found using the geometry of the NB and a Suniva OPT340- 72-4-100 module. Two configurations were explored, one tilting at 35°with two rows on the top of the NB while the next row could be located at a sufficient distance to keep it out of the shade during the summer solstice. The second configuration mounts the PV panels directly on the surface, utilising the inherited tilt angle of the NB, these designs are shown in figure 3.3.1.

3.3.2 CORRECTION FACTORS

PVGIS is a free tool from the European commission JRC, to enhance public access to solar potentials. It was used to find how the solar potential deviated with tilt angle and orientation, these have been coined as a correction factors. They have been assigned values between 0 to 1, which together will help determine the overall loss in performance that each NB is likely to experience when compared to the optimal annual yield, these can be seen in figure 3.3.2. It can be seen that the orientation can result in a larger loss in solar potential if orientating north, however, in this situation the reverse side of the NB is likely to be utilised unless results in negative inclination. For the tilt angles found in section 3.1.5, it is seen that the NBs will incur a correction of between 0.85 & 0.7.

Multiplying this by the number of modules located on the NB allows for an easy to handle dataset based on solar energy potential considering the geometries of the NBs. This could be used to find the



(a) Model presented by Aleksandrova [20] 35°tilt, consideration for summer solstice elevation in Delft

(b) Configuration consisting of placing solar panels flat on the surface

Figure 3.3.1: Two solar configurations considered for the design of the Energy wall

single highest potential NB or highest energy density per meter in length. Allowing NBs to be selected for the next stage.

3.3.3 WIND

For hybrid systems turbines from wind challenge are to be placed every 6m on the NBs posts, which support the structure and holds the sounds reflecting or absorbing material in place; this is the standard for modular NB design [21]. The wind challenge is a HAWT (Horizontal Axis Wind Turbine) which is the more common type used for energy production and matches the one mounted on the N470 NB.

Wind resource data was taken from KNMI at the Rotterdam airport, this was translated to each NBs location in order to find the wind speed at each site. To do this the logarithmic law was applied which relied on the local roughness data for every 30°, this roughness was founded by applying a DEM (Digital Elevation Model) on data from Eurostat. Only one roughness plot was made per NB segment where in reality the entire length should be found as the surrounding environment changes. The roughness area only considered a thin strip of land instead of the entire 30°arc. Therefore, not all data is encapsulated in this roughness factor but with the analysis being carried out for the Netherlands; known to be one of the flattest countries in the world, this simplification is justified.

The wind speed was translated from the measurement site to each site by applying equation 3.2 to find the wind speed at a height where ground roughness no longer effects wind speed; the meso height

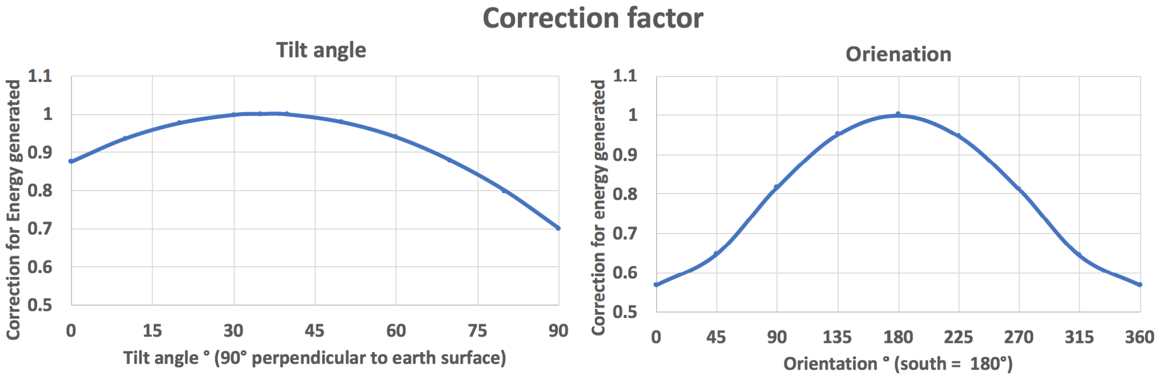


Figure 3.3.2: Correction factors applied for Delft to find solar potential, gained from PVGIS

(60m). Where Zo represents roughness at the measurement site = 0.03 and Z1 is the local roughness as found in the previously presented methodology. This speed was then brought down to each site by applying equation 3.3 with the local roughness at each site. Depending on the wind direction data the different local roughness for each section could be applied, this was carried out by an hourly Matlab script.

$$U(hmeso) = U(ho) \times \frac{ln\frac{hmeso}{zo}}{ln\frac{ho}{zo}} \tag{3.2}$$

$$U(hhub) = U(hmeso) \times \frac{ln\frac{hhub}{z1}}{ln\frac{hmeso}{z1}} \tag{3.3}$$

An additional phenomenon was incorporated based on the study [22], where depending on the wind direction, an increase or decrease in wind speed was experienced depending on whether the wind flow was perpendicular or parallel to the NB.

Chrysochoidis-Antsos [23] shows that if the wind direction falls within a range of ±50° perpendicular to the face of the barrier, an increase in wind speed can be achieved. This measurement setup was carried out on the N470 NB at Delft and measured tilted flows caused by the NB.

The distribution of wind speeds around the Rotterdam ring can be seen in figure 3.3.3. Using a power curve, it was found that with the wind challenge turbine mounted 2.5m above the NB the wind resource was on average 3.8m/s which is too low; operating between 40W & 80W, of the rated 700W.

The wind turbine aspect has been investigated more intensely in [8]. It could be the case that a wind turbine better suited to lower wind speeds should be used. It should be noted that these winds are likely to be turbulent because of the effects of traffic and the NBs itself, so VAWTs (Vertical Axis Wind

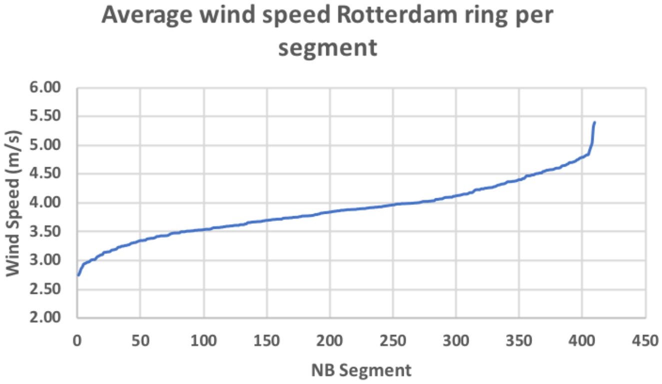


Figure 3.3.3: Ascending ordered wind speed for all Rotterdam ring segments

Turbine) may perform better. The wake effect was not considered between neighbouring turbines which would result in lower wind speeds depending on orientation.

3.4 SUMMARY

The GIS infrastructure study started by working on the original dataset from RWS, which contained over 1071km of NB. It was found that many of the key attributes required for finding the potential were not included. Consequently the missing data had to be calculated by using other resources such as the LIDAR data for the Netherlands to find the height of the NBs.

The height and orientation were the biggest determinant attributes in energy potential. Based on literature it was understood that not all NB materials would be suitable for NB conversion. Therefore, a filter was applied which left 590km of NBs in the country or leaving 55%, for the Rotterdam ring, 78% remained.

Showing that there is a considerable expanse of infrastructure in the Netherlands, making it a good country for the application for the Energy wall. However, due to the lack of computing power the entire methodology was not able to be applied nationwide.

To understand the potential of the NBs, correction factors had to be implemented as gained from PVIGS.

Two mechanical configurations were considered, it was found that in 94% of situations around Rotterdam that the flat surface mount configuration out performed the optimally inclined one. This is due to the lower space utilisation of the surface left due to mutual shading consideration.

Some trouble cases were encountered and manually changed with the methodology related to height data and face direction, this meant that the same analysis couldn't be applied nationwide.

After conducting an hourly wind potential analysis, considering local wind speeds, direction and roughness', it was found to not be beneficial to mount turbines because of the low wind speeds with the turbines considered. Which is in agreement with [8] in which the price for micro-wind is currently too high to justify the hybrid system.

The remainder of the thesis therefore focuses on the solar aspect of the Energy wall. From this analysis, each segment around the Rotterdam ring gained an energy potential indicator, which can be used to prioritise sites according to expected potential as an entity or per meter.

4

Stakeholder & Economic Incentives

To understand whether the Energy wall will represent a positive investment, the range of stakeholders and subsidies should be explored. To determine the benefit the stakeholder will experience, the current price paid for the energy should be compared against, indicating the savings that can be made. MilieuCentraal [24] indicates that for small scale connections in 2018, the price of electricity in the Netherlands is €0.20/kWh [25]. €0.05/kWh of which is for the energy while the remaining is from VAT & Tax. Large consumers are likely to pay closer to just the cost of energy depending on their agreement with the utility company.

4.1 Stakeholder Analysis

Some business case opportunities for different organisations of stakeholders have been identified, where possible exploring the specific priority of each.

The land on which the NBs are located and the NB structures themselves are owned by RWS, they will be maintained by RWS or a third-party company, who may carry out other nearby maintenance on their behalf as well.

These projects could appeal to nearby residents and companies looking for financial gain, assisted through incentives. They could have motivations to self-consume the energy, for either financial, environmental or public image purposes.

4.1.1 ORGANISATIONAL STRUCTURE

Five scenarios are found in Meppelink [15] and presented below, it should be noted that a permit from RWS is needed for activities around national roadways, called 'Aanvraag Wbr beschikking'.

- **RWS (Rijkswaterstaat)** owns the land and system, as well as the electricity that it produces.

  This option requires the electricity to be cheaper than what RWS currently pays per MWh, as it's a large-scale consumer, it will receive cheaper rates because of lower taxes for large consumers. Self-consumption would make sense to increase the share of renewables in RWS' supply, where these sources could be on the site of consumption namely the street lighting and signs which in 2013 accounted for 36% of RWS' total electricity [26].

  RWS has the target for its infrastructure to be energy neutral by 2030, but do not have the ambition of becoming an electricity supplier, requiring additional permits. In order to mitigate some of the risks associated with such a project, RWS will often accept tenders for such projects under a DBFM (Design, Build, finance & maintain) contract, in which they relinquish much of the responsibility and will gain certain guarantees. Currently these projects have only been undertaken as pilot projects in collaboration with other companies, depending on their success it may result in more projects being realised such as the Solar highways one.

- A **Third party company** has ownership over the hardware and electricity by renting the land and NB from RWS.

  If the company consumes the power themselves they would increase their share of renewables, which may be at a more competitive price than they can purchase from the grid. If the system is equal to or smaller than $3x80A$ (Three phases of 80A) the RGO considers it to be a small connection and are obliged to purchase the electricity from this connection [27]. Connection sizes greater than this are considered large, the RGO is not obliged to purchase the energy from them which may only leave the self-consumption option. RWS would benefit from using the land for extra sources of revenue, it is not clear how much RWS would charge for this. This option is believed to be an attractive one to nearby companies around the Rotterdam Ring. However, RWS would have to oversee what operations are being carried out on their land for safety, ensuring regulation is being followed.

- **Utility company** owners the hardware and electricity while renting the land and NB from RWS.

  Either building the Energy wall themselves or making use of a DBFM contract. The electricity would have to be produced at a competitive price, the benefit from this method is that utility company already has the rights to sell electricity. This could see administration costs reduced, with an added value based on the price the company places on publicity or increased image due to renewables.

- **Cooperation of consumers**

  Under schemes, such as the postcoderoosregeling (virtual net metering), owners of the project can claim refunds on their energy taxes. While still having to pay RWS for the use of the land and NB, a price which as of yet is unclear. The contractor used is up to the cooperation, but it should be a registered and experienced company so that the system is up to standards and regulations. The maintenance should also be considered, which could be carried out by the same contractor or another. These schemes are of particular interest, they can instil a sense of community spirit, giving homeowners and small businesses an interesting investment opportunity. It is in line with high customer awareness regarding renewables, if well managed can be run fairly independent of input from RWS.

- **RWS owns** the Energy Wall and **leases** its use to nearby companies or buildings.

  Through this method RWS is not actually selling the energy but allowing these companies to directly use the energy produced by the wall. This would be handled by rijksvastgoedbedrijf, the Central Government Real Estate Agency which is in charge of leasing and sales of government property. RWS is likely to outsource the construction to again mitigate risks. This method would require significant input from RWS, which may make it a less attractive structure to them.

4.2 Policies in the Netherlands

A number of supportive schemes are available in the Netherlands which are very well documented making the administrative process for applications easy and fast. Websites such as *Energie Subsidiewijzer*, which checks whether the resident is eligible for any subsidies based on location, supplier, renewables installed etc. While *Energie Leveren* connects small-scale owners to RGO to register their renewable system, whereby the energy is able to be fed into the grid at what could be, a negotiable rate.

Schemes have changed in recent years but the latest will be discussed, differences arise between schemes based on system size, ownership and responsible authority.

Net metering is the process of turning back the electricity meter when on-site renewables generate excess power, which is then fed to the grid, as none of the NBs are on the site of a residence or property this cannot be employed.

Policies are categorised based on grid connection size or installation capacity. Grid connection size is defined by the grid operator, if an 80A connection is in place the grid operator has an 80A fuse connected, the customer side will have a *group* fuse of at least one size smaller [28]. As a rule of thumb the system fuse, known as the group fuse should be 1.6 times smaller than the main fuse, owned by the RGO. Meaning that if an 80A connection is in place, 80A cannot be drawn by a consumer but closer to 50A.

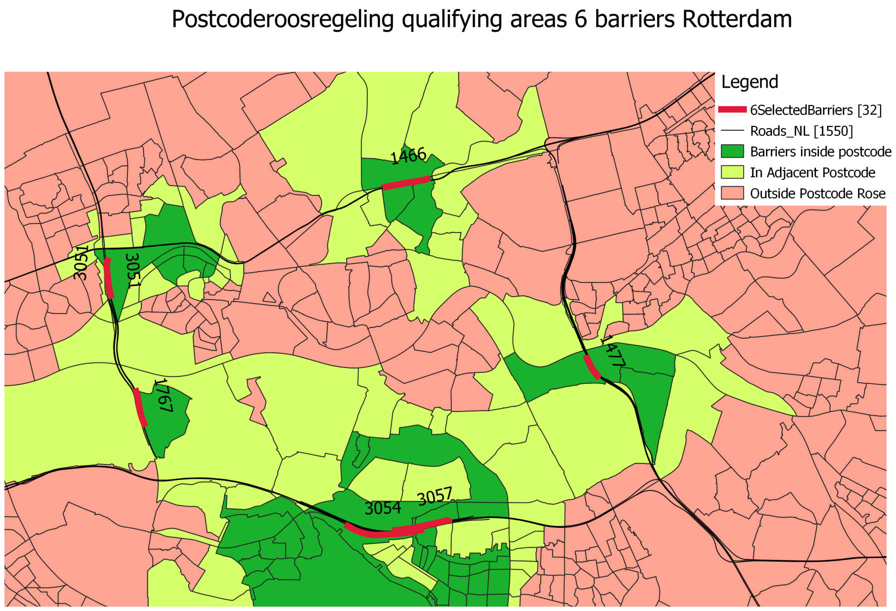


Figure 4.2.1: Map showing areas around Rotterdam that qualify for Postcoderoosregeling from just the 6 NBs based on 4-digit area code, Green contains the NB while yellow is an adjacent area code which in total contain a population = 705,000 (2016)

For net-metering a limitation is that you cannot be a net exporter, meaning that you will not be reimbursed if you inject more energy into the grid than you consumed. Therefore, this scheme is more of a cost saving than a revenue stream.

4.2.1 POSTCODEROOSREGELING

This scheme is a form of virtual the net metering, expanding the scheme to residents that do not have the finances for a complete system or the land on which to locate one. A group of residents or small business owners can collaborate to finance a project within their own 4-digit postcode or one of the adjoining postcode areas as shown in figure 4.2.1. Where this figure shows the areas that would be eligible under this scheme for six NBs around Rotterdam ring. They will earn a specific share of the system and the energy generated will count as a tax discount on their energy to the sum of €0.1226/kWh including VAT [29].

Under this scheme the connection size is limited to $\leq$ 3x80A, companies cannot own more than 20% and each participant can claim back a maximum of 10,000kWh in tax providing they consumed

Table 4.2.1: Solar PV rates and conditions Spring SDE+ 2018 [30] for solar PV only considering grid feeding

Solar PV	Phase 1 (€/kWh)	Phase 2 (€/kWh)	Phase 3 (€/kWh)	Correction amount	Maximum Full load (hours)	subsidy term (years)	Commissioning time (years)
≥15kWp & <1MWp	0.09	0.11	0.112	0.038	950	15	1.5
≥1MWp	0.09	0.107	0.107	0.038	950	15	3

more energy than they claim back tax for.

4.2.2 SDE+

Stimulering Duurzame Energieproductie (Stimulating Renewable Energy Production), this is the latest scheme aiming to attract utility scale investors, and is classed as a sliding premium tariff. This works by offering suppliers a premium price on top of the market price for electricity as an incentive for RE projects. The sliding element means that the level of incentive fluctuates with market price, through this a guaranteed price is offered, assuring investors.

To qualify for the scheme, the proposed system needs to require a grid connection greater than 3x80A, the incentives are usually applied for before the project is realised because of the huge potential shortfalls that could be incurred if it is not selected. Unlike with the net metering scheme there is a finite amount of funds available for these projects which for spring of 2018 was equal to €6 Billion [30].

For a project to qualify for the subsidy it must submit a bid, indicating the price per kWh the project wants as a subsidy. The lower this bid, the more likely it is to be selected but the less income the project will receive, therefore experienced advise should be utilised here. SDE+ has different prices for different renewable technologies, where each phase has a maximum subsidy that can be applied for. As the phases progress, this amount (in some cases) increases. There are specific limitations as to the number of hours that can be reimbursed for in a year, this will be determined by the capacity factor of the system. Other conditions such as the commissioning time are also expressed, while the subsidy is usually valid for 15 years [30].

Solar PV SDE+

This is the most common financing system for solar parks with 20 of the biggest 25 solar parks in the Netherlands using SDE+ [3]. There are two main solar categories; solar PV and solar thermal. Within the PV category there are two system size categories; 15kWp to 1MWp while the other is for systems greater than 1MWp.

Table 4.2.1 shows the maximum values that can be applied for at each phase along with a correction factor which can be used to find quantify the amount eligible for.

4.2.3 EIA

EIA stands for Energy Investment Allowance which grants tax reductions on income or corporation tax for companies in the Netherlands, that investment in energy-saving or sustainable energy technologies. There is extensive documentation around what qualifies for EIA, specifically for solar there is the opportunity to get a maximum refund of €750/kW of peak power for grid-tie systmes while an off-grid could receive up to €1000. The connection must be $\leq 3x80A$ with an installed capacity of at least 25kW, cost more than €2,500 and should meet the legal requirements of being a business asset.

4.2.4 KIA

Kleinschaligheidsinvesteringsaftrek translates to small scale investment allowance, the extent of these reductions are tabulated in 4.2.2. Like the EIA this subsidy is only for businesses as they are only eligible if they corporate tax or income tax, as entrepreneurs. If the project is carried out under a partnership the entire project cost is considered for subsidy.

Table 4.2.2: KIA - Small scale investment deduction for 2018 categorised by cost

Investment	Small scale investment deduction	Category
$\leq$ €2,300	€0	(1)
€2,301 to €56,642	28% of the investment amount	(2)
€56,643 to €104,891	€15,863	(3)
€104,892 to €314,673	€15,863 minus 7.56% of the part of the investment amount exceeding € 104,891	(4)
$>$ €314,673	€ 0	(5)

The MIA (Environment Investment Allowance) and VAMIL (Random Depreciation of Environmental Investments) was explored but found to not be of use for solar projects, unless the energy is being used for the charging of electric vehicles or the production of fuels such as hydrogen.

4.3 SUMMARY

It is clear that a wide range of stakeholders could be interested in the Energy wall project, where one stakeholder is always RWS.Business proposals are laid out to show the organisational complexity of the situation the Energy wall could fit into.

Subjectively it is believed that a third party company or a cooperation will be the most likely organisational structures to take place. For a utility company to invest would require the LCOE to be low enough that it is competitive while considering the value the company places on expanding its green renewable share. A RWS ownership system is likely to only occur under a DBFM contract to mitigate risk, while it is thought that the leasing method would require too much interaction from RWS.

Analysis of the current subsidies for renewable energy projects are presented, indicating who they apply to, along with the rules and regulations that must be adhered to. The political climate in the Netherlands is currently very supportive of innovative renewable projects, which is why the subsidies can have a strong influence on the projects validity, economically.

The latest 2018 data has been used for this analysis but the rules can change over time. It is therefore recommended that any project that aims to utilise them, carries out sufficient research. Rules such as that KIA or EIA cannot be used if the asset is to be made available to third parties, which is the organisational structure of RWS owning the system and leasing it out [31].

KIA can be applied for with EIA, however it is not clear as to the specific clauses that should be followed to qualify for both. There has now been enough development that a trend towards reducing the reliance on subsidies is already happening for offshore wind [32].

Postcoderoosregeling and SDE+ allow for guaranteed prices for energy to be determined, providing investors with more certainty, ensuring a greater opportunity for businesses, entrepreneurs and homeowners.

5

Energy Wall Technology Consideration

This chapter will present a basic theoretical introduction and overview of the technology considered, justifying its suitability for application in the Energy wall. Design strategies and tools that can be applied throughout the design process will be explained. Investigating which system topologies are most suitable and finding location dependent characteristics.

5.1 Solar PV

Solar energy can be harnessed in several ways, it can make use of the photovoltaic effect or it can be used for its thermal capabilities, either through concentration or for thermal heating. There is high complexity and additional mechanical components required for concentrating the solar energy. This makes it unsuitable for these road side applications, therefore only the Photovoltaic method will be explored in this project.

5.1.1 Photovoltaic Theory

Photovoltaics produces energy by converting light into electrical current, through the Photovoltaic effect. Light is made up of photons which hold packets of energy, when they hit a material this can cause electrons to be released within the material. Usually this creates an electron-hole pair that will recombine almost instantly. Materials are doped to increase conductivity so that the released electrons and holes are free to move around the lattice. The bringing together of a positively and negatively doped

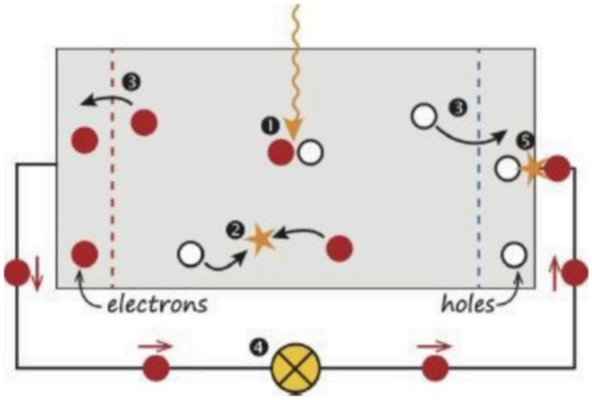


Figure 5.1.1: Smets et al [16] illustrates the steps performed when generating electricity from a solar cell. **1.** Absorption of a photon leads to the generation of an electron-hole pair. **2.** Usually, the electrons and holes will recombine. **3.** With semipermeable membranes the electrons and the holes can be separated. **4.** The separated electrons can be used to drive an electric circuit. **5.** After the electrons have passed through the circuit, they will recombine with holes.

material allows for an electric field to be produced between them. This electric field stops the previously released electron-hole pair from recombining as they cannot overcome this barrier produced by the electric field. When an electric circuit is connected this gives the electron-hole pair an alternative path in which to flow, causing an electrical current. This is illustrated in figure 5.1.1.

Power is defined by the voltage (V) and current (I), the best indicator for this in a solar cell is with an IV Curve as shown in figure 5.1.2. Maximum power is extracted when the point of operation is furthest from the origin, indicated by the MPP (Maximum Power Point), this point is represented on the axis by the $I_{MPP}\&V_{MPP}$. MPPTs (Maximum Power Point Trackers) are installed to find this point for variable conditions. Figure 5.1.2 shows, the IV curve varies with irradiance and cell temperature, operating at the wrong power point can severely reduce power output. Where irradiance influences the current and temperature influences the voltage, predominately.

5.1.2 SOLAR IRRADIANCE

To generate maximum energy the solar module should be perpendicular to the direction of the sun so that the maximum amount of photons land per unit area on its surface, this is known as DNI (Direct Normal Irradiance). To be in this state all year round would require a tracking system, something which is not feasible for the Energy wall project as already discussed. Globally inclined irradiance is a measure of the irradiance experienced at a fixed surface over the year. Such a measurement would

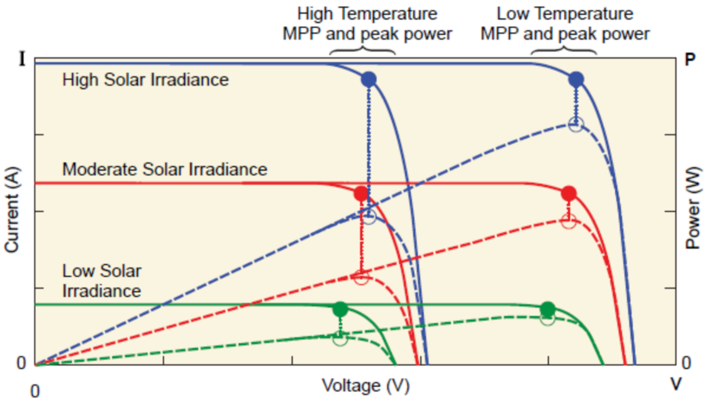


Figure 5.1.2: Effect of irradiance and temperature on solar IV and power curve [33]

indicate the energy present at the Energy wall if inclined to match the NB, which could also be used to assess performance of the system.

When dealing with a static PV panel the levels of solar irradiance will change daily due to the analemma, changing with respect to azimuth and altitude. To calculate the total incident energy all parts of equation 5.1 must be known for the specific location.

$$G_M = G_{Direct} + G_{Diffuse} + G_{Reflected} \tag{5.1}$$

The direct irradiance is determined by the angular difference between the module and the suns position. The energy wall would experience maximum solar irradiance when the sun is lower in the sky, during winter, early mornings or late afternoons depending on orientation.

The diffuse component of irradiance occurs due to scattering of photons in the atmosphere, which varies depending on solar position, cloud levels and the SVF (Sky View Factor).

The SVF becomes an important consideration for the Energy wall due to the abnormally steep tilt angle the PV panels will experience, when compared to conventional solar arrays. This is because as shown in equation 5.2 the portion of sky from which the PV can extract energy is reduced by between 50% to 32.9% for a vertical to 20°tilted NB respectively.

$$SVF = \frac{1 + cos(\theta)}{2} \tag{5.2}$$

Finally, another route that can be taken by photons is to be reflected from surfaces on the ground before reaching the PV panel. This could come from the tarmac, grass or even vehicles, due to the large tilt angle this is expected to have a stronger influence than for conventional systems, but is location dependent.

Table 5.1.1: Degradation rates by PV technology types (%/year) [34]

Solar cell type	Output loss (%/year)
Amorphous Silicon (a-Si)	0.87
Cadmium Telluride (CdTe)	0.4
Copper Indium Gallium Selenide (CIGS)	0.96
Monocrystalline Silicon (mono-Si)	0.36
Polycrystalline Silicon (poly-Si)	0.64

5.1.3 SHADING

Shading has a extremely negative effect on PV modules that can reduce performance at a rate far greater than the actual shaded area. This is because a shaded cell limits the whole flow of electrons for the entire module or array, unless lower performing cells/modules can be bypassed to mitigate the effect. Most PV modules will contain bypass diodes so that if a flow is limited by a shaded section, a separate route is activated. These will usually not be placed at every cell because of the additional costs, so the manufacturer will find an optimal layout considering cost vs energy production.

Shaded cells also create a voltage potential across them which causes it to dissipate energy in the form of heat, this can lead to cell damage and a reduced lifetime.

Shading from other modules, known as mutual shading, occurs when a big enough gap is not left between rows of PV. In the Energy walls roadside location shading will likely come from man-made objects and vegetation alike. Each site should be assessed to determine whether permanent structures like buildings will cause shading or if vegetative growth will occur and impede performance, in which case, maintenance regimes are considered. Uniquely for the energy wall the setback distance from the road should be considered as passing vehicles could cast a shadow on the PV panels. However, an accurate study of this would require a study of the transportation network and the type of vehicles in used, as the slow lane closest to the NB is likely to be larger vehicles.

5.1.4 MODULE DEGRADATION

Over time module performance is reduced caused by a range of factors, over heating can greatly increase this rate, often suppliers guarantee performance extending 25 years while maintaining 80% performance still. This fluctuates between types of PV with thin-film having a faster degradation than silicon for example [34]. The degradation rates used are shown by PV type and are shown in table 5.1.1.

5.1.5 PV MODULE MATERIAL

For the Energy wall study, it is imperative to find PV modules that will benefit from the attributes of the NB. The focus of the study was to find the best performing PV panels considering common types such as silicon as well as thin-film PV. Alternatives are explored because they have added benefits such as reduced weight and in some cases flexibility.

Mono and poly-crystalline silicon panels were considered, Mono-crystalline consists of a single lattice across the cell while a poly-crystalline is made up of smaller fragments of a lattice whose orientation is random. The poly-crystalline is easier to manufacture than mono, resulting in a cheaper manufacturing process but the edges of the fragments harbour defects which reduces performance.

CIGS (Copper Indium Gallium Selenide) which can range from CIS to CGS depending on the ratio of Indium and Gallium.

CdTe (Cadmium Telluride) which are known as Chalcogenide cells because of their inclusion of Selenide and Telluride respectively, however there are health concerns related to its toxicity.

A-Si (Amorphous Silicon) is similar to most conventional rigid panel PV panels except it is deposited in a far thinner layer on a flexible substrate, as such it has a lower efficiency but can accept a wider range of wavelengths.

CONSIDERED PV MODULES

The aim was to select a range of PV module types that represent average modules that can be found on the market currently. This being said, some PV types such as silicon have a far larger share of the global market than thin-film, as a result the price can often reflect this. A variety of suppliers were used to source prices for modules, however it was found that between suppliers there were large variation and no single supplier had all the modules available, a conversion rate of 1$ → €0.81 was used.

All modules have an efficiency rating, defined as the energy output under STC (Standard Test Conditions); $1000W/m^2$, cell temperature 25°C and an air mass of 1.5. The latter is the light spectrum that is experienced on the surface of the planet after light has travelled through the atmosphere. In reality these conditions are unlikely to occur, but it means that all modules are tested at a reference condition, making their efficiencies comparable.

The modules that were selected for the study are shown in table 5.1.2, where it can be seen that none of the selected modules are particularly close to the best research efficiencies [35], therefore representing commercialised modules.

All modules have a temperature coefficient, identified in table 5.1.2 which shows how the voltage, current and power change with temperature above 25°C. PV modules operate at higher power levels when in cooler conditions, while thin films have a particularly low temperature coefficient making them more attractive for high temperature locations.

Depending on the protocol of the company or organisation in charge of the project, a restriction

Table 5.1.2: Table of the main attributes from the selected PV panels.

Module name	**Company**	**Type**	**Rating (Wp)**	**η_m STC (%)**	**Weight (kg)**	**Area (m^2)**	**Best research [ ] efficiencies (%)**	**Temperature coeff (%/°C)**
FS-4 4122-3	First Solar	CdTe	122.5	17	12	0.72	22.1	-0.28
SF 175-S	Solar Frontier	CIS	175	14.2	20	1.228	22.6	-0.4
PowerFoil	HyET Solar	a-Si	165	8.5	1.3	1.927	14	-0.43
e-Flex FF120	Flisom	CIGS	120	9.4	2.4	1.276	22.6	-0.3
PowerFlex FG-1BTM	Global Solar	CIGS	300	12.6	9.3	2.83	22.6	-0.43
Optimus 340-72-4-100	Suniva	Mono c-Si	340	17.4	23	1.95	26.1	-0.42
TP660P	Talesun	Poly c-Si	275	16.9	14	1.62	22.3	-0.42

may be placed on where hardware can be sourced from. Requirement such as the hardware needing to be sourced from tier 1 company, this is enforced to ensure quality, but also as assurance that the company will survive to cover any warranty provided. RWS may have this requirement, while less knowledgeable organisations such as homeowner cooperation's may not have this requirement, this quality may be reflected in the price.

5.2 PV Systems

The PV system designed around the NB should have a lifetime of at least 25 years which is the standard for the PV modules and often how the economics are calculated. However, this can vary depending on technology used, conditions and level of maintenance carried out.

The target is to produce an efficient PV system that produces cheap energy to make the system a viable investment. 3 key areas for PV system future cost reductions have been identified in [36].

- DC-Voltage increase resulting in a reduction in cable cross section resulting in reduction in copper material and losses.
- System size through economies of scale, discussed in 2.3.3.
- Module efficiency, higher efficiency requires less panels to be installed, resulting in faster installation time, less support structure required, fewer cables, less site preparation, potentially also a reduction in planning and documentation due to the smaller land area required.

5.2.1 Roof and Ground-mounted PV Systems

Most conventional PV systems will be either roof or ground-mounted, where the roof-mounted is usually at residential or commercial scale because of the space requirement. Currently the largest solar park in Rotterdam is a commercial rooftop system consisting of 3100 modules, generating 750,000kWh [37]. While a ground-mounted system requires large areas of land on which to build.

It is advised that installers of these systems transfer as much of their knowledge from conventional systems to the Energy wall to lower costs.

IRENA [38] compares roof & ground-mounted systems, finding that ground-mounted systems cost less because of a lower site preparation and structural installation cost. This could be due to the roof requiring reinforcement as it may not be suitable for the extra weight. There is also the added difficulty of working at an elevated height which may result in additional costs.

Due to the utilisation of the NB, the Energy wall is closer to a roof-mounted system; workers will have to operate at height, and build around the current structure.

5.2.2 Building Integrated Photovoltaics

BIPV presents interesting similarities because of the verticality of the Energy wall. James et al [39] suggests that cost savings compared to conventional systems arise because less building material is required.

The design being developed near Uden, Netherlands, integrates bifacial solar cells into the noise reflecting glass material [40]. The integrated approach may be advantageous economically when there is no NB in place already because of the shared costs of labour and hardware, but is not the focus of this study. The Energy wall differs to BIPV in that no material savings are induced by the integration or retrofitting of the NB.

This means that integrated solar panels are not mass produced and would need to be specially designed and fabricated for this application, which ultimately increases costs.

Higher priority is given to aesthetics with BIPV systems which is why transparent modules might be used, however these properties often reduce the energy generation performance bringing the system cost up.

The level of integration or distance to the below mounting surface effects the cell temperature due to a limit on air flow. Smets et al [16] states, that when directly mounted, an increase of 18°C which can be detrimental.

5.3 Balance of System

Referred to as BOS, this makes up the components of a PV system that are not the PV modules themselves and varies between systems depending on requirements. These components are necessary to extract the energy from the PV panels to make usable energy.

5.3.1 Storage & Grid Transmission

Storage is used to preserve energy for later use, different methods of storage incur can posses a wide range of efficiencies and costs. The most conventional form is the battery because it is a relatively mature technology with high efficiencies, they do however leak energy over time and often consist of toxic and/or non-recyclable materials. Additional flexibility and security can be gained from storage's inclusion in the system, especially in stand-alone systems or areas where the grid cannot be relied upon.

It was found that the inclusion of a storage system significantly increased the CAPEX. Due to the well-developed grid in the Netherlands and the target for a low cost system, storage will not be included in the system design. The Energy wall is designed to further integrate renewable into the urban environment which would be more limited if a stand-alone system was designed.

Transmission on the grid must be facilitated by the RGO, which for Rotterdam would fall under the jurisdiction of Stedin. Stedin is in control of the distribution network for most of Zuid Holland and would therefore be responsible for facilitating the connection.

Well defined costs for the installation and maintenance of the connection are expressed by Stedin, priority is given to renewable energy depending on the size of the project. When large connections are installed grid reinforcement may be needed but is not explored in this study.

5.3.2 INVERTERS & DC CABLING

Inverters are used to convert the DC energy output from PV panels into AC power for AC loads or grid transmission. For continuity it was aimed to use a single inverter supplier as input into the model; 11 SMA America inverters were used. This was motivated by the availability of an online design web tool provided by SMA, which could be used to verify designs. It was found that there was a gap in the available product range provided by SMA, between 25kW and 50kW. To supplement the range it was deemed necessary to incorporate a 33kW inverter; a Zeversolar Pro 33k was chosen.

The range of selected inverters for the model ranged from 1.5kW to 60kW, larger inverters would require larger lengths of DC cabling to bring the power to a central location. This is a result of the low density of the Energy wall system, larger inverters also become bigger in size and weight which may be more difficult to install on the small strip of land adjacent to the NB. This allowed for a large system to be modularly divided up. All of these solar inverters incorporate at least one MPPT (Maximum Power Pointer Trackers). When multiple inputs are available then strings of different lengths can be attached to each, but the voltage should be as close to the MPPV (Maximum Power Point Voltage) of the inverter. If the inverter input limits are exceeded, irreparable damage will occur, resulting in a shorter life and need for early replacement.

DC Cabling is used to connect the modules together to create strings, each module in series increases the voltage of the string. These strings should be joined in parallel with others to increase the current of the array. Specific solar cables should be used which require MC4 connectors, the cables thickness is governed by the current that they will be carrying, but the voltage should not exceed the limit also.

5.3.3 MOUNTING STRUCTURE

The mounting structure is used to fix the PV panels in place, whether it be a rooftop or ground mounted system (the later would require foundations). An essential component for roof-mount systems are rails, on which the PV panels are connected via clamps.

The mounting structure must be strong, to withstand loading from the weight of the hardware, plus wind and snow but should itself be lightweight so as to not damage what it is standing on. Sometimes ballast is used to keep the system secure while other times through roof penetration occurs to secure the structure.

When on a roof a structural assessment is carried out to determine whether it can handle the weight or whether reinforcement is required. L-Feet and stand-offs are used to create a gap behind the PV modules to allow for air flow and for running cables.

5.4 TOPOLOGY

The interconnections of the system and the hardware have a strong influence on the behaviour and performance of the system, a priority to minimise hardware costs may lead to lower overall efficiencies resulting in a higher cost of energy.

5.4.1 SYSTEM ARCHITECTURE

A range of inverter topologies were considered, central inverters are one of the most common topologies for grid connected systems, it allows for a single inverter to convert all the energy generated by the array. String inverters are used to independently invert the energy from each string, allowing for a more localised conversion. Picault et al. [41] claims that the central topology is 1.5% less efficient but considering the fewer components required, can reduce the total cost of power conversion units by 60%.

A hybrid of this can be implemented which takes the central inverter architecture but splits the array into smaller sections which each have an independent inverter.

When several inverters are implemented across an array it could be the case that they operate in a master and slave configuration, where only the number of inverters needed for the amount of power being generated at any particular moment in time are used, thereby maximising efficiency [16]. This would require additional control and busses on which to transmit power.

5.4.2 MODULE LEVEL POWER ELECTRONICS (MLPE)

The incorporation of addition MLPE allows for more architectures to be explored, MLPE work at a module level ensuring that each performs at its optimum power point at all times. Aiming to mitigate the effects of shading and are said to potentially pay for themselves through an increased yield.

A comment from an interviewee was that apart from increasing the energy yield, MLPEs could reduce module degradation and likely have incorporated monitoring which can reduce maintenance. The two main types of MLPE will be explored here.

DC Power Optimisers

DC power optimisers work by keeping each module operating at its own MPP by varying the current output but ensuring that the entire string is at the V_{MPP} of the connected inverter. Some Power optimisers allow for two PV modules to be connected to a single power optimiser allowing for half the number to be installed while still allowing localised monitoring and performance control. This could result in a lower performance, but consideration must be given to how different the conditions will be for two adjoining modules.

Microinverters

Microinverters operate by converting the energy generated at each PV panel to AC, sometimes this is integrated into the module making an AC module and other times it is an additional component to be attached. This removes the need for another inverter to be used, this allows for direct feeding to AC loads or the grid when combined.

5.4.3 AC Vs DC

The choice of whether to design an AC, DC or hybrid network was considered. Minimal losses are desirable therefore the number of conversions between AC & DC should be minimised. Most transmission networks are AC but many household appliances are trending towards being DC loads.

While AC power has reactive power; power that cannot be used for work, ultimately reducing its efficiency. This is caused by inductive loads such as transformers, motors and generators, of which the system has none. The level of reactive power is determined by the PF (Power factor) which has a range of 0 to 1.

This means that a purely DC system will have a kW rating = to the KVA rating, which is the case for PV.

Starke et al [42] concludes that an advantage can come from using DC distribution if there are sufficient DC loads in the network where DC/DC converters should operate at high efficiencies. While 3 phase AC has the potential (depending on PF) to deliver 3 times the power compared to DC. One of the biggest factors in determining the best transmission method is to match the majority of the loads which in the grid-tie system is AC.

5.5 SUMMARY

The theory behind photovoltaics was introduced, followed by some of the effects that could reduce the energy walls abilities to convert light into electricity.

Comparisons of the would-be implemented technology is presented, showing some of their respective shortfalls. Justification was given to the selection of the PV modules, in hopes to represent typical PV modules on the market today. Introducing degradation rates and temperature coefficient that will effect performance.

Differences between the Energy wall and other PV systems were used to draw similarities, in order to determine which skills, technology or knowledge is transferable, in the hope of reducing overall costs.

Consideration must be given to the distance between the PV and the NB to allow for natural convection to occur. While an AC transmission system is advised when an AC load such as the grid is the system load.

The BOS for the grid-connection system was explored justifying the exclusion of storage, explaining the benefits that come from being a grid-connected system. Followed by system topologies that could be implemented with the introduction of MLPE and the role they could play in the Energy wall. This is used to inform the reader of the range of options available to the designer.

6

Multi-criteria Energy Wall System Design

The technologies that were introduced in the previous chapter are implemented to find advantages from their application in different environments within a relatively small geographic area; the Rotterdam ring. Six sites are selected and introduced along with geospatial and NB characteristics gained from the GIS analysis and site observations, these NBs were selected based on their variety of characteristics.

This section will aim to produce a model that incorporates a multitude of variables that will effect the final system cost and performance. The core data was transferred from GIS into excel, this is where the model was developed due to a need for table manipulation that other software makes more time consuming.

A large number of systems are simulated, using local meteorological data for each. With the target of finding trends that are applicable to larger data set, of varying NB, system size and technology.

Following the initial design procedures, a sensitivity analysis shows vulnerability of the system to external factors such as the local electrical infrastructure.

The project focuses on the conversion of the already existing NB infrastructure by mounting technology on the surface of, without replacing key NB components, i.e. retrofitting.

6.1 Rotterdam Ring Case Studies

The Rotterdam Ring was selected due to its high density of NBs in a relatively close geographical area where such a large variety of NBs are present. As such they should experience similar meteorological

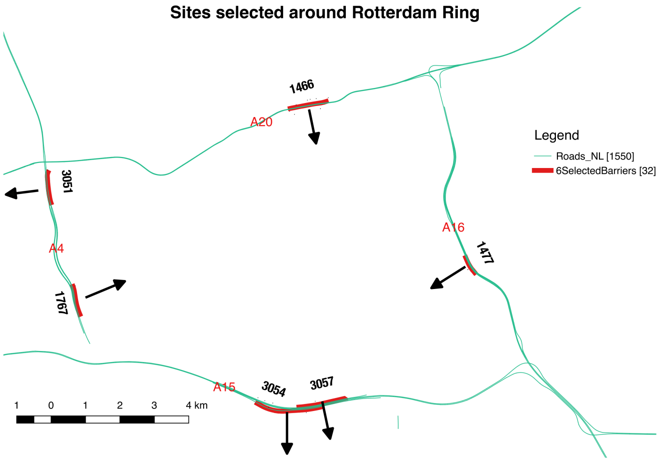


Figure 6.1.1: QGIS map showing the location of the six selected NBs (red), NB ID (black text), Arrow shows direction of face & Rotterdam ring roads (green)

conditions to facilitate a fair comparison between designs and sites.

To be suitable for Energy wall conversion the NB must be able to handle the additional mechanical loading from additional weight along with the extremes of wind and snow loading. This is why the data set presented in chapter 3 eliminated certain NBs based on structural material. The potential indicator as found from the developed GIS methodology contributed to the selection choice of the sites. Combined with a subjective assessment of the local shading, be it vegetative, buildings or proximity to vehicles. With a conscious effort to yield a diverse dataset; a case study of only south orientated NBs would severely limit the studies ability to provide insight into the Energy walls larger impact.

6.1.1 SITE INTRODUCTION

The sites selected are shown in figure 6.1.1 where the arrows indicate the direction that the PV panels will face, while red shows the entire NBs. Table 6.1.1 contains some of the main attributes for the selected sites and appendix 10 shows pictures and descriptions of the NBs and sites.

METEOROLOGICAL STUDY

Due to the tilt angle and range of orientations that NBs experience a high derivation from the GHI (Global Horizontal Irradiance) at each site is expected W/m^2, which is the irradiance on a flat surface.

Table 6.1.1: Attributes of the selected 6 NBs, where negative orientation indicates an easterly direction

ID Barrier	Orientation °west of south	Tilt	Height (m)	Length (m)	Number Segments	Material
1466	-12° (S)	10°	4-5.5	1000	7	Transparent Glass / Plastic
1477	55° (SW)	0°	5	510	6	Plastic and/or wood
1767	-105°(ENE)	20°	3	840	2	Metal and Transparent Glass/Plastic
3051	82°(W)	10°	4-7	900	9	Concrete
3054	-6° (S)	0°	9-16	1900	4	Concrete and Transparent Glass/Plastic
3057	-12° (S)	20°	4-5	1300	4	Concrete

These phenomena will be assessed to determine the effect they will have on the Energy walls performance.

Meteonorm is a software that was used to find the annual Global Inclined Irradiance for the tilt angles and orientations at each site. From this data, monthly averages are shown in table 6.1.2. This software was used because it allowed for the effect of shading to be incorporated into the final result, through horizon view.

A horizon, is a subjectively drawn contour, to mimic the outline of the horizon, as seen from each site based on google street view. This is used to determine at which points over the year, the sun would fall behind an object, thus incorporating shading into the irradiance calculations. A single horizon is used for each site as seen from Google maps, in reality, the horizon viewed from different locations along the NB are likely to change. Across all the sites it was observed that the horizon did not have dramatic changes due to the flatness of the terrain and the open area across the road. This simplification was made to best represent the horizon along the entire NB length, which resulted in large reductions of the data extraction time. It was found that when comparing a constant 0°& 10°horizon, an annual reduction in irradiance of 7% was realised.

The total yearly irradiance will differ from the irradiance incident upon a south facing surface at the optimum tilt angle of 36°. These annual irradiance values can be compared to the maximum global inclined irradiance for Rotterdam which is equal to $1221\frac{kWh}{m^2}$ while the GHI is $1042\frac{kWh}{m^2}$.

From Meteonorm it could be found that depending on the orientation different optimum tilt angles materialise. For example the north facing NB had an optimum of 0°.

Table 6.1.2 shows that the total solar irradiance for the 6 sites fluctuates greatly, with the largest difference between barriers 1767 & 3057 being 410kWh. This is a result of comparing a North-easterly facing NB to a south facing.

Table 6.1.2: Meteonorm annual irradiance/m2, including the expected horizon shading, peak months indicated in green and the worst in red

kWh/m2	1466 (S)	1477 (SW)	1767 (ENE)	3051 (W)	3054 (S)	3057 (S)
Jan	40	33	10	20	43	43
Feb	43	32	17	21	43	47
Mar	91	71	43	54	87	99
Apr	120	103	78	88	108	133
May	105	100	95	93	89	121
Jun	103	93	107	88	84	120
Jul	103	93	106	88	84	119
Aug	91	86	72	79	80	104
Sep	92	79	51	64	86	101
Oct	70	56	30	40	71	78
Nov	38	29	12	18	39	41
Dec	28	23	7	12	31	31
Total	**924**	**799**	**628**	**666**	**845**	**1038**

Due to the tilt angle, most of the barriers have their peak irradiance earlier in the year when the sun elevation is lower in the sky, the temperature is cooler, and the daylight hours are longer than in the winter. NB 1767 has its peak irradiance in June when the sun is highest in the sky, this is because this NB faces towards the northern hemisphere. It is therefore exposed to a greater proportion of diffuse light, as a result the system benefits most from longer daylight hours. Despite the variation in peak months, the poorest months consistently occur in December for all sites.

To find the highest level of irradiance that each site will be exposed to over the year, the irradiance curve for the peak month of each site was found. Due to a software limitation of monthly resolution in Meteonorm, daily profiles could not be calculated. To achieve this, PVGIS was used, from this daily irradiance profiles could be found, while not considering the local shading.

From figure 6.1.2 it becomes clear which are the east and west facing NB, as the east facing NB achieves its peak power early in the morning (1767) and the west facing in the evening (1477). Organising by peak performance power the tilt angle becomes apparent for the south facing NBs; with 3057 having a tilt of 20°down to 1466 with no tilt. The optimal tilt from vertical is around 55°for Rotterdam [16]. NB 3051 possess the same peak power as the south facing 1466 NB but achieves it a month later, but with a noticeably wider curve.

The peak values as seen in figure 6.1.2 were the maximum irradiance levels the system would experience. Due to the extreme tilt angles, irradiance levels close to STC would not be reached; 1000W/m2. Therefore, if the system were to be designed for currents at 100% STC, as specified on the data sheets, the system would be oversized because they are found to peak at between 45% & 60% of 1000W/m^2. The current (A) is proportional to irradiance meaning the photo-generated current would be much

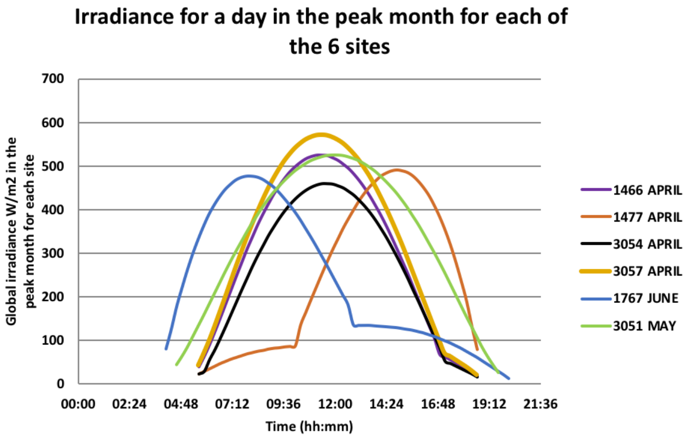


Figure 6.1.2: Irradiance on surface of each of the 6 sites around Rotterdam for the peak month as found from figure 6.1.2

lower also.

If sized for STC, this could have a detrimental effect on system performance and costs, however, to design for this maximum calculated in figure 6.1.2, would leave the system vulnerable to abnormal conditions. Therefore, a safety margin of 25% is added to the found maxima. These new found values are indicated in table 6.1.3, these values represent the current (A) that the system will be designed for.

Table 6.1.3: Peak W/m2 for each site in peak month

ID Barrier	1466	1477	1767	3051	3054	3057
kW/m2 (peak)	0.522	0.489	0.476	0.526	0.459	0.572
% of STC + 25%	65.2	61.1	59.5	65.7	57.3	71.5

Data from measurements taken by KNMI (Royal Netherlands Meteorological Institute) at Rotterdam airport were used to gain ambient temperature data. With this data the lowest temperature can be found and used to size the strings of the PV array. The minimum is critical because with lower temperatures sees a rise in voltage, if the voltage rises above the rating for the connected inverter it will be incur irreparable damage. While high temperatures would only result in lower voltage and power output with no risk of damage. Temperature coefficients vary between module technologies, the minimum ambient temperature for 2017 was found to be -6.6°C while the highest was of 31.1°C.

6.2 DESIGN METHODOLOGY

A model has been designed to allow the simultaneous testing of a large number of Energy wall systems. The model should allow different PV modules and system sizes to be accurately compared, thereby gaining an insight into the vulnerabilities and potentials of the system. For this reason, several system configurations were created, looking at exploring the benefits associated with modular designs and economies of scale. The original RWS dataset holds data of all NBs in the Netherlands, with each entry having a unique ID. This unique ID is a concatenation of the unique ID and the segment in that barrier, i.e. NB 1023-1. The three system configurations developed are introduced here.

- **Modular** - a fixed 20m of Energy wall, built modularly & independently of the next. Exploring the advantages that might arise from modular designs and the propositions put forward by Aleksandrova [20], shown on the left of figure 6.2.1.
- **Segment** - is defined by the original dataset as a length of NB over which none of the NB attributes change. Investigating economies of scale for a range of NB lengths, Centre of figure 6.2.1.
- **Entity** - entire lengths of NBs that are structurally connected which can contain multiple segments, for even longer Energy walls while attributes are able to change, shown on the right of figure 6.2.1.

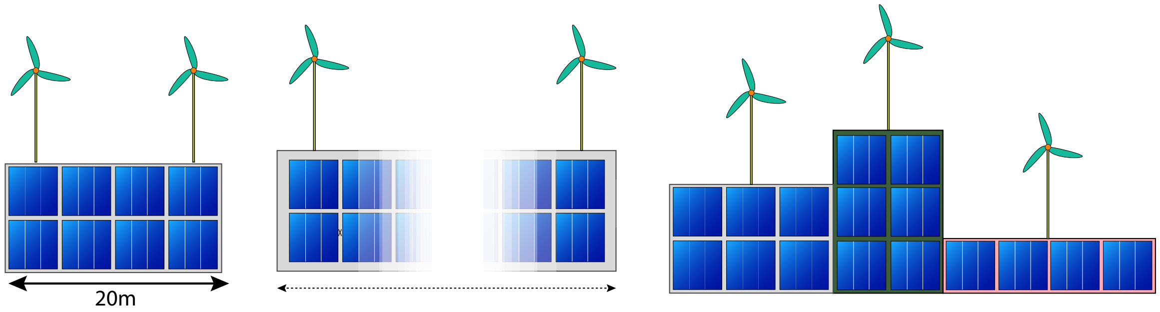


Figure 6.2.1: System configurations tested, Left: Modular design, Centre: Segment, Right: Entity

The 6 barriers consisted of 32 segments with a length from 11m to 779m, each design would be tested with 7 PV modules. To create the Modular design the lengths were divided into 20m sections, this meant that some sections were too small to qualify for this configuration, this resulted in 196 Modular Energy wall combinations. As the Segment design had no restriction on length, this configuration

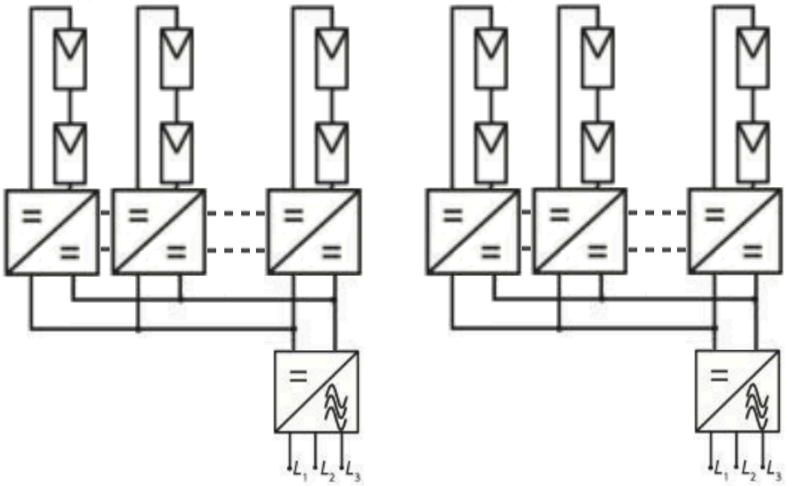


Figure 6.2.2: Selected topology, a central inverter with power optimisers, where larger systems would be connected by an AC bus to the grid connection point [16]

contained 224 systems. The Entity bought all connected segments together, establishing 42 Energy wall configurations; 6 sites with 7 types of PV.

Firstly, the design process for the Modular Energy wall will be discussed as many processes were transferable. Following this, the different techniques that were required for designing the Segment and Entity systems are introduced.

The system design followed on from the results of the GIS analysis, simply by attaching the modules flat to the surface of the NB. Thereby maximising potential per unit area and reducing the need for additional tilting structures as presented in [20].

6.2.1 Implemented Topology

The possible system topologies were discussed in section 5.4, where it was objectively decided that a grid-feeding system would be the most appropriate design for the Energy wall. Allowing for minimal components, utilising the already well-established electricity grid. Consequently a grid-tie system is disconnected if the grid fails, as is the protocol for grid connected generation devices, this is called anti-islanding. However, the grid availability remains one of the best in Europe at more than 99.99% [43].

A central inverter topology was considered with DC power optimisers as shown in figure 6.2.2. Where capacities greater than the 60kW were installed more than one *central* inverter would be used, whose jurisdiction wouldn't overlap. The master slave concept has not been considered. For the larger systems with more than one inverter an AC bus would be connected with AC combiners to transmit to the grid connection point. When multiple grid-tie inverters are used they are required to be synchronisable. This maximum size introduces the ability for the systems to run independently of each other which can improve reliability.

DC inverters were selected as they were found to increase performance and can be found for relatively cheap. While microinverters were found to be more expensive and have a small voltage range with a high failure rate. Utilising the power optimisers ensures that the power is only converted once before being fed into the grid as well as increasing the efficiency because of the small range of input voltages [16].

6.2.2 Modular design process

As the Modular design is restricted to 20m section the number of PV panels that could reside on its surface were highly dependent on the NB height and dimensions of the PV modules. They were orientated either length or edge-wise depending on which orientation allowed for more modules to fit, a combination of the two orientations were not explored.

Using the irradiance (G) data for each barrier in kWh/m2 it is possible to find the expected yearly power (E) output. This was calculated by applying equation 6.1 which uses the number of modules, system & module efficiencies and panel area.

$$E(\frac{kWh}{year}) = Modules \times Area(m^2) \times \eta_{module}(\%) \times \eta_{system}(\%) \times G(\frac{kWh}{m^2 \times year}) \tag{6.1}$$

6.2.3 Maximum power

Finding the maximum power output of the system can be determined by multiplying the V_{MPP} & I_{MPP} by the number of modules. However as mentioned in section 6.1.1, the power is affected by temperature and irradiance. The V_{MPP} was therefore corrected based by applying the temperature coefficient to the voltage, and the I_{MPP} defined in table 6.1.3.

6.2.4 Inverter sizing

Once the maximum potential power was found, the inverter could be sized. A maximum DC/AC ratio of 1.3 was selected, meaning the capacity of the solar panels would be 1.3 of the rated inverter in order to increase inverter utilisation year-round. This value was selected because Zipp [44], suggests between 1.3 & 1.6 to be the best ratio when maximum financial output is the priority, which in the study it is. This would mean that sometimes power would be clipped if the maximum power was reached, this is the process of dissipating excess energy that is above the rated output of the inverter.

Table 6.2.1: Based on grid connection size, voltages could be assigned. Alongside the corresponding voltages assigned to each level, where intermediate tension is for distribution [45] [46]

Connection Capacity	Nominal supply Available Voltages Network Level	Voltage
$\leq$ 3 x 80A	Low voltage	0.23 & 0.4kV
3x80A to 175kVA	Low/ Medium voltage	0.23 & 0.4kV / 3, 6, 10 & 23 kV
1,751kVA to 10,000kVA	Medium voltage	3, 6, 10 & 23 kV
$>$ 10,001kVA	Intermediate tension	25, 50 & 66kV

However, this maximum power above the rating of the inverter is seldom likely to be achieved over the year.

This is limited by the inverter sizes available so a 1.3 ratio may not actually be achieved as the priority was to fit maximum panels on the NB. The maximum inverter size was 60kW, for systems greater than this multiple would be used, if larger inverters were to be used the energy would have to travel huge lengths of DC cable to reach the inverter. This allowed for a modular approach to be taken, where inverters in the order of MW can be container size and weigh several tonnes, making them less suitable for siting on the thin strip of land adjacent to the NB.

6.2.5 Grid connection

To establish the size of the grid connection that would be needed, the maximum power value was used. Grid connection sizes are represented in either Amps or Kvar, as shown in table 6.2.1, with the available voltages for each level. To associate this with the maximum power of the system would require a conversion into kW. For Amp rated connections the rating is simply multiplied by the voltage level. For Kvar the power factor should be considered, Kvar is used for larger connection sizes. Although discussing that the system was DC, a PF (Power Factor) of 0.9 was used; KW = Kvar $\cdot cos(\theta)$. A PF of 0.9 was selected as a conservative value, this results in a larger grid connection size being selected acting as a safety factor.

Once the current is found, using equation 6.2 (for a 3-phase connection) a group fuse 1.6 times smaller than this current is used to limit the connection. This is the current that the connection can handle as discussed in [47]. This value should then be multiplied by the number of phases for the power of the connection.

$$I = \frac{1000 \times kW}{\sqrt{3} \times Voltage} \tag{6.2}$$

Table 6.2.2: Effect of -6.6°C ambient temperature on selected module voltages

Module	Suniva	First Solar	Flisom	Global	HyET	Talesun	Frontier
Temperature coefficient (%/C)	-0.42	-0.28	-0.3	-0.43	-0.43	-0.42	-0.4
V_{MPP} (V)	37.8	71.5	38	54.3	28	31.7	89.5
V_{MPP} + Temp (V)	42.8	77.8	41.6	61.6	31.8	35.9	100.81

Stedin charges a one-time connection fee + a cost per meter over 25m to the nearest grid connection point. The distances to the nearest transformer were used. as discussed in section 3. For the analysis, only the minimum distance for the particular NB was used, this would simulate the conversion of a 20m section closest to the transformer. Thereby leaving the potential for connection costs to vary along the same NB. Only transformers that were on the same side of the road as the energy wall were considered to avoid crossing roads which, it was assumed would be more expensive and disruptive.

The costs used from Stedins website includes cost of cabling, labour and tools are shown in appendix 10. On top of this, an annual maintenance fee must also be paid which is considered to be included in the O&M price.

6.2.6 STRING SIZING

Sizing of the PV strings lengths determines the voltages and the number in parallel determines the current. These must remain in the limit of the connected hardware such as the inverter to maximise lifetime and safety. Lengths of strings were found using equation 6.3 where the V_{MPP} of the PV module was corrected according to the temperature coefficients from KNMI. The results are shown in table 6.2.2 where the voltage increased between 8% & 14%.

$$Max_{StringLength} = \frac{V_{MPP\_Inverter}}{V_{MPPModule+TempEffect}}. \tag{6.3}$$

To find the number of strings in parallel the total number of modules were divided by the string length to find the best combination, however this results in some cases of string length mismatch. Depending on the number of inverter inputs this would normally negatively affect PV performance if put in parallel due to string mismatch. The inclusion of DC power optimisers allows for mismatch to not result in additional losses so the maximum number of PV panels for the section can be incorporated, if power optimisers are not incorporated then compromises have to be made.

Additionally, when using power optimisers, longer strings can be established as they control the voltage of each PV module independently to keep the entire string at the optimum voltage for the connected inverter. This therefore changes the string length equation based on the specific power optimiser used, now the inverter rating is divided by the rated power of the PV panel to find the length of the string.

6.2.7 Design Verification

A comparison was made between the inverters selected by the model, against the free online design tool provided by SMA, for three separate systems. The compared systems did not have power optimisers, this check was to compare the original sizing methodology.

It was found that there was a good match between the model designs and the SMA guide, there were however some variations. An example of this was that the model selected a single inverter to meet the system requirements, while the online tool sometimes suggested two or more smaller inverters better matching the rating. This is likely to achieve maximum efficiency, while selling more inverters, as a result the model was not changed.

6.2.8 Cable sizing

With the safety factor currents known, the cables could be sized, it was decided that a maximum of 2% in cable loss was acceptable using equation $P_{Loss} = I^2 \times R$.

Where R is found by using the specific conductance of copper (σ) at 20 °C [16], this value will decrease as the cables become hotter which in turn causes higher losses. Equation 6.4 shows how the % of total power that is lost can be calculated.

$$\frac{I^2 * \frac{1}{\sigma} * \frac{Length}{Area}}{P_{Total}} = P_{Loss}(\%) \tag{6.4}$$

Where length of the cable used is the distance between source (PV modules) and inverter. For interconnecting PV modules, the included cables were to be used. However, the thin-film modules include short cables that are not sufficient in length to make the connection to the next module depending on orientation. Therefore, additional cable had to be included in the estimations for required DC cable length, this is shown in equation 6.5, distance to next module (D) was subtracted from the included cable length (L). The Modular configuration model used 2 times the height of the NB plus an arbitrary length of 40m, which is believed adequate to find a suitable location for the inverter at the base of the NB.

The additional connectors that would be required have not been included in the model.

$$2H + 40m + n_{modules} \times (D - L) \tag{6.5}$$

The flexible thin-film modules are often long and narrow, resulting in 78.5% of systems fitting more modules in edge-wise orientation.

6.2.9 MECHANICAL STRUCTURE

The design of the mechanical structure consisted of using a rail system fastened to the face of the NB, upon which PV modules would be attached. It was not concluded whether NB penetration would be required to secure the structure or whether self-weight was sufficient. For the flexible thin-film modules, adhesive tape was modelled to be used on the perimeter of the modules to connect them to the NB. The lower temperature coefficient of thin film PV will result in less consequence from the lack of ventilation behind the modules.

This completes the design procedure considering modules, inverters, cabling, grid connection & mechanical structures. Further components such as connectors and (AC/DC) disconnects have not been investigated but during implementation will contribute to increasing the overall system cost but in a small proportion. This will be included in the costs by using a contingency cost, calculated as a % of system costs.

Following the completion of the modular level design the utilisation of entire segments and NBs will be explored to take advantage of larger installed capacities.

6.2.10 SEGMENT AND ENTITY DESIGN

This section will discuss how the design methodology that was developed had to be adapted for Segment and Entity designs.

Due to the larger amounts of power available from these designs, larger inverters were needed, despite the fact that sufficiently sized inverters are on the market they were not used in the model. The justification behind this was that it was anticipated that the additional lengths of cables would cost more and induce greater transmission losses, which would outweigh the savings of investing in a larger inverter. This is based on the distributed nature of the systems resulting in a low density, when compared to a field of ground-mounted array. As a result larger systems consist of multiple 60kW inverters. The length of DC cables required to connect the modules to the inverters would be larger than the 40m length previously designated. For the Segment and Entity configurations the length of DC cable was calculated as shown in equation 6.6. As the sum of twice the height multiplied by the number of inverters plus twice the NB length plus the additional cable where required.

$$2H \times n_{inverters} + 2 \times NB_{length} + n_{modules} \times (D - l) \tag{6.6}$$

Flexibility is now gained for the grid connection as the closest part of the segment or barrier can be selected. This means that the power may have to travel a larger distance following conversion. As mentioned previously in the case of multiple inverters, the power will need to be synchronised to a common bus.

6.3 System Losses

The system losses will define the systems eventual output power are analysed in this section.

In Smets et al [16] it can be seen that for Delft, the system losses amount to 78.6% which are a combination of many factors, these losses have been assessed and modified for each Energy wall around the Rotterdam ring.

Delft's proximity to Rotterdam meant that where appropriate the same losses can be applied in the model. Module degradation is not considered here as it is already used to determine the reduction in DC output power from the PV modules over module lifetime. Losses between PV module type are not considered in this study.

6.3.1 Soiling

Literature recommends annual cleaning of the modules due to the accumulation of traffic dust [48], where it is believed that over the year, rain will provide sufficient cleaning which is why only annual is recommended. While an interviewee mentioned that a more regular regime may be needed, due to the emission of diesel particles which cannot be washed off by rain. This is especially relevant near roads and ports, the latter of which Rotterdam is the largest of in Europe. Considering this the soiling effect was kept at 1%, with a recommendation that the maintenance includes regular cleaning as necessary. This should be done through visual inspection and monitoring of system efficiency.

6.3.2 Reflection

Reflection losses occur when light is incident away from perpendicular, this is determined by the refractive index of the module, only capturing light from within a specific range of angles into the module, known as the critical angle. Sjerps-Koomen [49] showed that in Blit Netherlands the losses of a 90°tilted system amounted to 5.5% for south facing but changed with orientation as show in figure 6.3.1. This loss mechanism will be applied for all tilts based on the orientation of the case study sites, creating variable losses across Rotterdam.

6.3.3 Module Mismatch

Module mismatch occurs when modules or cells are not operating homogeneously, this could be due to shading or deformities within the cells from the manufacturing process. If power optimisers are used this loss is removed as the modules connected to each optimiser operate in isolation from one another thereby not reducing the performance of the entire string. The same loss mitigation occurs when strings of different lengths are also connected, therefore this loss was not included in the model.

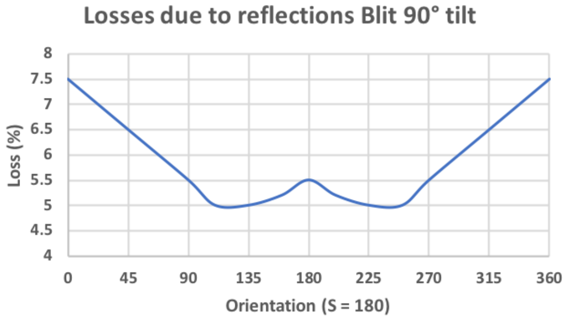


Figure 6.3.1: Reflection losses for a 90°tilt PV System in Bilt Netherlands by orientation [49]

6.3.4 TEMPERATURE LOSSES

Module temperature has been discussed in section 5.1.5 which was used to find the effect on the V_{MPP} of the modules. As a time series model was not created the temperature at each moment in time was not applied, therefore the effect of the different temperature coefficients could not be applied. Smets et al [16] suggests that due to the cool climate of the Netherlands this could be between 2-3% for a free-standing system, with the proximity to the NB, defined by the mounting structure the airflow may be limited, therefore 4% was used.

6.3.5 MODULE IRRADIANCE

The number of photons incident upon the surface of the module which will not be equal to STC conditions of $1000W/m^2$. As irradiance deviates from STC losses occur where a function of efficiency vs irradiance could be found. The same loss of 4.5% is assumed for Rotterdam as is used in [16] for Delft, this was assumed due to their close proximity. The reduced levels of irradiance is already considered as the irradiance level for each site for the respective tilt and orientation.

6.3.6 OHMIC LOSSES

Ohmic losses are caused by resistances, in the cell contacts, junctions, connections and cabling. The losses at any moment in time depend on the current flowing which depends on levels of irradiance, therefore the same loss of 1% is assumed as in Smets et al. [16]. Considering the cables are designed to allow only 2% loss at maximum conditions.

6.3.7 INVERTER

Inverters operate best within a certain range of DC input voltages, with adequate sizing they should have an efficiency in the high 90%s. With the incorporation of power optimiser the optimal voltage for

Table 6.3.1: Summary of the losses applied in the model, based on C-Si module in delft [16], a range is present dependent on orientation.

Loss Mechanism	**Annual loss (%)**
Soiling	1.0
Reflection	5.0-7.5
Module Temperature	4.0
Module Irradiance	4.5
Ohmic	1.0
Inverter	2
Total	**17.5 - 20**

that inverter is achieved, resulting in higher efficiencies. Therefore, a loss of 2% is assumed, while the power optimisercan extend the life of the inverter because of its more optimal operating condition.

6.3.8 MPPT (Maximum Power Point Tracking)

MPP tracking finds the optimum point for the inverter to operate at, shading and changing conditions may mean that, depending on the algorithm used it will not operate at its maximum. When DC power optimisers are employed every module operates at its own MPP mitigating the effects of shading, therefore this loss is likely to reduce to 0%.

The implemented losses are presented in table 6.3.1 where a variation in loss occurs due to orientational reflection losses and not between PV types.

6.4 Monitoring, Safety & Security

Theft of the solar panels has to be consider, which is especially an issue with the adhesive tape method, while security screws can be used to attach to the modules to the rails [50]. Copper cabling and other hardware components that may be located at the base of the barrier are also highly accessible. Stopping theft is not practical with on-site security because it is expensive and less than ideal at the roadside sites, CCTV being an additional cost to the overall cost if implemented.

Electrical safety is of paramount importance, which is why an experienced installer should be used, extra consideration should be given to what would happen if the NB was was struck by a vehicle. A form of rapid shutdown should be implemented, either remotely or manually on site as is already required by the NEC 690.12 for PV installations on buildings. The NB itself and the metal parts of the PV system need to be grounded adequately to avoid the potential of shocks.

Inspections are to be carried out for official inspection, this is to be carried out by a qualified inspector, again this is less of a concern when a experienced installer is used.

The incorporation of DC power optimisers allows for module level monitoring, for both performance and safety, with some manufactures including remote monitoring and automatic shutdown of dangerous modules.

6.5 RESULTS

Following the design of the model which was based on the 6 selected sites around Rotterdam, energy potentials could be found. The data was normalised by altering the NB characteristics and the resulting meteorological data, at the site using PVGIS. This was achieved by fabricating inputs into the model by setting NBs attributes to be equal; heights of 5m, distance to grid at 100m and running the model 3 times for the different tilt angles shown in figure 6.5.1. These normalised values are seen as typical values from the NB infrastructure study; the three tilt angles represent 99% of NBs in the Netherlands and the height as the average for Rotterdam.

To find a more accurate trend, all NBs were simulated by changing the sign of the orientation resulting in symmetrical data points, where 0°is (South). Figure 6.5.1 shows how the performance of the Energy wall is likely to deteriorate as the NB orientates away from south. The model only explores the implementation of mono-facial PV, while in the field a north facing system wouldn't be realised. Instead the reverse side would likely be utilised, tilt angle and shading permitted. Looking 90°East/West shows justification for the need for bifacial PV where a 25% reduction in total energy production is realised.

The orientations ±180 represent north facing NBs where the annual energy output falls to between 37% and 33% of the south facing NBs depending on the tilt angle. These solar irradiance values do not account for shading at these fabricated sites.

The effects of orientation have been shown in figure 6.5.2 where it can be seen that the the south facing NB can expect more homogeneous production due to intense peaks early and late in the year while the longer daylight hours balance the production with diffuse light. When the NB is orientated to the West as shown a more traditional summer-peak profile appears where production extends to the late evenings. The inverse will be seen for an eastwards orientation, depending on the nearby energy demand this could result in a better matching with certain loads. Southwards facing PV having a seasonal grid-balancing effect and orientated away from south can have interday grid-balancing effects.

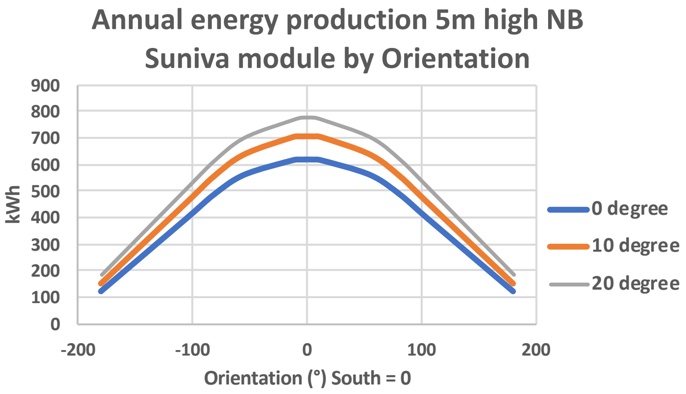


Figure 6.5.1: Annual energy output per meter with Suniva modules on a 5m NB at 3 tilt angles, including all system losses

6.6 SUMMARY

Based on the GIS analysis 6 case study NBs were selected around the Rotterdam ring, they were selected on the basis of studying a variety of NBs. Chosen by location, orientation and tilt angle, thereafter a meteorological study was performed.

A PV system model has been developed to allow for the creation of a multi-criteria analysis of the Energy wall, developed based on the selected sites. It was found that due to the tilt angles, the majority of cases experienced their peak irradiance early in the year. Daily profiles were found for the peak months to find the highest levels of irradiance, that could be used for system sizing. Safety factors were incorporated into the sizing of the arrays and grid-connection.

A design Methodology was developed around 3 core configurations; Modular, Segment & Entity. This was based on the original dataset from RWS, aiming to explore the cost opportunities that might arise from each. This resulted in 426 systems being simulated, implementing 7 types of PV.

The proposed topology is a grid-tied, central inverter with DC optimisers. Verification of some of the resulting PV systems was carried out to test the realised systems, it was found to be in good agreement.

Analysis of the expected system losses was carried out which resulted in a range of losses, as dictated by the systems orientation. The foundation of this analysis was based off of a study carried out for Delft [16]. The resulting system efficiencies were found to be between 82.5% and 80%.

Constraints of the model were that a time series analysis was not implemented so hourly effects such as the temperature effects on module performance could not be implemented but instead were assumed.

The development of the model highlighted issues that had to be considered such as the limitation

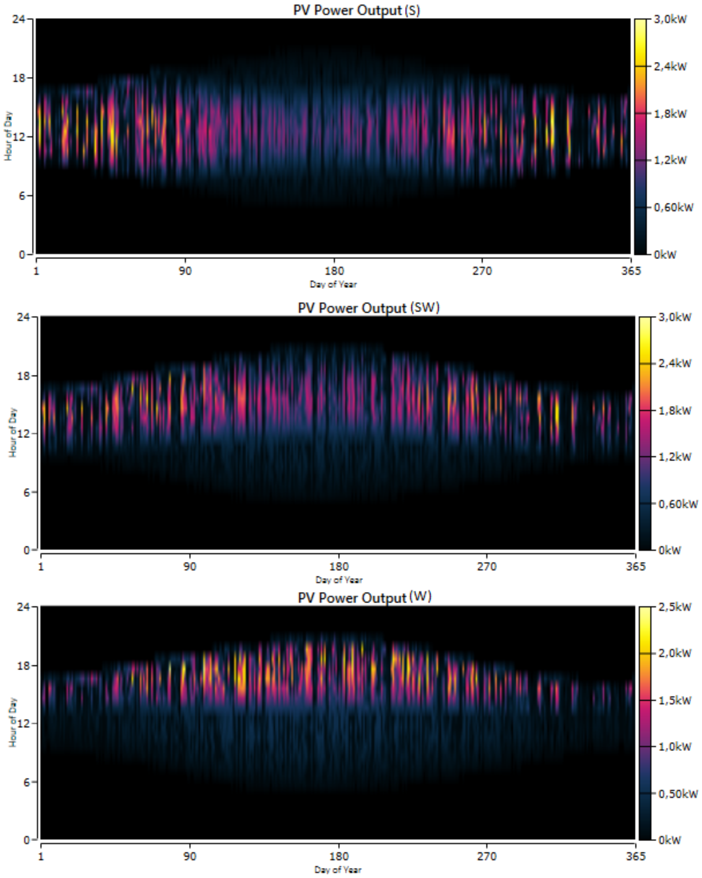


Figure 6.5.2: PV power production by orientation on a vertical wall, Top: South, Middle: South west, Bottom: West

of included cable lengths for some of the PV modules used.

Out of the model a normalised input dataset showed a curve in performance based off of the resulting power curves. The ability to normalise the inputs into the model proved that it was successfully implemented model and can be used to identify key parameters in designing Energy wall systems for the most cost effective price.

Finally, recommendations were given for system implementers regarding security, safety and monitoring, that should be considered when built in the field.

7

Implemented System Costs

The aim of the project is to prove the Energy wall as an economically feasible innovation in the area of urban energy generation, exploiting the cost opportunities discussed previously. Cost analysis and comparisons are taken from various projects to find similarities and costs opportunities that arise from utilising the structure of the NB.

The subsidies and mechanisms discussed in section 4.2 are implemented to determine potential revenue streams.

The current economic climate in the Netherlands will be assessed to see how the Energy wall can fit in to determine whether it makes a sensible investment.

7.1 ENERGY WALL SYSTEM COST BREAKDOWN

The PV system cost is comprised of all the hardware components, such as PV modules and BOS, but also the installation and soft costs that will get the components connected and generating energy while adhering to regulation.

In 2016 Sark and Schoen [51] claimed an average system cost of €1150/kW. A prediction for a further 870MW of PV to be added in 2018 [52] would increase capacity by 84% in 2 years. If Swanson's law (a PV module price decline trend by cumulative capacity) is applied a reduction of around 17% should be realised. If this is assumed to make up 47% of the total system cost as suggested in [53], a resulting price of around €1050/kW could be expected not including other cost reductions.

Due to a lack of specific data from international institutions on the situation in the Netherlands, a

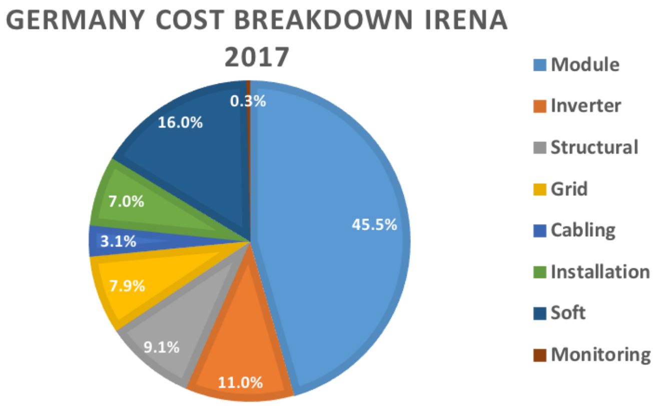


Figure 7.1.1: Germany cost breakdown of Utility PV [54]

target cost breakdown has been presented in 7.1.1. This percentile cost breakdown will be used as a benchmark cost and is attained by translating the German cost breakdown (2016) for a utility system of €950/kW according to [54].

In Europe, Germany has the cheapest prices for PV systems, by deploying policies like the EEG (Erneuerbare-Energien-Gesetz/ Renewable Energy Act) uptake in renewables grew hugely and prices dropped. The Netherlands has followed this lead by reducing red tape around RE projects to make their implementation easier and subsidies easier to claim as discussed in section 4.2.

It is important to identify the skills that can be transferred from the well-established rooftop and utility scale PV industry to reduce the costs of installing PV on NBs.

7.1.1 PV Module

Initially through a market review, commercially available prices were implemented in the model, which had significant differences in prices between PV types and supplier. On top of this through consultation, it was found that the commercial prices were inflated compared to what a supplier would pay for modules. If used this would severely hinder the ability to propose the most economically advantageous systems.

Literature and interviews showed that prices per watt had fallen to around €0.40/W for mono-crystalline, with poly-crystalline being slightly cheaper.

However, for the already selected modules a price of this order could not be found. A cost comparison between PV types found in [54], showed that different module technologies were not greatly different. Although the source stopped supplying data for a-Si and CdTe in 2013, from here an assumption is made to model all types of PV with a cost per watt. The selected prices were; €0.5/W, €0.4/W and €0.3/W.

The model also considers economies of scale, where the benefit may be significant in larger systems, based on wholesale marketplace, one supplier trend was applied. To purchase 100kW or less of PV modules no price reduction was included, therefore, €0.40W is used. Above this a reduction in price of $0.993(x)^{-0.012}$ where x is multiples of 100kw, was applied which saw the price of 2.5MW or 25 times the 100kW base price purchase realise a cost of 95.5%. This price has been deemed reasonable after research for module prices in China resulted in prices as low as $0.24/W [12].

7.1.2 INVERTER

The prices for inverters were taken from commercial websites which monotonically declined for increasing capacities, from a 1.5kW to 60kW. The prices can be seen in appendix 10. However, it should be considered that due to the inclusion of an inverter from a different manufacturer the €/kW varies when comparing all 12 inverters. No economies of scale are applied here.

7.1.3 DC CABLING

Prices for DC cabling were taken from a commercial website. Large cable diameters were used when there was a long current path to ensure that the losses remained below 2%, prices are presented in appendix 10.0.2, no economies of scale were applied here.

7.1.4 MODULE LEVEL POWER ELECTRONICS (MLPE)

It is estimated in [55] that DC Power optimisers can cost €25/unit, in [53] (2016) it is estimated that this can be as low as €0.09/W, this can be compared to a micro-inverter at €0.33/W. A price of €40/optimiser is applied, split between two modules to reduce the cost, for the different PV this resulted in a price per watt range of between ¢6 to ¢16. This can contribute to the monitoring of the system which takes less than 1% of the cost in the cost breakdown of figure 7.1.1.

The inclusion of power optimisers means that the string voltage output will be maintained within a smaller range, this may allow for the incorporation of a lower priced inverter. This was not reflected in the inverter costs, but in some projects may go so far as to negate the cost of the power optimisers themselves when coupled with the extra generated energy. If found to be the case in the field then individual power optimisers per module should be used.

7.1.5 GRID CONNECTION

The prices for grid connection were taken directly from Stedins documented prices and confirmed through a quotation. It was clearly expressed from an interviewee that there is currently no price difference for a consumer vs producer connections, which it is believed is a political barrier that should in future be addressed. The applied prices are shown in appendix 10.0.3.

The grid connection costs consist of two parts, an installation cost based on the connection size and an additional fee for distance to the nearest grid connection over 25m. After this, a maintenance fee is to be paid annually. From the cost breakdown in figure 7.1.1 it can be seen that the grid connection cost can be around 8%.

7.1.6 Structural costs

For the modular based PV, traditional mounting structures are to be used, they are to be attached to the surface of the NB. Comparing the costs of a flat roof vs tilted roof installation, it is found that the tilted roof system cost 7.5% less [51]. This is in part due to the additional material required to tilt the modules optimally on a flat roof, adversely labour costs can increase for tilted roofs because of the additional difficulty at which labourers can move around the site. The energy wall will utilise the tilt of the barrier to reduce the material used but the tilt angles of the near vertical wall mean that labour will have a much more difficult time in installing the hardware.

In [54] the cost of racking and mounting in the USA was around €243/kW while in Germany this was as low as €60/kW representing 14% and 9% respectively of the overall system cost.

Due to the expected reduction in mechanical costs based on an NB literature study, costs will be focused on rails running down the face of the barrier hooked from the top. While for thin-film PV the adhesive method is considered, this is included in the price for some modules which is where the idea originated from. A price of €1.5/m is applied for an all-weather tape that would be fitted around the perimeter of the modules. It is unclear as to the lifetime of this tape vs a mechanical alternative so over time may need to be replaced as part of the O&M, on top of this security concerns are present.

The mechanical structures material was selected to be Aluminium because it is strong and lightweight [56]. Compared to a ground mounted system the removal of foundations also will see a price reduction compared to conventional systems.

All of these factors combined with the potential for prefabrication meant that a cost of €60/kW were applied, with no economies of scale. A source for rails was found and this price is in line with this value, including the clamps. The modules with the highest $\frac{W}{m^2}$ in reality will have the best potential of achieving this price or better, which for the selected PV ranges from 174$\frac{W}{m^2}$ to 85$\frac{W}{m^2}$.

7.1.7 Installation costs

In [57] an average of €0.34/Wp for the Netherlands is found. Sark et al [51] shows prices that for installations in the Netherlands between 0.6kW and a 500kW, a decrease in price from €0.60/W to €0.15/W is found (2016). On the other hand, an interview with a lead engineer on a similar project suggested that a 1MW installation could experience costs of €0.05/W.

Germany and the US split the installation costs down into three sub categories; Mechanical, Electrical and Inspection. In Germany this made up around 7% of the total system cost and in the USA this was around 14%. The costs in both countries were dominated by the mechanical installation, which took up 70% of the installation cost while inspection was only 10%.

A difference in module performance vs weight between the roll-on modules and the heavier modules could not be decided upon. One would require more modules for the same installation size while the other, more time per module to install.

The large inclination means that installers will need scaffolding or some machinery in order to operate at the top of the NB which could increase installation costs, again this cost was assumed mitigated by modular prefabrication. The prices for installation were directly used from [51], because the age of the paper is over 2 years old, it is assumed that the price decrease since its publication has been enough to negate the price concerns presented. For systems of more than 1MW a price of €0.10/W, smaller systems saw a trend of $450.14 \times P^{-0.201}$, where P represents the installed capacity.

There is a lack of literature regarding the speed at which installations can be sped up through the deployment of roll on PV. Due to this, a cost benefit associated with the installation of this PV type could not be applied.

7.1.8 SOFT COSTS

Soft costs does not include any hardware, predominately focused on areas such as administration and fees, for this study installation costs are NOT included in soft costs.

Soft costs have been rising in their overall contribution to PV system costs, as technological advancements and cost reductions see hardware prices fall.

Lawton [58] suggests that one of the key ways to reduce soft costs is through standardisation, effecting system design, permitting, inspection and installation.

These costs include Land, Permitting, Interconnection, Inspection, Sales tax, Overheads and Profit. Each must be understood to determine how it would be applied to the Energy wall and the relevant stakeholders.

LAND

If approval is granted by RWS a leasing agreement is needed because this land is not for sale as it is state property. For small test sites this may be given for free to stimulate the early innovations, but if the Energy wall becomes widely implemented they will likely need to be paid. This cost should not be higher than the price of purchasing an equivalent field from a land owner.

PERMITTING, INSPECTION & INTERCONNECTION

Used to ensure that the local government allows the construction of the project, by determining whether it will interfere with any other parties or the public's safety. This may be more complicated due to the proximity to the roadway. SDE+ states that if the solar array is in a field or in sight then an environmental permit is required, this should be considered too. Inspection must take place to ensure that codes and regulations have been adhered to, this is an area where an experienced solar installer will speed up the process. Response to permit applications should take less than 8 weeks [59]. Applying for a grid connection in the Netherlands is very easy as DG is obliged to be connected to the grid if it is below $\leq$3x80A [27]. When connecting to the grid the process is easy and the prices are readily available on Stedins website. Working towards reducing soft costs is the development of plug and play PV systems, this is done through electronic permitting, inspection and interconnection [60].

CUSTOMER ACQUISITION, MARKETING, OVERHEADS & PROFIT

These costs have a larger impact on smaller projects, as was shown in figure 2.3.1. Uniquely, the Energy wall project will be in view of an exceptional number of passers-by (if on the roadside), which may result in reducing the costs of acquisition of future customers and sales & Marketing.

Overheads and profit are dependent on the organisational structure of the project; if the energy is intended for self-consumption and the company has the internal experience required to build such projects, this cost will be far lower than if an external company would carry out the works.

The best cost reduction strategies come from standardisation of PV system designs, so that they become more modular [58]. This is the motivation behind the modular 20m design, which is why the residential-scale projects should see a significant reduction in soft costs.

Soft costs have a larger impact for smaller projects because of one-time engineering and legal processes, a way to reduce these is by reusing documentation for similar projects [61].

The German soft costs at utility scale are 16% while in the USA they account for 24% [54]. Based on this information, with the future innovations focusing on reducing the soft cost a linear reduction from 20% to 15% of system costs, between 10kW and 1MW. For larger systems a constant 15% is adopted.

7.1.9 O&M

It has been found in literature that often O&M is assumed to be 1% of total system costs, [57], [51].

System size must also be considered as a highly dense site means that equipment and skilled labour have an overall shorter travelling time. While the Energy wall can have a large size it is uniquely thin in its land usage. NREL [14] indicates that the price actually increases from 0.75% for residential to 1.49% at utility scale.

Maintenance will fall into different categories whether it is inspection, preemptive or corrective [62]. O&M costs are not likely to be constant over the lifetime of the project, as components age the likelihood that they will need to be repaired only increases [62].

As the system is close to highways it is of the utmost importance to keep the system safe, extra consideration must be given to the potential additional costs attributed to its location. Accessing the site may be more difficult and require more coordination such as closing lanes, which is certainly not ideal.

Based on these findings O&M of 1% of installation costs is applied annually for the lifetime of the project.

7.1.10 Monitoring

Whether to ensure performance or safety of the system, monitoring can vary in resolution from a modular level using MLPE, to a visual inspection carried out during maintenance or monitoring power output. With different quality of monitoring comes different costs but MLPE is advised to be the best route to take. Some kinds of monitoring may also be included in the inverters; as is the case for all the SMA inverters. Additionally, remote monitoring of meteorological conditions on site may be added too but will require extra hardware and internet connection which has not been included in the model.

7.1.11 Contingency, Miscellaneous and Unknown costs

Contingency costs are included as a method to buffer the impact of unforeseen costs, in [14] between 3-4% is assigned for this purpose. This will also cover the cost of the post inverter section of the system including the AC cabling and AC combiner box between inverters where multiple inverters were used. This is used to bring the outputs of the inverters to a single in phase line for transmission to grid. Components such as junction boxes & cable connectors which were not specifically explored are implemented here. Unknown and potentially variable costs over time such as the renting of land from RWS is not known because RWS themselves are not sure on the value they place on this land. It is likely that if these systems are proven to be highly profitable the cost of land will increase as more projects are developed, this cost is included in the soft costs but could increase so will also be considered here. This value was set at 5% of the hardware and installation costs, but as more Energy walls are realised this cost may be mitigated with experience.

7.2 Social Benefits of the Energy Wall

If implemented, the benefits go beyond the value of the energy produced, such as increasing the Netherlands share of renewables to meet European targets. Depending on the stakeholder other social benefits may be made such as improving public image which would have extra impact for innovative project. The NBs sole purpose currently is to improve the conditions of the nearby citizens, which has itself, a social value.

7.2.1 CO2

In the Netherlands, 2020 a cost for CO2 emission will be set at €18/tonne of CO2 emitted in the energy sector, meaning that for every kWh of energy produced by natural gas, would seen extra 1¢per kWh [63].

7.2.2 GRID BALANCING

Although the price between an optimally positioned PV systems vs an Energy wall can be compared using the total produced energy, a direct price cannot yet be placed on the benefits of installing a system with improved winter production etc. These systems are less-optimal with regards to maximum annual energy production, but can have a positive effect on the electricity grid. It makes sense that systems aim to produce the maximum electricity over the year for maximum financial benefit but no value is currently assigned to time of production.

Having all solar panels orientated to the same direction concentrates the power produced to a single peak, while a more diverse range of renewables, or orientations of PV would help widen the production curve. The same idea cannot be applied to wind because its yawing mechanism.

Matching the consumption and production of energy is a constantly changing picture with the number of renewables only increasing the mismatch is growing. If an additional value were to be placed on renewable energy generated during peak demand on an intraday and seasonal basis a more advantageous scenario would be presented.

7.3 ECONOMIC VARIABLES AND CALCULATIONS

To make economic analyses, understanding the influencing factors is essential, it will be shown that they are strong determinants for investors in deciding which projects are profitable or not. Understanding that citizens and businessmen alike may be searching for investments for their money because of the 0% interest rates currently in the Netherlands [64].

7.3.1 INFLATION

Inflation rate is the rate at which prices increase over time, as a result money has more value today than it will in the future. As a result, a stagnant value of a product in real terms will diminish over time. For this study an inflation rate of 1.4% is used as an average taken from the past year [65]. Forecasting only predicts a slight increase over the next 5 years to 1.6% [66].

7.3.2 Discount rate

A discount rate is used by investors as a way to compensate them for the risk they will take by investing in a specific venture, therefore, they will want more money for a riskier investment. RE projects which have large upfront cost are often deemed as riskier investments so will incur a higher discount rate. The effect of the discount rate is determined by many factors such as the type of technology used, geographical location, knowledge and governmental support. This can vary between stakeholders, determined by the proportion of project funds that come from debt, equity or their own funds.

In Germany for a ground mounted PV system a discount rate of 4.25% is shown [67]. Using this as a benchmark and considering the positive political stance in the Netherlands for renewables. With support for such projects from municipalities and the cost advantages that have been presented, a discount rate of 5% will be used.

Using formula 7.1 the real discount rate can be found that accounts for inflation, where i' stands for nominal discount and f for inflation. A discount rate of 5% is used which results in a real discount rate of 3.55%.

$$i = \frac{i' - f}{1 + f} \tag{7.1}$$

7.3.3 LCOE

The Levelised Cost of Energy is used for comparing similar systems as it allows the cost per unit of energy produced over the lifetime of the project to be found, considering replacement parts, O&M and the expected energy production. However, it fails to incorporate other characteristics such as CO2 emissions and control-ability. It was therefore used as a tool for comparing the systems following the multi-criteria design of the Energy wall. Equation 7.2 is based on [68].

$$LCOE = \frac{Io + \frac{R}{(1+i)^t} + \sum_{t=1}^{n} \frac{O\&M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^n}} \tag{7.2}$$

Where:

- Io = Initial investment cost
- R = Replacement cost (inverter at year 15)
- t = Year of occurrence
- i = Real interest rate
- O&M = Operation and Maintenance each year costing 1% of Initial investment

- n = lifetime of project (25 years)
- E = Energy generated (kWh)

7.3.4 NPV

Net present value is the value of future money brought to present values, comparing the investment cost to future money generated when a discount rate applied. This compares the future revenue of one venture vs a safe alternative investment. This safe investment is set by the real discount rate of 3.55%. Using the NPV function in excel this discount rate is the first variable, followed by the yearly cash flows as generated by selling of the energy subtracting the price of replacement parts.

7.3.5 IRR

Internal rate of return is an indicator for investors as to the profitability of a particular investment, with a higher positive IRR more financial return in proportion to the initial investment will be seen. Therefore, a positive IRR will see a net increase in cash flow for an investor, this does not consider the discount rate. IRR relates to NPV, in that it indicates which discount rate will result in a return of the initial investment; NPV of 0. This would not represent a positive investment because no benefit is taken from undertaking the project. The IRR function in excel calculates the cash flows over the lifetime of the project where the first cash flow at year 0 is the negative of the installation cost.

Both NPV and IRR are used to assess the economic potential of the systems presented in chapter 8. It is possible to have a negative NPV with a positive IRR, this means that the return is lower than the safe investment discount rate used.

7.3.6 Other variables

For this analysis the cost of decommissioning the project at the end of lifetime has been assumed to be zero keeping in mind the vision of circular economy. Considering that the value of the scrap covers the costs associated with the safe dismantling and recycling of materials.

Additionally depreciation of the value of assets has not been considered in the implemented model.

7.4 Summary

Cost breakdowns of PV systems has been discussed, data specific to the Netherlands is more difficult to come by so a Germany breakdown was translated to costs founds for a typical Dutch systems. Caution is advised when using data from the USA because of huge divergences in costs between there and Europe.

To complete the model, costs had to be applied to each component of the system, each has been identified and justified where savings have been applied. These costs are sourced from literature, research and from industry interviews or meetings.

Initially problems occurred with module pricing, in that the commercially advertised prices were so inflated in comparison to what would be paid by a large scale PV installer. It was therefore decided that costs should be applied on a per watt basis instead.

Economies of scale was applied to PV modules, installation and soft costs. While for other components such as the inverters and cables, the price per watt reductions were included in the supplied prices, however, in reality maybe further savings could be made on these components. With power optimisers and mechanical components maintaining a constant price per unit or kW installed.

Contingency and O&M were kept as a fixed % of the final system costs, while other benefits of the implementation of the Energy wall are also discussed but did not have any weight in the final cost analysis of the systems.

Finally economic variables that are to be used in calculating the profitability of the system and indicators such as the LCOE used for the analysis are introduced.

8
Design Analysis and System Proposals

This chapter will discuss the findings from the multi-criteria analysis following the cost implementation, to determine what data can be interpreted from its results that might apply to a wider array of NBs. Extrapolating data related to performance based on PV types, NB orientation and height and their effect on the economics. Establishing these trends and focusing on specific examples allows for business proposals to be made for relevant stakeholders, to determine whether the investment will make a positive financial return. The priority of the engineering study was to determine locate the systems with the highest financial benefit.

The determining factor was the final LCOE of all 462 systems which was calculated for a lifetime of 25 years, this allows for fair comparison between the systems to find the most attractive investments. The cheapest installed capacity (€/kW) did not directly correspond to the cheapest energy produced because of the different available resources between sites.

8.1 Multi-criteria Analysis Results

From the developed model different NBs, locations and technology were simulated. These resulted in systems ranging from just over 4kW to 4.9MW with costs ranging from €16,500 to €5.1M.

The PV modules were simulated with a range of module prices for €0.30/W to €0.50/W to see the effect of module price on the system cost. Figure 8.1.1 shows which module had the lowest LCOE for each configuration, Suniva dominates most situations. The Suniva Optimus module is the highest rated module at 340Wp with an efficiency of 17.4%. While Flisom and HyET were the worst perform-

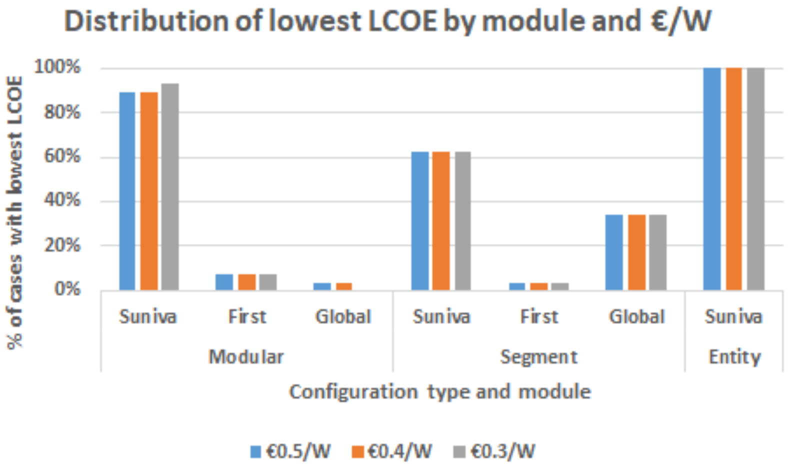


Figure 8.1.1: Results from multi-criteria analysis based on LCOE, % of cases in which a PV module had the lowest LCOE for Modular, Segment & Entity designs

ing modules with respect to LCOE at 120W, 9.4% and 165W, 8.5% efficiency. This indicates that the lowest price for energy comes from the highest capacity and efficiency modules.

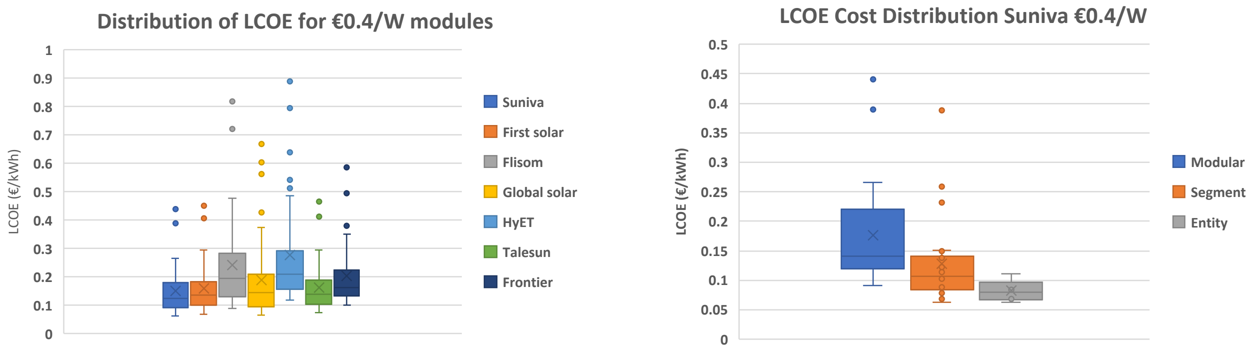
It was found that the effect of reducing the module price from €0.5W to €0.3/W lowered the final LCOE by between 1.33¢/kWh to 5.29¢/kWh for all systems. From here on, the main focus will be on the €0.4/W model based on interview discussions regarding expected module prices on the market currently.

Figure 8.1.2a shows the resulting LCOE distribution for the different PV modules at €0.4/W. Outliers were found in all cases indicated by the dots, these are as a result of the variation between sites and the NB infrastructure. This is a box and whisker plot where the bottom and top of the box represent the middle 50% of values. The horizontal line in the middle of the box represented the median value while the cross is the mean.

To explore why there is such variation when using the same module, the Suniva module will be dissected based on system type as shown in figure 8.1.2b. A clear difference in LCOE which is based on scale can be seen, where the smaller systems can incur a larger cost & range of costs.

The reduction in LCOE comes from cost savings attributed to scale as evident in figure 8.1.2b, this is most obvious from Modular to Segment. The Entity sees further improvement for the same reason when compared to the Segment but the Entity incorporates potentially more expensive segments together but realises further economies of scale. The lowest LCOE comes from a Segment and not an Entity but overall the Entity has a smaller range of LCOEs that are in general better than Segment.

Figure 8.1.3a shows the distribution of grid connections used in the multi-criteria design. From this



(a) LCOE cost distribution of all simulated PV modules for the 3 designs

(b) LCOE cost distribution for the Suniva module divided into categories

Figure 8.1.2: Distribution plots as a result of the multi-criteria analysis with PV modules at €0.4/W

it can be seen that 96% of the Modular designs require a small connection size; $\leq$ 3x80A, compared to 33% for the Segment designs. All Entities are considered as large connections.

Figure 8.1.3b shows that for modular designs the 10kW was the most frequently selected inverter. Larger systems could take advantage of a better cost per kW, but only up to 60kW. It is found that 528 60kW inverters were used on the Segment designs while 524 were used by the entity designs. A close match between those used is expected because both designs consider the same lengths of NB but grouped together under Entity or separately as Segments.

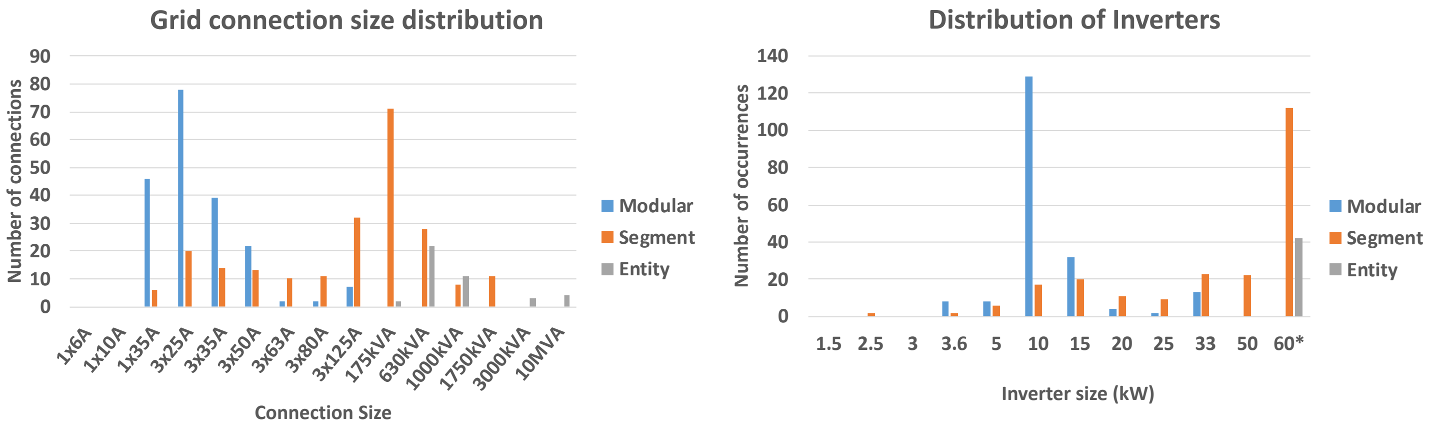
A 60kW inverter covering a 5m tall NB would allow for nearly 230 Suniva modules, therefore a 60kW inverter would cover 90m of Energy wall.

8.2 LCOE by Attributes

Some of the key attributes for the Energy walls potential were found to be the NBs orientation and height. This section will analyse how these attributes effect the final LCOE of the proposed systems, whereby an objective estimate of the Energy walls profitability can be found.

8.2.1 Performance By Orientation & Module type

To calculate how the LCOE changed with orientation the data had to be normalised as was done in section 6.5. However, this time different PV and NB heights were compared, logically, the inverse shape can be seen, where lower energy yield results in higher LCOE. All simulated PV modules are



(a) Distribution of the grid connection sizes for all sites and PV types

(b) Distribution of the inverters for multi-criteria analysis

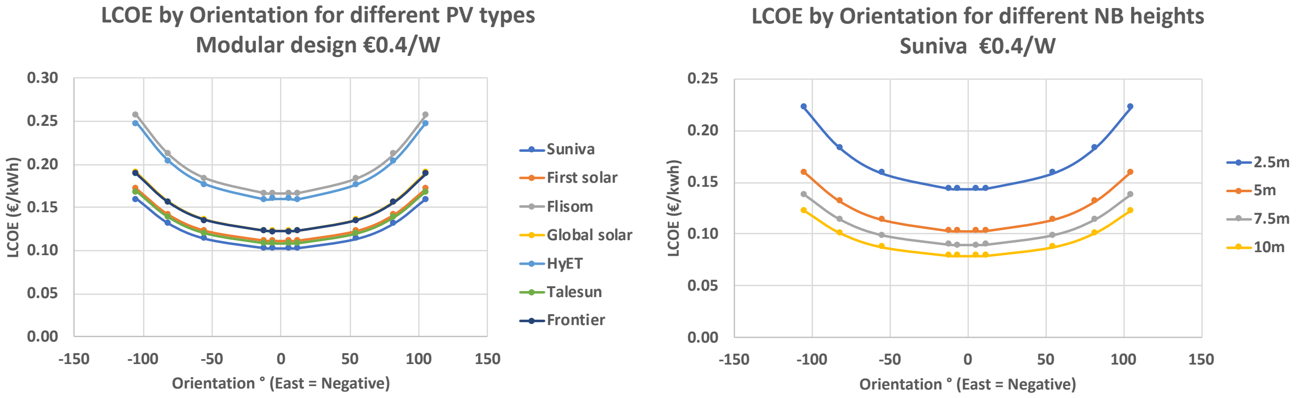
Figure 8.1.3: Distribution plots as a result of the multi-criteria analysis

included here to show the effect of the module performance on the LCOE when the same cost per watt is applied.

This simulation resulted in figure 8.2.1a which shows the results for the modular configuration because of its fixed length. It is found that depending on PV technology used, orienting ±90°from south would result in a 36% increase in LCOE for Flisom & a 28% for Suniva. This demonstrates that the lower performing modules do not improve in performance as they deviate from south, but consideration is not given to a wider critical angle or frequency spectrum.

8.2.2 LCOE By Height

A similar approach was taken to determine the effect of NB height on LCOE, this was done by simulating NB at 2.5m intervals at the same sites to measure this influence. Only the results for the Suniva module are presented in figure 8.2.1b. It is established that the effect of height on the LCOE is not linear, where a 2.5m tall NB would result in an 80% increase when compared to a 10m NB. This is a result of the cost savings with increased capacity per meter in length, despite to the fact that the normalised systems are exposed to the same irradiance. This is due to economies of scale alongside the utilisation of larger components, such as the inverter with cheaper cost per watt, for increased inverter sizes.



(a) LCOE by orientation for Modular design, Height 5m, tilt angle 10°, Grid 100m

(b) LCOE by Orientation for different NB heights in 2.5m intervals with Suniva

Figure 8.2.1: Effect of Orientation on the LCOE of the normalised NBs

8.3 OTHER DECISIVE ATTRIBUTES

It was observed from the multi-criteria analysis that several system characteristics were decisive in finding the cost of energy at each site. Where any single attribute could result in a poorly performing system or inflated costs making them unfeasible. Figure 8.3.1 shows the cost breakdown per component for the segment design with the Suniva module.

The largest column from figure 8.3.1 can be attributed to the length of the NB being only 10m in length, so very limited amount of PV could be installed. Coupled with the distance to grid being 650m so this price dominates the breakdown.

8.3.1 MODULE COST

Figure 8.3.1 shows that the cost of the module can take up a significant proportion of the system cost when looking at the cheaper €/kW systems. Noting that this is a critical cost that can drastically inflate, depending on geographical location, installed power and supplier. Through interviews it was established that costs between €0.40-0.45/W are more accurate for mono-crystalline, with further reductions expected due to increasing numbers of Chinese modules on the market. The model does not explore the cost differences between module type.

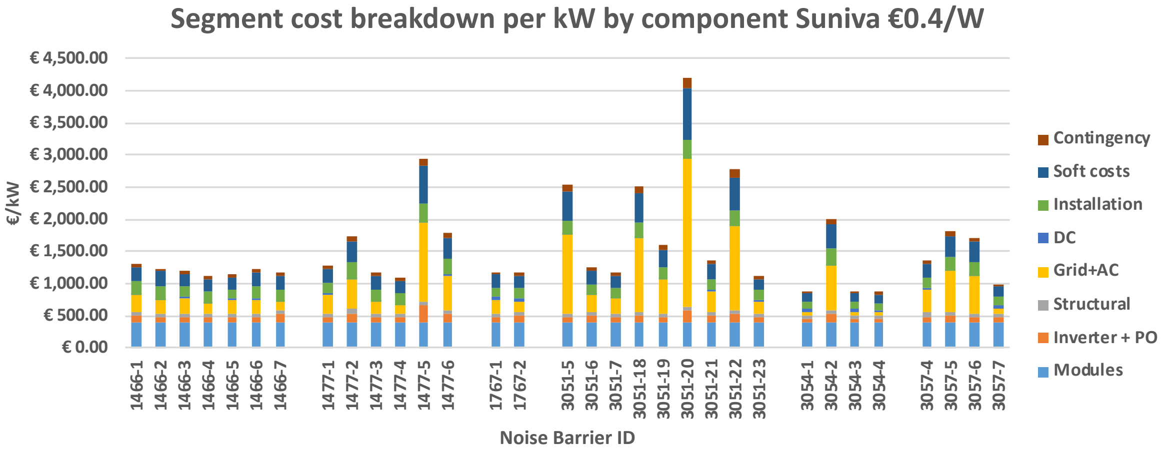


Figure 8.3.1: Cost breakdown of the segment design for €0.4/W Suniva

8.3.2 Mounting Structures

Originally seen as one of the key areas for cost reduction of the Energy wall through utilisation of the NB. Furthermore, there was as an expected cost reduction through the implementation of flexible thin-film vs modular PV modules.

For the PV modules a roof-mount railing system design was considered, this mature technology can be found for relatively low prices already. The Energy wall costs were expected to be lower than those of a ground-mount systems because of its requirement for posts and foundations.

Between the flexible thin-film and the modular PV designs an adhesive tape attaching method was explored using an all-weather tape costing €1.5/m. It was found that due to standardised railing mechanism, these mounting structures can be purchased for a low price. This meant that at this cost for tape often was not at a competitive price, coupled with the additional risk of theft. It is expected that this is not a practical method for mounting PV, with little data relating to other cost savings.

Comparing to the cost breakdown of 9% shown in figure 7.1.1, a large reduction is seen. It was found that on average the cost of the rail mechanical structure was between 2-4% of system cost. While the systems utilising adhesive tape saw a smaller reduction. No economies of scale were applied in the model for the cost of purchasing the tape or rails, therefore percentile contribution to system cost increased with system size, when comparing Modular to Entity.

Between the modules utilising the adhesive tape method, it was observed that fewer larger modules had a lower cost attributed to mounting because of the reduced perimeter. Unless a significant decline in the price for the tape while addressing the security concerns with this method the traditional rail method is seen as the best.

Table 8.3.1: The number of Energy walls that would qualify for respective subsidies

Design	Subsidy	Number qualified
Modular	Postcode	187
	KIA (2)	160
	KIA (3)	36
	KIA (4)	0
	EIA	8
	SDE+	9
Segment	Postcode	74
	KIA (2)	45
	KIA (3)	53
	KIA (4)	83
	EIA	23
	SDE+	150
Entity	SDE+	42

8.3.3 GRID CONNECTION

In some cases, seen in figure 8.3.1 that the cost from Grid + AC connection can dominate the overall system costs, this primarily comes from the distance to the connection point. Charges incurred from larger connection sizes have less effect on the final costs as the price per watt declines with bigger connections. The distance to connection point arises because NBs are predominately located at the edge of the residential districts while the connection point is more likely to be optimally centred for the local network.

Grid connection size becomes an important variable when considering subsidies as it determines whether the system falls into a large or small connection category.

8.3.4 SUBSIDIES

Table 8.3.1 shows how many NBs qualify for subsidies and which ones, this is found to have a significant effect on the economics of the projects. It can be seen that due to the size of the Entity Energy walls, they are all too large for any of the subsidies (apart from SDE+) that some of the Segment and Modular designs can exploit.

Significant improvements can be made in LCOE by increasing the length of the Energy wall from 20m to 200m due to scale. However, when the KIA subsidy is applied to them, they both achieve closely related LCOEs as shown in figure 8.3.2. Both the 20m and 200m fail to qualify for the EIA subsidy because they must remain >25kWp which the 20m NBs do not meet while the 200m NBs are above the 3x80A maximum connection size for Suniva. To demonstrate the benefits of EIA a 50m Energy wall was simulated which qualifies, as a result sees the lowest overall LCOE. The greatest re-

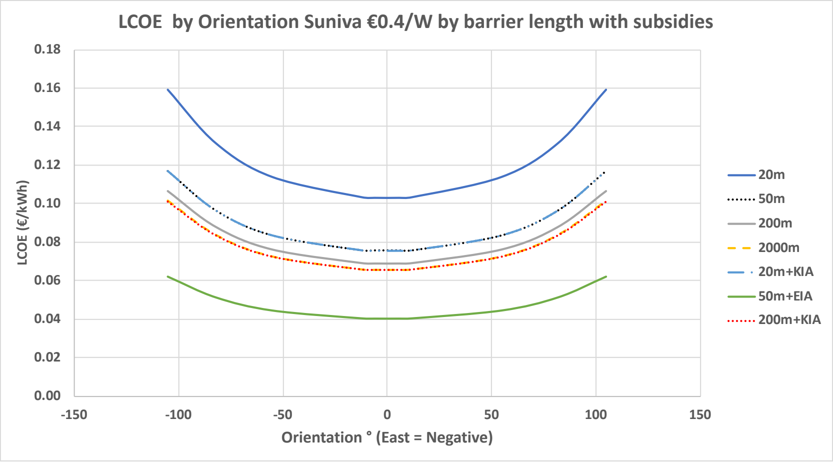


Figure 8.3.2: LCOE by orientation for the Suniva module with the applicable subsidies, 2000m does not qualify for KIA, 5m, 10°tilt & 100m to grid

duction from KIA occurs on smaller projects, while the 200m with KIA is nearly equal to the 2000m without subsidy; which does not qualify for any subsidy.

These subsidies work by reducing the investment cost of the system and therefore do not rely on the price placed on the energy. For a positive return, the energy should be sold for more than the LCOE; the price it costs to produce.

Figure 8.3.2 shows an increase in LCOE of between 33% & 39% from south by ± 90°, for the simulated NB with Suniva.

8.4 System Proposals

This section will discuss specific cases that were the result of the multi-criteria analysis. When analysing the systems, the dataset with €0.40/W modules were used and one design was selected from each of the Modular, Segment and Entity designs.

All systems were assessed based on the following criteria, 3.55% real discount rate, 25-year lifetime, and a module degradation rate specific to each type of PV as discussed in 5.1.4.

The CAPEX has been indicated in the costs of each system as the total investment cost, while OPEX accounts for 1% of initial investment each year for the life of the project. A replacement inverter is installed at year 15, adjusted for inflation.

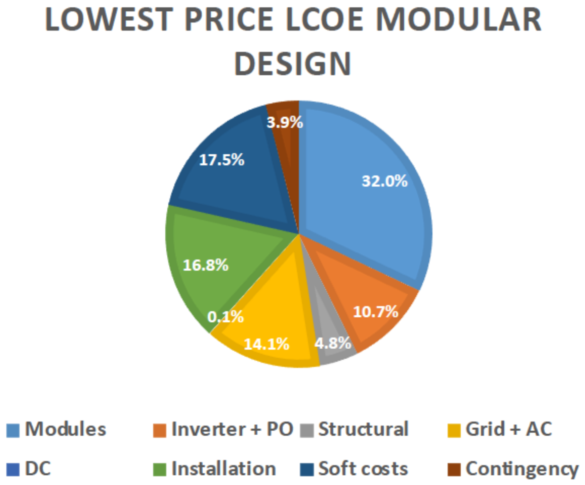


Figure 8.4.1: Lowest price LCOE Modular design from multi-criteria analysis

Table of Attributes for the Modular design

ID	3054-1
€/kW	1,248
LCOE (¢/kWh)	9.08
CAPEX	€55,190.84
Installed capacity (kW)	44.2
Year 1 production	31MWh

Table 8.4.1: Main characteristics of the proposed Modular design

8.4.1 MODULAR DESIGN COST BREAKDOWN

The description of the lowest LCOE modular based system can be found in table 8.4.1. These costs are for the closest 20m to the grid connection, this segment of barrier could realise 30 Modular Energy walls. This system would produce enough energy for 9.5 Dutch households, as found in the GIS analysis.

The cost breakdown when compared to the IRENA breakdown presented in 7.1.1, shows that the modules contribute 13% less while the cost of grid connection and installation see much larger costs. This can be attributed to the lower cost of PV modules used in the model, compared to 2018. Considering the German breakdown is for a utility scale project, this means that other cost savings are not implemented yet. Installation costs more than doubled for the modular design. Despite the short distance to grid of 50m the 3x125A grid connection fee of €4979 plus the rate of €55/m have a large influence on the system cost. While reductions are seen for structural and cabling costs.

STAKEHOLDERS

This project is too small to be attractive to RWS or utility companies themselves because it's on such a small scale. While it is more likely to be attractive to a nearby company or housing cooperation.

Table 8.4.2: Showing IRR for different values placed on energy

€/kWh	IRR
0.05	-6.31%
0.10	0.53%
0.20	8.6%

SUBSIDIES

An IRR depends on the value placed on the energy, this could vary between a base rate for energy currently on the grid to the value agreed in a contract. To highlight the effect of the price of energy on the IRR, table 8.4.2 has been produced, where €0.05/kWh is the base price for energy in the Netherlands and €0.20/kWh is the average cost for households. Therefore if the energy is cheaper than the current supply, savings can be made.

- Postcoderoosregeling A project on such a small scale could attract local citizens or businesses looking to utilise the postcoderoosregeling programme however the system is only just too large with a grid connection greater than 3x80A. It is therefore advised to lower the number of modules in the design if it is the priority to receive this subsidy as a tax relief. Assuming the rate of postcoderoosregeling was achieved this would result in a tax relief of €3,416 in year 1 as long as the parties involved consumed the same quantity of energy that they were claiming the tax back for. They would also require a cooperation with other parties because it is above the individual limit of 10,000kWh.

- SDE+ An SDE+ subsidy can be achieved, with a rate of €0.09/kWh an NPV of -20,995 and IRR of -0.54% is seen. The better rate of €0.112/kWh would see an NPV of -10,209 and an IRR of 1.7%. Using the real discount rate of 3.55%, this shows that for this system as a revenue stream is not attractive.

- EIA If a company wanted to take full ownership of the Energy wall and apply for EIA considering only the solar system, a maximum of €750 per kw of peak power can be refunded. For this design there is expected to be 35kW of peak power, which results in a final system cost of €28,940. This would result in an actual LCOE of 4.82¢/kWh making this a positive investment for a company looking to self-consume the energy. If energy were sold at a rate of €0.05/kWh the IRR would be -0.16% while a rate of €0.10 would see an IRR of 7.86%.

- KIA If a company wanted to take full ownership of the Energy wall and apply for KIA, the project falls into the most advantageous category in table 4.2.2. Whereby it could receive a subsidy of 28% of the invested amount, bringing the price down to €39,737.40 resulting in an LCOE of

6.5¢/kWh. Again, if this project was for self-consumption it would be cheaper than the grid price so makes a positive investment.

NEARBY LOADS

The NB is located near a residential district called Smitshoek to the west end of the NB is a gas station that could benefit from direct consumption of the Energy wall. Based on data from CBS Netherlands it is calculated that in 2015 the total residential electrical energy consumption for the neighbourhood closest to the 3054-1 NB was 382MWh. This neighbourhood, called Buitengebied could therefore achieve 8.1% of its required energy. 2015 data was used because this is the latest up to date information containing energy electrical energy consumption data. Although the energy would not be produced at the time of consumption.

8.4.2 SEGMENT DESIGN COST BREAKDOWN

An Energy wall on the 3057-7 NB would produce energy for the lowest price of all segments simulated when using the Suniva module. Table 8.4.3 shows the key characteristics, where a price of less than €1/W has been reached. When compared to the IRENA cost breakdown in 7.1.1, there is again a reduction in PV module prices and structural, soft and installation costs. Compared to the Modular design the price reduction can be attributed to the system size. An increase in the price of the inverter + power optimiser is seen, which may be a direct result of the design decision to limit the inverter sizes to 60kW.

STAKEHOLDERS

This could be of interest to RWS depending on whether the cost of energy is competitive with the market cost, also utility companies that want to sell more green electricity. It is less likely that a third-party company would be interested in such a project because of its sizeable investment and they would have to use a large amount of energy to justify this investment. Depending on the terms of any produced DBFM contract, a PPA of more than €0.06/kWh would result in profit for the system owners.

SUBSIDIES

This project is too large for Postcoderoosregeling, EIA & KIA requiring a grid connection of 630kVA and costing over €650,000. However, it does qualify for SDE+ subsidy, it falls into the smaller of the two categories which is eligible for better rates than a system over 1MW. The system would have to be up and running within one and a half years of receiving the subsidy from SDE+. All of the generated hours can be claimed under the limit of 950 hours of rated power.

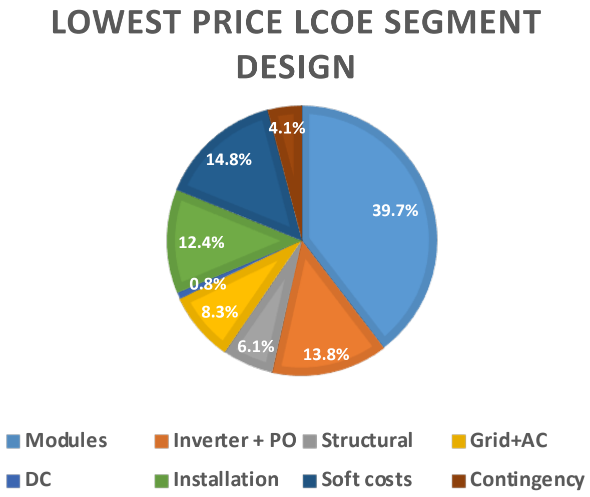


Figure 8.4.2: Lowest price LCOE Segment design from multi-criteria analysis

Table of Attributes for the Segment design

ID	3057-7
€/kW	979
LCOE (¢/kWh)	5.8
CAPEX	€657,476
Installed capacity (kW)	671
Year 1 production	578MWh

Table 8.4.3: Main characteristics of the proposed Segment design

If the highest rate for phase 1 of €0.09/kWh was achieved, the project would have an NPV of €395,408 while the best rate in phase 3 would result in an improved NPV €700,421 representing an IRR of 3.89% and 6.61% respectively.

NEARBY LOADS

This NB is located near an industrial area consisting of car dealerships and garages, not heavy industry, due to their business types it is less likely to be a venture of interest to them. However, a utility company could be attracted by this offer because of the low LCOE compared to the SDE+ subsidy, however because of the size the RGO is not obliged to connect the system so to gain more certainty a lower price could be offered. This installation would provide enough energy for over 174 households annually. Using the CBS data it can be seen that the total residential electrical energy consumption for the closest neighbourhood; Charlois Zuidrand was 580MWh, the Energy wall would therefore result in producing nearly all of the annual electricity demand.

8.4.3 ENTITY DESIGN COST BREAKDOWN

An Energy wall on the entire NB 3057, could consist of a 1.05MW installation costing €1,095,537 allowing a 1.05MW system costing of €0.054/W. This system is expected to generate 905MWh in its first year of operation which surpassed the current largest solar installation in Rotterdam by 142MW, therefore having a significant impact on the quantity of renewables in the Rotterdam. When compared

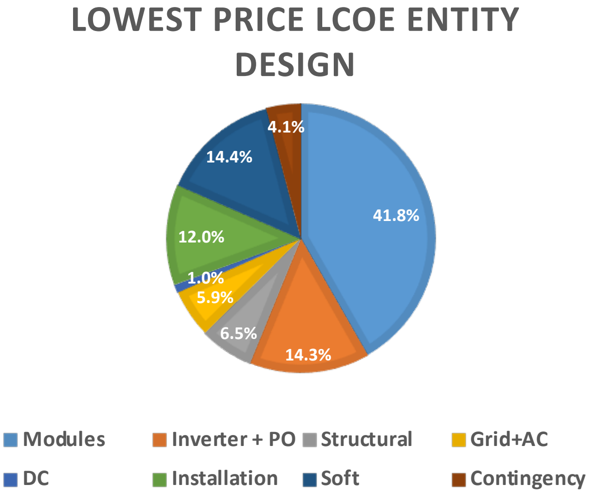


Figure 8.4.3: Lowest price LCOE Entity design from multi-criteria analysis

Table of Attributes for the Entity design

ID	3057
€/kW	923
LCOE (¢/kWh)	5.4
CAPEX	€905,293
Installed capacity (kW)	1050
Year 1 production	905MWh

Table 8.4.4: Main characteristics of the proposed Entity design

to the IRENA breakdown in figure 7.1.1, it is noticed that the contribution of the PV modules has a closer share as other prices have declined towards utility scale.

Stakeholders

Due to the size of this project it is likely to be interesting to utility companies or nearby businesses. RWS may be interested as again, a competitive price for the energy can be realised on a large scale. While the scale is too large for coordination, with postcoderoosregeling not possible.

Subsidies

This project only qualifies for the SDE+ tariff but can receive rates at in phase 1 of €0.09/kWh or phase 3 €0.107 resulting NPVs of €132,526 and €375,797 with IRR of 4.8% and 7% respectively.

Nearby loads

This NB is just the combination of the best segment presented in the Segment design but stretches another 599m with an additional 3 segments. It would therefore, provide all of the required residential electricity consumption for the Charlois Zuidrand area.

Projects of this size will be of extra interest to the Rotterdam municipality because of their production target of 20GWh by 2018 and 100GWh by 2030. In August 2016 an installation in Rotterdam was

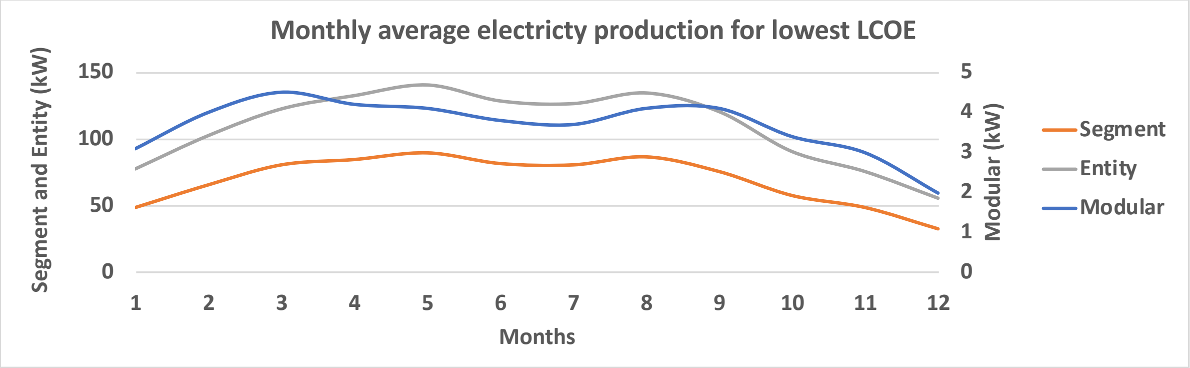


Figure 8.5.1: Figure of the average monthly energy output for the three before mentioned systems, performed in HOMER

added with the capacity to supply 750MWh annually was said to boost the cities renewable capacity by 25%. This installation would contribute hugely to this target from just a single project [37].

8.5 HOMER

Hybrid Optimisation Model for Multiple Energy Resources software was used to perform checks on the outputs of the system, it can be used to find out more accurately when the energy will be generated. Figure 8.5.1 shows the relatively homogeneous production that can be expected from the systems discussed. It is found that for these systems that comparing the peaks against the lowest month (December) a production of between 35% & 45% is seen, while the same systems optimally inclined realise a winter performance around 27%.

The heat maps can be seen in appendix 10 which directly correspond to figure 8.5.1, it can be seen that greater intensity irradiance occurs in the early and late months of the year while the daylight hours are shorter than in the summer months. Where the modular design sees much shorter daylight hours because of its vertical tilt compared to the Segment and Entity that tilt at 20°and experience a much flatter PV power output.

8.6 SUMMARY

This chapter has presented an overview of the findings from the developed model, identifying which modules performed best at lowering the final cost of energy for the different implemented system configurations; Modular, Segment & Entity.

The output of the model present a myriad of system sizes and costs, it was shown that large variation

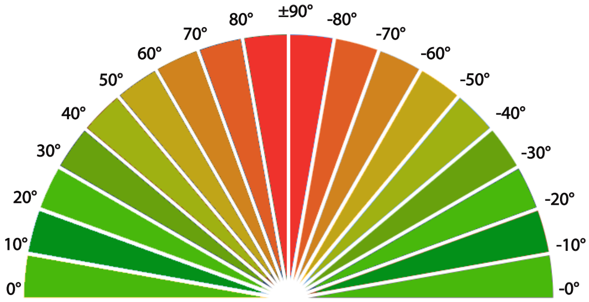


Figure 8.6.1: Orientation of NBs were 0°is south and ±90°is East/West, colour coordinated by CF

Orientation (°)	Length (km)	Production (GWh)	CF
±0-10	68.7	41.3	8.0%
±11-20	67.3	42.8	8.5%
±21-30	59.2	35.5	8.0%
±31-40	57.5	29.5	6.9%
±41-50	58.1	26.9	6.2%
±51-60	65.8	24.6	5.0%
±61-70	77.4	22.5	3.9%
±71-80	64.6	14.9	3.1%
±81-90	73.3	11.9	2.1%

Table 8.6.1: Netherlands estimation of Energy production by grouped orientations, assuming height of 5m, Suniva modules and backwards tilt

can occur between different systems on the Rotterdam ring based on the NB infrastructure and the size of the system implemented.

Further development was made towards understanding key attributes to the success of an Energy wall. Based on these, a critical analysis was made, that could be applied to all NBs being considered for Energy wall conversion.

The effect on the final cost of the system by orientation is presented for different PV modules and different NB heights. Resulting in highest efficiency modules surpassing the expected savings from thin-film modules, due to cheap mounting structures and poor thin-film performance.

Figure 8.6.1 shows the distribution or orientation for NBs in the Netherlands where 0°represents a south facing NB and ±90 represents east/west facing NBs. The corresponding table 8.6.1 shows how these segments divide up lengths, based on average height data from the Rotterdam ring for NBs equalling 5m, Suniva modules were located on these NB. The total length of NBs within these orientation ranges are found and trends based on the Rotterdam ring are applied. It is found that the CF does not monotonically decline with orientation away from south. This is because of the tilt angles of the NBs within the group where ±0-10°contains more 0°tilts than the ±10-20°.

It was found that in order to develop a economically attractive system for investors, key areas should be focused on. The sourcing of cheap PV modules, utilising the NB to reduce mounting costs by using mature technology, selecting a site near to a grid connection point and designing to maximise usage of the available subsidies.

Business proposals have been made for the lowest LCOE price of the Modular, Segment and Entity designs. Where the NPV and IRR are calculated, while comparisons are made to the cost breakdowns found in literature.

Subsidies can have a significant impact on the LCOE of projects but are mostly applicable to smaller projects making them attractive to small businesses, however, the organisational structure of the project should be understood to ensure that the full subsidies can be applied for.

The largest modelled system was the cheapest CAPEX system, but not the on an LCOE basis. This is attributed to the system tilt angle where lowest LCOE comes from the 20°tilt system, while the largest system has no tilt angle, but could realise an installation of 5MW.

Large Energy walls can be of such a vast size that they could dramatically increase the cities renewable infrastructure, because of the lack of space for such systems.

The Energy wall does represent a positive investment for specific stakeholders, ensuring guaranteed prices and relevant subsidies are attained.

This has shown that the Energy wall can be a positive investment on small and large-scale. Making use of cooperation schemes between homeowners up to utility scale installations where cost can be competitive with conventional arrays and reach grid parity. It is noted that all the cheapest systems occur with the Suniva module, it is found that this is not a tier 1 company so may not be the module selected by RWS; a governmental body.

9

Conclusions and Future recommendations

This chapter will highlight the findings from the study that can be used to answer the initial research questions presented in chapter 1.

The study was conducted in such a way so as to move the development of PVNBs/ Energy walls away from the experimental domain into the financially viable one, thereby hoping to stimulate investment. This was done through an engineering study, prioritising financial benefit over all.

What design advantages/opportunities can be realised from implementing the Energy wall system in the urban environment?
The implementation of the Energy wall in an urban environment could unlock some major environmental and economical opportunities, for the city. With large-scale projects significant impacts on the energy mix of the city can be achieved which was previously much more difficult to integrate into the city. On the small scale, projects can represent a sensible investment for homeowners and businesses who want to reduce their energy bills, while always utilising otherwise redundant land. With the co-operation scheme, community projects can be initiated which can be available to a large number of people. With the Modular design the same project can be repeated adjacent which could speed up the process and reduce costs.

It has been found that despite the lower capacity factor the systems will realise, the systems can result in grid balancing benefits. These can manifest themselves as either seasonal balancing through a more homogeneous production year round for south facing systems. While, East/West orientating systems can have intraday balancing through early morning or late evening production.

What is the potential of the Energy wall in the Netherlands, based on the current infrastructure?
It is found that a sizeable infrastructure is already in place, by retrofitting the 590km of already built NB constructed from a suitable material in the Netherlands, a sizeable potential could be realised. Estimates were made using the results from the Rotterdam ring using the averages which couldn't be found on a country wide basis, but effects of shading are neglected.

Can specific cost opportunities be found from mounting renewables on noise barrier, and what are they?
Based on literature, research and interviews, cost opportunities arise from the reduction of mounting structures with the application of roof-mount technology to the surface. An alternative method of adhesive tape for mounting flexible thin-film PV was explored but found to be expensive and less secure/permanent. It should be kept in mind that this study only focuses on the retrofitting of current NBs, while cost advantages could come from integrated designs through sharing NB construction and PV installation together. This being said, the integrated PV is expected to still be considerably more expensive.

What technology and in which topology should be implemented on the Energy wall to realise the best design?
The application of high efficiency PV allows for the maximum utilisation of space, this is true so long as there is not a significant cheaper module with lower efficiency modules, which is unlikely with the forecast for further reductions in mono-crystalline PV. The application of lower efficiency PV will consequently result in higher installation costs, while advantages from a lower temperature coefficient are not expected to effect performance much because of the low temperature climate in the Netherlands. The implemented topology is based on a centralised design, up to a 60kW limit which for an average NB height of 5m with Suniva modules, would cover around 90m. Above this rating the design turns into a modular one with multiple inverters connected to an AC bus, this was used to reduce lengthy DC transmission which emerge because of the unique site layout. This strategy does see the cost of inverter increase proportionally because larger single inverters are not used. DC power optimisers are used to improve inverter efficiency and shade tolerance.

Can a model be developed to give a wider understanding of the critical design parameters of the Energy wall?
The developed model for the Rotterdam ring allows for the comparison of different system sizes and technology for all orientations. For the engineering design study six sites around the Rotterdam ring are considered, with the final results of the 3 design types shown on a map in figure 10.0.1.

Normalisation of the input variables, namely the height, tilt angle, length, distance to grid and corresponding solar irradiance at each location allow for trends to be plotted that represent a large range of systems. This can be used to estimate potential on a wider scale, highlighting characteristics such as the LCOE by orientation.

It is found that the orientation, distance to grid and module performance are all critical parameters, that should be considered before selecting the site, while the latter depends on hardware sourcing.

Can an implemented Energy wall in the field represent a return on investment, and who might these investors be?
Given the prices implemented in the model, systems can reach grid parity at small and large-scale, resulting in saving investors money on their energy bills or guaranteeing a price for the energy produced. Entrepreneurial subsidies can reduce the initial cost of investment which again makes the investments more attractive, with EIA offering up to €750/kWp and KIA a maximum of 28% based on investment size and cost.

What price and quantity of energy can the Energy wall achieve and how does this deviate across NBs and local infrastructure?
It has been shown how the orientation can effect the energy production which directly effects the LCOE of the system, as expected it is more advantageous to orient south while directing east or west can increase the final cost of energy by more than a third.

A range of stakeholders which are eligible for subsidies were found, this was used to develop business models to highlight examples of the most favourable systems. Where the financial benefit was expressed in IRR and found that the system has the potential to represent a positive investment for a wide range of system sizes.

9.0.1 Discussion

A critical analysis of the work carried out is performed. When comparing the PVNB in Pijnacker to the 6 case studies around Rotterdam ring it is found that the Energy wall achieves an energy density between 3.4 to 5.8 times larger. This is believed due to a lower surface utilisation in Pijnacker to allow for transparency, an example of how aesthetics can effect the system. It is recognised that aesthetics will play a role in the acceptance from the local population. A concession could be to utilise less of the area of the NB if it is transparent, however, for opaque NBs this will not be a concern.

The largest system modelled has the potential to produce an estimated 3.4GWh, this would have a very large impact on the local electrical infrastructure. Having a significant impact on the city's sustainability and image on the global stage.

The module prices implemented in the model it is believed will be harder for smaller installers to attain and the neglection of price differences between PV types may introduce bias into the model. Installation costs need to be verified for the retrofitting approach, making as much use of pre-fabrication as possible to increase the speed of installation. A vulnerability arises from the uncertainty around the price RWS could charge for the use of the land and NB, this may fluctuate with time and organisation exploiting it.

When considering the system the lower energy yield compared to an optimally inclined system should be looked past, realising the other benefits that can arise from its implementation. If the costs are verified in the field, this will unlock a large area in urban areas on which to site renewables.

For a cooperation organisation the system should be designed to maximise the usage of subsidies which can make them some of the most attractive investments, allowing for guaranteed rates. KIA & EIA have large benefits but mostly if the system falls within the most advantageous categories, which are only relevant to specific parties. If it is found that the system does not adhere to the conditions, it could have a detrimental effect on the project.

To understand the system flexibility the model runs with a 10% increase in system costs and a 10% decline in energy production, finding that on average the LCOE increased by 22%.

Bifacial may be beneficial at a specific orientation based on the results of LCOE or energy production, if further work is used to incorporate bifacial into the model a point at which bifacial PV is more favourable can be found. However, it should be considered that bifacial PV needs to either be integrated in the glass or mounted on the top at a limited height. Already increasing the cost through customised integration or lower surface utilisation.

Overall it is believed that the implementation of the Energy wall can be successfully implemented, both on a large and small-scale considering the critical attributes discussed. First deploying on the most advantageous NBs to gain experience for the procedures of mounting & installing, administration and project organisation, thereafter retrofitting a much wider array of NBs.

9.0.2 Recommendation for future work

To develop this work further, a more practical approach should be taken by implementing some of these systems in the field. Verifying energy yields and costs used in the model.

Work relating to the further development of the GIS methodology should be carried out, relating to the DEM and tilt direction on a nationwide level. Shading was initially considered at the selected sites but an automated approach could be developed, utilising tools such as TEM (Terrain Elevation Models) to predict shading, based on sun path, roughness and NB height.

Simulation of the proposed systems could be implemented to verify the topology selection.

10
Appendix

APPENDIX A

This section holds the key parameters of the selected NBs along with pictures as taken from Google maps

1. - **1466** is to the north of the Rotterdam ring on the A20 road.
   - Bent or curved along its height
   - PV mounted roadside
   - Close to traffic

2.

- **1477** is on the A16 which is the road to east of the ring, it lies on the Briennordbrug to the south of the river.
- PV mounted backside
- Mostly open expanses with some trees concentrated at one section

3.

- **1767** is on the A4 to the west of the ring, before the entrance to the tunnel on the south side of the river.
- PV mounted on back side*
- Trees to rear with metal poles supporting the forward tilt section

4.

- **3051** on the a4 road to the north of the river
- PV mounted road side
- Set back from road by a lane with large open expanse in front

5.

- **3054** on the A15 road to the south side of the ring A15 road
- PV mounted on backside
- little to no shading on PV side

6.

- **3057** on the north side of the A15 at the south of the Rotterdam ring
- PV mounted roadside
- Setback from the road by a lane and barrier with regular lamp posts

APPENDIX B

This appendix shows the prices for components that were implemented in the model, as sourced from suppliers

Table 10.0.1: Table of the applied inverter prices

Inverter	Output power (kW)	€/unit
SMA Sunny boy 1.5	1.5	589
SMA Sunny boy 2.5	2.5	779
SMA Sunny boy 3.0	3	959
SMA Sunny boy 3.6	3.6	1019
SMA Sunny boy 5.0 TL	5	1149
Sunny Tripower 10000TL	10	2179
Sunny Tripower 15000TL	15	2599
Sunny Tripower 20000TL	20	2809
Sunny Tripower 25000TL	25	2909
Zenersolar pro 33k	33	3298
Sunny Tripower 50	50	5207
Sunny Tripower 60	60	6446

Table 10.0.2: Costs applied in the model for DC cables

mm^2	AWG	€/m (inc VAT)
1.5	16	0.464
2.5	14	0.464
4	12	0.65
6	10	0.82
10	8	0.733
16	6	0.745
25	4	1.02
35	2	2.01
50	1	2.34
>50		3.43

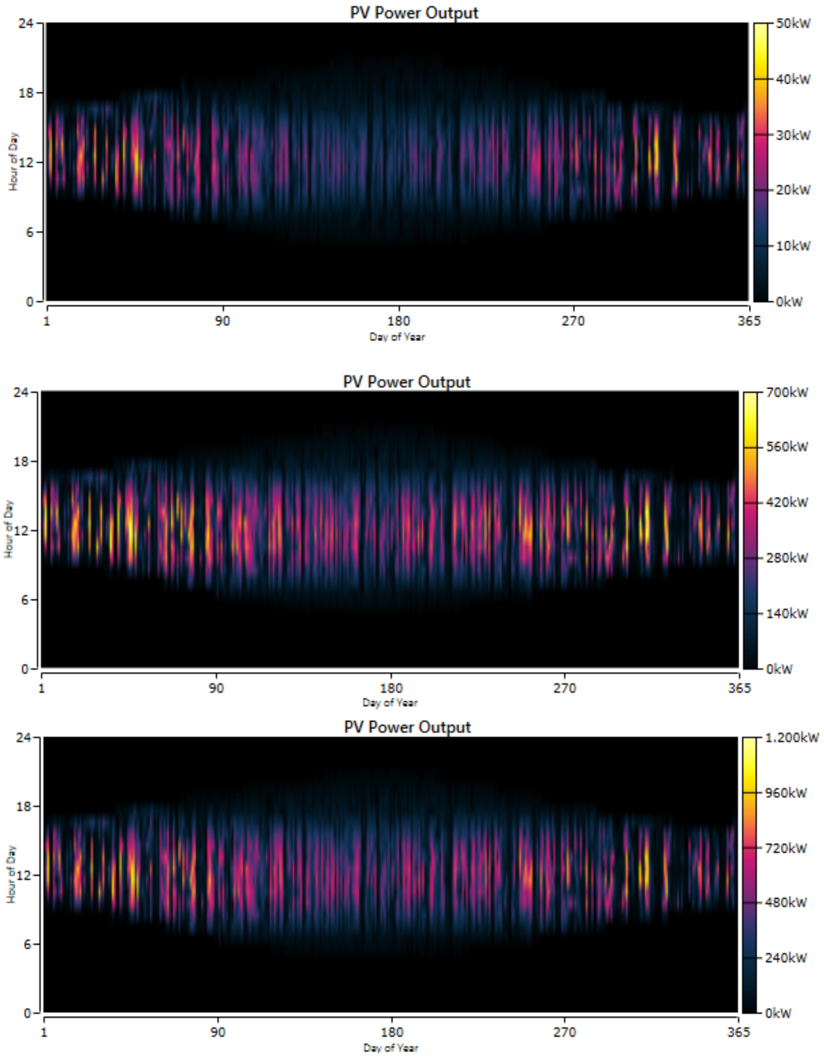
Table 10.0.3: Grid connection cost as advertised by Stedin [45]

Connection size	Installation (€)	Cost per meter over 25m (€/m)	Maintenance €/year
<1x6A	1190.56	33.39	13.01
1x10A	1190.56	33.39	98.39
1x35	1190.56	33.39	236.96
3x25A	1190.56	33.39	236.96
3x35A	1656.6	35.06	885.09
3x50A	1656.6	35.06	1281
3x63A	1656.6	35.06	1676.91
3x80A	1824.44	38.02	2072.82
3x125A	4979.33	46.1	73.71
175kVA	6306.23	48.57	73.71
630kVA	43571.01	80.82	674.85
1000kVA	45015.01	89.45	674.85
1750kVA	55270.05	92.24	1427.52
3000kVA	233728.09	125.29	7369.07
10MVA	319338.07	143.55	7369.07

APPENDIX C

This appendix shows the output from Homer for the 3 selected systems with the lowest LCOEs from the model and a map of Rotterdam indicating the lowest prices of the three designs.

Table 10.0.4: Top: Modular Energy wall on 3054-1, Middle: Segment Energy wall on 3057-7, Bottom: Entity Energy wall on 3057



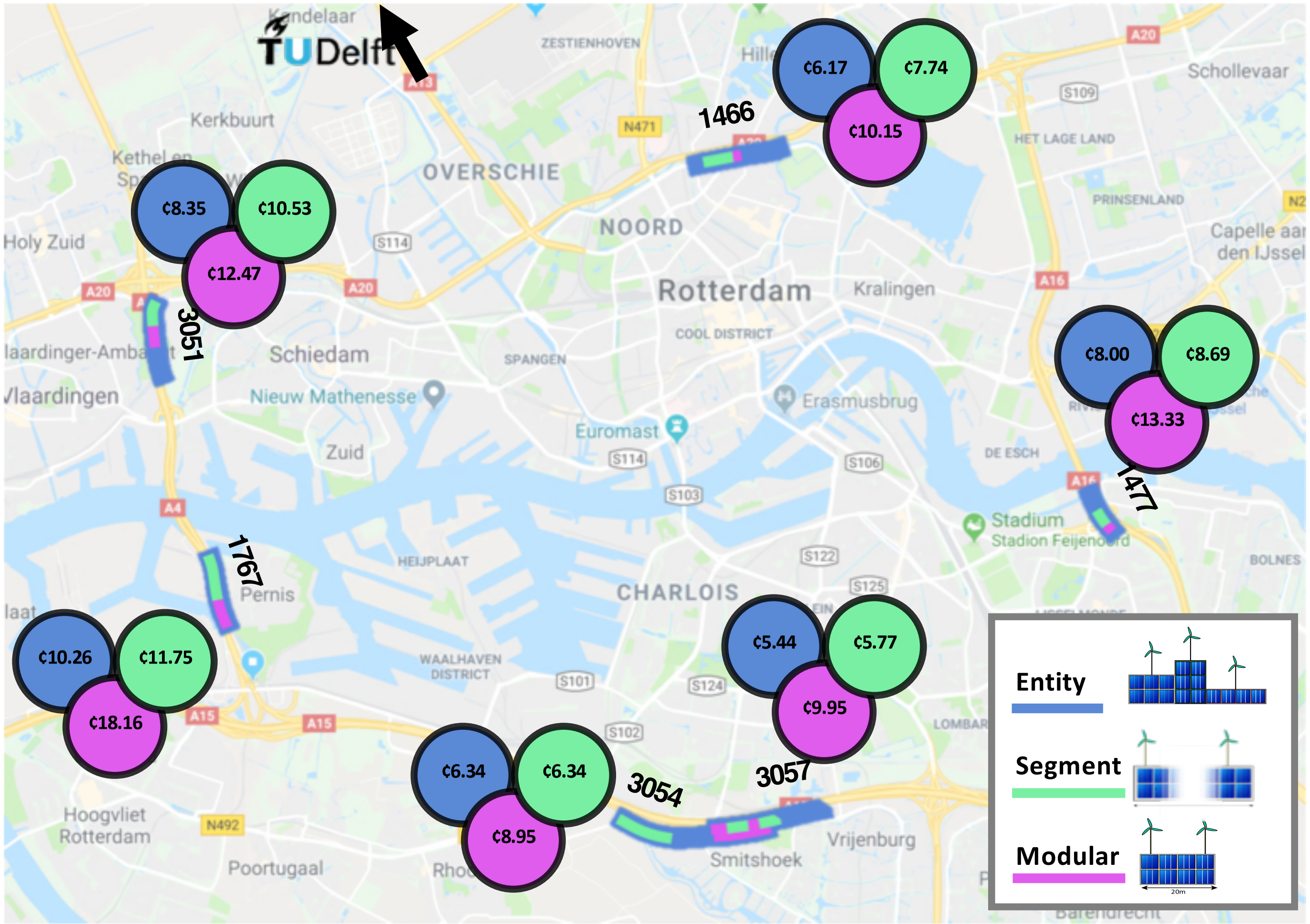


Figure 10.0.1: Map of Rotterdam ring road indicating the lowest LCOE of the six case study sites for the three configurations

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