The potential of photovoltaics along the Dutch national high- and expressways (Rijkswegen)

An analysis of the potential of PV noise barriers

Master thesis

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Rijkswaterstaat

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Preface

This 30 ECTS master thesis was written and presented as part of the Sustainable Development program at Utrecht University. Research has been done as part of a research internship at Rijkswaterstaat.

I would like to thank my supervisors Wina Crijns-Graus (Utrecht University) and Willem Traag (Rijkswaterstaat). Furthermore, I would like to thank Rik Jonker and others at Rijkswaterstaat for their guidance and input.

Abstract

As fossil fuels are becoming scarce and GHG emissions are increasing, renewable energy sources are increasingly the focus of the policy agenda. As a result, the EU has implemented goals to achieve a larger share of renewables with all their members by 2030. As a government agency, Rijkswaterstaat can play a role in offering available land necessary for the use of photovoltaic (PV) electricity generation. This study focuses on the potential of PV noise barriers (PVNB) along the Rijkswegen by 2030. The goal was to quantify this potential by calculating the solar irradiance at the location of current noise barriers, thereby identifying suitable locations. The annual electricity production for several different potentials was calculated to give an answer to the research question.

By using detailed digital elevation maps (DEM) of the Netherlands and geographic information systems (GIS) datasets, it was possible to calculate the solar irradiance using GIS software and the Esri Solar Analyst tool. All noise barriers with a length more than 500 metres were studied. Added was the likelihood of noise barriers being replaced or upgraded. This can create an opportunity for the building of a PVNB. The PV potential and other relevant data for all these samples were added to graphical overview maps to easily identify suitable locations.

For the study area and the scope of the study, the short-term potential is the most relevant. This potential describes the electricity production for all noise barriers that are likely to be replaced by 2030 and with a high PV potential. This study estimates that potential to be between 5,828 MWh and 6,938 MWh annually.

Several cases were analysed in more detail. These cases represent three projects where a PVNB is planned (or was planned in one case). The results of this detailed analysis were used to see what the effects of varying angle and orientation were and how this compared to the used methodology.

Table of Contents

1. Introduction

1.1 Background

Worldwide, the energy demand is increasing year after year. While the total final energy consumption in 1973 was only 4,672 Mtoe or 54,335 TWh, this has almost doubled by 2012 to 104,426 TWh (8,979 Mtoe) **(IEA, 2014a)**. And even though the share of renewables has increased significantly over the same period, the issue remains that there still is an absolute increase in conventional fossil fuel based energy production. Even the total consumption of coal, that saw a significant decrease 1988, has been increasing since 2002 again to the point where it now surpassed the 1988 levels. The related issues are numerous and include the increase of greenhouse gas (GHG) emissions resulting in high concentrations in the atmosphere, leading to an increase in global average temperature. Seeing as the energy sector is responsible for two-thirds of all anthropogenic GHG emissions, improvements in this sector can prove very useful. The challenge is to limit global warming to an average of no more than 2 °C, relative to pre-industrial levels. This has already been adopted as an objective by governments during the COP16 in Cancun in 2010 **(IEA, 2015)**.

In order to decrease the energy use and emissions in all energy related sectors, different (inter)governmental organizations are taking action with agreements and targets, besides the COP16 objective. The year 2030 is a key year as it is set by the European Union as the year by which member countries need to meet certain mandatory targets in the field of environment **(European Commission, 2014)**. The EU agreed to set the goal to at least a 40% reduction of GHG emissions in 2030 as compared to 1990. The share of renewables should be at least 27% and the energy efficiency is to be improved by 27%. Member countries are free to set higher goals, but the minimum is mandatory. Therefore, there is a need to study the possibilities of renewable energy to decrease energy use and GHG emissions. Electricity consumption in the Netherlands accounted for 119,000 GWh in 2013, with electricity production at 101,000 GWh. The shares of renewables accounted for 12% of total production **(CBS, 2015)**.

One energy related sector is the transport sector. Transport has been a constantly evolving sector. Over the last few centuries and even more during the last few decades, new technologies have enabled us to travel further and faster than before. All resulting in an increase of mobility, globalization and economic welfare **(Van Wee and Dijst, 2002)**. This increase in transport leads to the necessity of a sufficient infrastructure: the goal of the construction of new infrastructure is to cope with the growing transport of society. This has led to a total road-length in the Netherlands of 138,641 kilometres. This includes highways, but also smaller provincial and local roads. The Rijkswegen (national government owned roads) make up 5,242 kilometres of the total length **(CBS, 2014a)**. Roughly half of this length is made up by highways, while the rest is classified as expressways.

Incidentally, the increase in transport also means an increase in energy consumption and emissions. The transport sector constitutes a major share of energy consumptions and emissions worldwide. This is no different for the Netherlands. The transport sector makes up roughly 20% of the total national energy consumption **(CBS, 2014b; Compendium voor de Leefomgeving, 2014a)**. In both passenger and freight transportation, road transport is the dominant form. In 2012 road transport accounted for 407 PJ in the Netherlands (total energy use in the transport sector was 557 PJ). The main reason for this high energy use is the aforementioned increase in mobility, kilometres driven and number of cars. While improvements in car technology and efficiency have been plentiful **(IEA,**

2008), they are not enough to compensate for this increase, making the transport sector one of the sectors with the largest growths in energy use **(Blok, 2007)**.

The same goes for emissions: the transport sector is responsible for roughly 20% of total national CO_2 emissions. This amounts to 37 million ton of CO_2. Road transport takes a share of 32.9 million tonne of CO_2 **(Compendium voor de Leefomgeving, 2014b)**. This is an increase of 22% compared to 1990. This trend is gradually, but data shows a small decrease after 2009, in part because of fiscal incentives for energy efficient cars.

1.2 Problem definition

As the transport sector, and in particular road transport, is responsible for one of the largest growing sectors and contributing significantly to global emissions, compensating these emissions can be seen as a necessity in order to maintain acceptable levels. While there is a large potential in addressing energy use and emissions of the transport sector itself, the aim of this research is to look at the possibilities of generating renewable electricity along the Dutch national high- and expressways (Rijkswegen). Other roads are under responsibility from different parties. Only looking at Rijkswegen allows for a focus on the largest share of roads under one single party, in this case Rijkswaterstaat. Rijkswegen are under property and responsibility of the Dutch government. The executive agency in charge of construction and maintenance of these roads is Rijkswaterstaat. Given that this research is done partly for Rijkswaterstaat, results can be of use for the agency.

The technology that is researched is photovoltaics (PV) as this can be installed in the relatively small areas along the Rijkswegen. Photovoltaics can be used to convert solar energy into electricity. Wind turbines have the disadvantage that they cannot be placed too close to the roads. On top of that, other restrictions due to birds, transmission towers, etc. make that possible locations are far less present **(Riedstra, 2005)**. Growing crops for biomass is also very dependent on large stretches of land, making it a less suitable alternative. In the case of geothermal energy, we see that converting this energy to electricity is a very inefficient process **(Hoekstra, 2010)**.

Rijkswaterstaat has the mission to be “the leading, public oriented, sustainable executive agency of the government” **(Rijkswaterstaat, 2012)**. There is an opportunity for Rijkswaterstaat to use the land directly next to these roads for the production of electricity. This can attribute to their mission, both in offering a sustainable energy production and in fulfilling an example role towards the public.

While using the available areas next to the Rijkswegen for PV technology seems like a good fit, it is vital to know to what extent this is true. It is unknown what the possibilities are and how useful they are. With the year 2030 chosen as the end of the temporal scope comes uncertainty. To that respect and in that context, this thesis includes the (expected) advances in technology. In general, this thesis looks into the potential of PV technology in the context of the Rijkswegen.

1.3 Research question

There has already been done significant research on what the options, yields and general possibilities of different renewables along the Dutch Rijkswegen are. A lot of these were commissioned by Rijkswaterstaat. Hoekstra **(2010)** explores the different options and has lot of information on generating electricity from solar energy. He mentions the, then hardly researched, option of installing PV panels under a glass layer in the road. This possibility greatly increases the total area available for electricity production. Also, a report by Weijers and De Groot **(2007)** focuses on different applications of photovoltaic systems along the highways. What these reports still lack though, is insight in the total potential of PV in this context. Another report from Goetzberger et al. **(1999)** does look at the potential of PV noise barriers in Europe. However, due to the larger scope of the research, it gives a broader overview of the potential in the Netherlands based on global irradiation data and the length and orientation of (then) current and planned noise barriers. It lacks more detailed results of specific locations. This thesis can offer the input to decide if, where and how PV is to be implemented along the Dutch Rijkswegen. Thereby focusing on the potential of PV noise barriers, as these are identified by Hoekstra **(2010)** and Weijers and De Groot **(2007)** as of the most promising and universally applicable implementation in the context of highways. Especially in the temporal scope of this thesis where it is not expected that relatively new implementations will see significant application along the Rijkswegen.

The research question of this research is:

What is the potential of photovoltaic (PV) noise barriers along the Dutch national high- and expressways (Rijkswegen) by 2030?

In order to answer this question, there will be several sub-questions.

1. ***What are the different possibilities of implementing PV along the Rijkswegen and how is the PV technology developing till 2030?***
2. ***What is the area available for PV noise barriers and what is the solar irradiance on these locations?***
3. ***How much electricity can be generated by PV noise barriers along the Rijkswegen?***
4. ***What is the influence of the angle and orientation on the solar irradiance and performance of PV noise barriers?***
5. ***What are the practical factors associated with implementing PV noise barriers?***

1.4 Relevance

This results of this thesis can possibly help to get a clear sense of what the contribution of PV along the Rijkswegen can be. In that, it can take a share of the total increase in renewables that the Dutch government needs to achieve. Of course, the total potential is several orders too low: research by Hoekstra **(2010)** estimates the capacity of PV when installed on all noise barriers, 11 MW. Compared to the total installed capacity of the Netherlands of around 26,000 MW **(TenneT, 2014)**, this is just a small contribution. While the main focus of this research is PV noise barriers, the thesis also focuses on other options of implementation, adding up to a higher total capacity. Also, another focus point will be autonomous systems that, although not contributing to the electricity production, can prove to have a real advantage for local energy needs. One can think of lighting next to the roads. Recently, Rijkswaterstaat decided to turn off lighting along certain roads to reduce costs **(Rijkswaterstaat, 2013a)**. As decided in the Energieakkoord (an agreement in the Netherlands between businesses, governments and environmental organizations on energy use), government bodies have to reduce their energy use. One of the areas where reduction is anticipated is lighting. Not only by disabling lighting at certain locations and/or certain time periods, but also by changing the lighting technology. One of the changes is switching to LED lighting **(Rijkswaterstaat, 2015a)**. Autonomous PV systems can be of use in these situations.

In 2012 a new program within Rijkswaterstaat was started exploring the possibilities of energy production utilizing their property. Part of this program focuses on solar energy. The current coordinator of this part of the program, Rik Jonker, expressed interest in this thesis **(Jonker, 2015)**. The goal is to have the results be available for government workers at different local departments of Rijkswaterstaat, possibly helping the decision process of implementing PV along the Rijkswegen.

This thesis is written as part of an internship at Rijkswaterstaat. The results of this thesis can be used to not only gain knowledge on potential renewable capacity that can be installed, but also on the more practical factors involved. Results can be used to identify opportunities for secondary use of land, possibly opening new income streams. Rijkswaterstaat, together with many other government agencies, is experiencing extensive budget cuts leading to the start of a new program called 'RWS Partner' (Rijkswaterstaat Partner; meaning finding partners for secondary use of land). The program explores new business models for the government agency to compensate for the budget cuts **(Rijkswaterstaat, 2013b)**.

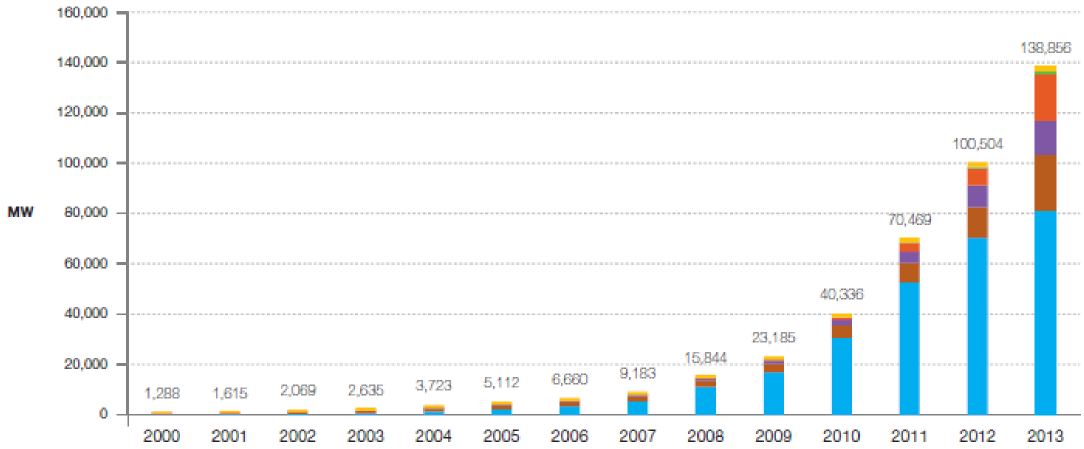
2. Literature review

2.1 Photovoltaics technology

The potential of solar energy in meeting today's energy demand is enormous. The potential exceeds those of all other renewable energy sources. The solar flux that reaches the Earth is 1.37 kW/m^2. This number is called the solar constant. At any time, this flux is intercepted by a cross-sectional area (πr^2) of the Earth. However, the value is averaged over the complete surface area ($4\pi r^2$) of the Earth. Therefore, the solar flux that is averaged for time and space equals 1,370 / 4 = 342.5 W/m^2. Also accounting for solar flux that is absorbed (19%) and scattered (30%), a final value of $342.5 \cdot (1 – 0.49) = 174.7$ W/m^2 is obtained that represents the average flux reaching the Earth's surface **(Wallace and Hobbs, 1977, pp. 320-321; Tsao et al., 2006)**. Of course this is an average value and changes with, for example, the distance of the Earth from the sun.

From this value we can get the (theoretical) potential of solar energy by multiplying it with the Earth's surface area (510,072,000 km^2). This gives a total potential of 89,110 TW. The extractible potential is estimated at 58,000 TW and the technical potential at 7,500 TW **(Tsao et al., 2006)**. Under the technical potential we understand the potential that is possible with today's technology and its limitations. The extractible potential only assumes limitations as the thermodynamic limit to the efficiency of conversion to electricity, giving a maximum of what can be extracted possibly in the future. The technical potential however gives a far more realistic picture. Not only is current technology considered, but also suitable locations. A large share of the Earth's surface is covered by oceans where theoretically solar energy can be converted to electricity. In practice however these proves to be quite difficult with current technology. The technical potential incorporates this limitations. On a yearly basis this equates to 65,700,000 TWh of energy. Compared to the world electricity consumption in 2012 of 17,839 TWh **(IEA, 2012)** it is easy to see that solar energy by itself could be more than sufficient. Of course this is only a technical potential and there are many factors significantly limiting the potential, like political and societal reasons. Even so, already a small part of this potential is very promising.

Many countries worldwide are increasingly tapping into this potential. The European Photovoltaic Industry Association **(EPIA, 2014)** notes an ever increasing trend in the installed PV capacity each year as shown in **Figure 1**. More importantly they note an increasing share in the electricity mix as well: PV is now the third most important renewable energy source in terms of globally installed capacity. For Europe, PV produces 3% of the total demand (6% of peak demand).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
RoW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,098
MEA	n/a	n/a	n/a	n/a	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,600
Americas	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,727
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	129	265	399	601	1,306	2,291	3,289	5,312	11,020	16,854	30,505	52,764	70,513	81,488
Total	**1,288**	**1,615**	**2,069**	**2,635**	**3,723**	**5,112**	**6,660**	**9,183**	**15,844**	**23,185**	**40,336**	**70,469**	**100,504**	**138,856**

RoW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.
Methodology used for RoW data collection has changed in 2012.

Figure 1: Evolution of global PV cumulative installed capacity 2000-2013 (EPIA, 2014)

This trend is expected to continue, making PV a technology that is increasingly more important in providing a renewable energy source capable of significantly contributing to the world electricity demand.

An important factor for this trend to continue is the cost-effectiveness and competitiveness to other energy sources. The so-called dynamic grid parity is a term that describes the moment where the price of PV can compete with local energy prices. This is vital in securing PV as a technology. Dynamic grid parity is different from area to area. Factors herein are the solar radiation on the surface, energy price and also financial incentives. For example, subsidies and feed-in tariffs can make PV more attractive. Thanks to price drops in PV technology, financial incentives and the high local energy prices, and depending on circumstances, there is already grid parity for consumers in the Netherlands **(Stichting Monitor Zonnestroom, 2013)**.

2.1.1 Solar radiation

The solar radiation reaching the Earth is fairly constant. The factors that have the most influence on this are the location (latitude), time (season and time of day), and effects in the atmosphere. The first two determine the exact positions of the Earth in respect to the solar radiation and thus the solar radiation that is to be expected to reach the researched location. The atmospheric effects, however, have a significant effect. Not only local variations in clouds, pollution, etc. have an effect, but also what happens to solar radiation when it enters the atmosphere in general **(Honsberg and Bowden, 2015)**.

When solar radiation passes through the atmosphere it is absorbed, scattered and reflected. This affects the solar radiation that reached the surface of the panel. This is measured in terms of direct, diffuse and reflected radiation. Watson and Watson **(2011)** state the direct and diffuse radiation as the two main components. Direct radiation is the solar radiation reaching the surface in a straight line. Diffuse radiation is the radiation that is scattered in the atmosphere. Therefore, the angle it reaches the surface can be different. On a clear day and when the sun is at its highest, there is roughly 5 times more direct than diffuse radiation. At sunset, both reach almost 50%. Atmospheric condition can have a large effect on the ratio: on a cloudy day the percentage of diffuse radiation can reach almost 100%.

The ratio between the two is also important for the placement of PV panels. To have the most direct radiation reach the surface of the panel, it should be placed incident to the sun. This limits the diffuse radiation reaching the surface. In general, most diffuse radiation is gathered when the panels are placed horizontally. The intensity of direct radiation is much higher. Thus, depending on the atmospheric conditions, more power output is achieved by focusing on direct radiation.

The third component is reflected radiation. This is the radiation that is reflected on objects (like the roads, buildings, but also snow). In general this radiation is not suitable for PV panels, because it requires the panels to be tilted towards the surface. While this would increase the reflected radiation it can gather, it would greatly reduce the direct and diffuse radiation reaching the surface. As these two are more important, reflected radiation is often ignored.

Measuring the solar radiation that reaches a certain surface requires some terminology. The solar irradiation is the total amount of solar radiation energy on a given surface during a given time. Another name for solar irradiation is insolation. Both can be expressed in kWh/m^2. Irradiance is the power per unit area and can be expressed in W/m^2.

The irradiation and irradiance can be measured over a given surface. Depending on the surface we speak of different components. One of the most important components is called the Global Horizontal Irradiance/Irradiation (GHI). The GHI consists of two separate components called Direct Horizontal Irradiation (DHI) and Diffuse Horizontal Irradiation (DIF). Both express the irradiation that reaches a horizontal Earth surface. The first however expresses the direct radiation and the latter the diffuse radiation **(GeoModel Solar, 2015)**.

Another component used to measure irradiance/irradiation is Direct Normal Irradiance/Irradiation (DNI). It is the component of solar radiation that reaches a surface that is normal to the direction of the sun. Depending on the time of year and location, there can be a large difference between GHI and DNI. What can be concluded from this is that the right orientation and angle of the PV modules is important for an optimal performance. This is shown in **Figure 2** where GHI and DNI for the same location are shown next to each other. Especially during the winter, when the angle of the sun is lower than in the summer, the difference between GHI and DNI is significant.

The relation between GHI and DNI is defined by the irradiation yield factor. The GHI is to be multiplied by the yield factor to achieve the DNI. In case of the DNI at the optimal angle of a certain orientation, we speak of the optimum irradiation yield factor **(Goetzberger et al., 1999l; Betcke et al., 2002)**.

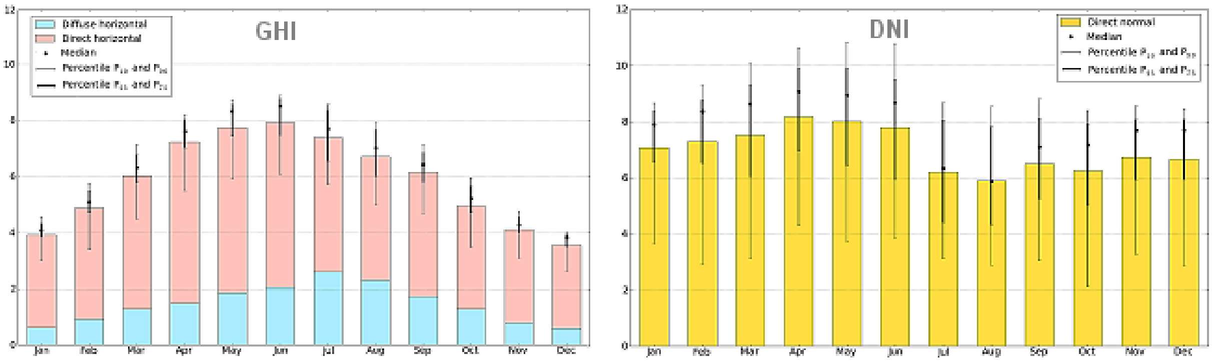


Figure 2: Difference between GHI and DNI for a location in North Africa (GeoModel Solar, 2015)

2.1.2 Calculating photovoltaic potential from solar radiation

PV technology is the technology that converts solar energy in electricity **(Andrews and Jelley, 2007)**. To do this, PV panels consist of multiple PV cells that in turn are made up of layers of semi-conducting materials. When photons reach the cells it creates an electric field across the layers, and thus electricity flows. It follows that solar radiation reaching the PV panel is a requirement for this technology to work. However, even with limited (diffuse) solar radiation reaching the panel, there will still be electrical output. This enables the technology to work on cloudy or rainy days (a higher radiation does mean a higher output).

The power output or performance of a solar panel is highly dependent on many factors, like solar radiation, solar spectrum and temperature. To compare the output of different solar panels, these are tested under standard test conditions (STC). Under the STC the solar radiation is 1,000 W/m^2, a solar spectrum of AM 1.5 and a temperature of 25 °C. The output under these conditions is termed the watts peak (W_p) **(Plastow, 2011)**. The cost of panels is often given in W_p to compare based on performance of panels. This can be a method to express efficiency: an output of 1,000 W/m^2 under STC would mean an efficiency of 100% while an output of 500 W/m^2 under STC would mean an efficiency of 50% **(Andrews and Jelley, 2007)**. Note however that this does not necessarily corresponds to actual performance. The performance can be significantly different depending on conditions. This difference can be larger or smaller for different solar panels and can mean that two panels with the same watts peak have quite different performance under real-life conditions. Currently commercial modules peak at roughly 20.4% efficiency or 204 W_p/m^2 **(Stichting Monitor Zonnestroom, 2014)**. The same report concludes that the average price for solar panels is currently between 1.332 €/W_p and 1.382 €/W_p, depending on the type of roof where it is installed.

The above paragraph illustrates how PV panels can be compared on efficiency. However, it does not give the full picture. As explained above it only gives the efficiency at STC conditions. In reality, these conditions can be compared to a clear day at noon and the panel faced incident to the sun. But even then, it means that the rest of the day the conditions are significantly different. The actual performance of the PV panels are therefore quite different.

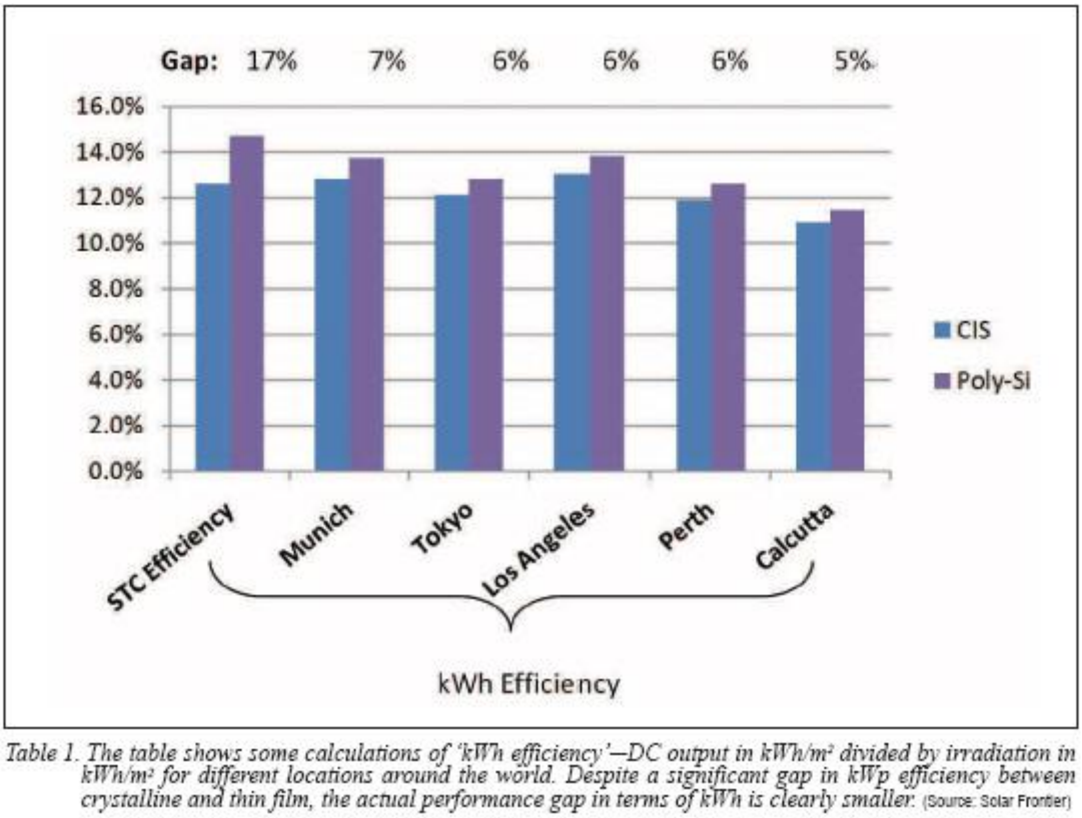


Figure 3: kWh efficiency for two PV technologies for different locations (Plastow, 2011)

Figure 3 shows the kWh efficiency (DC output in kWh/m^2 divided by irradiation in kWh/m^2) for two different PV panels (both different technologies) for different locations. The STC Efficiency shows that there is a difference of 17% between the two panels. In real-life locations, though, it shows that the difference is far lower. In 5 different locations, the gap in kWh efficiency is between 5% and 7%; far lower than the 17% difference under STC conditions. Of course, STC efficiency is important to be able to compare different panels under the same (agreed on) conditions, but it can also be seen that real-life performance can vary significantly.

When calculating the power output of a PV system the following formula can be used **(PVGIS, 2015a; Suri et al., 2006)**.

$$P = G / 1000 * A * eff_{nom} * PR$$

Where:

- P is the power (W),
- G is the irradiance (W/m^2),
- A is the area (m^2),
- eff_{nom} is the STC efficiency (W_p/m^2),
- PR is the performance ratio (%).

The formula can also be used over a given time so Power (P) in W is replaced by Energy (E) in kWh and Irradiance (G) is replaced by Irradiation (G_{rel}) (kWh/m^2).

The performance ratio is why the output in real-life differs from those under STC conditions. It is the actual output (in kWh) divided by the output under STC conditions (in kWh) **(SMA, 2010; Suri et al., 2006)**. Under good conditions this ratio can be higher than 100% (where the conditions are better than STC conditions). The factors that influence the PR are environmental (temperature, shading, dirt on the system). They also include factors of the PV system itself. These include the used technology, conduction losses, other losses, efficiency of the inverter, degradation of the panels, and more. Of course these factors can vary a lot between two installations. But it also shows that external conditions can affect the performance ratio over time for one installation. It is common practice to take a typical value according to location, technology and assumed system losses. The default value that PVGIS **(PVGIS, 2015c)** uses for system losses is 14%. These system losses include system specific (location independent) losses, like losses when converting from DC to AC. For the other effects (that contribute to the PR), it is dependent on location and technology.

Some of the difference in properties will come inherent to the type of PV cell that is used. For instance, PV models show decreasing efficiency with low light intensity (as compared with STC conditions). The strength of this effect varies between module types. Temperature is also affecting performance. Again, this effect varies between module types. Thin film cells perform better under high temperature than crystalline silicon cells do. In practice this means that a thin film panel will likely output more kWh per W_p as compared to crystalline silicon panels (all other conditions and variables equal).

According to PVGIS **(2015c)** the factors that affect the performance (besides the system losses) are:

- Temperature: PV efficiency decreases with increasing temperature (strength of effect dependent on technology).
- Light intensity: PV efficiency decreases with lower light intensity (strength of effect dependent on technology).
- Reflected light: some of the light is reflected of the panels. This is dependent of the angle of the PV panel to the sun (strength of effect dependent on technology (not strongly)).
- Spectrum of solar radiation: depending of the spectrum of the solar radiation (visible light, near-infrared, etc.), some PV technologies perform better than others (strength of effect dependent on technology).
- Long-term variations in performance: modules can have long-term variations in performance due to long-term exposure to light and temperatures (strength of effect dependent on technology).

All the factors that influence the performance are taken into account by the STC (minus the reflected light). This is what makes the STC useful. It does also show that real-life conditions can greatly influence the performance of a PV system. Therefore, it is important to have the performance ratio (PR) reflect real-life conditions as good as possible. PVGIS **(2015c)** uses PR for the Netherlands in the order of 75%-85% for near-optimal conditions. The PR value depends on technology, system setup and location. When having to use a value independent of location (or for multiple locations, like in this thesis) it is recommended to choose the more conservative 75%. Higher values can be used, but only in near-perfect conditions. In practice, lower values are also very possible when conditions are less optimal **(De Jong, 2015)**.

2.1.3 Current technology available

The first practical silicon solar cell was demonstrated by Bell Labs in 1954 **(APS News, 2009)**. Since then, PV technology has come a great way. A factor in triggering development was the advantage that PV has by supplying electricity with a renewable, everlasting ‘fuel’ supply. In the 1950’s this was utilized in the space industry to power satellites and spacecrafts. Following an increase in interest and development in PV, partly because of the oil crisis in 1973, this led to a dramatic decrease in prices of PV cells. Uses were expanded and solar power for terrestrial applications became more popular **(Avrutin et al., 2011)**.

The PV technology development delivered several kinds of cells. The basic PV panel consists of multiple solar cells connected together to form PV panels that are used in applications. These cells are ‘glued’ together and enclosed between transparent and weatherproof covers. The panels can be linked in series to increase the capacity of the whole system.

The different cells available can be classified in three generations. The first is the basic crystalline silicon (c-Si). The second generation consists mainly of thin film technologies. The third generation is often somewhat broader defined as an umbrella term for multiple technologies. Some of them include concentrator photovoltaics and organic cells.

Currently, the National Renewable Energy Laboratory (NREL), keeps track of efficiencies of every PV technology. The latest chart is published on 6 August 2015 and is added below as **Figure 4**. In the technology descriptions, the best efficiencies are added from this source **(NREL, 2015)**.

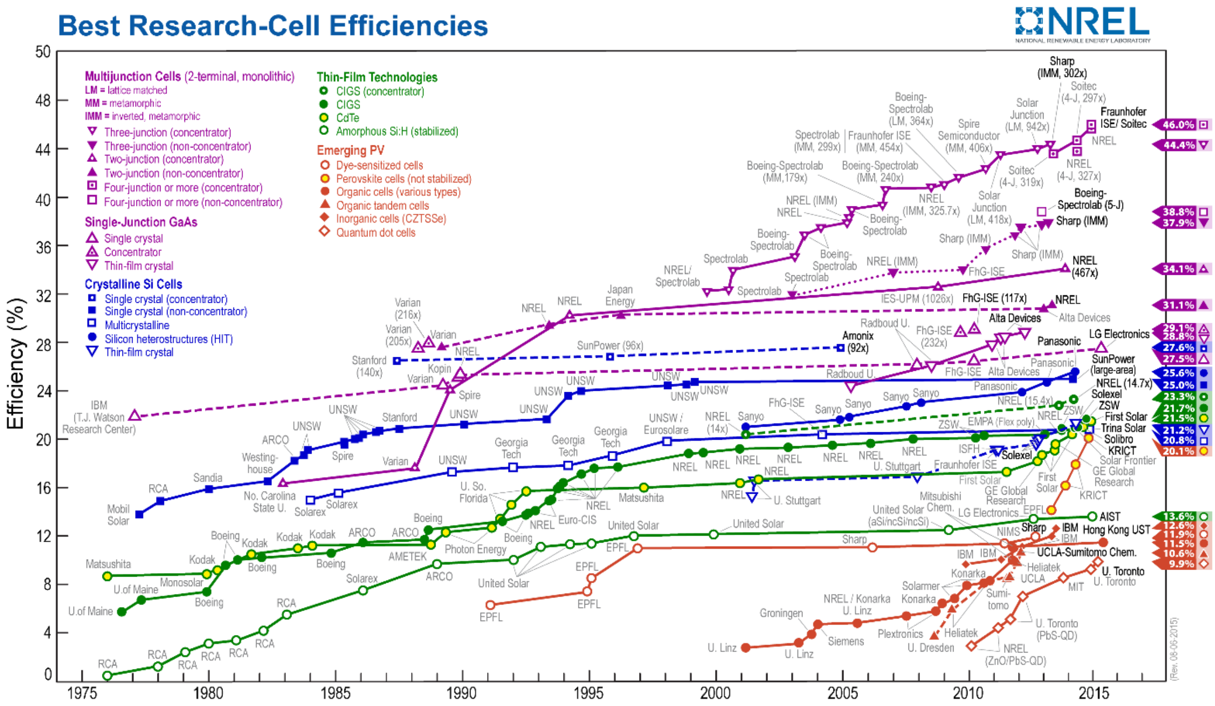


Figure 4: Best Research-Cell Efficiencies (NREL, 2015)

2.1.3.1 First generation (crystalline silicon (C-Si))

The first generation of PV technology constitutes of multiple crystalline forms of silicon. It is the dominant material used in PV technology (about 80% of the market), partially because they were developed in the 1950s and have since seen improvements in product and process efficiencies.

Essentially crystalline silicon cells are made out of blocks of silicon. Very thin slices called wafers are cut from the original block. Herein are different processes, all resulting in different PV cells **(EPIA, 2011)**.

- Monocrystalline (mc-Si) (record lab cell efficiency: 25.0%)
- Polycrystalline or multi crystalline (pc-Si) (record lab cell efficiency: 20.8%)
- Ribbon and sheet-defined film growth (ribbon/sheet c-Si)

2.1.3.2 Second generation (thin film technologies)

Thin film technologies have especially broadened the flexibility of PV technology. First generation PV modules need a frame to support the module, as it can easily break without it. Thin film technologies, however, do not need a frame due to the flexibility in the material.

The process behind thin film technologies is depositing extreme thin layers of photosensitive material on a backing (often glass or plastic). This is then laser-cut in smaller cells. The modules comparable to the first generation are enclosed between two layers of glass. But thin film technologies also allow for depositing the material on flexible plastic. This creates a module that is flexible as well, allowing for more applications of the module **(EPIA, 2011)**. In short there are four types of thin film technology modules available.

- Amorphous silicon (a-Si) (record lab cell efficiency: 13.6%)
- Multi-junction thin silicon film (a-Si/μc-Si)
- Cadmium telluride (CdTe) (record lab cell efficiency: 21.5%)
- Copper, indium, gallium, (di)selenide/(di)sulphide (CIGS) and
  Copper, indium, (di)selenide/(di)sulphide (CIS) (record lab cell efficiency: 21.7%)

2.1.3.3 Third generation

While there is no real consensus on what is to be called third generation PV technology, the choice here is made to include the following technologies for the reason that the technologies are significantly different from first and second generation technologies. Some organizations, like the NREL **(2015)** rather speak of emerging technologies (which does not include CPV), but most share the same classification as used in this thesis **(Fraunhofer, 2014; IEA, 2014b; U.S. DOE, 2012)**.

- Concentrator photovoltaics (CPV) (record lab cell efficiency: 46.0%)
- Dye-sensitized cells (DSSC) (record lab cell efficiency: 11.9%)
- Organic cells (OPV) (record lab cell efficiency: 11.5%)

2.1.4 Developments in PV technology

Over the last 30 years, efficiency of PV cells have been significantly improved and prices of cells have steadily decreased. Continuous technological development and scaling of processes will most likely ensure this trend to continue **(Ganzevles and Van Est, 2011)**. This continuous development also rises expectations: a roadmap by Holland Solar **(2005)** sketches a scenario where PV can supply 25% of the total energy demand. To achieve these expectations prices need to decrease and efficiencies need to increase.

An important factor that drive the viability of PV projects (also in the context of PV noise barriers) is of course price. Where grid parity has (arguably) been reached for consumers in the Netherlands **(Stichting Monitor Zonnestroom, 2013)**, this is for a large part because of financial stimulants like subsidies. Another factor is the composition of electricity prices: a large share of this is government mandated taxes. Depending on the party (residential, commercial or utility sector), net prices can be significantly lower than those for residential use (in 2013 Rijkswaterstaat paid €0,06/kWh). It is therefore more important that the cost price of PV will match (or be lower than) those of the current cheapest sources **(AT Osborne, 2013)**.

Expected is that PV applications will advance towards a larger scale and therefore becoming competitive at more levels **(Holland Solar, 2005; Ganzevles and Van Est, 2011; IEA, 2014b)**. The roadmap from the IEA **(2014b)** expects PV to become competitive at utility-scale with wholesale electricity prices in certain regions of the world. Applications on residential and commercial scales are expected to be competitive throughout the world by then. In total, three phases of competitiveness are defined that can be seen in **Figure 5**. This decrease in PV prices will most likely result in gradually phasing out current economic incentives for PV.

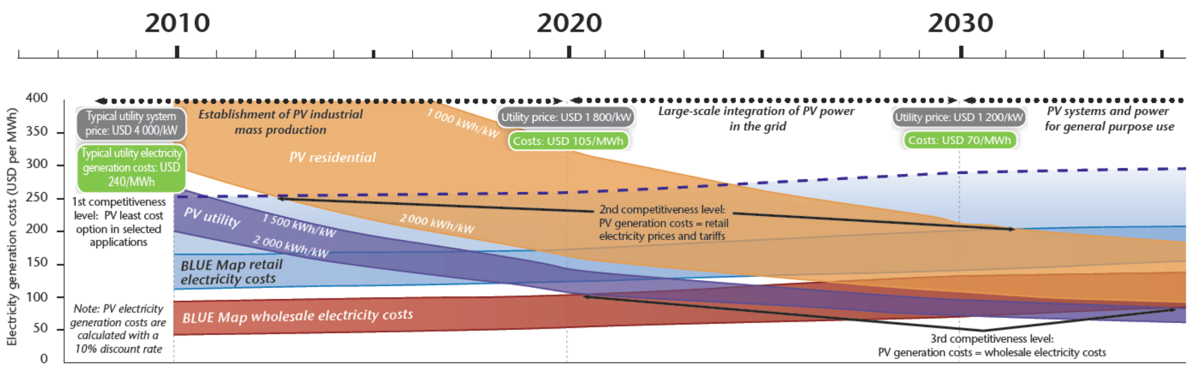


Figure 5: Development of PV price competitiveness (IEA, 2014b)

Apart from that, it is interesting to see what the actual developments in technology will bring with regards to efficiencies. Again, the roadmap from the IEA **(2014b)** expects improvements in existing technology as well as new technologies that either significantly increase the efficiency or hold other advantages in the flexibility of applications.

Predictions are made for most technologies described above, where it has to be noted that the predictions for the third generation technologies are more speculative than those of the first and second generations. For that reason, plus the current and expected future market shares, only the development of the first and second generation are described. The combined market share of first and second generation PV is more than 90%. The combined market share is expected to be more than 50% by 2030 **(Ganzevles and Van Est, 2011)**. All predictions are included in **Table 1**.

Table 1: Expected efficiencies for commercial modules (IEA, 2014b)

Technology	2010 – 2015	2015 – 2020	2020 – 2030 / 2050
Single-crystalline	21%	23%	25%
Multi-crystalline	17%	19%	21%
Thin film Si	10%	12%	15%
CIGS	14%	15%	18%
CdTe	12%	14%	15%

These expected efficiencies are used in later chapters for calculating the potential electricity that can be generated. By taking the current best-available efficiency of 21% and the best-available efficiency in 2030 of 25%, the associated results will provide a sensitivity analysis for the expected potential.

2.2 PV applications along the Rijkswegen

It seems evident that photovoltaics are promising in a lot of different applications. The technology is already matured to a level where it positioned itself as a major player in the energy market. Figures show that PV ranks second in net generation capacity added in Europe in 2013. Here PV only falls behind wind energy. In total 11 GW of PV technology was installed in that year. This does show a small decrease in capacity added since 2011 and 2012. A decrease that is not seen globally, as Asia (and especially China) is currently the new leader in terms of new PV installations **(EPIA, 2014)**.

Besides the trend of PV establishing itself as a significant technology in energy production for the grid, PV has a history of being used to provide electricity in remote areas where connection to the grid is either too complex or too expensive. These autonomous systems only account for 1% of total installed capacity in Europe **(EPIA, 2012)**. There are places, like the USA, where these systems account for higher shares (10% for USA). This is for a large part caused by the fact that USA have a lot of remote locations that can benefit of these systems for rural electrification. Another cause for the 1% share in Europe is the function of autonomous systems. Where grid-connected systems are used for large scale energy production, autonomous systems are used for a specific function that often only requires little energy. Examples are solar-powered street lighting. Especially in the case where LEDs are used, the required capacity of the PV panels is not very high.

In the case of applications that are possible along the Rijkswegen, again we make the distinction between autonomous (‘stand-alone’) systems and grid-connected systems.

The autonomous systems are producing electricity to stand-alone equipment, either directly and/or through storing it in batteries. This is mainly used for very specific or temporary functions. In some countries the electricity grid can prove to be unreliable. In those cases, autonomous systems are perfect in providing a more reliable energy source. The grid-connected systems are connected to the existing electricity grid. The electricity produced is fed into the grid.

2.2.1 Autonomous systems

Autonomous or off-grid PV systems are used for electricity supply at locations where usage of the grid is not preferable. This can be due to the distance to the grid and the costs necessary to connect to the grid. Another possibility is that the system is of a temporary and mobile nature, therefore it is easier to place along the road without (too much) maintenance work. In general these systems have a relatively small capacity. They provide a clean (no emissions) method of electricity generation **(Weijers and De Groot, 2007)**. The report of Weijers and De Groot also specifically looks at the possibilities of autonomous PV systems along highways. The selection relevant for this thesis is listed below. All options are briefly explorer to give an overview of the possibilities.

- Solar-powered illuminated reflector (road markers or cat’s eyes)
- Highway guide signs lighting
- (Mobile) electronic message signs
- Lighting
- Lighting, specifically in tunnels

2.2.1.1 Solar-powered illuminated reflector (road markers or cat's eyes)

The idea of a solar-powered illuminated reflector goes back to a patent of Roberts **(1987)**. These road markers are used to illuminate the sides of the road, allowing for increased visibility for people driving on the road.

Instead of relying exclusively on reflecting light from the vehicles for their visibility, these markers (as can be seen in **Figure 6**) have the added benefit of lighting under all conditions. If there is no light to reflect the markers can still illuminate the road. Under certain weather conditions (like fog) it might prove difficult for traditional reflectors to be visible. The solar-powered road markers are visible from up to 2 km away. There are several companies who have these solar-powered road markers on the market **(Smartstud, 2015; ROADLED, 2014)**. The ROADLED road markers can function for 30 days without daylight, so use during the winter is less likely to be a problem. Electricity is stored in small batteries. They all use LEDs, allowing for a small design and low energy use. With the use of photovoltaic sensors, it is possible to have the lights turn on when necessary. With no need to connect these to the grid, installation will not be different from traditional reflectors. Companies also offer comparable road markers that can be integrated in barriers and poles, making the application suitable for a variety of situations.

Figure 6: Solar-powered road markers (Weijers and De Groot, 2007)

2.2.1.2 Highway guide signs lighting

In some cases (especially where street lights are not abundant) it might prove difficult to read guide signs. To overcome this problem, most signs nowadays are retro-reflective, meaning that the light is reflected in the angle where it reached the sign. This allows for good visibility by vehicles from multiple direction. Still, in the case of no or insufficient lighting from a vehicle, the signs are not well readable.

A possible solution to this problem is the addition of a lighting system on the guide sign **(Dunlop, 1990)**. By having it be powered by a PV panel, this system can be completely autonomous. The PV panel is installed on top of the guide signs, preventing vandalism or theft and allow for maximum exposure to sunlight. A battery allows to store the electricity during the day, so it can be used at night.

2.2.1.3 (Mobile) electronic message signs

There are several applications in the area of electronic message signs. In the case of lane control signals ('rijstrook signalering' in Dutch), it is sometimes necessary to install a mobile vehicle that provides this functionality if permanent lane control signals are not available. These can be powered by PV panels **(TSNed, 2015)**.

In the event where information (for example information of an accident) needs to be communicated to road participants, mobile vehicles with text signs are available. These as well can be powered by PV panels. These examples emphasize the use of autonomous systems: the temporary, mobile applications.

2.2.1.4 Lighting

In order to reduce its energy use and limit the effects on the environment, Rijkswaterstaat **(2013)** has decided to turn off street lights along its highways between 23:00 and 05:00 hours. Roads are illuminated for several purposes, safety being one of them. By providing alternatives that have a low energy cost, illuminating the highways can be reconsidered. One of the measures is using LED technology for lighting. LED uses significantly less energy. By powering these with PV panels, there is no need to connect the street lamps to the grid. One of these solar-powered street lights is developed in cooperation with Rijkswaterstaat **(ROADLED, 2014)**. It is completely autonomous through the use of its PV panel and storing electricity in the battery. This can be a great advantage in isolated places, although situations like these are not very common in the densely populated Netherlands. Also, research by Hafez et al. **(2012)** shows that the cost of PV lighting systems are still significantly higher than their conventional counterparts. They state that PV lighting systems should only be used if the other advantages outweigh the added costs. In the case where the alternative is no lighting (current policy), PV lighting is not likely to be a viable alternative. If the goal is purely to show traffic participants the course of the road, a better solution might be road markers. These are more subtle while still providing the drivers with illuminated roads. The cooperation between Rijkswaterstaat and ROADLED **(2014)** coincidentally focuses more on the latter in the use of autonomous road markers.

2.2.1.5 Lighting, specifically in tunnels

Weijers and De Groot **(2007)** see a specific use for solar-powered lighting in tunnels. Contradictory, tunnels require brighter illumination during the day than at night. This is because the transition from outside the tunnel to inside the tunnel (and vice-versa) needs to be as smooth as possible. During the day, when the sunlight outside the tunnel is bright, the illumination inside the tunnel needs to be brighter as well. Powering this with solar energy can prove to be a logical choice, as there is more electricity required the moment there is more solar intensity. Of course placement of PV panels is important for viability of the application. Not in all cases it is possible to install panels on top of the tunnel.

2.2.2 Grid-connected systems

In contrast with the autonomous systems, the grid-connected systems are installed with the goal of electricity production on a larger scale. The produced electricity has no direct use at the site of production and instead is fed back into the grid. When looking at the case of solar energy in the context of available space, especially in the case of a densely populated country as the Netherlands, there is an interest in locating available area for PV installations. There is a large area available in the form of highways and its direct surroundings.

The implementation of PV installations alongside highways is already done on an experimental scale in Europe since the late 1980s. Historically, quite a lot of projects are based on (retro)fitting noise barriers with PV cells. Even though this specific type of implementation has seen most development, there are other technologies possible. As the focus of this thesis is mainly on PV noise barriers, this type of implementation is described in more detail than the other implementations in the next chapter. The other applications as discussed here are to provide an overview of the possibilities.

2.2.2.1 PV arrays next to highways in available space

When a large area of land is available next to a highway this could prove a suitable location for maximum solar energy production. These can compare to solar parks as they are built throughout the world. Required is that the area in question is free of objects and preferably free of objects (buildings, trees, etc.) in the direct vicinity, to prevent shading. Most often these kind of installations are found in uninhabited areas, where there are no buildings. An example is shown in **Figure 7**.

Figure 7: Howell solar farm next to Route 33 in USA (Willis, 2015)

These kind of installations are not suitable for the Netherlands, or at least not in the context of this thesis, as Rijkswaterstaat owns just the land a couple of meters wide from the roads **(Rijkswaterstaat, 2013c)**. The idea behind this is that Rijkswaterstaat only uses the land it needs, where a few meters can prove useful for maintenance, placement of noise barriers, safety. Besides the limited amount of land Rijkswaterstaat has under property, the Netherlands is very densely populated. These reasons make it very unlikely that large solar farms, like the Howell solar farm in the USA, have a future in the Netherlands next to highways.

Figure 8: PV array next to highway in Oregon, USA (Schwartz, 2008)

Of course, smaller PV arrays are possible in the Netherlands. So in places where there is a clear stretch of land available, a small array can still be built. **Figure 8** shows a PV array built in Oregon, USA. It consists of a 104 kW PV system, producing 112,000 kWh per year **(Schwartz, 2008)**.

Potential locations for these arrays also includes earth berms next to the highways. These berms inherently provide an angle for PV modules to be placed on. Depending on the orientation and the angle of the berm, these locations might prove to be suitable. Currently, there are ambitious plans to build the world largest PV array on a berm next to the A7 at Oostwold. At this point the focus is on creating support with the stakeholders involved **(Zonnewal-Oostwold, 2015)**.

2.2.2.2 PV arrays covering tunnels and roads

PV panels can not only be built next to the roads, but also over. This eliminates the problem of little land available next to roads. All depends of course on the use of land (if there even is land on top of the tunnel). There is only a small stretch of the Rijkswegen going through tunnels, most of them under water **(Rijkswaterstaat, 2013c)**. There are however examples of situations where tunnels were built for different reasons. The high-speed rail line from Paris to Amsterdam comes through Belgium where it passes a forest. To prevent trees falling over the track, a 3.6 kilometres long. Later this tunnel was fitted with 16,000 solar panels, earning it its new name, the Solar Tunnel. The Solar Tunnel has a capacity of 3.3 MW **(Gifford, 2011)**. The produced electricity is used to power rail infrastructure and trains. Another example is provided by a project in Germany (see **Figure 9**). The German government had a 2.8 MW solar array constructed on top of a 2.7 km long noise-barrier tunnel **(U.S. DOT, 2012)**. In the context of this thesis, comparable situations on the Rijkswegen could prove to be a good fit. There are several noise barriers that stretch over the highway essentially making a roof. One of these is located on the A28 at Zeist. If these areas prove suitable (high solar insolation, possibility of retrofitting a PV array), areas like these can be fitted with PV panels.

Figure 9: Solar array on roof of noise-barrier tunnel near Aschaffenburg, Germany (U.S. DOT, 2012)

2.2.2.3 PV panels integrated in the road surface

November 2014 marks the month that a PV integrated bicycle road was opened in Krommenie, the Netherlands. The project of TNO, Ooms, Imtech and the province of Noord-Holland is called SolaRoad **(SolaRoad, 2015)** and is meant as an experiment to test the possibility of integrating PV modules in roads. This is achieved by covering the modules by a 1 cm thick glass layer. This is transparent (to allow light to reach the modules), while also protecting the system from the bicycles riding on top of it.

When thinking of this application it has a great potential. To reach a larger share of PV, a large surface area is needed. All Dutch roads together offer a large surface of roughly 450 km^2 **(CBS, 2014a; SolaRoad, 2015)**. The integration offers no restriction on the primary use of the roads. Therefore, PV integration into roads can help to increase the share of PV. In order to scale up this experiment to national highways, a lot of extra research and development is needed **(SolaRoad, 2015)**. They do state that it is difficult to predict if a future application on national highways is going to be possible. But as highways only make up 5% of the total road surface area in the Netherlands, there is little need for this specific application. Other roads, with less load than highways, are a more suitable alternative.

In America, a company called Solar Roadways is experimenting with a modular PV integrated road system **(Solar Roadways, 2015)**. A road can be built up with several individual hexagonal road sections (**Figure 10**). The goals of the project are ambitious: not only do they want to generate electricity using PV cells, they also want to use the system to make a smart highway. This is achieved by adding LEDs to the road sections that can be used for dynamic lining, signals, messages, etc. Another functionality is integrated heating that can melt snow that lands on top of the panels. For future iterations of the panels, the company is looking at inductive charging of electric vehicles. While they claim that the technology should work when used for highways, no real-life tests have been undertaken as of yet.

Figure 10: Solar Roadways (Solar Roadways, 2015)

A limitation of PV integrated roads is that the exposure to sunlight cannot be improved. It is a horizontal surface, no angle relative to the ground is possible. Placing PV panels under an angle can greatly improve the performance. The performance is also affected by shadowing. The difficulty therein is that there will be vehicles driving on the road that will result in (temporary) shadowing of the panels. Other than that, dirt and other materials can accumulate on the surface. There is no data as of yet to the exact consequences in performance.

While the scenario described above sounds great, a lot depends on costs, performance, durability, strength and safety. All factors that are still unknown and need additional testing. Also those factors are still behind improved on by research and development. The requirement set for the Dutch highways concerning strength, safety and traction are higher than those for bicycle roads **(Yntema, 2012)** and do require further R&D. Lastly, it is not expected that the technology will be available by 2030 (as per the temporal scope of this thesis).

2.3 PV noise barriers

A large challenge with PV in the Netherlands is the availability of suitable locations. Installation of large solar farms on empty stretches of land is an option that is used in several other countries **(Ganzevles and Van Est, 2011)**. The Netherlands is densely populated and land is both relatively expensive and used for other purposes. Large stretches of land are therefore unavailable for PV. Looking for alternative locations, noise barriers along highways offer an economic application of grid-connected PV systems. With long stretches of land allowing for large scale plants and at no extra land consumption, the use of this application has been long recognized. This type of application offers a method to produce electricity through renewable sources, above its primary function of noise mitigation.

2.3.1 Noise barriers

The large road network of the Netherlands and the fact that it is very densely populated result unavoidably in noise pollution. This is not only true for areas where highways are situated near buildings, but also where they cross nature reserves. There are regulations that describe what is classified as excessive noise pollution and consequently action is required when levels of noise pollution exceed the maximum allowed. In the case of Rijkswegen, this is regulated by the environmental law ‘Wet milieubeheer’ **(Rijkswaterstaat, 2015c)**. When these levels are exceeded, Rijkswaterstaat has three options that, according to its policy, are applied in order. The first is the prevention of noise being generated through source measures (silent asphalt). The second is the prevention of noise reaching the object. And last is reducing noise by, for instance, additional isolating of buildings.

As the first option is not sufficient in preventing noise being generated, the second option is necessary in strategic places. The most common application hereof is the noise barrier. These noise barriers are constructed from sound absorbing or reflective materials. Most of them a combination of concrete and steel. At the moment Rijkswaterstaat is focusing on the use of modular noise barriers. These noise barriers, while still allowing for different designs, use a limited number of elements resulting in a few different types. This reduces cost, and allows for easier maintenance and upgrading. The individual elements are 6 m wide and 1 m high. Several other requirement are defined in the document **(Rijkswaterstaat, 2006)**. Noise barriers built after 2000 additionally have to meet a norm on lifespan expectancy of 50 years. Before 2000, this norm was 15 years **(Movares,**

2014). This also shows in the average lifespan of current noise barriers, but this is expected to increase as noise barriers are replaced. In practice this means that there are a number of noise barriers that reach their technical lifespan somewhere before 2025. Between 2025 and 2050 there are almost no noise barriers to be replaced due to the change in norms for technical lifespan.

At present there are almost 1,000 km of noise reducing measures installed along the Rijkswegen **(Rijkswaterstaat, 2013c)**. In total, 641 km of this consists of noise barriers, the rest is made up of dikes and earth berms. According to its policy **(Rijkswaterstaat, 2015c)**, Rijkswaterstaat installs as little noise barriers as possible, first focusing on reducing the sound generation at the source. This limits the available length of noise barriers for PV applications to current and planned noise barriers. No new noise barriers will be built for this purpose alone.

2.3.2 PV noise barriers

The application of PV systems in noise barriers can be done in several different ways. All PV systems however consist of individual PV modules (that in turn consist of PV cells). All modules are connected to each other and to an inverter that converts the DC power to AC power so that it can be connected to the grid. As previously discussed, all parts of the system can affect the performance and careful choice of materials and components is therefore important.

The PV noise barriers (PVNB) can be classified in two different categories: PV retrofitted noise barriers and PV integrated noise barriers **(De Jong, 2015)**. The first is the most applied option for the oldest projects. Only later projects (and projects that are currently planned like Solar Highways **(2015)**) incorporate the PV modules in its design. As the PV modules alone do not absorb or reflect enough sound, additional mass needs to be added to the design.

There are several studies done to the potential of PV noise barriers in Europe as well as the different technologies available **(De Jong, 2015; Goetzberger et al., 1999)**. In these studies the different designs possible are described. The most common design is where the PV modules are top mounted with an angle for an increase in solar irradiation on the surface area. A top mounted overhang design can offer a larger surface area per linear meter. Both variations are shown in **Figure 11**. Other variations include multiple rows installed along the height of the noise barrier. While designs like these increase the surface area, they can also cause additional shadowing to the system itself **(Goetzberger et al., 1999; Snow and Prasad, 2000)**. Both sources stress the importance of the surface area per meter of noise barrier for analysis on PVNB potential. The state-of-the-art designs offer a surface area of 1.3 to 2.6 m^2 per meter of noise barrier. The value depends on design and regulations. The minimum distance required between roads and objects can limit the size of the installation.

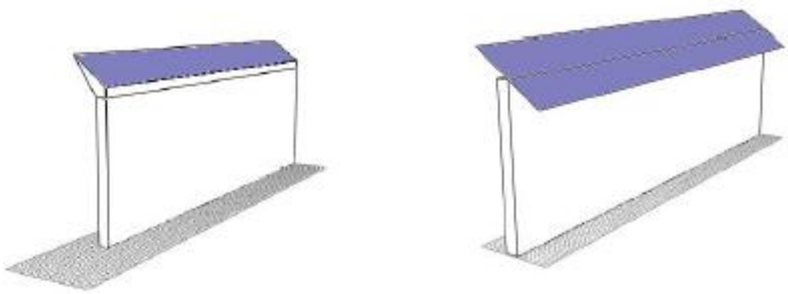


Figure 11: Top mounted flush design (left) and top mounted overhang design (Snow and Prasad, 2000)

Most of the current PVNB are inclined so they face towards the road. There are however examples of PVNB where the PV modules face away from the road. The first being located in Zürich, Switzerland and the second located in Giebenach, Switzerland **(Goetzberger et al., 1999)**. There may even be advantages in facing the PV modules away from the road: depending on the design and inclination, further noise absorption and reflection is possible **(Snow and Prasad, 2000; Yang et al., 2013)**. This would greatly increase the potential of PVNB and makes it possible to install PVNB at both sides of the road. However, the design does require careful consideration of public safety: the PV modules, under certain inclination, can potentially reflect light in the direction of traffic. One way to minimize these risks is by ensuring the height of the installation is sufficient.

One of the more promising designs is the bifacial PVNB. PV modules are installed vertically facing both the west and east directions. This design enables the system to produce electricity mainly in the morning and the afternoon. With the combined performance of both sides, the total system produces roughly the same electricity output annually as an optimally inclined system to the south **(Goetzberger et al., 1999)**.

2.3.3 Current PV noise barrier projects

Research from Goetzberger et al. **(1999)** and De Jong **(2015)** shows the current PVNB installations in Europe. The data is not complete, but gives a sufficient overview. **Table 2** combines data from both sources, showing a selection of the installations. The selection is made to include earlier as well as modern projects. Also, the projects with the largest capacity are included. The angle of the tilt is in relation to a horizontal surface and the azimuth is defined with 0° as north, 90° as east, 180° as south and 270° as west.

Table 2: Overview of PV noise barriers in Europe until 1999 (Goetzberger et al., 1999; De Jong, 2015)

Location	Planning institution / investor	Date	Costs [ECU/kW$_p$]	kW$_p$ installed	Tilt	Azimuth
Zwitserland	TNC AG / Bundesamt für Energie	1989	16500	103	45°	
Zwitserland	TNC AG / Bundesamt für Energie	1992	13500	103		200°
Austria	OKA	1992	13500	40		160°
Germany	TST (DASA)	1992		30		200°
Zwitserland	TNC AG / Kanton Basel & Bundesamt für Strassen	1995	8800	104	45°	
Germany	Stadtwerke Saarbrücken	1995	8000 (9400)	60		

Netherlands	R&S et al.	1995	10500	55	50°	245°
Germany	TNC GmbH / Bayernwerk & BMFT	1997		30		
Germany	TNC AG	1997/98		30		
Netherlands	Shell&ENW / EU Commission	1997/98		220	50°	200°
Germany		2007		1,000	45°	210°
Germany	Evergreen solar GmbH	2009		2,065	45°	150°
Germany	Apfelböck Ingenieurbüro GmbH	2010		1,000	45°	150°
Germany	Exaphi GmbH	2012		1,200	45°	210°

Table 2 shows the first PVNB being built in Switzerland in 1989. As the chapter on PV technology and its development already illustrated, technology enabled higher efficiencies and lower prices. Whereas the price for the Swiss project was €16,500.00 per kW_p, the system price for residential installations in 2014 was around €1,357.00 per kW_p **(Stichting Monitor Zonnestroom, 2014)**. This is shown by the fact that the first installations were all implemented as experiments, but later installations are built for financial reasons: the price of solar electricity can compete with conventional electricity (so-called grid parity). However it has to be noted that grid parity depends on the owner of the PV installation: for example Rijkswaterstaat (being a government agency) can buy its electricity almost at cost price **(AT Osborne, 2013; Jonker, 2015)**.

From what is known, all projects use silicon-based PV technology. Most of them use crystalline silicon, but a few use amorphous silicon **(De Jong, 2015)**. The tilt and azimuth of the projects are (except for one exception) all roughly south faced with an angle of roughly 45°. This is close to the optimal inclination. This optimal inclination varies per location, but is in general close to 40° **(PVGIS, 2015c; Goetzberger et al., 1999)**.

Of these projects, there are two projects that are initiated in the Netherlands along national highways (and thus fall within the scope of this study). These two projects are described in detail below.

2.3.3.1 PV noise barrier A27

The first of these projects is the PV Noise Barrier A27 **(PVdatabase, 2015a)**, installed along the (as the name suggests) A27 highway at De Bilt, Utrecht. **Figure 12** shows the PVNB in use.

Figure 12: PV noise barrier A27 (PVdatabase, 2015a)

This noise barrier, under contract of Rijkswaterstaat, has a length of 590 meters. The mounted grid-connected PV system has a capacity of 48.5 kW_p. The system consists of 1,116 modules, coupled through a 40 kW inverter to the grid. This 48.5 kW_p capacity has a surface area of 402 m^2 at a 12.5% STC efficiency. According to a report on the findings of this experiment **(PVdatabase, 2015a)**, the total system delivers 33,000 kWh per year. This equates to 680 kWh/kW_p per year. The PV array has an orientation facing SW (236°) and WSW (254°) (the road is slightly curved). The inclination of the array is 50° compared to the horizontal plane.

A more extensive final report elaborates on the results of the PVNB **(Betcke et al., 2002)**. Measured was an annual GHI of 986 kWh/m^2. The irradiation incident to the array is less then optimal, resulting in an irradiation yield factor of 0.93 compared to GHI. The optimum irradiation yield factor for the orientation is measured at 1.13. This results in an actual irradiation incident measured of 947 kWh/m^2. The measured performance ratio measured in the first year was 0.73 and in the second year 0.70. Argued was that the cause was pollution by traffic.

Recommendations from Betcke et al. **(2002)** include an improvement in design. The current design makes theft relatively easy. This is because they are not placed very high, the area at the back of the noise barriers is easy to reach and the PV modules are small (can be carried easily).

2.3.3.2 PV noise barrier A9

Figure 13 shows the second PVNB project initiated in the Netherlands. Started in 1998, the PV noise barrier A9 **(PVdatabase, 2015b)** provides a significantly larger installation at 205 kW_p. Located along the A9 highway near Ouderkerk aan de Amstel with a total PV surface of 1,555 m^2, this installation delivers 176,000 kWh per year. This equates to an annual 859 kWh/kW_p. Significantly higher than the A27 project.

Figure 13: PV noise barrier A9 (PVdatabase, 2015b)

According to Van der Borg and Jansen **(2001)**, the system consists of 2,160 modules installed at an inclination of 50° compared to the horizontal plane. The orientation of the array is facing SSW (193°-207°), significantly better (more optimal orientation) than the A27 project. The STC efficiency of the system is roughly 13.2%.

The measured performance ratio lies between 58% and 75%. This can be explained by the accumulation of dust and other pollution on the PV modules. Results showed that the performance ratio increased again after the modules were cleaned.

3. Methodology

The literature review explored the varied uses of PV in the context of the Rijkswegen. A significant part of the thesis however revolves around the analysis of PV noise barriers (PVNB). This analysis is divided into several parts that are described here in the methodology. The following describes in detail what is researched, what methods are used (and why) and how data will be collected and later used in answering the research questions. Appendix I includes further, more detailed, information on the use of ArcGIS in this thesis.

3.1 Study area

While the focus of this study is on the Rijkswegen in the Netherlands, the resulting study area still includes large shares of the country. The Netherlands is a country with one of the most dense road networks in the world **(CBS, 2014a)**: the highways alone stretch for over 5,000 kilometres. When studying the potential of PV installations along the Rijkswegen, one of the most important factors is solar irradiance. This solar irradiance (or solar power per unit area) is not only different for different areas in the country, but also dependent on surroundings that may limit the solar irradiance on the panels. Therefore it was important to have detailed data on the study area. Furthermore, this large study area required an automated process where possible, for practical reasons. For this purpose, several datasets were used with data on the relevant roads and heightmaps (or in this context rather digital elevation models). For the purpose of this research, all datasets used were of high detail and resolution.

3.2 Data

The Dutch national road data was obtained from Rijkswaterstaat. The dataset is offered under the name of Nationaal Wegenbestand (NWB) and includes all roads that are managed by a governing body like the national, provincial or municipal governments. The dataset is actualized 4 times per year and the one used in this research dates the 1st of April 2015 **(Rijkswaterstaat, 2015b)**. In the context of this research, only the roads under management of the national government are used. The data consists of shapefiles of the road sections that can be used by GIS software.

For extra information on the roads (specifically noise barriers), an extra dataset ‘weggeg’ (short for ‘weggegevens’ which means ‘road data’) was used. This data is also publicly available from Rijkswaterstaat **(Rijkswaterstaat, 2013c)** and includes information on speed limits, number of lanes, location of noise barriers, area next to the roads, etc. This data was also used by GIS software and listed as metadata for the roads. This data was used to identify the noise barriers currently installed that could serve as possible locations for PV panels. It also includes data on the noise barriers that can identify them and show what the length is. The dataset used in this research is dated 15-03-2015.

In further identifying suitable locations for PVNB, additional data is used to identify the priority for them to be replaced and/or maintained. The data used for this comes from a report by Movares **(2014)** commissioned by Rijkswaterstaat.

For easier reference and making out different objects next to the roads, both a topography map and an aerial photo of the Netherlands were used as a base reference. The topography map, Topo Basiskaart (in RD), is supplied by Esri **(2015)**. It is a simple reference map with data collected from several sources (including Rijkswaterstaat). The aerial photo has the same resolution as the DEM used in this research (0.5m). The data originates from Cyclomedia **(CycloMedia, 2014)** as they supply recent (2014) information. To complement this data, and to verify options, satellite and street level images from another source were used. The source used for this is Google Maps **(Google, 2015)** with its Map and Street View options. Using this extra data source allows for a quick and easy method to confirm or disconfirm a PV suitable location.

In order to calculate the solar irradiance on a certain location, a digital elevation model (DEM) is used. The Dutch government is aiming to make a lot of geographical data publicly available as Open Data. One of these datasets (since March 2014) is the comprehensive Actueel Hoogtebestand Nederland (AHN) **(AHN, 2015)** which translates roughly to Current Height-file Netherlands. It covers the topography of the Netherlands and shows the height of every square meter in great detail and with little error. This DEM dataset is used as input in GIS software to calculate a solar map with the solar irradiance on any given location. The data in the AHN is gathered by the use of LiDAR. LiDAR is a remote sensing technology that measure the distance to an object. It works by emitting small laser pulses with a fixed wavelength. The pulses reflect on objects and the reflected light is then analysed. By using this technology from a helicopter or plane, it is possible to create a DEM for a large area or even a whole country. The AHN is available in different formats: point clouds and rasters. Point clouds show the measurements by points with a (height-) value on the map, allowing for a 3D-representation. Because point clouds are rather large (in file size) and need a lot of computing power to be processed, this format was rejected. The other option is more practical. Rasters are a continuous pattern where every cell registers 1 height-value. Depending on the resolution of the raster, it is more or less detailed. For this research, the most detailed raster is chosen where cell sizes are 0.5m by 0.5m **(Van der Zon, 2013)**. The most current version of AHN, and also the one used for this research, is AHN2. The data for AHN2 is gathered between 2007 and 2012.

Because the DEM data used comprises a large area (the whole of the Netherlands), another dataset was used to enhance the DEM by removing parts that were unnecessary. The dataset 'staatseigendommen' from Rijkswaterstaat **(2015d)** has information on the state-owned lands. This information includes the borders identifying where the land next to the Rijkswegen is still under administration of Rijkswaterstaat and where other parties (like municipalities) take over.

3.3 PV noise barrier analysis

What is the area available for PV noise barriers and what is the solar irradiance on these locations?

The aim of this part of the research is the selection of the study area, identifying the potential locations for PVNB and calculating the associated solar irradiance. With this and additional data, the suitability of the locations can be assessed. Results are also presented in a spreadsheet (Appendix II) and overview maps (Appendix III). The resulting data is then later used to calculate the potential electricity that can be generated by PV. This subchapter elaborates on the methods used, a description of the software environment (GIS) and how the relevant theory on the modelling of solar radiation is applied.

Where the first part of this research mainly consists of a literature review, this second part relies heavily on GIS. GIS stands for Geographical Information System and enables one to easily link data with geographical objects. In the case of this research, GIS can help to analyse the previously mentioned data. For this purpose a GIS application is chosen: Esri ArcGIS. ArcGIS is chosen for its feature set, which allows analysing the data with a number of tools and plugins. It is also the tool of choice for Rijkswaterstaat, meaning all data is perfectly compatible.

In short, this part of the research entails locating possible (and suitable) locations for PVNB and calculating the corresponding solar irradiance. This was done by combining the data of all previously mentioned datasets in ArcGIS. All datasets are layered in the software, allowing for all necessary data for a certain location to be found. All results are presented by a list of all possible locations for PVNB with their respective values for all parameters. This is also graphically presented in 13 maps (all focused on an individual RWS district).

The DEM data necessary for the irradiation calculations, was limited to only the relevant data. Much of the data gathered, covers too much ground, areas of the Netherlands that are not covered by the scope of this thesis. Since the data in itself is already quite extensive and the calculations (in part because of that) require a lot of computational power, this allows the process to be more efficient. In the case of the AHN2 digital elevation models, the data for the whole of the Netherlands is split up in more than 1,000 separate files. Each one of those files is roughly a few hundred megabytes. By using an overlay index of all these separate files on top of the map of the Netherlands identifying state property along the Rijkswegen ('staatseigendommen'), it was possible to cut the DEM data down to the bare minimum required.

When preparing the data from the Nationaal Wegenbestand that includes all roads in the Netherlands, the first step was to select only the roads under management by the national government (Rijkswaterstaat). This includes highways and expressways. All other data was removed.

The calculation of the radiation model (that shows the solar radiation on a location) was done with an Esri ArcGIS tool called Solar Analyst (part of Spatial Analyst). This tool is known for quickly and accurately generating irradiance maps. The digital elevation models are used as the main input in this tool. It calculates the viewshed for each cell in the DEM. The viewshed is a line of sight analysis that makes sure that obstructed or shaded objects are recognized and the incoming radiation is appropriately measured. The calculation includes direct and diffuse solar radiation. The tool does not take reflected radiation (from surfaces) into account, but this does not have a significant effect on the insolation on solar panels since they tend to be tilted away from the surface **(Watson and Watson, 2011)**.

The Solar Analyst tool **(Esri, 2012)** can calculate the direct and diffuse solar radiation for each cell in the raster. As input it uses the DEM, but also the latitude and longitude (extracted from the DEM). It can incorporate the position of the sun (and thus incidence) over time (during the day and through the year). There are many variables to be set in the tool that help get a result that is as accurate as possible. These variables vary from location to location and from time to time. Since the analysis is done for a large number of locations, the variables are not set specifically for each location, but rather the same values for all (except latitude and longitude). Based on the documentation **(Esri, 2012)** and research by Jakubiec and Reinhart **(2012)** the choice was made to use the default value for most of the variables, as they are argued to be the best to use when analysing multiple locations. Only the variable transmittivity was changed slightly to better reflect real-life irradiation data (this is explained later). In the case of the time period, a full year was chosen (starting 1 January 2014 and ending 31 December 2014). The irradiation data was calculated for the whole area of Rijkswegen including the land directly next to it as defined by the dataset 'staatseigendommen'. The irradiation data is the GHI (global horizontal irradiation) and is measured in Wh/m^2).

The 'weggeg' dataset was used to identify all noise barrier segments currently in use along the Rijkswegen. From this selection only the segments with a minimum length of 500 meters were selected. This was done to remove the segments that were not very interesting for PV noise barriers to begin with. This is based on analysis of current PVNB and the fact that PV noise barrier projects tend to be more economically interesting when they can be installed over a significant length **(Goetzberger et al., 1999)**. While this selection will probably remain the most interesting, future price and technology changes could result in smaller sections becoming more interesting. The remaining segments larger than 500 m made up the samples for this thesis that were further analysed. All additional data was added for these segments. The dataset already includes information on the length of each segment. It also includes data that can identify the segment (roadside, road number, location along the road).

Furthermore, for all noise barrier segments the maintenance priority was obtained (if available). Based on research by Movares **(2014)**, this value indicates the risk of failure of a noise barrier and therefore a possible recommendation of maintenance and/or replacement priority of the noise barrier. Their classification defines low, medium and high risks. These risks are based on factors like the life span, the building materials, the condition, the location and many more. The risk is the accumulated score of three separate risk scores: impact on traffic (how long would the road need to be closed), impact on safety (risk of people getting hurt or killed) and impact on costs (how expensive is repair or replacement). The recommendation of the report is to use the accumulated risk scores as a priority on which noise barrier segments to maintain or replace. These accumulated scores are called maintenance priority in the context of this thesis and higher scores help identifying short-term suitable locations. Following the recommendations of the research, a high risk is associated with maintenance or replacement before 2030.

For each noise barrier segment the orientation was defined by aligning the segment with a compass rose in ArcGIS. Orientation is defined as the direction from the noise barrier facing towards the road and is classified in 16 different orientations (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW). Each orientation corresponds to an optimum irradiation yield factor (also described in the literature review). Since PV modules can be installed facing to or from the road, this yield factor for all north directions equals its opposite. Also, values are equal for directions symmetric to the south orientation (i.e. E-W, SE-SW, etc.). This yield factor defines the enhancement of yield by an optimal inclination angle compared to horizontal installations **(Goetzberger et al., 1999)**. This factor can be used to multiply with the GHI data to acquire the DNI (direct normal irradiation). This is the irradiation incident on the plane of the PV modules (when optimally inclined). The yield factor varies per location (latitude) and orientation. In the case of the Netherlands this factor varies very little due to the size of the country. Goetzberger et al. **(1999)** defines the yield factor as the irradiation in the optimum plane divided by the irradiation in the horizontal plane or DNI/GHI. PVGIS **(2015c)** was used to identify the optimum angles for each of the 16 orientations. It was then used to calculate GHI and the DNI for these angles. Finally the yield factors for all orientations could be calculated as can be seen in **Table 3**.

Table 3: Orientations, their optimum angles and the corresponding irradiation yield factors (all for the Netherlands)

Orientation	Optimum angle	Optimum irradiation yield factor
South	39°	1.182
South South West / South South East	37°	1.164
South West / South East	34°	1.118
West South West / East South East	25°	1.045
West / East	0°	1.000

For the calculations of the irradiation specific to the noise barrier segments, the irradiation data calculated for the whole area was used. The next step was to draw the areas (polygons) of the targeted PV noise barrier locations on the map in ArcGIS and calculate the average solar irradiance on the location. Important for this was to draw these polygons not on the actual noise barriers as this would cause a deviation in the results due to self-shadowing. Instead the polygons were drawn right next to the segments, limiting the negative effect of self-shadowing while still measuring the local effects on irradiation. Again, the Solar Analyst tool outputs the irradiance in Wh/m^2 for each cell in the raster. For each polygon, the average irradiation per area was calculated. This is the annual insolation in Wh/m^2 and corresponds to the GHI.

These annual insolation values were then multiplied by the optimum irradiation yield factors. The results of this corresponds to the DNI or the adjusted annual insolation (Wh/m^2). This is the actual irradiation incident on the PVNB (considering the orientation and assuming optimum angle).

All locations were then compared on their adjusted annual insolation, their maintenance priority and their length. The results are presented in spreadsheet format (Appendix II) and in 13 different district maps (Appendix III). The maps are exported from ArcGIS and show the locations with their adjusted insolation score (translated to a 1-5 scale and a corresponding colour). The maps allow to quickly get an overview of suitable locations for PVNB. By presenting these results for each separate Rijkswaterstaat district, it also allows in a tool for decision making. This 1-5 scale is achieved by calculating the average and standard deviation (using Excel) of the adjusted insolation. **Table 4** shows the ranges associated to each score.

Table 4: Translation insolation score to 1-5 scale

Bottom value **Top value**	0 (Mean – 2SD)	(Mean – 2SD) (Mean – SD)	(Mean – SD) (Mean)	(Mean) (Mean + SD)	(Mean + SD) (Mean + 2SD)
Range adjusted insolation (kWh/m^2)	0 – 874	874 – 959	959 – 1044	1044 – 1128	1128 – 1213
Score	1	2	3	4	5

Because irradiation is influenced by many factors, an estimate on the yearly average can be significantly different from real-life results. A warmer or colder year, a year with a lot of cloudy days having an effect on transmittivity, the proportion of direct and diffuse radiation: they all have their effect on the results **(Fu and Rich, 1999)**. Moreover, as explained by Jakubiec and Reinhart **(2012)**, the Esri Solar Analyst tool assumes fixed values for these properties, while in real-life they differ throughout the year. Therefore it is important to realize the results obtained are to be seen as an indication. However, by comparing the results in between locations, it is possible to identify the locations with a relatively higher solar irradiation. And therefore to identify the more suitable locations. As there currently already are implementations of PV (with extensive testing data) similar to what is researched, it is also possible to compare the results to those cases.

These values measured can be used to calibrate the model to known real-life situations, therefore fine-tuning the input values in ArcGIS. This is important because, as stated before, Esri Solar Analyst uses fixed (average) values for dynamic properties. According to Jakubiec and Reinhart **(2012)**, the model uses reliable default values for most properties, but in the case of yearly averages it is important to fine-tune the transmittivity value for more valid results. Knowing the actual solar irradiation measured at a precise location and time, allows to change this value to reflect the real situation better. Again, results will be different from year to year and the results obtained here will not give an exact prediction to the solar irradiation and performance, but allow for a comparison in between current and possible installations.

The results were compared to existing irradiation data from the A9 project, described in the literature review **(Van der Borg and Jansen, 2001)**. For further confirmation, the acquired input values were tested against the results from a solar map called Zonnescan Amersfoort **(Aerodata Surveys Nederland, 2015)**. This tool has calculated the solar irradiation data for households in Amersfoort. The results from that tool were compared to the results from the methodology as described in this chapter. Locations were chosen for the property of a flat roof as the Esri Solar Analyst tool is most reliable with those input values.

3.4 Potential in electricity production

How much electricity can be generated by PV noise barriers along the Rijkswegen?

For this step the data of the previous steps was taken and a calculation was made of the potential electricity that can be produced. The electricity production can be calculated by using the irradiation data as described in the previous step.

The formula for calculating the electricity production, as described in the literature review, is as follows. The formula was slightly by measuring electric energy instead of power. Also, the area is now described as the product of width and height.

$$E = G / 1000 * width * height * eff_{nom} * PR$$

Where:

- E is the electric energy (kWh),
- G is the irradiation adjusted for the orientation (kWh/m^2),
- Width is the width of the PV system, corresponding to the length of the noise barrier (m),
- Height is the height of the PV modules (m) (value: 2),
- eff_{nom} is the STC efficiency (W_p/m^2) (value 2015: 210; value 2030: 250),
- PR is the performance ratio (%) (value: 0.75).

For three of the variables, input values were assumed based on the literature review. The average height of the PV modules is described by Goetzberger et al. **(1999)** as a value between 1.3 and 2.6 m per linear meter of noise barrier. An average of the two was taken and for this thesis a value of 2 m was assumed.

The STC efficiency values were again based on the literature review. A value for the current best-available market technology (21% or 210 W_p/m^2) was assumed. For 2030 a value of 25% or 250 W_p/m^2 was assumed.

It is difficult to argue a realistic value for the performance ratio (PR). This is because it is highly dependent on many factors. An average value for the PR is taken of 0.75 or 75%. This value, while not the highest possible, is seen as a reasonable average value for analysis of a large number of locations. The value of 0.75 is confirmed by literature **(PVGIS, 2015c; De Jong, 2015; Photovoltaic-software, 2014)** and is very close (slightly higher) to both the A27 and A9 projects **(Betcke et al., 2002; Van der Borg and Jansen, 2001)**.

The previous step described calculating the irradiation data. This irradiation data is the global horizontal irradiation (GHI) data adjusted for orientation with the optimum irradiation yield factor. This means that for all different orientations it is assumed that they are placed in their optimal inclination. While the width is already described by the length of the barriers, the height is the value that determines the actual area of the PV array.

By using two values for both 2015 and 2030, the outcome describes a range that describes the potential until 2030. Of course, the 2030 potential would assume all PVNB to be built with the 2030 best-available market technology. This is not realistic. But assuming every PVNB to be built with current best-available market technology is also unrealistic. Therefore, it is expected that the real potential lies between the two potentials.

For further analysis, the 2015 and 2030 potentials are both divided in three separate potentials. It is unlikely that all PVNB locations will be realized. Therefore, the four potentials all describe different levels of PVNB realization.

The extrapolated theoretical potential is simply the assumption that all analysed PVNB locations are realized. Either all noise barriers are retrofitted with PV or replaced by new noise barriers with PV integrated or mounted on top. For this potential, the sample size was expanded to include the noise barrier segments smaller than 500 m. While these are less interesting economically, this potential assumes all noise barriers to be fitted. For this purpose, the electricity production for this extra sample was obtained by extrapolating the results. As the analysed segments make up a decent sample and are spread over the country, this can give an indicative potential of all noise barriers. All segments analysed in the thesis add up to a total length of 187 km. The rest of the smaller noise barriers adds up to 454 km.

The technical potential includes PVNB that are technically the best performing. Chosen is to include locations with an adjusted annual insolation of 1,044 kWh/m^2 (corresponding to an insolation score of 4 and 5). This is a value that is higher than the average Dutch GHI. These classify the most efficient options (highest production per unit area or cost of PV panels). In deciding where PVNB is to be placed the goal is to have a production as high as possible for both the smallest area size and cost.

The short term potential lastly again only includes the best performing locations (measures by adjusted annual insolation with a score of 4 or 5). The difference with the technical potential comes from the additional requirement of a high maintenance priority. As described earlier (both in the literature review and earlier on in the methodology) this maintenance priority classifies the priority of maintenance and/or replacement of noise barriers with a score of low, medium and high. According to the source report used **(Movares, 2014)** a high priority are recommended to be maintained and/or replaced by 2030: therefore ideal for the temporal scope of this thesis. So the short term potential additionally requires locations to have a maintenance priority of high. In short, this short term potential describes the best performing locations that are likely to be maintained before 2030.

3.5 Detailed analysis of future PV noise barrier projects

What is the influence of the angle and orientation on the solar irradiance and performance of PV noise barriers?

The broader methodology used in chapter 3.3 uses average values for the irradiation yield factors. While this is useful in giving in indicative view on the suitability of several PVNB locations, it does not necessarily give the most accurate results. This section entails the more detailed analysis of three different future PVNB projects or three case studies. While the methodology used is for the most part the same as the methodology in chapter 3.3, there are some vital differences that are described below.

The selection of the three case studies was done based on several talks within Rijkswaterstaat **(Jonker, 2015; Stoeten, 2015; Pool, 2015; Van der Graaf, 2015)**. They were selected as future PVNB projects to analyse the potential and the influence of different configurations. By varying the orientation and angle of the PVNB, the results will give a better view on the added benefit of certain designs. The three cases are the A7 near Groningen, the A15 near Tiel and the A50 near Uden. For all cases a short description of the planned project is described.

Where the methodology differs from the previous, is the calculation of irradiation for all different configurations in ArcGIS without the use of irradiation yield factors. Previously, the irradiation in this horizontal plane (GHI) was adjusted for the angle and orientation with the irradiation yield factor. However, with the adjusted methodology specified here, it was possible to calculate directly the irradiation in the plane (under angle and orientation) without the irradiation yield factor. This way the irradiation in the plane reflects the actual irradiation more accurately as the irradiation yield factors are averages for the whole country.

While the use of fixed irradiation yield factors is no longer necessary, the yield factors can still be calculated based on the results. By then comparing the experimentally obtained values with the fixed values, it was possible to compare them and evaluate the accurateness of the fixed irradiation yield factors.

With this methodology, the conditions (like shadowing under certain angles) are incorporated more accurately. The initial methodology only incorporates shadowing effects for the horizontal plane. Depending on the surroundings (trees, buildings, etc.) of the featured location, a certain angle could result in relatively more shadowing than in another angle. For example, if there are trees only to the south of a south-facing installation, irradiation would be low. But a horizontal installation in the same surroundings would still receive irradiation when the sun is in the west or in the east. An average irradiation yield factor cannot account for this.

To achieve this, the actual designs of the PVNB (under certain configurations) were modelled with a 3D modelling tool called SketchUp **(Trimble Navigation Limited, 2015)**. The exact location for the PVNB was taken and the 3D model was designed to reflect the properties as accurately as possible to the actual planned PVNB. This includes height, length and location of the noise barriers. If the project entail multiple sections, all sections were modelled. To research the influence of angle, different designs were modelled. As a baseline model, a horizontal installation was included. However, the height of the noise barrier was included. The other design included was the optimum angle for each orientation as discussed in chapter 3.3. Results on this design show the highest irradiation possible at the location. If the plans for the project suggest a different angle, this is included in a third design as well. This allows for a comparison between the planned and the optimum designs.

3D models were imported in ArcGIS and each was separately integrated in the existing DEM file, creating a new DEM file for all different designs. With the newly acquired DEM files, the solar analysis was redone exactly using the methodology described in chapter 3.3. All results reflect the irradiation incident on the plane. A similar methodology is used by Chow et al. **(2014)**.

To give an estimate of the suitability of the projects, the irradiation values for all designs were presented together. This gives a view on the irradiation per m^2. The insolation scores, as described in chapter 3.3 and also used in the overview maps in Appendix III, were used as well to give a better indication of the suitability. Finally, the associated annual electricity productions were also calculated for the potential of the project. The used methodology is the same as in chapter 3.4. Important to note here are the assumptions made. Unless the plans of the project describe a property otherwise, the following assumptions were used: performance ratio at 75% (0.75); STC efficiency at the best-available market technology of 2015 (21% or 210 W_p/m^2); height of the PV modules at 2 m. To better compare the projects in between, the electricity production per linear meter of noise barrier is also considered. This reflects the performance per separate PV module and therefore cost of the module. Of course this does not give an estimate of the total costs, as the actual costs are also influenced by other factors, like installation. It does however give an indication of the effectiveness of the installation.

For one of the cases, the planned design incorporates a bifacial PVNB. Due to the fact that the Solar Analyst tool is unable to calculate irradiation over vertical surfaces, the methodology of this thesis proved insufficient. Instead, to still be able to have an indication of the potential electricity production, chosen was to use the PVGIS **(2015c)** tool. Because this tool uses global average irradiation maps as input values, it is less useful for specific local situations. Nearby objects and the associated shadowing are not considered.

The PVGIS **(2015c)** tool is used to calculate the irradiation yield factor associated with 90° angles for both west and east orientations. Results show equal results for both orientations (630 kWh/m^2) and a GHI of 1060 kWh/m^2. This results in an irradiation yield factor of 0.594.

3.6 Practical factors associated with implementation

What are the practical factors associated with implementing PV noise barriers?

There are many factors, besides technical suitability, that influence the actual decision of building a PVNB at a certain location. While this thesis focuses on the technical suitability, other factors are explored nonetheless. This makes sure that the results can be seen in the context of these other factors.

The feasibility of implementation was explored through literature review and interviews at Rijkswaterstaat. In order to sketch a picture of the specific, Dutch situation all sources were chosen to reflect this. Also, care was taken to include policy and direction of Rijkswaterstaat. Experimental data of current PVNB was added as an addition to this: lessons learned from experiments allow to better reflect on practical factors associated with new implementation.

4. PV noise barrier analysis

The following chapter shows the results of the GIS modelling as described in the methodology. All current noise barriers installed along the Rijkswegen (as of 15 March 2015 as included in the datasets from Rijkswaterstaat) were analysed. The chapter starts with calibrating the input values with a current PV installation and results were also checked with a completely different sample with data from a public source on solar irradiation. This is meant to make sure the methodology is correct and the results are accurate.

The results itself were analysed per district of Rijkswaterstaat (16 divided over the Netherlands). This allows for a better overview of the whole study area where results are clearer. At the same time it also allows individual districts to better adjust their policies using these results. Especially the generated maps can function as a useful tool in decision making.

4.1 Calibration with current PV noise barrier

At the moment there are already a few locations where PV noise barriers are installed (either retrofitted or designed to incorporate PV from the start). The noise barrier along the A9 at Oudekerk aan de Amstel, Noord-Holland is one of those examples. Operations having started at 1998, it was one of the first PV noise barriers in the Netherlands.

In this project, the PV panels are mounted on top of the structure. According to Van der Borg and Jansen **(2001)** and PVdatabase **(2015b)**, the total installed PV peak power is 205 kW_p over an area of 1,555 m^2. The electricity generated accounts to 176,000 kWh every year. This corresponds to yields of 859 kWh/kW_p. Additional data like GHI was also measured. For the sake of a correct and accurate methodology, the results from this thesis ought to match these numbers. During a 2-year period the PV installation has been carefully monitored, resulting in an extensive report **(Van der Borg and Jansen, 2001)** with monthly data. Part of the data gathered is the irradiation on the planes of the panels. In the 2-year period they measured an irradiation of 1,902 kWh/m^2 in the horizontal plane. For one year this equates to 951 kWh/m^2.

By using the method described in the methodology chapter, it was possible to identify the most accurate transmittivity value. Already the default settings gave a fairly accurate result, but by changing the value from 0.5 to 0.535 the results were corresponding to the values measured in the test. The calculated yearly solar irradiation is 972 kWh/m^2 with a value of 0.5 and 955 kWh/m^2 with a value of 0.535. Given that this is a model that reflects the real-life data of 951 kWh/m^2, the model seems to hold up quite well.

4.1.1 Sample check

In order to make sure the obtained calibration values are valid, a point of reference was chosen on which the methodology is applied to. The results were then compared to the data for the same location in a publicly available solar map.

In this case a building with a large flat roof was chosen as this allows for a large area to extract the average solar irradiation from. The location chosen is in Amersfoort at the Basicweg 10. Coordinates are 52°10'26.4"N 5°25'22.8"E. The solar map used is called Zonnescan Amersfoort **(Aerodata Surveys Nederland, 2015)**. A screenshot of the location with its solar irradiance is shown in **Figure 14**. The solar map shows that the by far largest share (94%) of the address has an average solar irradiance of 1,035 kWh/m^2 every year.

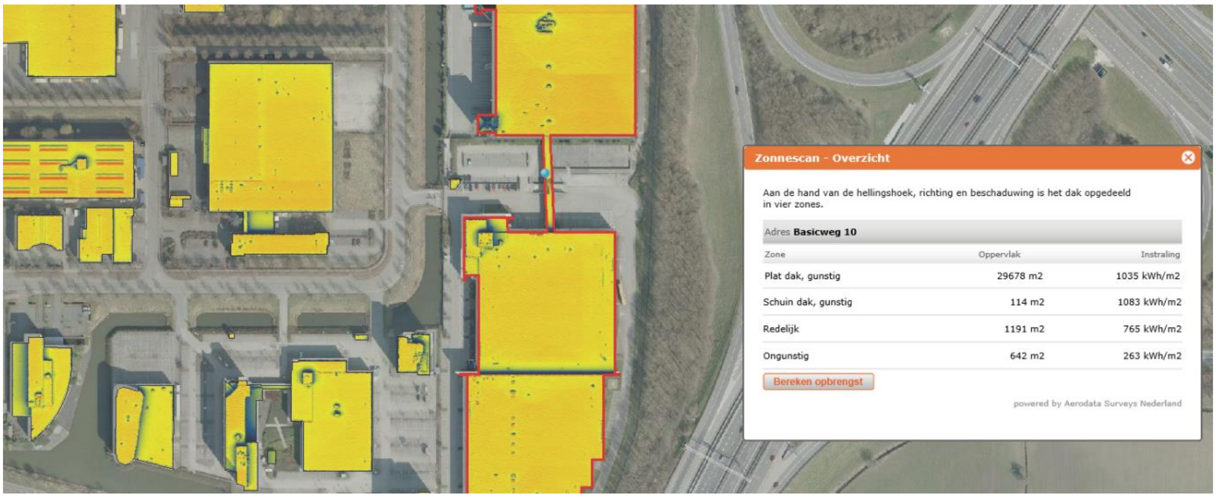


Figure 14: Analysis with Zonnescan Amersfoort (Aerodata Surveys Nederland, 2015)

The results from Zonnescan Amersfoort are divided in several different kind of roof areas (flat, sloped, mediocre and unsuitable). Even though 94% of the roof is flat and suitable, it was important to select an area that complies with these properties as much as possible. The location to be tested was chosen in the middle of the roof with a large square. The following screenshot shown in **Figure 15** shows the output with the solar irradiance for the whole area (also surrounding the building) in ArcGIS. A square can be seen on the roof of the building with dots. This represents the location for which the statistics window is shown to the right in the same screenshot. The average solar irradiance for that area is 1,048 kWh/m^2 every year.

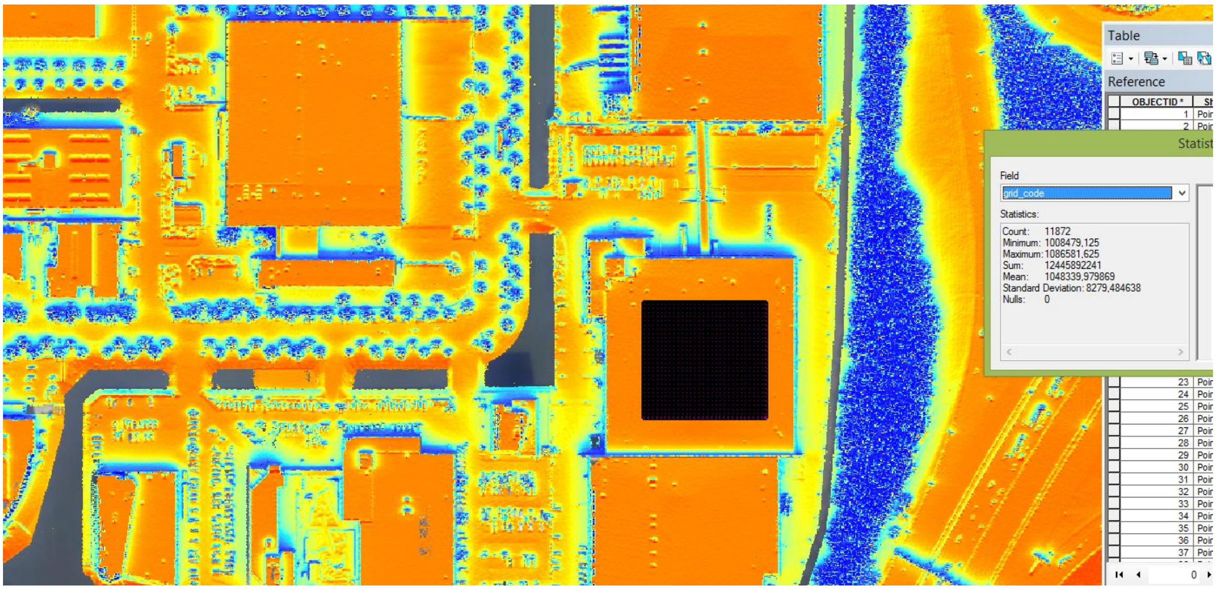


Figure 15: Analysis of same location to test methodology

As the methodology and input data used in this research, are probably slightly different from what is used in the case of Zonnescan Amersfoort, it is to be expected that the results are slightly different. Given that both are modelling the real world, neither of the results are completely true. Even so, the results show that the methodology in this thesis delivers comparable results to the Zonnescan Amersfoort. **Table 5** shows the results together with those of two other addresses. They show that the ratio changes accordingly, but that they are always slightly higher. This is something to be noted.

Table 5: Sample check

Address	Zonnescan Amersfoort (kWh/m^2/year)	Results (kWh/m^2/year)
Basicweg 10	1,035	1,048
Basicweg 1	1,031	1,043
Brabantestraat 6	1,005	1,034

4.2 Results

When applied to the selection of suitable noise barriers, the results were successfully calculated. The complete results can be found in Appendix II. Geographically based overviews are provided in Appendix III. The average irradiation and associated standard deviation over all data points are included in **Table 6**. The amount of dispersion of the individual data points was small, indicated by a small standard deviation. This can be explained by the fact that the measuring took place over a long time period (one year), thereby evening out most of the outliers. This results in an average for each location, but in reality performance varies from spot to spot (a single tree can shadow a segment of a PV system). This thesis does not allow for a very detailed analysis of the actual (potential) PV noise barriers, but does allow for an indicative analysis of the location. More detailed analysis can show the performance on a smaller scale.

Table 6: Average and standard deviation for insolation results

	Annual insolation (kWh/m^2/year)
Average for all data points	950.26
Standard deviation for all data points	59.23

The annual insolation (or solar irradiation) that is calculated with the used methodology is the global horizontal irradiation (GHI), because the measured areas are (mostly) horizontal. By comparing these results with statistics on GHI per country, it is possible to see that these results are comparable to the statistics. Statistics from GeoModel Solar **(2014)** show an average for the Netherlands between 975 and 1,100 kWh/m^2 per year. These slightly higher values are to be expected due to the statistics not incorporating shading (by local objects), which is a factor in the results from this thesis.

When looking at the results there are several results with low values below roughly 900 kWh/m^2. There is however one result with a value of 361.75 kWh/m^2 where the next lowest value is 713.25 kWh/m^2. When inspecting the data in ArcGIS this seems to be caused by a deepening of the highway and the associated construction zone causing an uneven area with a lot of shadowing (by the highway being deepened and surrounding high objects). The construction zone is for restructuring and the widening of the highway A4 near Leiden **(W4info, 2015)**. This segment is identified by RW4_5 which can be found in the results (both later in this chapter and in Appendix II. Ironically, there are plans to have the deepened highway partially covered by canopies. These are to be fitted with solar panels **(Gemeente Leiden, 2015)**. Unfortunately, like explained above, the results for this specific area cannot be used to validate its suitability.

All other low values are to be expected (as explained due to shadowing). Analysis of some of these results show areas with a significant number of trees and high buildings around the areas measured. The highest value of all data points is 1,020.80 kWh/m^2 and with that within the expected range defined by the average annual insolation that statistics show **(GeoModel Solar, 2014)**.

The optimum irradiation yield factor defines the enhancement of yield by an optimal inclination angle compared to horizontal installations **(Goetzberger et al., 1999)**. Values were calculated in the methodology in chapter 3.3 and an overview is again shown in **Table 7**. Note that these adjusted insolation values assume installation of PV modules at the optimum angle for each orientation.

Table 7: Orientations, their optimum angles and the corresponding irradiation yield factors (all for the Netherlands)

Orientation	Optimum angle	Optimum irradiation yield factor
South	39°	1.182
South South West / South South East	37°	1.164
South West / South East	34°	1.118
West South West / East South East	25°	1.045
West / East	0°	1.000

It shows that the optimal orientation and inclination can make a big difference. In general south oriented arrays have the highest irradiation. An exception can be made for east-west orientations where both directions are utilized (bifacial). Performance can be equal to (or even higher than) optimal south oriented installations **(De Jong, 2015)**. However, these were not included due to limitations in the methodology. Instead, results are shown for either east or west with an inclination of 0° (horizontal).

When looking at the country as a whole, the following is a selection of all the noise barrier segments with the highest insolation score (5). This insolation score corresponds to the adjusted insolation (and as such purely based on insolation and orientation).

Table 8: Selection of noise barrier segments with highest adjusted annual insolation based on insolation and orientation

Segment	District	Length (m)	Maintenance priority	Orientation	Annual insolation (kWh/m²)	Adjusted annual insolation (kWh/m²)	Insolation score (1-5 scale)
RW2_417	ZN Midden	507	No data	N	1,005	1,188	5
RW58_4	ZN West	734	High	NNW	1,021	1,188	5
RW15_1	ON Zuid	1430	Medium	N	1,001	1,183	5
RW59_6	ZN Midden	636	Medium	NNW	1,016	1,182	5
RW59_5	ZN Midden	754	No data	NNW	1,012	1,178	5
RW200_1	WNN Zuid	792	Medium	N	995	1,176	5
RW76_2	ZN Zuid	634	Medium	NNE	1,008	1,174	5
RW59_8	ZN Midden	572	No data	N	992	1,173	5
RW59_2	ZN Midden	962	High	NNW	1,007	1,172	5
RW59_4	ZN Midden	772	Medium	SSE	996	1,160	5
RW5_1	WNN Zuid	907	No data	N	981	1,160	5
RW58_5	ZN West	653	No data	SSE	995	1,158	5
RW28_8	ON Noord	710	Medium	N	980	1,158	5
RW50_1	ZN Midden	1075	No data	NNW	993	1,156	5
RW28_2	MN Zuid	1526	High	N	977	1,155	5
RW15_6	WNZ Zuid	676	No data	NNE	992	1,155	5
RW28_7	ON Noord	734	Medium	NNW	991	1,154	5
RW28_4	ON Noord	977	Medium	S	976	1,154	5
RW12_1	MN Zuid	1542	Medium	NNE	990	1,152	5
RW12_5	MN Zuid	916	Medium	S	971	1,148	5
RW2_442	ZN Midden	602	No data	S	971	1,147	5

RW7_4	NN Oost	702	Low	N	970	1,146	5
RW1_118	MN Zuid	978	No data	NNE	979	1,140	5
RW76_1	ZN Zuid	651	Medium	NE	1,020	1,140	5
RW58_7	ZN West	512	No data	SSE	979	1,139	5
RW35_1	ON Oost	881	No data	S	962	1,137	5
RW7_5	NN Oost	670	High	N	962	1,137	5
RW50_6	ZN Midden	502	High	NW	1,017	1,137	5
RW11_3	WNZ Noord	571	No data	SSE	974	1,134	5
RW73_8	ZN Zuid	892	High	NW	1,014	1,134	5
RW59_1	ZN Midden	1056	No data	SSE	973	1,133	5
RW58_3	ZN West	737	Medium	NNW	972	1,131	5

The noise barrier segments with the highest scores are shown in **Table 8**. They show that orientation is an important factor in the score: all can be faced between SSW and SSE (where they face north, the arrays can be installed so they face away from the highway, reversing the orientation). Within these results a few roads stand out with a high frequency. Out of a total 32 results, Rijksweg 59 stands out with 6 results. Rijksweg 58 and Rijksweg 28 both appear 4 times in the list. Based on districts, RWS Zuid-Nederland District Midden (ZN Midden) has the most suitable locations (10 out of the 32). Appendix III includes these results in overview maps divided by district. These show perfectly the suitability of district ZN Midden.

When analysing all possible locations, the best locations would be those with the highest insolation score (based on insolation and orientation), length and maintenance priority. This would result in the highest electricity production and factor in the rate at which noise barriers are replaced and/or maintained. Appendix III includes graphical overviews of all Rijkswaterstaat districts with all PV noise barrier options and their results. These figures allow for analysing the best locations. One of these figures is included below as an example as **Figure 16**.

RWS Zuid-Nederland District Midden			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
2_171	3	513	medium
2_180	3	744	no data
2_185	4	799	no data
2_196	4	522	no data
2_203	3	505	no data
2_206	4	808	no data
2_247	2	638	no data
2_256	3	557	no data
2_263	4	1984	no data
2_282	3	511	medium
2_293	4	1722	medium
2_334	3	545	no data
2_362	3	1377	no data
2_379	3	717	no data
2_400	3	1056	no data
2_417	5	507	no data
2_442	5	602	no data
2_498	3	589	no data
50_1	5	1075	no data
50_4	4	627	medium
50_6	5	502	high
59_1	5	1056	no data
59_2	5	962	high
59_3	4	833	high
59_4	5	772	medium
59_5	5	754	no data
59_6	5	636	medium
59_8	5	572	no data
59_9	4	569	medium
59_10	4	547	medium

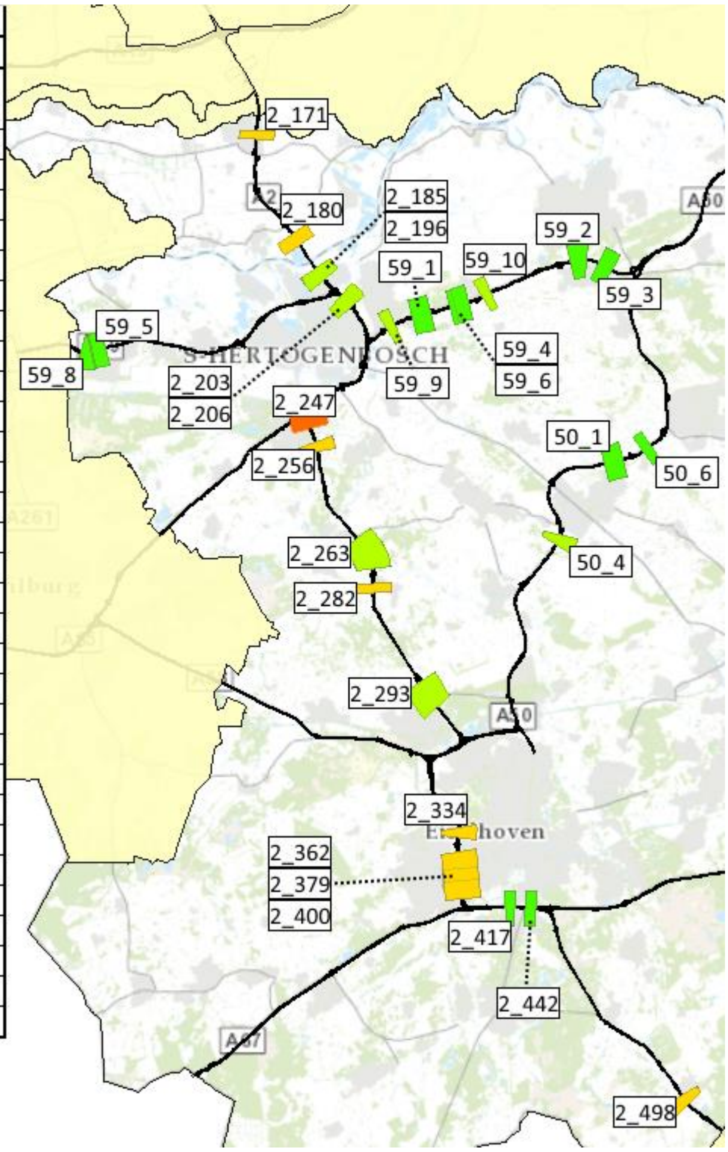


Figure 16: Cropped overview of RWS ZN District Midden

Figure 16 shows a district with a relatively large number of PV noise barrier options (30). The locations that score high (5) are mostly located on highways that run from west to east (and thus where the PV array would face south and at an angle of 39°). In this case Rijksweg 59 shows a lot of potential locations with high insolation scores and lengths. The same conclusion was drawn from the overview of the whole country, where Rijksweg 59 is the road with the most segments in the top list. Some of these have a high replacement and/or maintenance priority as well. Especially when these segments are already considered to be replaced and/or repaired, these might prove good locations for PV arrays.

On Rijksweg 2, there are two segments RW2_263 and RW2_293 that are good options as well. Although these segments do not have the maximum score, they are very long. The length of these options is a very important factor when considering locations. One or two longer arrays (even with slightly less insolation or a non-optimal orientation) might prove to be more attractive than several shorter arrays.

5. Potential in electricity production

The following chapter shows the results of the potential electricity production of the previously described potential locations for PV noise barriers. Results were calculated for both the current best-available and the 2030 best-available PV module efficiencies. While the advances in PV technology enable higher efficiencies by that year, chosen was to use more realistic values of what is available on the market by 2030. Combining the results of the electricity production with both length and the maintenance/replacement priority of the noise barriers, allowed the calculation of several production potentials for the whole study area. To illustrate the electricity production of individual PV noise barriers, a few calculations were done for interesting samples. Again, all results are included in Appendix II.

As an example, **Table 9** shows the potential electricity production of the noise barrier segments with the highest adjusted insolation, described in chapter 4.

Table 9: Noise barrier segments with highest adjusted annual insolation plus the associated electricity production

Segment	District	Length (m) (Area (m^2))	Maintenance priority	Annual electricity production 2015 (MWh)	Annual electricity production 2030 (MWh)
RW2_417	ZN Midden	507 (1014)	No data	190	226
RW58_4	ZN West	734 (1468)	High	275	327
RW15_1	ON Zuid	1430 (2860)	Medium	533	634
RW59_6	ZN Midden	636 (1272)	Medium	237	282
RW59_5	ZN Midden	754 (1508)	No data	280	333
RW200_1	WNN Zuid	792 (1584)	Medium	293	349
RW76_2	ZN Zuid	634 (1268)	Medium	234	279
RW59_8	ZN Midden	572 (1144)	No data	211	252
RW59_2	ZN Midden	962 (1924)	High	355	423
RW59_4	ZN Midden	772 (1544)	Medium	282	336
RW5_1	WNN Zuid	907 (1814)	No data	331	394
RW58_5	ZN West	653 (1306)	No data	238	284
RW28_8	ON Noord	710 (1420)	Medium	259	308
RW50_1	ZN Midden	1075 (2150)	No data	391	466
RW28_2	MN Zuid	1526 (3052)	High	555	661
RW15_6	WNZ Zuid	676 (1352)	No data	246	293
RW28_7	ON Noord	734 (1468)	Medium	267	318
RW28_4	ON Noord	977 (1954)	Medium	355	423
RW12_1	MN Zuid	1542 (3084)	Medium	560	666
RW12_5	MN Zuid	916 (1832)	Medium	331	394
RW2_442	ZN Midden	602 (1204)	No data	218	259
RW7_4	NN Oost	702 (1404)	Low	254	302
RW1_118	MN Zuid	978 (1956)	No data	351	418
RW76_1	ZN Zuid	651 (1302)	Medium	234	278
RW58_7	ZN West	512 (1024)	No data	184	219
RW35_1	ON Oost	881 (1762)	No data	316	376

RW7_5	NN Oost	670 (1340)	High	240	286
RW50_6	ZN Midden	502 (1004)	High	180	214
RW11_3	WNZ Noord	571 (1142)	No data	204	243
RW73_8	ZN Zuid	892 (1784)	High	319	379
RW59_1	ZN Midden	1056 (2112)	No data	377	449
RW58_3	ZN West	737 (1474)	Medium	263	313

The data shows large variations in actual electricity production. Apart from this, it also shows that the segments with the highest adjusted insolation do not necessarily have the highest electricity production. This is due to the length being incorporated (where it wasn't for the adjusted insolation). Selecting the segments with the highest electricity production would be less indicative for the most suitable locations for PV noise barriers, as it does not show the most efficient. The best locations are those that produce the most electricity per unit area.

When comparing these results to the electricity production of the existing PV noise barrier at the A27, a large improvement is seen. Annual electricity production for that installation is 33 MWh. The system itself has a 48.5 kW_p capacity over an area of 402 m^2 **(PVdatabase, 2015a)**. To put that into context: the STC efficiency of the system is 12.5%, where the results for this thesis assume efficiencies of 21% (2015) and 25% (2030). Also, the area of the total PV array is significantly smaller than those of the samples described above. A better comparison can be made when comparing the production per unit area. Then, the A27 array produces 82 kWh/m^2 at its original 12.5% efficiency or 138 kWh/m^2 at 21% efficiency. The top result of the samples above has an annual electricity production of 187 kWh/m^2 at 21% efficiency. The remaining differences can be explained by several reasons. The first being that the samples selected are those with the highest adjusted insolation of all samples. In the case of the A27 project, the orientation and angle of the array was less than optimal **(Betcke et al., 2002)**. The other being that the A27 project is an already old experiment (started in 1995), where system losses could have resulted in a lower performance ratio.

While the above results and **Table 9** show a selection of the locations with the highest insolation, another selection with the highest annual electricity production is also included below and in **Table 10**. It is important to realize that the locations with the highest insolation are favourable due to their high efficiency. This is because those locations will produce the most electricity per m^2. Still, when the goal is simply to achieve the highest electricity production possible it is interesting to see where this is done best. The insolation score is added to evaluate the share of the factor in the list.

Table 10: Noise barrier segments with highest electricity production

Segment	District	Length (m) (Area (m^2))	Maintenance priority	Insolation score (1-5 scale)	Annual electricity production 2015 (MWh)	Annual electricity production 2030 (MWh)
RW2_263	ZN Midden	1984 (3968)	No data	4	690	821
RW2_293	ZN Midden	1722 (3444)	Medium	4	600	714
RW2_23	MN Zuid	1884 (3768)	Medium	3	594	707
RW32_1	NN West	1786 (3572)	No data	3	560	667
RW12_1	MN Zuid	1542 (3084)	Medium	5	560	666
RW28_2	MN Zuid	1526 (3052)	High	5	555	661
RW73_1	ZN Zuid-Oost	1657 (3314)	High	4	553	659

RW2_8	MN Zuid	1647 (3294)	Medium	3	536	638
RW15_1	ON Zuid	1430 (2860)	Medium	5	533	634
RW16_1	ZN West	1574 (3148)	Medium	4	531	632

Looking at the potential for the whole study area, the Netherlands, three different potentials were classified in the methodology. The first being the extrapolated theoretical potential that assumes all noise barriers are upgraded with PV, including the noise barriers under 500 m. The second is the theoretical potential without the noise barrier segments under 500 m as per the sample analysed. The technical potential includes only those that are deemed the most suitable with an insolation score of 4 or 5 and a length of 500 m or more. These classify the most efficient options (highest production per unit area or cost). The last is the short term potential. This includes only samples with an insolation score of 4 or 5 and on top of that have a high maintenance/replacement priority. This identifies those samples as likely to be maintained and/or replaced relatively soon (before 2030). All potentials are included in **Table 11**.

Table 11: Annual electricity production potentials for 2015 and 2030

	Annual electricity production 2015 (MWh)	**Annual electricity production 2030 (MWh)**
Extrapolated theoretical potential	210,628	250,748
Theoretical potential	61,447	73,151
Technical potential	34,588	41,176
Short term potential	5,828	6,938

Based on the assumptions made for these calculations, the data above shows the potential annual electricity production for PV noise barriers in the Netherlands. Depending on the year the PV noise barriers are build, the actual potential will be somewhere within the range of the 2015 and 2030 potentials.

6. Detailed analysis of future PV noise barrier projects

This chapter elaborates on three PV noise barrier (PVNB) projects. While two of these are still planned to be constructed, the third is no longer considered. However, all three were analysed in order to get more insight in the electricity potential of the projects. The adjusted methodology used here allows for a slightly more accurate calculation because the exact planned situation is recreated in ArcGIS with help of the 3D modelling tool SketchUp. This allows to calculate the solar irradiation directly on the plane instead of having to rely on the horizontal irradiation (GHI) and adjusting for the angle with the irradiation yield factor (not in the least because this factor is an average for the whole country).

6.1 Groningen

With a length of 12 km, the southern bypass in Groningen runs straight through the city. It is an important road both for local and through traffic. In order to create a situation where the city is better accessible, more liveable and also safer, a large project is planned for 2016 till 2020 to improve the southern bypass. This project focuses on increasing the capacity of the A7 and N7 and will mainly entail the construction of new connections, extra lanes and flyovers **(Rijkswaterstaat, 2015e)**.

One of the specific goals of the project is increasing the liveability of the area. At the construction in the early 1960’s, some neighbourhoods of Groningen were cut in two by the bypass. This resulted in many residents now facing the then newly constructed noise barriers. With this project, the goal is to take the opportunity to improve on the urban planning and landscape of the area. Noise barriers will therefore need to be replaced or upgraded. Early on in the planning phase, the idea of PVNB was suggested for this project. For unknown reasons, this suggestion was abandoned **(Pool, 2015)**.

For this thesis, the noise barriers appointed to be constructed were still analysed. While the realization is no longer an option, the results of the analysis can give an idea of the potential electricity that could have been produced with PVNB at the location. **Figure 17** shows the location of the noise barriers. The barriers on both side of the road were considered. The location of the planned noise barriers is at the A7 from hectometre marker 194.5 to 195.2 (approximately). Total length of the noise barriers on both sides is roughly 660 meters **(Aanpak Ring Zuid, 2014)**. The total capacity of the PVNB would equate to 277 kW_p for each section, 554 kW_p for both.

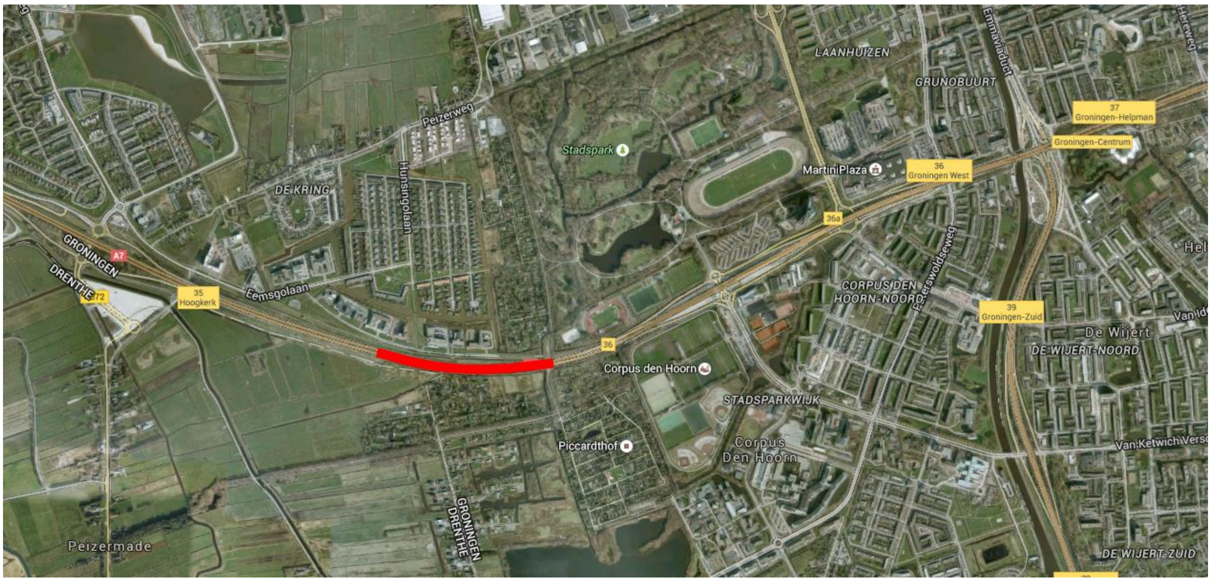


Figure 17: PVNB area Groningen marked with red (Google, 2015)

6.1.1 Analysis

With an orientation to the south, the optimum angle is 39° (as used in chapter 4). Two 3D models were constructed for analysis: one with a horizontal plane on a 3 meter high noise barrier and one with an angled plane at 39° on top of the 2.5 meter high noise barrier. The 2.5 meters are taken from the current plans for the project. **Table 12** shows the annual insolation of both designs for both locations. The insolation score (the same as used in chapter 4) is added as well.

Table 12: Annual insolation Groningen

Annual insolation (kWh/m^2)	Design 1 (0° angle)	Design 2 (39° angle)
Section 1 (northern)	945 (score: 2)	1,092 (score: 4)
Section 2 (southern)	851 (score: 1)	924 (score: 2)

The results stand out in the fact that the values are far apart. While a lower insolation is expected at the (less than optimal) horizontal design, the 39° angled design would have one expect similar results. Even more because there are not a lot of high objects (several trees) surrounding the area. However, a possible explanation could be that the limited height of the design (2.5 m) results in shadowing of the objects anyway. Especially in the winter, when the sun is at its lowest, the objects could cast a shadow over the low design. For the northern location, this effect is negligible as it is located north of the road itself. It has to be noted that the effect of shadowing from traffic can be significant for this location though. This effect was not measured.

The ratios between the two designs for both locations are 1.16 for section 1 and 1.09 for section 2. The difference in ratio suggests that section 2 performs relatively better in the horizontal design (or worse in the angled design). This could again be explained with shadowing from objects reducing the irradiation (more so at the angled design than at the horizontal design). Also, the DEM data used for section 2 has missing values, possibly affecting the reliability of those results.

To evaluate the fixed irradiation yield factors used in chapter 4, these are compared to the ratios between the two designs described here. Like described above, the ratio for section 1 is 1.16 and for section 2 it is 1.09. The optimum irradiation yield factor for south oriented installations is 1.182. If section 2 is disregarded due to the aforementioned lack of reliability, section 1 shows a ratio that confirms the used fixed irradiation yield factor for south oriented installations.

For the potential electricity production, the same assumptions were made as in chapter 4 (performance ratio, best-available market technology 2015 and height of modules). The results of the electricity production are included in **Table 13**.

Table 13: Annual electricity production Groningen

	Length (m)	Annual electricity production with 0° design (kWh)	Annual electricity production with 39° design (kWh)
Section 1 (northern)	660	196,466	227,027
Section 2 (southern)	660	176,923	192,100
Total	1320	373,389	419,127

Under an optimum design, the total annual electricity production would be 419,127 kWh. This equates to an average performance of 318 kWh per linear meter of noise barrier.

6.2 Tiel

The A15 at Tiel will be the location of a new PVNB project. A third party by the name of Energie van Hollandsche bodem B.V. has initiated this project and applied for a permit for construction, maintenance and exploitation of PV modules mounted on local noise barriers around Tiel. The PV modules and all related peripherals (wiring, inverter, etc.) will remain under property and responsibility of the third party. At the same time, they also receive the sole right to exploit the produced electricity. Rijkswaterstaat, as owner of the plots and noise barriers in question, will receive money for the lease on the use of the plots. As of August 2015 it is unknown what the price for the lease will be **(Stoeten, 2015)**.

Energie van Hollandsche bodem B.V. is an initiative to allow residents to participate in an energy cooperation where small PV arrays are installed in the vicinity of these people. All participants invest in this array and in return receive a share of the profits and additionally (under certain conditions) qualify for a lower energy tax rate **(Energie van Hollandsche bodem, 2015)**. In the case of this project in Tiel, participants are residents living in the neighbourhood behind the noise barriers.

Figure 18: PVNB area Tiel marked with red (Google, 2015)

The project consists of three section as illustrated in **Figure 18**. The first section is approximately 428 meters long, the second one is 717 meters long and the third one is 319 meters long. All modules are placed on the south side of the highway facing away from the road. Therefore, orientation of the modules is south as well. Due to a slight curve in the road, orientation is between SSE and S. According to the plans, modules will be placed at an angle of 50° and have a height of 1.86 meters. The total height of the noise barriers is 7 meters, with the modules being installed at roughly 4 meters high. **Figure 19** gives an impression of what the finished project could look like **(Zweers, 2014)**. The total capacity of the PVNB would equate to 167 kW_p, 280 kW_p and 125 kW_p respectively. In total, the capacity would be 572 kW_p.

Figure 19: Impression of PVNB project in Tiel (Stoeten, 2015)

6.2.1 Analysis

For analysis of this project, all three sections of the project were analysed. All three were considered in three different designs and analysed as per the methodology. As a baseline design, a PVNB with a horizontal plane was modelled. This horizontal plane corresponds to the methodology of the previous chapter with the broad analysis of all Rijkswegen. The second is a design with an angle of

50° (as per the actual design) and the last is a design with an optimum angle. The optimum angle varies per orientation. The first section is considered SSE oriented (optimum angle: 37°) and the second and third are considered S oriented (optimum angle: 39°). The three designs are analysed for all sections.

Coincidentally, the PVNB project corresponds to one of the samples of the broad analysis in chapter 4. Noise barrier segment RW15_1 overlaps with the third (most eastern) part of the proposed project. Interesting is that RW15_1 has the highest adjusted annual insolation of all samples in the district (RWS Oost-Nederland District Zuid). **Table 14** shows the annual insolation and the adjusted annual insolation for RW15_1.

Table 14: Insolation values of RW15_1

	Annual insolation (kWh/m^2)	Adjusted annual insolation (kWh/m^2)
RW15_1	1,001 (score: 3)	1,183 (score: 5)

In the case of RW15_1, the adjusted annual insolation was calculated by multiplying with the optimum irradiation yield factor (orientation to the south, so yield factor is 1.182). This situation allows for a comparison between the previously calculated sample and the 3D modelled method. **Table 15** shows the annual insolation for all three designs and all three sections of the project. Small variations, like these are expected, as even a small number of objects can have an effect on the insolation due to shadowing. However, as measurements are done over several hundred meters, the average values for the whole sections are similar. Comparing the results with the results from RW15_1 from chapter 4, the adjusted annual insolation is higher than the values measured in the case study. This means that the fixed average values for the irradiation yield factor are, in this case, slightly too high. It also shows that, while the planned design (50° angle) of the project increases the irradiation as compared to a horizontal plane, it is not at the optimum value. A design with a 37° and 39° angle (depending on the orientation) allows for a higher irradiation and therefore a higher potential electricity production.

Table 15: Annual insolation Tiel

Annual insolation (kWh/m^2)	Design 1 (0° angle)	Design 2 (50° angle)	Design 3 (37° or 39° angle)
Section 1 (western)	998 (score: 3)	1,105 (score: 4)	1,124 (score: 4) (37° angle)
Section 2 (middle)	982 (score: 3)	1,096 (score: 4)	1,115 (score: 4) (39° angle)
Section 3 (eastern)	1,015 (score: 3)	1,143 (score: 5)	1,163 (score: 5) (39° angle)

The potential electricity that can be produced with the configurations described above are highly indicative, as there are no details known on the technology that will be used in the project. However, assuming 2015 best-available market technology and a performance ratio of 0.75, the following potentials were calculated as presented in **Table 16**. These values allow for a comparison between the actual and the optimum design. Under the optimum design, the annual electricity production is 483,814 kWh.

Table 16: Annual electricity production Tiel

	Length (m)	Annual electricity production with 0° design (kWh)	Annual electricity production with 50° design (kWh)	Annual electricity production with optimum (37° or 39°) design (kWh)
Section 1 (western)	428	125,132	138,548	140,930
Section 2 (middle)	717	206,264	230,209	234,200
Section 3 (eastern)	319	94,852	106,815	108,684
Total	1,464	331,396	475,572	483,814

The annual electricity production for the actual plan, according to this methodology, will be 475,572 kWh. This value is likely to be different as compared to the real value, as there are still many uncertainties in the project. Because of these uncertainties, assumptions had to be made. The performance of the whole project per meter of noise barrier is 330 kWh per meter.

6.3 Uden

The project in Uden is significantly different from the first two: it entails a bifacial PVNB. It is called Solar Highways and is a project from Rijkswaterstaat. It fits the policy of Rijkswaterstaat, focusing on more sustainable and innovative initiatives. This is expressed by setting up projects that follow this policy. The same policy that drives the Solar Highways project. Objectives of the project are to demonstrate the technical integration of bifacial PV cells in noise barriers. Other objectives are to study the environmental, social and financial benefits **(Solar Highways, 2015)**.

While the project is already underway (started in June 2014), actual construction has not started yet. Initially the aimed project location was Dordrecht along the A16, but since then this location was changed to Uden along the A50. Although the new location is expected to be the final location, no definitive choice has been made as of August 2015 **(Van der Graaf, 2015)**.

The bifacial PVNB is aimed for an optimal location in the sense that the road runs in a north-south direction, resulting in the PVNB facing both east and west. The planned design outlines a PVNB with a length of 450 meters and a height of 6 meters. The actual height of the PV cells is aimed at 4 meters. Rijkswaterstaat estimates that the energy yield will be 275 MWh per year.

It is difficult to set the exact location for the project as it is not yet decided. It is stressed however that no 'unnecessary' noise barriers are placed. So assumed is that the projected location will be one where there is currently already a noise barrier constructed. There are roughly two locations that satisfy these properties. For comparison a third location (located in between the other two) is added where there currently are no noise barriers, but is seen as the technically best location due to the immediate surroundings being mostly absent of trees, buildings and other objects. **Figure 20** shows these locations.

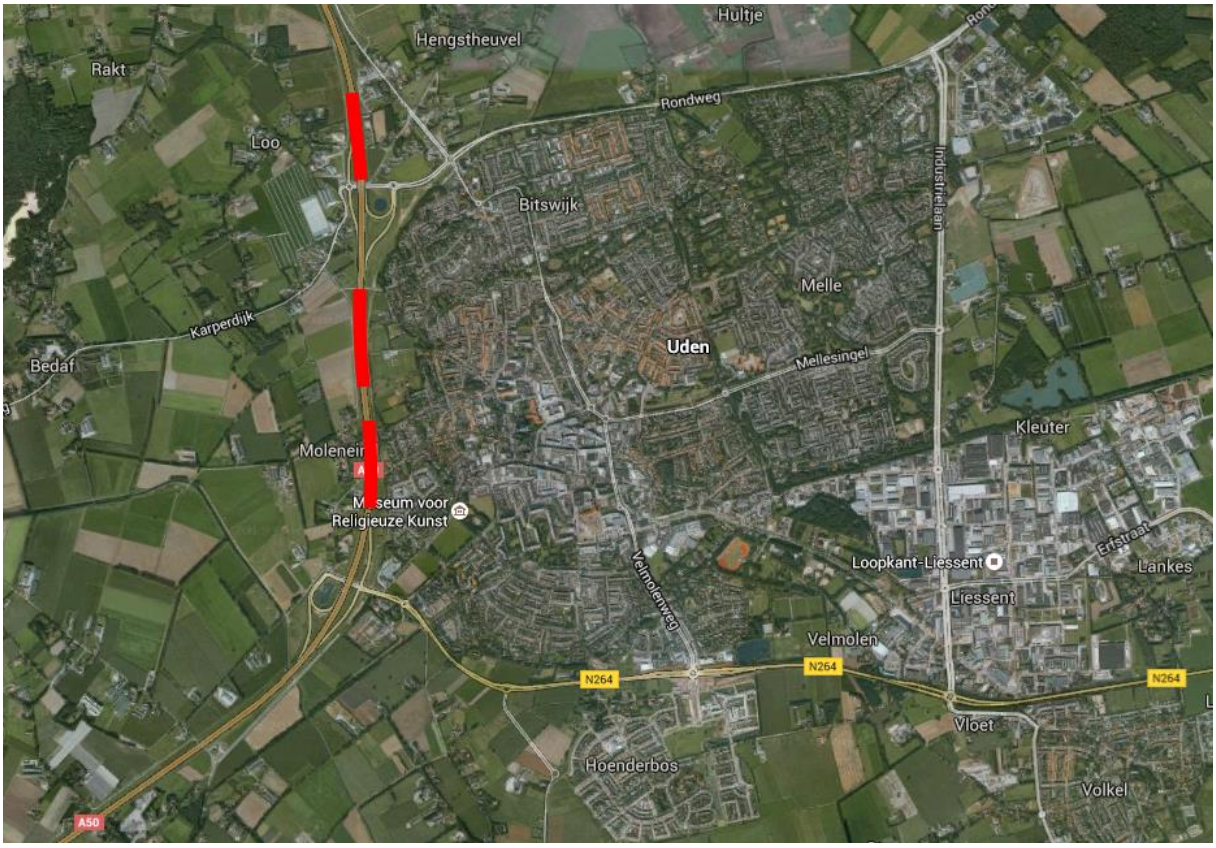


Figure 20: PVNB area Uden marked with red (Google, 2015)

The problem with this specific case is that the ArcGIS solar analyst methodology does not work with vertical surfaces. Instead, the next best design was considered. For east and west oriented installations, this is the horizontal plane. For an indication of the bifacial performance, other sources were used.

6.3.1 Analysis

With an orientation to the east and west, the optimum angle is 0° (as used in chapter 4). Like mentioned earlier, bifacial designs cannot be analysed through 3D models and the Solar Analyst tool. Instead, the GHI is calculated like in chapter 4 and the irradiation yield factor for east/west oriented installations is used to adjust these values. The yield factor, as calculated in chapter 3.5 is 0.594. **Table 17** shows these results.

The total capacity of the PVNB would equate to 189 kW_p for design 1 and 378 kW_p for design 2. It is assumed that design 2 (bifacial PVNB) utilizes the same STC efficiency and due the larger surface area available, the total capacity of this design is larger as compared to design 1.

Table 17: Annual insolation Uden

Annual insolation (kWh/m^2)	Design 1 (0° angle)	Design 2 (90° angle) (approximate results through irradiation yield factor)
Section 1 (northern)	994	590
Section 2 (middle)	1,002	595
Section 3 (southern)	1,003	596

This shows the effects of a less than optimum design: insolation values are almost half of the GHI. Of course the advantage of a bifacial design comes from the fact that every day there are two surfaces incident on the sun. Also related to that, with a vertical design there is a large surface available for PV modules. Since the insolation is expected **(Goetzberger et al., 1999)** and measured to be almost the same for east and west orientations, all advantages simply correspond to an increased surface area available.

The planned design assumes a length of the noise barrier of 450 m. The height of the PV modules will be 4 m. This means that the total surface area available is 450 * 4 * 2 (east and west). This equal to 3600 m^2. A traditional PVNB at the same location with an angle of 0° would have an available surface area of 450 * 2 = 900 m^2. This is a factor 4 smaller. Also note that non-bifacial PVNB are commonly not installed at these orientations and angles, since other locations are more suitable.

Table 18: Annual electricity production in Uden

	Length (m)	Annual electricity production with 0° design (kWh)	Annual electricity production with bifacial 90° design (kWh)
Section 1 (northern)	450	140,900	334,530
Section 2 (middle)	450	142,034	337,365
Section 3 (southern)	450	142,175	337,932

Table 18 shows the annual electricity production with both a 0° design and the bifacial 90° design. Because of the lack of a uniform methodology, these results are highly indicative. Still, the results look promising for bifacial designs. The production is more than 2 times that of a 0° design. Of course, this is for a large part due to the surface area being 4 times larger than that of the 0° design. Based solely on the insolation per m^2 though (**Table 17**), the results are comparable to an optimum angled (39°), south oriented design. This is also confirmed by De Jong **(2015)** and Goetzberger et al. **(1999)**.

7. Practical factors associated with implementation

While the focus of this thesis is on quantifying the technical potential, there are several other, more practical factors associated with actual implementation. Chapters 4, 5 and 6 all include the factors orientation, irradiation, length, and likelihood of maintenance or replacement. This enables Rijkswaterstaat and possible third parties to select the best available locations based on those values. However, a final decision can only be made after all factors and conditions are considered. The scope of this thesis does not include an analysis of these practical factors, but does list them in order to comprehend the complete implementation process.

7.1 Organisational and financial aspect

First and foremost is the financial aspect: while PVNB has the advantage of providing electricity and reducing emissions, implementation has to be economically feasible. Much of this depends on the organisation of the PVNB project. It is important to have a clear overview of the stakeholders involved and their respective roles. Rijkswaterstaat owns the land and noise barriers and is therefore an important stakeholder. Other stakeholders depend on the ownership and exploitation. For instance with the A27 PVNB project, the complete PVNB (noise barrier and PV modules) is owned by Rijkswaterstaat. The exploitation of the electricity production was the responsibility of REMU **(Betcke et al., 2002)**. Jochems **(2013)** identifies 5 different constructions for ownership of PVNB projects. These constructions are described below.

- **Rijkswaterstaat owns and exploits PVNB**
  It is not likely for Rijkswaterstaat to assume a role wherein they exploit the electricity produced. For their electricity supply, Rijkswaterstaat has large-scale agreements with utility companies. These agreements result in a low price per kWh close to the cost price **(AT Osborne, 2013)**. While this is beneficial, it also severely limits the use Rijkswaterstaat itself has for electricity production, because it requires PV technology to become cheaper before it can be competitive.
  Also, supplying the electricity to consumers over the public grid is questionable. Without a permit it is illegal for Rijkswaterstaat to become an electricity supplier to end users. While it is possible to apply for a permit, this would result in additional responsibilities. It is policy of Rijkswaterstaat to not assume this role of electricity supplier.
  Currently, an increasing share of Rijkswegen is maintained in close cooperation with public and private parties. Rijkswaterstaat assigns a project (like the construction and/or maintenance of a highway) to a consortium through a so-called DBFM-contract. Within this construction, the highway and noise barriers are, for the length of the contract, under responsibility of the consortium. Potential PVNB would then be under ownership of the consortium. These parties can purchase electricity through Rijkswaterstaat, joining in the favourable conditions. Prices are slightly higher, but are fixed for the length of the contract **(AT Osborne, 2013)**.
  For an electricity supplying role, the consortium needs to adhere to the same conditions as Rijkswaterstaat, meaning they have to fulfil to the requirements of a permit and the associated responsibilities. While a decision on this is dependent on the consortium, it would still involve an agreement with Rijkswaterstaat and the utility companies.
- **Third party owns and exploits the PVNB**

For this construction, an interested third party with the necessary resources to invest is the owner of the PV modules. The land and noise barriers, or more specifically the use of it are under lease from Rijkswaterstaat. The third party can be a company in the vicinity of the road. It is most interesting for these companies to directly consume the produced electricity. While utility companies are obliged to purchase electricity from small end-users, they are not obliged to buy it from large end-users. On top of that, net energy metering is not possible for these large end-users. For these reasons, this construction seems only feasible when the company who owns the system directly consumes the produced electricity.

- **Utility company owns and exploits the PVNB**
  Again, the construction is that a third party (in this case a utility company) leases the use of the land and the noise barrier from Rijkswaterstaat. The utility company invests in the PV modules and exploits the electricity. The added benefit is that the utility company already adheres to all regulations and has the necessary permit to act as a supplier of electricity.
- **Cooperation of consumers owns and exploits the PVNB**
  In this construction several small energy consumers join an energy cooperation for the construction and utilization of a PV array. According to the most recent laws, a cooperation can build and exploit a PV array in the direct vicinity of the members of the cooperation (the same postcode area or an adjacent postcode area). All members of the cooperation receive a rebate on their energy taxes. Additionally, all members receive part of the profits after the costs for the lease, maintenance, etc. are deducted **(Energie van Hollandsche bodem, 2015)**. The PVNB project in Tiel, described in chapter 6.2 follows this construction. In these and future projects, Rijkswaterstaat, as owner of the land and noise barriers, leases the land to the cooperation. The cooperation has the responsibility of construction and maintenance. In order to obtain permission of the noise barrier, all potential projects need to meet several conditions. A so-called 'aanvraag Wbr beschikking' (application for the use of Rijkswaterstaat property) needs to be submitted and then granted. This is necessary when using said property for other purposes than intended for **(Jochems, 2013)**. This construction is recognized by Rijkswaterstaat as particularly interesting.
- **Third party leases the use of a PVNB from Rijkswaterstaat**
  In this construction Rijkswaterstaat (or the consortium under the DBFM-contract) is the owner of the complete PVNB and leases the PVNB to third parties like gas stations and adjacent car parks. These are often located in the vicinity of potential PVNB locations. Possible applications are the charging of electrically powered vehicles **(Jochems, 2013)** on the car parks.

Of the above constructions, most is seen in those where a third party (cooperation or (utility) company) leases the land and noise barrier use of Rijkswaterstaat. Rijkswaterstaat expresses the willingness to make government owned land available for third parties for societal and commercial use through RWS Partner **(Rijkswaterstaat, 2013b)**. This also means that Rijkswaterstaat is able to make money with the lease for PVNB projects. These specific constructions are new to Rijkswaterstaat; the project in Tiel is the first of its kind. Therefore, Rijkswaterstaat has to decide on a price they are willing to ask to third parties for the lease. This decision is made by Rijksvastgoedbedrijf (RVB). As a government body, it is responsible for deciding on the leases of state property. As of August 2015 it is unknown what the lease price will be for the project in Tiel and possible future projects **(Jonker, 2015; Stoeten, 2015)**.

7.2 Operational aspect

Depending on the organizational construction as mentioned in chapter 7.1, the owner of the PVNB can vary. This in turn can influence the responsibilities like maintenance or cleaning. Current PVNB projects throughout Europe show that responsibilities are sometimes unclear, depending on the construction. As a result, some projects experience a lack of response in cases of vandalism, theft and maintenance of the PV modules **(De Jong, 2015)**.

- **Maintenance**
  There can be several reasons for maintenance. Again, depending on the organisational structure, this could mean that Rijkswaterstaat or a third party is responsible for maintenance. When Rijkswaterstaat is the responsible party, maintenance can be (partially) combined with the maintenance on the noise barriers itself. In the case of other parties being responsible, it is important that clear agreements are made. Maintenance of PV modules should cause as few hinder to Rijkswaterstaat or traffic as possible. Specifically, safety aspects should be adequate **(Jochems, 2013)**.
  Recommended is to keep monitoring the installation. This enables the owner to adequately respond to failing modules. At the same time, periodic cleaning of the array is important as pollution due to traffic significantly reduces the performance of the installation **(Betcke et al., 2002)**.
- **Surroundings**
  The surroundings are already incorporated in the analysis of the performance of certain locations in chapters 4, 5, and 6 by measuring the shadowing on certain locations. However, the PVNB project in Münsingen **(De Jong, 2015)** showed that surroundings are important during operation as well. This specific project suffered from increasing shadowing from vegetation. No efforts were made to reduce the vegetation surrounding the PVNB. Especially when there are two different parties responsible for the PVNB and the surroundings, it can be difficult for the PVNB owner to have the other party act on this.
- **Vandalism and theft**
  Several PVNB projects **(De Jong, 2015; Goetzberger et al., 1999; Betcke et al., 2002)** suffered from vandalism and theft. De Jong **(2015)** argues that vandalism in the form of graffiti is already a problem with existing noise barriers. Graffiti can significantly reduce the performance of installations and although it is easily removed from glass, it does pose a potential problem. In the case of the PVNB project in Zürich, the project was abandoned partly because of continuing graffiti nuisance.
  In the case of other forms of vandalism and theft, De Jong **(2015)** emphasize the importance of an adequate design. The design should make access (for undesirable people) as difficult as possible. This can be achieved by PV modules that are installed high and are integrated as much as possible within the noise barrier. The same goes for cabling and inverters.

7.3 Design choices

Apart from the initial design choices following the technically best performance (orientation and angle), there are certain other design choices to be considered.

- **Noise reflection and absorption**
  The primary goal of a noise barrier is to reduce the noise pollution behind the noise barrier. In the case of a PVNB (both integrated designs and retrofitted designs), the addition of PV

can result in an improved noise reflection and absorption **(Snow and Prasad, 2000; Yang et al., 2013)**. However, the opposite is also possible. Studies and/or simulations on the resulting noise measured behind such a noise barrier design, should be performed before such a design is constructed. In the case of bifacial PV noise barriers, the mass density of just the installation is not enough and further material needs to be used to ensure sufficient absorption **(De Jong, 2015; Goetzberger et al., 1999)**.

- **Performance**
  Besides the performance as measured in chapters 4, 5 and 6, the design can contribute significantly to the performance of a PVNB. While the angle was previously assumed at an optimum value, the actual design should adhere to this for best results. Also, self-shading can be a factor in decreasing performance. This is the shadowing of parts of the PVNB on other parts. Supports of the PV modules are, especially for bifacial PVNB, a large contributor to shadowing **(De Jong, 2015)**.
  More general, the aim should be to have the performance ratio as high as possible. Many PVNB projects in Europe **(Goetzberger et al., 1999)** experienced a disappointing performance due to low performance ratios. Reasons include pollution of the modules, faulty installation and less than optimal equipment (like inverters with a low efficiency).
- **Current situation**
  The current situation is important for several boundary conditions. On one hand there is the design of the current noise barrier. While effort is made to adhere to the modular design of noise barriers **(Rijkswaterstaat, 2006)**, suitability for PV retrofitting is not guaranteed. The other condition is that the location of the noise barrier is suitable in the sense that the construction of a PVNB is possible due to the surroundings. Noise barriers with little available space between them and the road, can require roads to be closed for construction and maintenance. This is not desirable. A final consideration could be the local availability of a low voltage or medium voltage grid along the roads.
- **Safety**
  Regarding safety it is important that the materials used for PV modules and the PVNB in general do not pose a significant risk when breaking down. One of the issues is the use of glass. This could prove a hazard when it breaks. The risk however can be minimalized by using tempered glass **(De Jong, 2015)**. This is already used in regular noise barriers fitted with glass.
  Another risk can come from electrical wiring within the PVNB. Exposed wiring can pose a threat to people around it. This can be solved by making direct access difficult for unauthorized people and making sure cabling is covered sufficiently.
  A third risk can come from glare. Light sources can be reflected in the PV modules and potentially blind traffic. While the effect is limited and not worse than with glass, efforts can be made with the design to limit the negative effects.

8. Discussion

While care was taken that the methodology was accurately followed throughout the process, the fact remains that the results presented in this thesis are based on a methodology that simplifies the real-world conditions. As with all models a finite number of parameters is taken to analyse the system. It is important to see the results within the context of the assumptions made and the limitations of the methodology.

8.1 Used data and assumptions

In the implementation of the methodology a wide range of datasets was used. The accuracy of the results is reflected by the quality of the data. Therefore it is important that the data is adequate. Much of the data consists of datasets from Rijkswaterstaat detailing on roads (location, width, etc.), property borders, noise barriers and their properties and more. This kind of data is fixed (unless changed by Rijkswaterstaat) and periodically updated to ensure an up-to-date dataset. All data used was updated shortly before analysis started.

Another dataset was the AHN2, the so-called DEM or heightmap. The use of this dataset was essential for the methodology as it was the main input for the calculation of the solar irradiation at the sample locations. The AHN2 is a very accurate and detailed dataset **(Van der Zon, 2013)**. In that respect there is little doubt that this affected the results. One thing that could possibly influence the results is that the heightmap is recorded by LiDAR and initially includes mobile objects (like traffic). Care is taken to remove such objects, but cannot be completely guaranteed. An inherent problem of heightmaps is that these are snapshots of surfaces. When objects like houses or trees are constructed/planted or demolished/cut this results in the snapshot no longer reflecting the real world accurately. In the case of the AHN2 all data was acquired between 2007 and 2012.

Due to the large number of samples analysed, the potential equations utilized were constructed using averages and assumptions for several parameters. Specifically for the calculation of electricity production, the values for performance ratio, STC efficiency and height of the PV modules were fixed. The STC efficiency was derived from literature review and two separate values were assumed for 2015 and 2030. Assumptions were based on best-available market technology to achieve results that are possible to realize. For the performance ratio and the height of the PV modules, accurate values are more difficult. This is due to the fact that these are highly dependent on a large number of variables, including those related to the location and external factors like weather, pollution, design of noise barrier, used equipment, etc. Studies on existing PVNB installations **(Goetzeberger et al., 1999; De Jong, 2015)** show that the height of the PV modules varies a lot. An average is taken based on existing designs and available surface area on different designs of noise barriers. In reality, the design and location (vicinity to the road) as discussed in chapter 7 influence the maximum available surface area. For the performance ratio these studies show ranges between 50% and 80%. The 75% assumption is closer to the top value of the range, but this is due to some of these experimental PVNB installations performing under expectation due to several factors that are avoidable. Limiting factors include lack of maintenance and unnecessary energy losses due to faulty or inefficient technology. The assumption of 75% for the performance ratio was further backed by literature review. While these assumptions are not extremely ambitious, they do require certain effort on the design and operation of the PVNB.

It has to be noted that all the mentioned values (STC efficiency, height of PV module and performance ratio) have a direct and significant effect on the electricity production and therefore the potentials. Half the average of the height results in half the electricity produced. **Table 19** shows the short-term potential from chapter 5 and added to it the adjusted potentials for both lower and higher average values for the height and performance ratio.

Table 19: Sensitivity analysis short-term potential

	Annual electricity production 2030 (MWh)
Short-term potential	6,938
Short-term potential (height: 1.5m; PR: 0.70)	4,857
Short-term potential (height: 2.5m; PR: 0.80)	9,251

The results of the potential analysis can be compared to one other quantitative analysis on PVNB installations. Goetzberger et al. **(1999)** previously analysed the potential of PVNB in Europe, including a potential for the Netherlands. While this research is both dated and based on global data instead of detailed local data, it can still serve as a way of comparison for the resulting potentials. Two of their potentials do not match any of these potentials, but one of them is a potential that includes all noise barriers (existing and planned in 1999). This would correspond to the extrapolated theoretical potential of this thesis. Goetzberger et al. **(1999)** show a potential of 91,800 MWh per year for the Netherlands. This is less than half of the extrapolated theoretical 2015 potential in this thesis (210,628 MWh per year). However, they assume a STC efficiency of 13% and also a total length of 475.9 km. Since 1999, the STC efficiency has increased significantly (21% assumed for 2015 in this thesis). The length used in this thesis adds up to 641 km, significantly more than the 475.9 km used in their potential. This could be explained by the addition of noise barriers and possibly a different, incomplete dataset. By correcting for both length and STC efficiency, their potential would result in 199,738 MWh per year. More closely to the 210,628 MWh from this thesis and a difference of roughly 5%. This corroborates the results from this thesis.

As discussed in the methodology, the maintenance priority for noise barriers is acquired from the research from Movares **(2014)**. While their methodology is extensive and incorporates different conditions and properties of the noise barriers, it is unknown to what extent the recommendations from that research translate to actual policy and replacement and/or maintenance of noise barriers. However, the effect of this is limited in this thesis, since its value is only used in the short-term potential.

Finally, the use of irradiation yield factors in this thesis, assumes average values for the Netherlands. These yield factors are used to calculate the adjusted irradiation in a plane at a certain angle and orientation. While the irradiation yield factor does not vary much within the latitude of the Netherlands, it is still an average. The results from the cases in chapter 6 show that the used yield factors were slightly too high in those cases. However, with just three cases, it is difficult to conclusively state that the yield factors are consequently too high.

In the case of the third case (Uden) in chapter 6, a comparison was made with between the planned design (bifacial) and a standard PVNB design. The calculation of the performance of the bifacial design is not supported by the used methodology. Therefore, results are approximated with an irradiation yield factor and therefore only to be used indicative.

8.2 Limitations and future research

The scope of this thesis is limited to the use of noise barriers for PV technology. The choice for this is based on both existing implementations of PV technology and expected future improvements in this. Both in the context of the Rijkswegen and the Netherlands. This does exclude potential other types of implementation as discussed in chapter 2.2. Especially, the use of earth berms next to the Rijkswegen might be an interesting development. There is approximately 346 km of earth berms located next to the Rijkswegen. While the used methodology does not apply to this type of PV implementation, future research could incorporate this possibility.

Another limitation is that the assumed minimum length of interesting PVNB location was argued to be 500 m. While this is true in the sense that these locations are economically more feasible and are also supported by the length of most current installations **(De Jong, 2015; Goetzberger et al., 1999)**, it does not mean that shorter noise barriers could not be feasible (now or in the future). This is already incorporated for the potentials, where the potential of all noise barriers (including those smaller than 500 m) was calculated. These were not included in the individual calculations. For a more complete overview of noise barriers and their irradiation, future research could include these slightly less interesting locations. Especially when these become more interesting in the future, due to decreases in price and improvements in technology.

In a broader sense, the analysis is limited to current noise barriers. This means that future noise barriers are not included. New city development and road development can form the necessity of building new noise barriers. Also, other factors, like changing noise regulations could result in more noise barriers being constructed. Essentially this means that the available locations for PVNB also increase. This could increase the potential of PVNB on a national scale.

For roads that run in the north-south direction, the use of bifacial PVNB significantly increases the potential. Literature shows that performance of such a PVNB could potentially parallel that of south oriented optimally angled PVNB installations **(De Jong, 2015; Hoekstra, 2010; Solar Highways, 2015)**. Due to limitations of the methodology, bifacial technology could not be analysed. The ArcGIS tool Solar Analyst does not work with vertical surfaces **(Esri, 2012)**. Since the potential for bifacial technology is so large and could significantly increase the total potential of PVNB in the Netherlands, it is recommended to incorporate this in future research. The methodology would have to be extended to be able to calculate this performance.

9. Conclusion

The goal of this thesis was to answer the question: What is the potential of photovoltaic (PV) noise barriers along the Dutch national high- and expressways (Rijkswegen) by 2030? This was done by analysing all current noise barriers with a length more than 500 metres. A model was proposed to analyse the solar irradiation on these locations using LiDAR data. Supplemented with substantiated values, calculations were made to express the potential by 2030.

Based on a literature review (chapter 2), other applications in the context of the Rijkswegen were explored. Autonomous PV systems can (and already have) a significant role in this as they provide a solution to supplying electricity in cases where the use of the electricity grid is not possible or preferable. Some examples include lighting and signalling. The potential electricity production is more interesting when looking at grid-connected systems. These allow for large PV arrays to contribute to a larger share of renewables in the national energy mix. The required space for these arrays is difficult to find in a densely populated country like the Netherlands. Land owned by Rijkswaterstaat is often limited to several metres wide next to the highways. This limits the options, but also highlights the possibility of PVNB.

With the use of GIS, a national high resolution digital elevation model (AHN2), and several other datasets, the solar irradiation was calculated for the complete sample size. While the irradiation (insolation) calculated was the global horizontal irradiation (GHI) for those areas, these values were adjusted using irradiation yield factors to better reflect the actual irradiation in the plane according to the orientation and angle of the noise barrier. Together with the length of the noise barrier and the maintenance priority, these values can be used to identify suitable locations for PVNB. For an overview of all measured locations, Appendix III offers overview maps divided by organisational districts of Rijkswaterstaat.

Based on the annual insolation of these locations, the projected annual electricity output could be calculated. Several assumptions were made to reflect current and future technology. These assumptions were based on literature review and are taken for best-available market technologies in both 2015 and 2030. Different potentials what can be expected by implementing PVNB on different scales. **Table 20** shows these potentials.

Table 20: Annual electricity production potentials for 2015 and 2030

	Annual electricity production 2015 (MWh)	Annual electricity production 2030 (MWh)
Extrapolated theoretical potential	210,628	250,748
Theoretical potential	61,447	73,151
Technical potential	34,588	41,176
Short term potential	5,828	6,938

While the different potentials all have their use, for the scope of this thesis the short-term potentials are the most interesting. These show the potential of the most interesting noise barriers (based on expected performance), that are expected to be upgraded or replaced by 2030 anyway due to the age and condition of the noise barriers. While the 2015 potential shows the annual electricity production assuming current (2015) best-available market technology, the 2030 potential shows the electricity production assuming 2030 best-available market technology. Since the rate of implementation is unknown, these two values can be used as a range wherein the actual potential lies. Therefore, the potential of PV noise barriers by 2030 in the Netherlands is expected to equate to an annual electricity production between 5.8 GWh and 6.9 GWh. This could potentially represent slightly less than 0.005% of the total electricity consumption of the Netherlands in 2013 (119,000 GWh) and around 0.006% of the total electricity production. The technical potential would represent a share of 3%. This would mean that an active policy to build PVNB could increase the share of renewables from 12% towards the 27% targeted by the EU.

A more in-depth analysis was performed for three different cases. These cases were selected as locations where a PVNB is (or was) planned. A slightly enhanced method, where 3D models of the noise barriers were imported in GIS, was used for more accurate results. These results did highlight small differences between the actual and the average irradiation yield factors used in the broader analysis. This stresses the values as being indicative: while it is not possible to calculate exact irradiation values, it is possible to make an estimate using average values for the Netherlands.

While the used method can be used for an indicative potential, in reality actual implementation on all expected PVNB locations is dependent on multiple other factors of a more practical nature. Depending on policy and resulting organisational constructions, different stakeholders are involved. Current policy of Rijkswaterstaat (with program like RWS Partner) could lead to a stronger focus on collaboration with third parties. Except for the monetary benefits of the lease of the land and noise barriers, this would also benefit Rijkswaterstaat and national government in supporting renewable energy production, possibly becoming a leading expert on PVNB compared to other countries. The location of PVNB also ensure the visibility to the public.

9.1 Recommendations

The outcomes of this thesis can serve as a tool for policy makers (especially within Rijkswaterstaat). Besides the regular results (chapters 4, 5, 6 and Appendix II), great care is taken in the creation of the overview maps in Appendix III. More than anything, these maps can be used for quickly identifying and comparing possible PVNB locations. The maps are divided per organisational district of Rijkswaterstaat, thereby providing only relevant information for policy makers.

Suggested is to use the overview maps and results to come to a preliminary verdict of the suitability of a location. After this, further more detailed research on the location can be done. The solar irradiation can be recalculated for the exact design of the planned PVNB, but more importantly other factors that are outside the scope of this research, should be explored.

Important is to consider the limitations of the research (chapter 8). Locations not being included in the results or on the map do not necessarily mean that they are not suitable. Also, noise barriers located along a north-south oriented highway could perform better than appears from the results (as bifacial technology is not supported by the used methodology).

For the electricity production of a PVNB to be as high as possible, it is important to design the PVNB with this in mind. If possible the orientation and angle of the PV modules should be following the optimum values (discussed in chapter 4.2). Of course, there are other factors that could limit the possibility of optimizing these values. For example: the Tiel project (chapter 6.2) will have PV modules placed under an angle of 50 degrees, due to the design of the noise barrier not permitting other angles easily.

Recommended is to incorporate the data from this thesis in the GIS datasets on noise barriers (weggeg). Missing data on noise barriers smaller than 500 metres and earth berms could be acquired by future research and added at a later time. This would provide policy makers with the data to use and present as they see fit. While the overview maps presented here are a great starting point, policy makers could require direct access to the data and/or other forms of presenting this data. This could be done by the suggested addition in datasets.

For an increased rate of implementation it is vital that the concept of PVNB needs to be accepted and supported within Rijkswaterstaat. This can be done by making the process straight forward, with as little uncertainties as possible. Currently the PVNB project in Tiel is expected to be the first that will form this process. The agency of the government responsible for the use of government property, Rijksvastgoedbedrijf (RVB) needs to decide on the conditions under which third parties can make use of noise barriers for this purpose. When projects have been successfully started, these can serve as guidance for future projects.

It can be useful if experiences of all relevant PVNB projects (past, current and future) are described and collected. The same goes for other data, like performance of the PV modules. A central program like ‘Programma Energie’ can play a coordinating role in this and make the information available to local policy makers in each district. Successful projects can serve as examples and prospects. By making the process as easy as possible, implementation can be maximized.

10. References

Aanpak Ring Zuid, 2014. *Tracébesluit - Bijlage D3b deelrapport Specifiek bijlagen B – E*. [online] Available at: <http://www.aanpakringzuid.nl/files/9214/1172/1990/Bijlage_D3b_deelrapport_Specifiek_bijlagen_B_-_E.pdf> [Accessed 20 August 2015].

Aerodata Surveys Nederland, 2015. *Zonnescan Amersfoort*. [online] Available at: <http://solar.aerodata-shop.nl/Amersfoort> [Accessed 5 June 2015].

AHN, 2015. *AHN – Actueel Hoogtebestand Nederland – homepage*. [online] Available at: <http://www.ahn.nl/index.html> [Accessed 20 May 2015].

Andrews, J. and Jelley, N., 2007. *Energy science – principles, technologies, and impacts*. New York: Oxford University Press Inc.

APS News, 2009. *April 25, 1954: Bell Labs Demonstrates the First Practical Silicon Solar Cell*. [online] Available at: <http://www.aps.org/publications/apsnews/200904/physicshistory.cfm> [Accessed 1 August 2015].

AT Osborne, 2013. *Opwekken van zonnestroom met geluidsschermen langs de snelweg*. Baarn: AT Osborne.

Avrutin, V., Izyumskaya, N. and Morko, H., 2011. Semiconductor solar cells: Recent progress in terrestrial applications (Review). *Superlattices and Microstructures*, 49(4), pp.337-364.

Betcke et al., 2002. *Opbrengstgegevens van het PV-geluidsscherm langs de A27 na twee jaar systeembedrijf – Eindrapport*. Utrecht: Utrecht University.

Blok, K., 2007. *Introduction to Energy Analysis*. Amsterdam: Techne Press.

Borg, van der, N.J.C.M. and Jansen, M.J., 2001. *Photovoltaic noise barrier at the A9-highway in The Netherlands*. Sine loco: ECN.

CBS, 2014a. *Lengte van wegen; wegkenmerken, region*. [online] Available at: <http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=70806ned&D1=0-1,8,14&D2=0,5-16&D3=a&HD=090330-1643&HDR=G2&STB=G1,T> [Accessed 9 February 2015].

CBS, 2014b. *Energiebalans; kerncijfers*. [online] Available at: <http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=37281&D1=a&D2=0-1,4,7-12&D3=122&HDR=G2,G1&STB=T&VW=T> [Accessed 10 February 2015].

CBS, 2015. *Statistics Netherlands: Electricity use 16 times as high as in 1950*. [online] Available at: <http://www.cbs.nl/en-GB/menu/themas/industrie-energie/publicaties/artikelen/archief/2015/electricity-use-16-times-as-high-as-in-1950.htm> [Accessed 12 June 2015].

Chow, A., Fung, A.S. and Li, S., 2014. GIS Modeling of Solar Neighborhood Potential at a Fine Spatiotemporal Resolution. *Buildings*, 2014(4), pp.195-206.

Compendium voor de Leefomgeving, 2014a. *Energieverbruik door verkeer en vervoer, 1990-2012*. [online] Available at: <http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl0030-Energieverbruik-door-verkeer-en-vervoer.html?i=6-40> [Accessed 10 February 2015].

Compendium voor de Leefomgeving, 2014b. *Emissies naar lucht door verkeer en vervoer, 2012*. [online] Available at: <http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl0129-Emissies-naar-lucht-door-verkeer-en-vervoer.html?i=23-69> [Accessed 11 February 2015].

Conibeer, G., 2007. Third-generation photovoltaics (Review). *Materials Today*, 10(11), pp.42-50.

CycloMedia, 2014. *Luchtfoto (2014)*. [online] Available at: <http://www.arcgis.com/home/item.html?id=5c621f71daf34eef8d2973caa94a7b3b> [Accessed 30 May 2015].

Dunlop, J.P., 1990. Design and operational performance of a photovoltaic-powered highway guide sign lighting system. *Proceedings of the … Annual Meeting, American Solar Energy Society, Inc*, 1990(), pp.223-228.

Energie van Hollandsche bodem, 2015. *Energie van hollandsche bodem: jouw zonnepanelen in een zonnepark in de buurt*. [online] Available at: <http://www.evhb.nl/> [Accessed 20 August 2015].

Esri, 2012. *An overview of the Solar Radiation tools*. [online] Available at: <http://resources.arcgis.com/en/help/main/10.1/index.html#/An_overview_of_the_Solar_Radiation_tools/009z000000t4000000/> [Accessed 18 May 2015].

Esri, 2015. *ArcGIS – Topo Basiskaart (in RD)*. [online] Available at: <http://www.arcgis.com/home/item.html?id=7aea6fa913a94176a1074edb40690318> [Accessed 12 May 2015].

European Photovoltaic Industry Association, 2011. *Solar generation 6 - Solar photovoltaic electricity empowering the world*. [online] Available at: <http://www.greenpeace.org/international/Global/international/publications/climate/2011/Final%20SolarGeneration%20VI%20full%20report%20lr.pdf> [Accessed 18 February 2015].

European Photovoltaic Industry Association, 2014. *Global market outlook for photovoltaics 2014-2018*. [online] Available at: <http://www.epia.org/fileadmin/user_upload/Publications/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf> [Accessed 16 April 2015].

European Commission, 2014. *2030 framework for climate and energy policies*. [online] Available at: <http://ec.europa.eu/clima/policies/2030/index_en.htm> [Accessed 18 February 2015].

Fraunhofer, 2014. *FRAUNHOFER INSTITUTEFOR SOLAR ENERGY SYSTEMS ISE*. [online] Available at: <http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf> [Accessed 25 July 2015].

Fu, P. and Rich, P.M., 1999. *Design and Implementation of the Solar Analyst: an ArcView Extension for Modeling Solar Radiation at Landscape Scales*. Sine loco: Esri.

Ganzevles, J. and Van Est, R., 2011. *Energie in 2030 – Maatschappelijke keuzes van nu*. Boxtel: Aeneas.

Gemeente Leiden, 2015. *Ruimtelijke onderbouwing - Zonnepanelen op luifels verdiepte A4 – Ontwerp*. [online] Available at: <http://gemeente.leiden.nl/fileadmin/files/Projecten/Ruimtelijke_Ordening/00WABO/Zonnepanelen_A4/O/Ruimtelijke_onderbouwing_Zonnepanelen_A4_klein.pdf> [Accessed 15 August 2015].

GeoModel Solar, 2014. *Global Horizontal Irradiation Netherlands*. [online] Available at: <http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-Netherlands-en.png> [Accessed 15 August 2015].

GeoModel Solar, 2015. *Solar and PV data*. [online] Available at: <http://solargis.info/doc/solar-and-pv-data> [Accessed 12 July 2015].

Gifford, J., 2011. High-speed rail line installation powers first solar train, *pv magazine*. [online] Available at: <http://www.pv-magazine.com/news/details/beitrag/high-speed-rail-line-installation-powers-first-solar-train-_100003253#axzz3eoy07CIH> [Accessed 26 June 2015].

Goetzberger, A, et al., 1999. *Evaluation of the potential of PV noise barrier technology for electricity production and market share - Volume 1*. Brussels: EU.

Google, 2015. *Google Maps*. [online] Available at: <https://www.google.nl/maps/> [Accessed 20 May 2015].

Graaf, van der, D., 2015. *Conversation on PVNB Uden*. [conversation] (Personal communication, 30 June 2015).

Hafez, A.A.A, Montesions-Miracle, D. and Sudria-Andreu, A., 2012. Autonomous photovoltaic lighting system. *Journal of Electrical Engineering*, 12(3), pp.147-154.

Hoekstra, A., 2010. *Energieke wegen, Innovatie Informatie Inspiratie*. Sine loco: Rijkswaterstaat.

Holland Solar, 2005. *Transitiepad zonnestroom. De roadmap van Holland Solar*. Utrecht: Holland Solar.

Honsberg, C. and Bowden, S., 2015. *PVEducation*. [online] Available at: <http://pveducation.org/> [Accessed 12 July 2015].

IEA, 2008. *Worldwide Trends in Energy Use and Efficiency*. [online] Available at: <http://www.iea.org/publications/freepublications/publication/Indicators_2008.pdf> [Accessed 10 February 2015].

IEA, 2012. *Electricity information 2012*. [online] Available at: <http://www.iea.org/media/training/presentations/statisticsmarch/electricityinformation.pdf> [Accessed 12 April 2015].

IEA, 2014a. *Key World Energy Statistics 2014*. [online] Available at: <http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf> [Accessed 21 July 2015].

IEA, 2014b. *Technology Roadmap – Solar photovoltaic energy*. Paris: IEA.

IEA, 2015. *World Energy Outlook Special Report on Energy and Climate Change*. [online] Available at: <http://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf> [Accessed 21 July 2015].

Jakubiec, J.A. and Reinhart, C.F., 2012. Towards validated urban photovoltaic potential and solar radiation maps based on lidar measurements, GIS data, and hourly daysim simulations. *Proceedings of SimBuild*, 2012, pp.101-103.

Jochems, P.M., 2013. *The potential of PV panels near road infrastructure in the Netherlands*. Master thesis. Eindhoven University of Technology.

Jong, de, M., 2015. *Solar Highways Benchmark Study – An overview and evaluation of existing photovoltaic noise barriers*. Eindhoven: SEAC.

Jonker, R., 2015. *Conversation on possibilities of PV in the context of Rijkswaterstaat*. [conversation] (Personal communication, 12 June 2015).

Movares, 2014. *Advies Vervangingsbehoefte Geluidbeperkende Constructies*. Amsterdam: Movares.

National Renewable Energy Laboratory, 2015. *Efficiency chart*. [online] Available at: <http://www.nrel.gov/ncpv/images/efficiency_chart.jpg> [Accessed 9 August 2015].

Photovoltaic-software, 2014. *How to calculate the annual solar energy output of a photovoltaic system*. [online] Available at: <http://photovoltaic-software.com/PV-solar-energy-calculation.php> [Accessed 25 March 2015].

Plastow, J., 2011. *kWh vs. kWp: Why STC Efficiency Doesn't Add Up*. [online] Available at: <http://www.interpv.net/market/market_view.asp?idx=715&part_code=04> [Accessed 16 April 2015].

Pool, R., 2015. *Conversation on PVNB Groningen*. [conversation] (Personal communication, 26 June 2015).

PVdatabase, 2015a. *PV Noise Barrier A27*. [online] Available at: <http://www.pvdatabase.org/projects_view_details.php?ID=74> [Accessed 7 June 2015].

PVdatabase, 2015b. *PV noise barrier A9*. [online] Available at: <http://www.pvdatabase.org/projects_view_details.php?ID=390> [Accessed 5 June 2015].

PVGIS, 2015a. *Performance of Grid-connected PV*. [online] Ispra: European Commission, Joint Research Centre, Institute for Energy and Transport. Available at: <http://re.jrc.ec.europa.eu/pvgis/apps4/PVcalchelp_en.html> [Accessed 14 July 2015].

PVGIS, 2015b. *Photovoltaic Geographical Information System (PVGIS)*. [online] Ispra: European Commission, Joint Research Centre, Institute for Energy and Transport. Available at: <http://re.jrc.ec.europa.eu/pvgis/> [Accessed 25 March 2015].

PVGIS, 2015c. *PV potential estimation utility*. [online] Ispra: European Commission, Joint Research Centre, Institute for Energy and Transport. Available at: <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php> [Accessed 25 March 2015].

Riedstra, D., 2005. *Windturbines op veilige afstand?*. [online] Bilthoven: RIVM. Available at: <https://rivm.openrepository.com/rivm/bitstream/10029/15776/3/riedstra.pdf> [Accessed 10 February 2015].

Rijkswaterstaat, 2006. *Modulaire Geluidsschermen Handleiding configuratie en implementatie*. Delft: Rijkswaterstaat.

Rijkswaterstaat, 2012. *Rijkswaterstaat toonaangevend opdrachtgever*. [online] Available at: <http://www.rijkswaterstaat.nl/images/Rijkswaterstaat%20toonaangevend%20opdrachtgever_tcm174-244717.pdf> [Accessed 10 February 2015].

Rijkswaterstaat, 2013a. *Minder verlichting op de snelwegen*. [online] Available at: <http://www.rijkswaterstaat.nl/actueel/nieuws_en_persberichten/2013/juni2013/minder_verlichting_op_de_snelwegen_vanaf_3_juni.aspx> [Accessed 11 February 2015].

Rijkswaterstaat, 2013b. *Nieuwe verdienmodellen, nieuwe kansen*. [online] Available at: <http://www.rijkswaterstaat.nl/zakelijk/innovatie/actueel/nieuwsflits_maart_2013/nieuwe_verdienmodellen_nieuwe_kansen.aspx> [Accessed 21 February 2015].

Rijkswaterstaat, 2013c. *Gebruikersinformatie WEGGEG v2.0*. [online] Available at: <http://www.rijkswaterstaat.nl/apps/geoservices/geodata/dmc/weggeg/productinfo/beschrijvende_documentatie/Gebruikersinformatie_WEGGEG_v2.0.pdf> [Accessed 20 May 2015].

Rijkswaterstaat, 2015a. *Goed op weg om Energieakkoord-doelstellingen openbare verlichting te halen*. [online] Available at: <http://www.rwsleefomgeving.nl/onderwerpen/ovl/energieakkoord/stand-2014/> [Accessed 12 July 2015].

Rijkswaterstaat, 2015b. *Online geografische gegevens Rijkswaterstaat*. [online] Available at: <http://www.rijkswaterstaat.nl/zakelijk/databestanden/online_geografische_gegevens_rijkswaterstaat/> [Accessed 20 May 2015].

Rijkswaterstaat, 2015c. *Verkeerslawaai*. [online] Available at: <http://corporate.intranet.rws.nl/Kennis_en_Expertise/Kennisvelden/Leefomgeving/Geluid/Verkeerslawaai/> [Accessed 10 August 2015].

Rijkswaterstaat, 2015d. *staatseigendommen*. [online] Available at: <http://www.rijkswaterstaat.nl/apps/geoservices/geodata/dmc/staatseigendommen/> [Accessed 12 May 2015].

Rijkswaterstaat, 2015e. *A7/N7: aanpak zuidelijke ringweg Groningen | Rijkswaterstaat*. [online] Available at: <http://www.rijkswaterstaat.nl/wegen/projectenoverzicht/a7-n7-aanpak-zuidelijke-ringweg-groningen/index.aspx> [Accessed 20 August 2015].

ROADLED, 2014. *Onze producten – ROADLED®*. [online] Available at: <http://roadled.eu/onze-producten/> [Accessed 25 March 2015].

Roberts, J.C., 1987. *Solar-powered illuminated reflector*. US4668120 A.

Schwartz, A., 2008. Oregon Launching First Solar Highway in the US, *Clean Technica*. [online] Available at: <http://cleantechnica.com/2008/08/13/oregon-launching-first-solar-highway-in-the-us/> [Accessed 26 June 2015].

SMA, 2010. *Performance ratio – Quality factor for the PV plant*. [online] Available at: <http://files.sma.de/dl/7680/Perfratio-UEN100810.pdf> [Accessed 12 July 2015].

Smartstud, 2015. *Smartstud® LED road marker*. [online] Available at: <http://www.3iinnovation.com/smartstud-5/> [Accessed 11 August 2015].

Snow, M. and Prasad, D.K., 2000. Power Without Noise - opportunities for integrating photovoltaic noise barriers under Australian Conditions. *38th Australia New Zealand Solar Energy Society Conference*.

Solar Highways, 2015. *Solar Highways*. [online] Available at: <http://solarhighways.eu/> [Accessed 10 August 2015].

Solar Roadways, 2015. *Solar Roadways – Introduction*. [online] Available at: <http://www.solarroadways.com/intro.shtml> [Accessed 11 August 2015].

SolaRoad, 2015. *Unieke innovatie – SolaRoad*. [online] Available at: <http://www.solaroad.nl/> [Accessed 11 August 2015].

Stichting Monitor Zonnestroom, 2013. *Uitgebreide inventarisatie zon PV producten toont grid parity*. [online] Available at: <http://www.zonnestroomnl.nl/nieuws/uitgebreide-inventarisatie-zon-pv-producten-toont-grid-parity/> [Accessed 15 April 2015].

Stichting Monitor Zonnestroom, 2014. *Inventarisatie PV markt Nederland – Status april 2014*. [online] Available at: <http://www.zonnestroomnl.nl/wp-content/uploads/2014/08/markt-apr2014def.pdf> [Accessed 17 April 2015]

Stoeten, B., 2015. *Conversation on PVNB Tiel*. [conversation] (Personal communication, 30 June 2015).

Suri, M., Huld, T., Dunlop, E., Albuisson, M., and Wald, L., 2006. Online data and tools for estimation of solar electricity in Africa: the PVGIS approach. *21st European photovoltaic solar energy conference and exhibition*.

U.S. DOT, 2012. *Alternative Uses of Highway Right-of-Way*. [online] Available at: <http://www.fhwa.dot.gov/real_estate/publications/alternative_uses_of_highway_right-of-way/altusesreport.pdf> [Accessed 11 August 2015].

TenneT, 2014. *Electricity production in the Netherlands continues to grow*. [online] Available at: <http://www.tennet.eu/nl/?id=327> [Accessed 22 February 2015].

Trimble Navigation Limited, 2015. *3D for Everyone | SketchUp*. [online] Available at: <http://www.sketchup.com/> [Accessed 20 July 2015].

Tsao. J, Lewis, N. and Crabtree, G., 2006. *Solar FAQs*. [online] Available at: <http://www.sandia.gov/~jytsao/Solar%20FAQs.pdf> [Accessed 16 June 2015].

TSNed, 2015. *Mobiele Rijkstrook Signalering (MRS)*. [online] Available at: <http://www.tsned.nl/producten/mrs> [Accessed 11 August 2015].

U.S. DOE, 2012. *SunShot Vision Study*. [online] Available at: <http://energy.gov/sites/prod/files/2014/01/f7/47927.pdf> [Accessed 18 February 2015].

W4info, 2015. *Van A4 naar W4*. [online] Available at: <http://www.w4info.nl/> [Accessed 15 August 2015].

Wallace, J.W. and Hobbs, P.V., 1977. *Atmospheric Science: An Introductory Survey*. San Diego: Academic Press.

Watson, A.M. and Watson, D.E., 2011. *Direct Radiation, Diffuse Radiation and Reflected Radiation*. [online] FT Exploring. Available at: <http://www.ftexploring.com/solar-energy/direct-and-diffuse-radiation.htm> [Accessed 20 May 2015].

Wee, van, B. and Dijst, M., 2002. *Verkeer en vervoer in hoofdlijnen*. Bussum: Coutinho.

Weijers, E.P. and Groot, de, G.J., 2007. *Energiewinning uit weginfrastructuur*. Sine loco: ECN.

Willis, D.P., 2015. *Solar farm built in Howell*. [online] App.com. Available at: <http://www.app.com/story/money/business/2015/01/30/solar-howell/22609169/> [Accessed 11 August 2015].

Yang, C., Pan, J. and Cheng, L., 2013. A mechanism study of sound wave-trapping barriers. *Journal of the Acoustical Society of America*, 134(3), pp.1960-1969.

Yntema, F., 2012. Weg aan het werk. *NWT Magazine*, juli/augustus 2012, pp.54-59.

Zon, van der, N., 2013. *Kwaliteitsdocument AHN2*. [online] Amersfoort: AHN. Available at: <http://www.ahn.nl/binaries/content/assets/hwh---ahn/common/wat+is+het+ahn/kwaliteitsdocument_ahn_versie_1_3.pdf> [Accessed 20 May 2015].

Zonnewal-Oostwold, 2015. *Zonnewal-Oostwold.com*. [online] Available at: <http://zonnewal-oostwold.com/> [Accessed 30 August 2015].

Zweers, E., 2014. *Aanvraag Wbr beschikking – PVNB Tiel*. Rijkswaterstaat: 33726930.

Appendix I

The following gives a more detailed overview of the steps taken in Esri ArcGIS for calculation of the solar irradiation. The process is illustrated by screenshots of the process. Please note that the process includes the steps taken for the enhanced methodology described in chapter 3.5.

The methodology described in chapter 3.3 uses the irradiation in the horizontal plane (GHI) and then adjusts for the angle and orientation with the irradiation yield factor. However, with the methodology specified for chapter 3.5, it was possible to calculate directly the irradiation in the plane (under angle and orientation) without the irradiation yield factor. This way the irradiation in the plane reflects the actual irradiation more accurately, because the irradiation yield factors are averages for the whole country. The way this is done, is by using 3D models of the envisioned PVNB.

The first part for this is to actually model the noise barrier. This is done by the computer program SketchUp. In SketchUp, the location for the noise barrier is looked up and the 3D model drawn as can be seen in **Figure 21**. When ready, the 3D model is imported into ArcGIS through the program ArcScene. This is necessary to give the 3D model the right coordinates, when it is later imported into the main program ArcMap as seen in **Figure 22**. Using the tools Multipatch to Raster and Mosaic to Raster, the 3D model is merged with the existing DEM data. This DEM data is the main input for the solar analyst calculations.

Figure 22: 3D model imported into ArcGIS (at the south edge of the road)

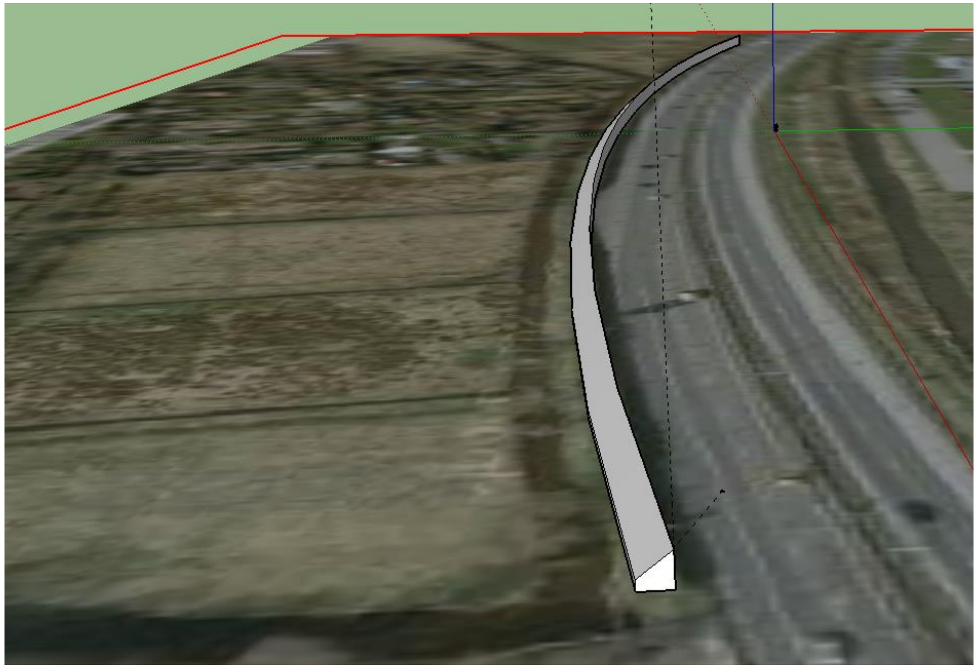


Figure 21: 3D model creation in SketchUp

The enhanced part of the methodology is comprised of creating an updated DEM file. Now this is complete, the methodology for both the cases and the broader analysis is the same. This part of the methodology is described below.

First the Area Solar Radiation tool is used to create a solar irradiation map of the relevant area and its direct surroundings. The parameters allow to specify the time period over which is measured. An example of this can be seen in both **Figure 15** and **Figure 23**. This is followed by drawing a polygon with the Draw tool at the location of the envisioned PVNB, according to chapter 3.3 and 3.5. This polygon is then used as the output extent to clip the solar irradiation raster with the Clip (Raster Processing) tool. The result can be seen in **Figure 24**. To calculate the average irradiation in the clipped area, a tool called Raster to Point is used. This tool converts the raster information to points and with the statistics option, the average value of all points can be obtained. This is what is used for the annual insolation for all PVNB locations.

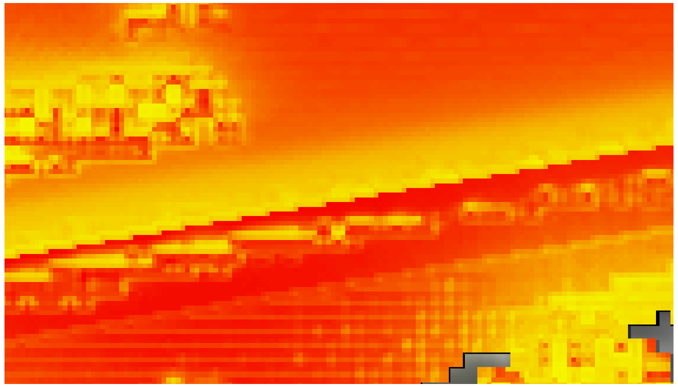


Figure 23: Solar irradiation map of PVNB and surroundings (note the yellow shadowing at the north of the PVNB)

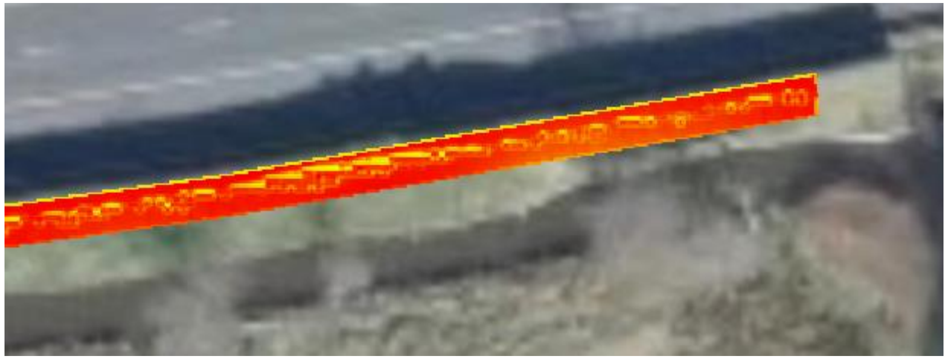


Figure 24: A clipped area of the solar irradiation map to calculate the irradiation in the plane of the PVNB

Appendix II

All results are presented below. Included are all researched potential PVNB locations and their respective data.

Explanation of data

Segment: For this thesis appointed ID value, where the first part before the underscore identifies the Rijksweg and the second part the unique ID.
Length (m): The length of the segment in meters.
Maintenance priority: The priority of maintenance and/or replacement of the segment.
Orientation: The orientation or azimuth expressed in cardinal directions, based on the orientation of the segment to the adjacent road.
Optimum irradiation yield factor: The used yield factor of the segment according to the orientation.
Annual insolation (Wh/m^2): The measured annual insolation of the segment expressed in Wh/m^2.
Adjusted annual insolation (Wh/m^2): The adjusted annual insolation of the segment, calculated by multiplying the yield factor with the insolation.
Insolation score (1-5 scale): A 1-5 scale score of the adjusted annual insolation.
Annual electricity production 2015 (kWh): The annual electricity production with 2015 best-available market technology.
Annual electricity production 2030 (kWh): The annual electricity production with 2030 best-available market technology.
BEGINKM: Meant for identifying the exact position of the segment. States the so-called hectometre marker at the start of the segment.
EINDKM: Meant for identifying the exact position of the segment. States the so-called hectometre marker at the end of the segment.
WVK_ID: Identifies a unique 'wegvak' or road section.
SCH_ID: Identifies a unique 'scherm' or noise barrier.
HGTE_GLG: Defines the height of the segment in meters. The first number defines the height at the start and the last number the height at the end.
IZI_SIDE: Defines the side of the road where the segment is located.

Results

Segment	Length (m)	Maintenance priority	Orientation	Optimum irradiation yield factor	Annual insolation (Wh/m^2)	Adjusted annual insolation (Wh/m^2)	Insolation score (1-5 scale)	Annual electricity production 2015 (kWh)	Annual electricity production 2030 (kWh)	BEGINKM	EINDKM	WVK_ID	SCH_ID	HGTE_GLG	IZI_SIDE
RW1_11	528	medium	SW	1,118	936434,2	1046933	4	174126	207292,8	4,475	5,028	252370012	806	6 -> 6	L
RW1_118	978	no data	NNE	1,164	979479,5	1140114	5	351235	418136,9	39,511	40,49	307337008	620	6 -> 6	R
RW1_123	625	medium	S	1,182	865349,8	1022843	3	201372,3	239728,9	50,794	51,42	322328019	406	3 -> 3	L
RW1_135	529	high	SSW	1,164	948305	1103827	4	183936,2	218971,7	79,64	80,17	382332022	469	5 -> 5	L
RW1_137	520	high	SSW	1,164	927855,4	1080024	4	176907,9	210604,6	80,253	80,774	382332022	469	5 -> 5	L
RW1_140	645	medium	SSE	1,164	955103,2	1111740	4	225877,8	268902,1	85,498	86,139	391330016	499	3 -> 3	L
RW1_148	526	medium	NNW	1,164	922725,2	1074052	4	177959,7	211856,8	94,151	94,682	407338009	2087	3 -> 3	R
RW1_26	795	high	NE	1,118	965171,4	1079062	4	270224	321695,3	5,66	6,46	254368035	730	5 -> 5	R
RW1_39	505	high	SSW	1,164	946908,2	1102201	4	175332,7	208729,3	11,502	11,973	264365030	827	5 -> 5	L
RW1_66	677	medium	SW	1,118	931161,7	1041039	3	222006,7	264293,7	23,48	24,16	282353043	842	3 -> 3	L
RW1_69	796	high	NE	1,118	911505	1019063	3	255519,7	304190,2	23,692	24,491	282353042	732	3 -> 3	R
RW1_93	707	medium	W	1	932002,2	932002,2	2	207561,5	247097,1	25,651	26,36	285350014	839	3 -> 3	L
RW1_97	651	medium	ENE	1,045	913921,7	955048,2	2	195847	233151,1	26	26,65	285350015	745	3 -> 3	R
RW10_1	895	medium	WNW	1,045	889208,3	929222,7	2	261971,1	311870,4	10,074	10,971	252370009	831	3 -> 3	L
RW10_2	733	no data	WNW	1,045	980724,2	1024857	3	236634,3	281707,5	27,487	28,252	236379061	n/a	6 -> 6	R
RW10_3	654	high	W	1	962005,8	962005,8	3	198182,8	235931,9	23,774	24,435	235373051	786	5 -> 5	R
RW10_4	597	medium	W	1	948786,4	948786,4	2	178424	212409,6	22,363	22,956	235369066	741	5 -> 5	R
RW10_5	579	medium	NE	1,118	956503,9	1069371	4	195037,3	232187,2	1	1,581	243385089	776	5 -> 5	R
RW10_6	504	high	NE	1,118	929830,6	1039551	3	165039	196475,1	4,963	5,468	249381052	757	3 -> 3	R
RW11_1	956	no data	SW	1,118	932099,6	1042087	3	313814,2	373588,3	14,999	15,964	213316018	1727	3 -> 3	L

RW11_2	871	no data	W	1	939026,2	939026,2	2	257635,9	306709,4	13,738	19,601	220310002	1442	3 -> 3	L
RW11_3	571	no data	SSE	1,164	974275,1	1134056	5	203977	242829,8	6,331	6,901	200319029	1431	3 -> 3	L
RW12_1	1542	medium	NNE	1,164	990041,3	1152408	5	559759,1	666379,9	51,99	54,13	257308004	393	3 -> 3	R
RW12_10	646	medium	NW	1,118	976734,5	1091989	4	222208,9	264534,4	31,215	31,861	216301006	1927	5 -> 5	R
RW12_11	625	medium	NNE	1,164	950372,4	1106233	4	217789,7	259273,5	51,99	54,13	255309025	393	3 -> 3	R
RW12_12	623	medium	SSW	1,164	904310,3	1052617	4	206570,9	245917,7	79,486	80,11	305306065	2069	3 -> 3	L
RW12_13	621	medium	NNE	1,164	934837,6	1088151	4	212858,6	253403,2	55,5	56,122	262307011	607	3 -> 1	R
RW12_14	604	medium	N	1,182	936766,4	1107258	4	210666,9	250793,9	110,588	111,188	346294027	1916	5 -> 5	R
RW12_15	592	medium	NE	1,118	987637	1104178	4	205907,1	245127,5	133,563	134,154	390288038	626	5 -> 5	R
RW12_16	585	no data	SW	1,118	962869,4	1076488	4	198369,8	236154,5	7,282	7,87	172305009	1535	5 -> 5	L
RW12_17	560	low	S	1,182	871969,5	1030668	3	181809,8	216440,3	11,946	12,51	180303005	1907	3 -> 5	L
RW12_18	545	medium	SSW	1,164	795707,2	926203,2	2	159005,9	189292,8	78,166	78,708	305306065	2069	5 -> 5	L
RW12_19	545	medium	SW	1,118	979361,4	1094926	4	187971,4	223775,5	133,606	134,151	390288040	500	5 -> 5	L
RW12_2	1400	medium	SW	1,118	961669,6	1075147	4	474139,7	564452	131,95	133,35	385294002	2019	6 -> 6	L
RW12_20	536	medium	SW	1,118	916129,9	1024233	3	172931,5	205870,9	104,388	104,922	337299005	413	1 -> 1	L
RW12_21	523	low	S	1,182	946056,1	1118238	4	184224,2	219314,5	13,707	14,227	184303067	1904	3 -> 3	L
RW12_22	511	no data	NE	1,118	957617,4	1070616	4	172331,7	205156,8	3,753	4,266	166309055	1440	3 -> 1	R
RW12_23	502	medium	S	1,182	919044	1086310	4	171778,2	204497,9	109,421	109,921	346294028	528	5 -> 5	L
RW12_3	1379	medium	NE	1,118	923758,3	1032762	3	448616,2	534067	131,867	133,238	384294003	641	6 -> 6	R
RW12_4	933	medium	SSW	1,164	916155,2	1066405	4	313411	373108,3	54,717	55,648	261307025	416	5 -> 5	L
RW12_5	916	medium	S	1,182	971143,3	1147891	5	331212,6	394300,7	65,995	66,91	278304017	535	1 -> 1	L
RW12_6	898	medium	SSW	1,164	938484,4	1092396	4	309006	367864,3	3,525	4,426	166309054	2004	5 -> 5	L
RW12_7	804	no data	NW	1,118	936316,9	1046802	4	265113,1	315610,9	28,578	29,37	213298035	1445	5 -> 5	R
RW12_8	692	medium	NNE	1,164	817842,4	951968,6	2	207510,1	247035,8	77,995	78,688	305306059	2067	6 -> 6	R
RW12_9	670	medium	ENE	1,045	869459,4	908585,1	2	191756,9	228282	131,048	131,72	384294003	641	6 -> 6	R
RW13_1	787	medium	SSW	1,164	713252,9	830226,4	1	205817,3	245020,6	18,837	19,686	178277086	2000	1 -> 1	R
RW13_2	778	no data	NNE	1,164	724076,5	842825	1	206551,1	245894,2	18,837	19,618	178277086	1462	1 -> 1	R
RW13_3	563	no data	SW	1,118	857864,7	959092,8	3	170090,3	202488,5	17,43	17,992	177280040	1457	5 -> 5	L
RW13_4	537	no data	WSW	1,045	935101	977180,5	3	165295	196779,7	9,846	10,369	171294075	1453	6 -> 6	L

RW14_1	852	no data	NE	1,118	812296	908146,9	2	243728,5	290152,9	11,381	12,234	170313006	1732	3 -> 3	R
RW14_2	568	no data	NE	1,118	906257,3	1013196	3	181281	215810,7	10,193	11,25	169315094	1415	3 -> 3	R
RW15_1	1430	medium	N	1,182	1000988	1183168	5	532957,9	634473,7	128,982	130,411	309267067	656	6 -> 6	R
RW15_2	1011	no data	SSE	1,164	921243,5	1072327	4	341498,8	406546,2	56,813	58,516	185261044	n/a	5 -> 5	L
RW15_3	950	no data	SW	1,118	953804,6	1066354	4	319106,3	379888,5	65,387	66,508	198263018	1486	6 -> 6	L
RW15_4	824	no data	S	1,182	948429,3	1121043	4	290978	346402,4	85,811	86,637	230252029	1526	6 -> 6	L
RW15_5	683	no data	SE	1,118	985862,9	1102195	4	237131,7	282299,6	202,018	202,706	436280049	1172	3 -> 3	L
RW15_6	676	no data	NNE	1,164	992057,9	1154755	5	245893,6	292730,5	80,966	81,64	222254032	1517	5 -> 5	R
RW15_7	647	no data	SSE	1,164	951561,5	1107618	4	225738	268735,7	86,7	87,348	230252029	1526	6 -> 6	L
RW15_8	610	no data	W	1	915548,3	915548,3	2	175922,6	209431,7	232,156	232,779	479300042	1031	3 -> 3	M
RW15_9	562	no data	SSW	1,164	962045,2	1119821	4	198241,9	236002,2	82,566	83,127	222254033	1519	6 -> 6	L
RW16_1	1574	medium	SW	1,118	958405,7	1071498	4	531259,2	632451,4	49,527	51,104	209221027	29	5 -> 3	L
RW16_10	671	no data	ESE	1,045	982126,2	1026322	3	216928,5	258248,3	60,6	61,402	217199007	11	3 -> 3	R
RW16_11	584	no data	W	1	989920,4	989920,4	3	182105,8	216792,6	37,148	37,73	208241007	1498	3 -> 3	L
RW16_12	559	no data	SW	1,118	957669,8	1070675	4	188529,8	224440,2	27,932	28,649	201259030	1489	5 -> 5	L
RW16_13	533	high	E	1	1003089	1003089	3	168413,6	200492,4	63,955	64,488	219193012	47	5 -> 5	R
RW16_14	514	medium	WSW	1,045	946063,6	988636,4	3	160070,1	190559,7	48,916	49,527	209221048	29	5 -> 5	L
RW16_2	1550	medium	ENE	1,045	994965,6	1039739	3	507652,6	604348,3	55,946	57,502	214211010	4	5 -> 6	R
RW16_3	1035	medium	W	1	937305	937305	2	305584,9	363791,5	68,57	69,598	220181004	281	1 -> 1	L
RW16_4	1001	medium	ENE	1,045	971580,9	1015302	3	320140	381119	57,502	58,515	214211010	4	6 -> 6	R
RW16_5	884	no data	ENE	1,045	956730,2	999783	3	278399,6	331428,1	16,065	16,958	192279040	1470	1 -> 1	R
RW16_6	881	no data	W	1	743810,7	743810,7	1	206418,6	245736,5	36	36,882	208241007	1705	6 -> 5	L
RW16_7	790	no data	E	1	950620,9	950620,9	2	236562	281621,5	59,81	60,6	217202086	11	5 -> 5	R
RW16_8	789	high	ENE	1,045	947758,2	990407,4	3	246150,9	293036,8	47,6	48,4	208224045	1987	5 -> 5	R
RW16_9	735	high	ENE	1,045	985816	1030178	3	238511,9	283942,7	62,21	62,94	218197017	47	1 -> 1	R
RW2_10	967	medium	ENE	1,045	986324,1	1030709	3	313959	373760,7	42,032	42,999	252349007	2072	5 -> 5	R
RW2_111	524	medium	NE	1,118	950254,6	1062385	4	175357,2	208758,6	73,074	73,601	268288033	345	5 -> 5	R
RW2_120	745	medium	SW	1,118	964808,8	1078656	4	253133,7	301349,6	73,05	73,791	268288032	481	5 -> 3	L
RW2_124	671	medium	NE	1,118	984590,2	1100772	4	232664,6	276981,7	78,614	79,283	271285012	1858	5 -> 5	R

RW2_141	729	medium	ENE	1,045	969365,5	1012987	3	232617,2	276925,3	85,708	86,441	283268005	1851	5 -> 5	R
RW2_144	682	medium	WSW	1,045	970020,4	1013671	3	217767	259246,4	85,761	86,442	283268004	1848	3 -> 3	L
RW2_147	651	medium	WSW	1,045	980719,1	1024851	3	210161,2	250191,9	87	87,655	283268004	1848	5 -> 5	L
RW2_150	504	medium	ENE	1,045	964358,2	1007754	3	159991,1	190465,6	92,55	93,053	289257007	260	5 -> 5	R
RW2_171	513	medium	E	1	966047	966047	3	156108,4	185843,3	101,15	101,665	292246012	78	5 -> 5	R
RW2_180	744	no data	SW	1,118	923907,1	1032928	3	242077	288186,9	107,917	108,66	295237070	1840	3 -> 3	L
RW2_185	799	no data	NE	1,118	983503,4	1099557	4	276741,9	329454,7	110,299	111,097	298233007	1842	6 -> 6	R
RW2_196	522	no data	SW	1,118	955477	1068223	4	175648	209104,7	110,414	110,936	298233005	1841	5 -> 5	L
RW2_2	1205	medium	WSW	1,045	975013,9	1018890	3	386745	460410,7	37,627	38,825	250353005	1847	6 -> 6	L
RW2_203	505	no data	E	1	984930,4	984930,4	3	156677,8	186521,2	111,662	112,313	300230049	1842	3 -> 3	R
RW2_206	808	no data	NE	1,118	961733,7	1075218	4	273664,5	325791,1	112,486	113,299	301229013	1838	6 -> 6	R
RW2_23	1884	medium	WSW	1,045	958081	1001195	3	594169	707344	52,965	55,059	257323026	1870	6 -> 6	L
RW2_247	638	no data	E	1	958100,8	958100,8	2	192549,5	229225,6	121,732	122,366	298215027	2133	5 -> 5	R
RW2_256	557	no data	ENE	1,045	979376,7	1023449	3	179569,2	213772,8	123,259	123,815	298212008	2031	3 -> 3	R
RW2_26	612	medium	SW	1,118	937887,4	1048558	4	202141	240644,1	55,059	55,977	259319007	1870	6 -> 6	L
RW2_263	1984	no data	NE	1,118	987503,7	1104029	4	689974,1	821397,7	129,518	131,5	300205044	121	5 -> 5	R
RW2_282	511	medium	W	1	985394,8	985394,8	3	158614,1	188826,3	132,372	132,878	305196012	247	3 -> 3	L
RW2_293	1722	medium	NE	1,118	989184,2	1105908	4	599877,6	714140	138,785	140,516	310185025	216	3 -> 3	R
RW2_33	680	medium	NE	1,118	938636,5	1049396	4	224780,5	267595,9	57,204	57,894	262317050	1949	6 -> 6	R
RW2_334	545	no data	E	1	973005,4	973005,4	3	167040,7	198858	160,453	161,008	314169014	1797	1 -> 1	R
RW2_362	1377	no data	E	1	975000,7	975000,7	3	422911,4	503466	161,88	163,258	312174019	1811	5 -> 5	R
RW2_379	717	no data	W	1	969196,6	969196,6	3	218897,9	260592,7	162,802	163,52	312173009	1814	3 -> 5	L
RW2_400	1056	no data	W	1	983767,4	983767,4	3	327240,4	389571,9	163,52	164,575	312173009	1814	5 -> 5	L
RW2_417	507	no data	N	1,182	1005440	1188430	5	189798,2	225950,2	167,419	167,93	320159021	1827	5 -> 5	R
RW2_42	593	medium	E	1	914637,8	914637,8	2	170849,8	203392,6	61,498	62,1	261317053	1855	5 -> 5	R
RW2_442	602	no data	S	1,182	970562,2	1147205	5	217544,4	258981,4	168,515	169,117	318159046	1823	3 -> 3	L
RW2_45	1215	medium	W	1	927261,3	927261,3	2	354886,1	422483,4	61,545	62,77	261317061	1853	3 -> 3	L
RW2_46	560	medium	W	1	980002,2	980002,2	3	172872,4	205800,5	62,1	62,668	261317053	1855	5 -> 5	R
RW2_49	909	no data	W	1	975513,5	975513,5	3	279323,6	332528,2	65,068	65,967	265300013	555	6 -> 6	L

RW2_498	589	no data	WSW	1,045	969064,2	1012672	3	187886,1	223674	183,314	183,906	340138031	288	5 -> 5	L
RW2_60	943	no data	W	1	924612,5	924612,5	2	274651,5	326966,1	66,777	67,738	265297035	555	6 -> 6	L
RW2_8	1647	medium	ENE	1,045	989331,8	1033852	3	536367,4	638532,7	40,343	41,984	252349007	2072	5 -> 5	R
RW20_1	811	no data	SSE	1,164	898663,3	1046044	4	267227,6	318128,1	32,347	33,155	185279085	1467	5 -> 5	L
RW20_2	762	no data	SSE	1,164	894029,5	1040650	3	249787,3	297365,8	31,319	32,08	183278101	1466	5 -> 5	L
RW20_3	738	no data	SSE	1,164	953525,6	1109904	4	258019,3	307165,9	35,255	36,018	191280035	1755	1 -> 1	L
RW20_4	636	no data	SSE	1,164	943847,9	1098639	4	220101,3	262025,4	36,48	37,119	193281039	1755	3 -> 3	L
RW20_5	540	low	NNE	1,164	964195,7	1122324	4	190907,3	227270,6	20,13	20,671	161274014	1915	3 -> 3	R
RW200_1	792	medium	N	1,182	994949,4	1176030	5	293396	349281	3,094	3,888	224377040	861	3 -> 3	L
RW27_1	1142	medium	E	1	978142,3	978142,3	3	351867,1	418889,4	2,648	3,805	231192009	3001	6 -> 6	L
RW27_2	1010	medium	SE	1,118	976888,9	1092162	4	347471,3	413656,3	103,848	104,896	294354028	453	6 -> 1	L
RW27_3	933	medium	E	1	973791,5	973791,5	3	286192,5	340705,3	14,444	15,378	239218015	287	5 -> 5	L
RW27_4	888	high	WNW	1,045	952438,5	995298,2	3	278404,8	331434,3	89,497	90,384	279324006	390	5 -> 3	R
RW27_5	641	high	NW	1,118	950338	1062478	4	214530,2	255393,1	77,518	78,154	277306024	651	5 -> 1	R
RW27_6	559	medium	ESE	1,045	959146,4	1002308	3	176491,4	210108,8	94,876	95,439	284337015	418	3 -> 3	L
RW27_7	552	no data	NW	1,118	990244,5	1107093	4	192501,4	229168,3	36,515	37,1	249256059	1522	5 -> 5	R
RW27_8	526	medium	SE	1,118	956935,9	1069854	4	177264,2	211028,8	96,494	97,18	287341009	2080	3 -> 3	L
RW27_9	501	no data	WNW	1,045	965538,9	1008988	3	159233,5	189563,7	45,42	45,922	254272008	1524	5 -> 5	R
RW28_1	1549	high	N	1,182	809847,6	957239,9	2	467070,8	556036,7	5,164	6,715	285313018	634	6 -> 6	R
RW28_10	660	low	NW	1,118	983806,3	1099895	4	228668,3	272224,1	82,41	83,075	392396018	335	5 -> 5	R
RW28_11	645	no data	NW	1,118	923632,1	1032621	3	209802,7	249765,1	3,75	4,408	284312010	n/a	3 -> 5	R
RW28_12	628	medium	ESE	1,045	847854,7	886008,2	2	175270,1	208654,9	20,251	20,88	313324023	454	6 -> 6	L
RW28_13	616	no data	SE	1,118	953296	1065785	4	206804,9	246196,3	94,179	94,8	405407050	1181	5 -> 5	L
RW28_14	610	no data	SSE	1,164	933879,5	1087036	4	208873,9	248659,4	97,217	97,83	409409016	1166	3 -> 3	L
RW28_15	597	no data	NNW	1,164	929444,1	1081873	4	203451,6	242204,3	96,597	97,185	409409017	1055	3 -> 5	R
RW28_16	588	high	NW	1,118	942427,4	1053634	4	195154,1	232326,3	94,2	94,8	405407051	934	5 -> 5	R
RW28_17	525	high	W	1	969372,9	969372,9	3	160310	190845,3	112	112,523	420436038	932	3 -> 3	R
RW28_18	512	medium	ESE	1,045	947949,9	990607,7	3	159765,2	190196,7	21,711	22,225	314326012	414	5 -> 5	L
RW28_2	1526	high	N	1,182	976989,3	1154801	5	555101,5	660835,1	6,828	8,354	285313018	369	6 -> 6	R

RW28_3	1315	high	SSE	1,164	920790,9	1071801	4	443966,6	528531,6	9,178	10,491	293315007	532	6 -> 6	L
RW28_4	977	medium	S	1,182	976138,2	1153795	5	355086,3	422721,8	49,502	50,477	338365031	496	3 -> 3	L
RW28_5	872	high	WNW	1,045	975914,1	1019830	3	280127	333484,5	32,145	33,011	317338031	647	5 -> 5	R
RW28_6	815	high	SSE	1,164	902083,9	1050026	4	269567,8	320914,1	10,605	11,483	297316011	532	6 -> 6	L
RW28_7	734	medium	NNW	1,164	991355,5	1153938	5	266802	317621,4	48,756	49,504	335363009	642	3 -> 3	R
RW28_8	710	medium	N	1,182	979999,9	1158360	5	259067,2	308413,3	49,504	50,215	335363009	642	3 -> 3	R
RW28_9	669	no data	NNW	1,164	825809,8	961242,6	3	202567,5	241151,7	97,185	97,86	409409017	1055	5 -> 3	R
RW30_1	859	high	WSW	1,045	970931,4	1014623	3	274541,8	326835,5	10,553	11,411	340305014	645	3 -> 3	R
RW30_2	692	medium	WSW	1,045	990025,5	1034577	3	225517	268472,6	19,818	20,514	334323024	1936	3 -> 1	R
RW30_3	638	medium	W	1	963325	963325	3	193599,4	230475,5	9,349	9,981	341301016	559	3 -> 3	R
RW30_4	594	medium	NE	1,118	992301	1109393	4	207578,4	247117,2	12,622	13,216	338309002	539	3 -> 3	L
RW30_5	501	medium	WSW	1,045	983980,3	1028259	3	162274,8	193184,2	12,65	13,151	338310013	401	3 -> 3	R
RW31_1	655	high	NE	1,118	960306,4	1073623	4	221515,2	263708,5	73,623	74,28	403544028	918	3 -> 3	R
RW32_1	1786	no data	ENE	1,045	953046,1	995933,1	3	560302	667026,2	42,956	44,745	384503011	1090	5 -> 5	L
RW32_2	986	no data	E	1	967847,1	967847,1	3	300603,6	357861,5	33,738	34,721	395487031	1089	6 -> 6	L
RW32_3	545	high	SW	1,118	972707,5	1087487	4	186694,3	222255,2	44,085	44,63	384503010	937	5 -> 3	R
RW32_4	538	high	WSW	1,045	879421	918994,9	2	155742,1	185407,2	45,772	46,3	383506009	924	3 -> 3	R
RW32_5	526	high	ENE	1,045	952447,3	995307,4	3	164912,5	196324,4	45,8	46,332	383506008	943	1 -> 1	L
RW35_1	881	no data	S	1,182	962280,7	1137416	5	315649,9	375773,7	46,598	47,455	479365007	1136	1 -> 1	L
RW37_1	1020	no data	SE	1,118	983953,3	1100060	4	353449,2	420772,9	2,567	3,593	455450020	1120	3 -> 3	L
RW4_1	894	no data	NW	1,118	978677,5	1094161	4	308126,8	366817,6	23,901	24,802	197329007	1420	3 -> 3	L
RW4_10	522	no data	WSW	1,045	953004,9	995890,1	3	163754,2	194945,5	74,643	75,167	171267034	1456	3 -> 3	L
RW4_2	774	no data	SE	1,118	889932	994943,9	3	242577,3	288782,5	42,625	43,402	175309091	1435	5 -> 5	R
RW4_3	737	no data	E	1	963292,9	963292,9	3	223633,3	266230,1	70,567	71,31	169275033	1455	3 -> 3	R
RW4_4	723	no data	SW	1,118	990672,6	1107572	4	252244	300290,4	54,365	55,087	162293010	1449	3 -> 3	L
RW4_5	697	no data	SE	1,118	361752,9	404439,8	1	88796,78	105710,4	32,178	33,038	189323036	1734	1 -> 1	R
RW4_6	642	no data	WNW	1,045	959351,5	1002522	3	202740,1	241357,2	53,301	54,365	162293030	1449	3 -> 3	L
RW4_7	598	no data	SE	1,118	916957,4	1025158	3	193109,1	229891,8	39,074	39,677	175309091	1434	3 -> 3	R
RW4_8	579	no data	SE	1,118	955482,5	1068229	4	194829	231939,3	43,402	44,16	173308067	1435	3 -> 3	R

RW4_9	535	no data	NW	1,118	972267,3	1086995	4	183185,8	218078,3	26,568	27,104	197329007	1423	3 -> 3	L
RW5_1	907	no data	N	1,182	981202,6	1159781	5	331355,4	394470,7	16,394	17,3	230379021	n/a	1 -> 1	R
RW5_2	904	medium	WNW	1,045	965740,8	1009199	3	287379,6	342118,5	11,99	12,901	224373005	2157	1 -> 1	R
RW5_3	825	medium	W	1	975882,1	975882,1	3	253607,4	301913,5	10,842	11,659	224373005	2156	1 -> 1	R
RW5_4	818	medium	E	1	974848,2	974848,2	3	251189,1	299034,7	10,889	11,714	224373004	2159	3 -> 3	L
RW5_5	741	medium	SE	1,118	983237,5	1099260	4	256583,7	305456,7	9,902	10,889	224373004	2159	1 -> 3	L
RW50_1	1075	no data	NNW	1,164	992954,9	1155799	5	391382,6	465931,7	116,44	117,514	329209004	130	5 -> 5	R
RW50_2	637	medium	E	1	949370,6	949370,6	2	190496	226780,9	160,027	160,657	362283006	447	3 -> 3	L
RW50_3	635	medium	ENE	1,045	969659,3	1013294	3	202684,1	241290,6	207,883	208,52	394347022	545	3 -> 3	L
RW50_4	627	medium	ESE	1,045	1006637	1051936	4	207762,6	247336,4	109,304	109,933	325199012	266	3 -> 3	L
RW50_5	522	high	SW	1,118	961500,1	1074957	4	176755,2	210422,8	248,907	249,43	377414047	342	5 -> 5	M
RW50_6	502	high	NW	1,118	1017018	1137026	5	179797,9	214045,2	118,8	119,472	335211006	98	3 -> 3	R
RW50_7	501	high	SW	1,118	966209,6	1080222	4	170475,3	202946,8	248,295	248,907	381410010	342	5 -> 5	R
RW50_8	501	no data	SE	1,118	934817,8	1045126	4	164936,6	196353,1	148,896	149,397	355261014	n/a	3 -> 3	L
RW58_1	974	high	SE	1,118	951816,4	1064131	4	326486	388673,8	56,915	57,895	228188019	88	5 -> 5	R
RW58_2	946	medium	NW	1,118	980763,6	1096494	4	326744,2	388981,1	56,228	57,174	228188015	255	3 -> 3	L
RW58_3	737	medium	NNW	1,164	972063,8	1131482	5	262679,3	312713,4	72,656	73,388	214197027	30	3 -> 3	L
RW58_4	734	high	NNW	1,164	1020798	1188208	5	274725,7	327054,4	71,442	72,171	216197004	47	3 -> 3	L
RW58_5	653	no data	SSE	1,164	995267,2	1158491	5	238295,8	283685,5	60,993	61,648	221186009	104	3 -> 3	R
RW58_6	524	high	WNW	1,045	972848,4	1016627	3	167804,4	199767,1	70,983	71,513	217198020	8	1 -> 1	L
RW58_7	512	no data	SSE	1,164	978721	1139231	5	183735,2	218732,4	72,603	73,12	214197032	11	5 -> 5	R
RW59_1	1056	no data	SSE	1,164	973058	1132640	5	376761,2	448525,3	142,851	143,904	310227008	181	3 -> 3	L
RW59_10	547	medium	SE	1,118	986929,9	1103388	4	190119,2	226332,4	147,056	147,602	317228003	318	3 -> 3	L
RW59_2	962	high	NNW	1,164	1006950	1172090	5	355178,5	422831,6	152,45	153,416	327233010	41	3 -> 3	R
RW59_3	833	high	NE	1,118	1001962	1120193	4	293933,2	349920,4	154,118	154,947	327233010	41	3 -> 3	R
RW59_4	772	medium	SSE	1,164	996424,2	1159838	5	282049,4	335773	145,38	146,15	313228002	318	3 -> 3	L
RW59_5	754	no data	NNW	1,164	1011991	1177957	5	279776,7	333067,5	119,696	120,454	271223018	1983	6 -> 6	R
RW59_6	636	medium	NNW	1,164	1015838	1182435	5	236889	282010,7	145,071	145,709	314228007	40	1 -> 1	R
RW59_7	608	no data	NNW	1,164	948719,6	1104310	4	211497,4	251782,6	114,609	115,2	261222009	1984	5 -> 5	R

RW59_8	572	no data	N	1,182	992332	1172936	5	211339,7	251594,9	119,037	119,6	271223018	1983	5 -> 5	R
RW59_9	569	medium	SE	1,118	953730,2	1066270	4	191113	227515,4	141,229	141,801	307225009	221	3 -> 3	L
RW7_1	1248	no data	E	1	953169,9	953169,9	2	374710,1	446083,5	34,855	36,104	261445028	n/a	1 -> 1	L
RW7_2	1192	no data	S	1,182	941482,2	1112832	4	417846,2	497435,9	222,208	223,4	508553004	1200	3 -> 3	L
RW7_3	971	high	WNW	1,045	943385,7	985838	3	301533,3	358968,3	15,039	16,03	248406016	782	3 -> 3	R
RW7_4	702	low	N	1,182	969908,1	1146431	5	253510,4	301798,1	216,946	217,645	495553029	2162	5 -> 5	R
RW7_5	670	high	N	1,182	962198,4	1137318	5	240031,1	285751,3	186,675	187,345	443556006	949	1 -> 1	R
RW7_6	650	no data	SSW	1,164	967248,6	1125877	4	230523,4	274432,6	192,13	192,795	455560019	1127	3 -> 3	L
RW7_7	584	medium	W	1	943309,2	943309,2	2	173531,2	206584,7	32,545	33,156	262439052	1917	3 -> 3	R
RW7_8	530	medium	ESE	1,045	930387	972254,4	3	162317,9	193235,6	6,115	6,907	236393011	2109	3 -> 3	L
RW73_1	1657	high	NW	1,118	948400,5	1060312	4	553435	658851,2	7,998	9,668	383099011	635	1 -> 1	R
RW73_10	833	medium	SSW	1,164	940230,6	1094428	4	287172,5	341872,1	110,28	111,112	360258025	613	6 -> 5	R
RW73_11	800	high	E	1	1001165	1001165	3	252293,5	300349,4	64,415	65,215	394190021	470	3 -> 5	L
RW73_12	731	medium	E	1	991736,5	991736,5	3	228362,2	271859,8	39	39,776	414140032	460	3 -> 6	L
RW73_13	720	medium	WNW	1,045	987630,2	1032074	3	234074,3	278659,9	38,177	38,896	414140031	627	5 -> 5	R
RW73_14	702	medium	ESE	1,045	990579,6	1035156	3	228904	272504,7	22,107	22,812	398116021	463	1 -> 1	L
RW73_15	672	medium	ESE	1,045	948244,9	990915,9	3	209757,1	249710,8	37,546	38,218	414140032	460	3 -> 6	L
RW73_16	654	medium	W	1	971801,7	971801,7	3	200200,9	238334,4	43,64	44,302	412151020	628	6 -> 6	R
RW73_17	608	medium	NE	1,118	1002955	1121303	4	214752	255657,2	39,949	40,545	417146030	1967	5 -> 5	L
RW73_18	574	high	WSW	1,045	975545,3	1019445	3	184325,8	219435,5	100,927	101,506	363251016	338	3 -> 3	R
RW73_19	537	medium	SE	1,118	930324,9	1040103	3	175938,7	209450,8	12,402	12,931	390105017	446	3 -> 3	L
RW73_2	1502	medium	NW	1,118	993749,7	1111012	4	525653,2	625777,6	24,514	26,012	399115034	621	6 -> 5	R
RW73_20	532	medium	SE	1,118	954769,7	1067433	4	178880,3	212952,8	38,218	38,75	414140032	460	6 -> 5	L
RW73_21	530	medium	ENE	1,045	1014007	1059637	4	176906,4	210602,9	58,112	58,657	400177017	546	3 -> 3	L
RW73_22	510	medium	WSW	1,045	1012644	1058213	4	170001,9	202383,2	56,194	56,701	402174009	616	1 -> 1	R
RW73_3	1218	medium	SE	1,118	906855,9	1013865	3	388989,5	463082,8	8,567	10,234	383099006	586	3 -> 5	L
RW73_4	1064	medium	SSW	1,164	951842	1107944	4	371338,5	442069,7	41,905	42,953	412151016	1969	6 -> 6	R
RW73_5	1049	medium	W	1	973567,3	973567,3	3	321700,7	382977	64,689	65,738	394189012	619	3 -> 3	R
RW73_6	1013	high	W	1	966827,4	966827,4	3	308509,8	367273,6	102,725	103,743	363252022	593	5 -> 5	R

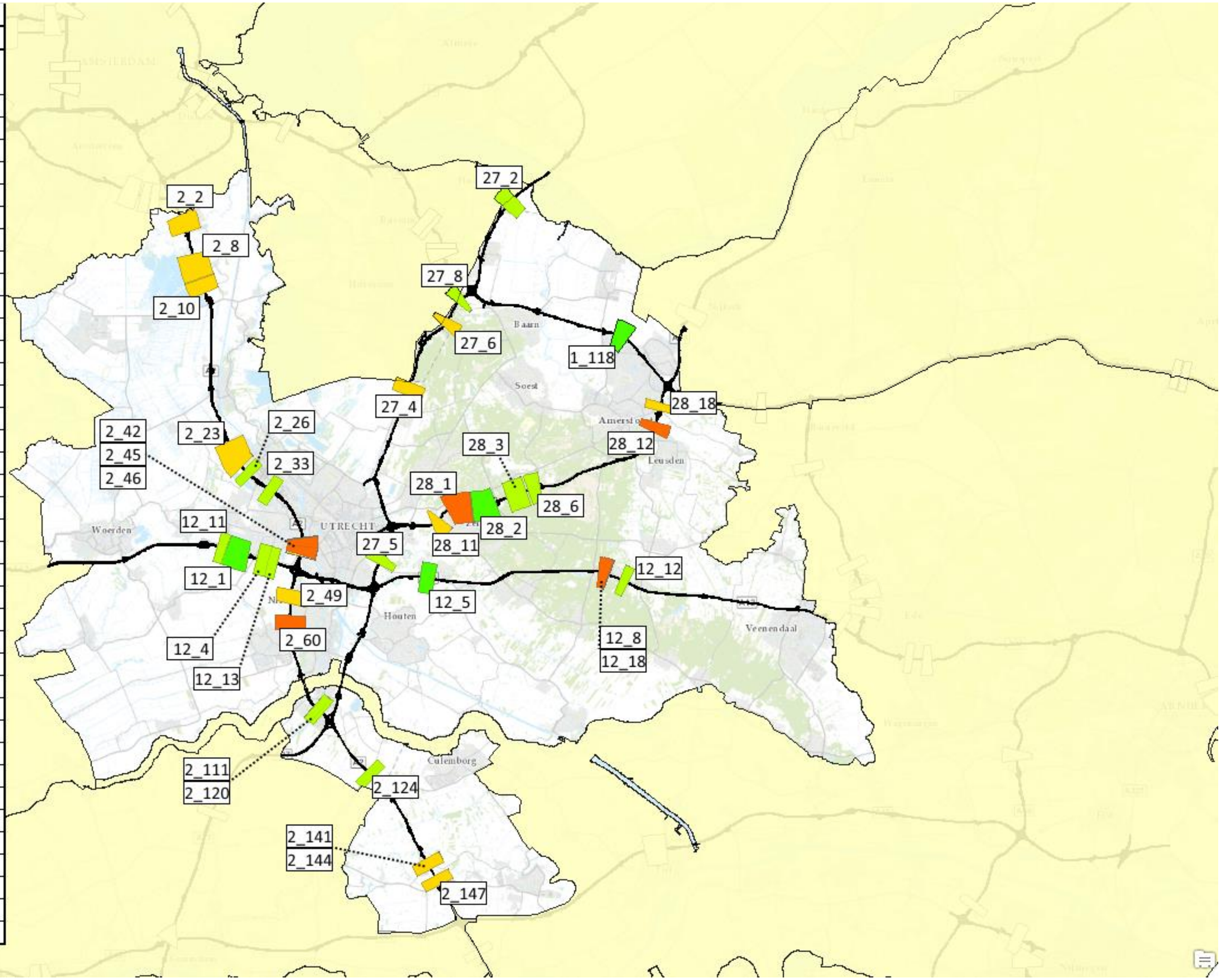
RW73_7	939	high	SW	1,118	969599,6	1084012	4	320634,6	381707,8	97,502	98,451	366246018	588	5 -> 5	R
RW73_8	892	high	NW	1,118	1014030	1133685	5	318542,9	379217,7	33,998	34,887	409133018	650	3 -> 3	R
RW73_9	874	medium	SE	1,118	944891,9	1056389	4	290834,5	346231,5	33,993	34,869	409134022	465	1 -> 1	L
RW76_1	651	medium	NE	1,118	1019579	1139889	5	233751,4	278275,5	5,301	5,95	370058031	85	5 -> 5	R
RW76_2	634	medium	NNE	1,164	1008410	1173789	5	234417,5	279068,4	8,695	9,33	375056014	63	5 -> 5	R
RW76_3	548	medium	SE	1,118	957917,8	1070952	4	184867,8	220080,7	0,923	1,475	362060016	236	6 -> 6	L
RW76_4	539	no data	NW	1,118	878137,7	981758	3	166687,8	198437,8	1,107	1,649	362060017	118	6 -> 6	R
RW8_1	1209	medium	W	1	867504,8	867504,8	1	330376,2	393305	0,7	2,005	239385029	2160	6 -> 6	R
RW8_2	970	medium	NNE	1,164	955289,5	1111957	4	339758,5	404474,4	6,147	7,124	231394083	840	5 -> 3	L
RW8_3	716	medium	NE	1,118	950464,3	1062619	4	239663,1	285313,2	3,974	4,688	236392028	2106	5 -> 5	L
RW8_4	574	no data	E	1	938488,9	938488,9	2	169688,2	202009,7	0,898	1,489	240386021	n/a	6 -> 6	L
RW8_5	519	medium	NE	1,118	941764	1052892	4	172132,1	204919,1	2,847	3,373	237389022	2166	6 -> 6	L
RW9_1	1513	medium	NE	1,118	959513,7	1072736	4	511260,8	608643,8	35,001	36,519	225368017	835	5 -> 5	L
RW9_2	1309	medium	SW	1,118	946727,6	1058441	4	436432,5	519562,5	34,991	36,3	225368016	701	5 -> 5	R
RW9_3	1121	medium	SSW	1,164	936252,5	1089798	4	384824	458123,8	24,378	25,467	242357021	777	5 -> 5	R
RW9_4	586	medium	NNE	1,164	959781,9	1117186	4	206221,4	245501,6	23,582	24,165	242357022	830	1 -> 1	L
RW9_5	554	medium	N	1,182	951605,4	1124798	4	196288,4	233676,7	22,957	23,512	242357022	830	1 -> 1	L

Appendix III

The figures below give an overview of the suitability of PV noise barriers per RWS district. In total there are 16 districts. Three of those are not included as there are no suitable PV noise barrier locations in those districts. These districts are: RWS Midden-Nederland District Noord, RWS Zee en Delta District Noord and RWS Zee en Delta District Zuid. The other districts are shown below.

RWS Midden-Nederland District Zuid

RWS Midden-Nederland District Zuid			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
1_118	5	978	no data
2_2	3	1205	medium
2_8	3	1647	medium
2_10	3	967	medium
2_23	3	1884	medium
2_26	4	612	medium
2_33	4	680	medium
2_42	2	593	medium
2_45	2	1215	medium
2_46	3	560	medium
2_49	3	909	no data
2_60	2	943	no data
2_111	4	524	medium
2_120	4	745	medium
2_124	4	671	medium
2_141	3	729	medium
2_144	3	682	medium
2_147	3	651	medium
12_1	5	1542	medium
12_4	4	933	medium
12_5	5	916	medium
12_8	2	692	medium
12_11	4	625	medium
12_12	4	623	medium
12_13	4	621	medium
12_18	2	545	medium
27_2	4	1010	medium
27_4	3	888	high
27_5	4	641	high
27_6	3	559	medium
27_8	4	526	medium
28_1	2	1549	high
28_2	5	1526	high
28_3	4	1315	high
28_6	4	815	high
28_11	3	645	no data
28_12	2	628	medium
28_18	3	512	medium

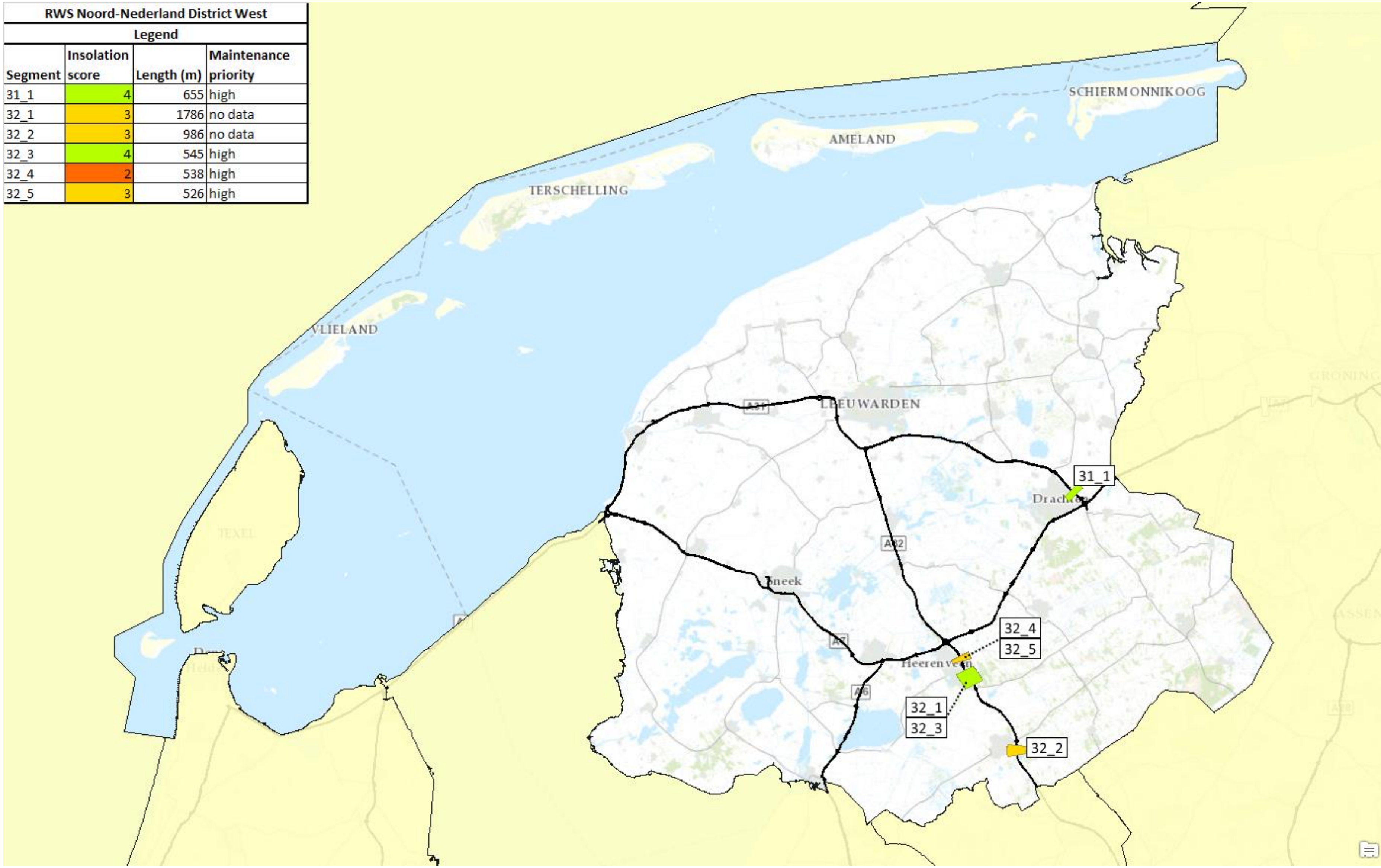


RWS Noord-Nederland District Oost

RWS Noord-Nederland District Oost			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
7_2	4	1192	no data
7_4	5	702	low
7_5	5	670	high
7_6	4	650	no data
37_1	4	1020	no data

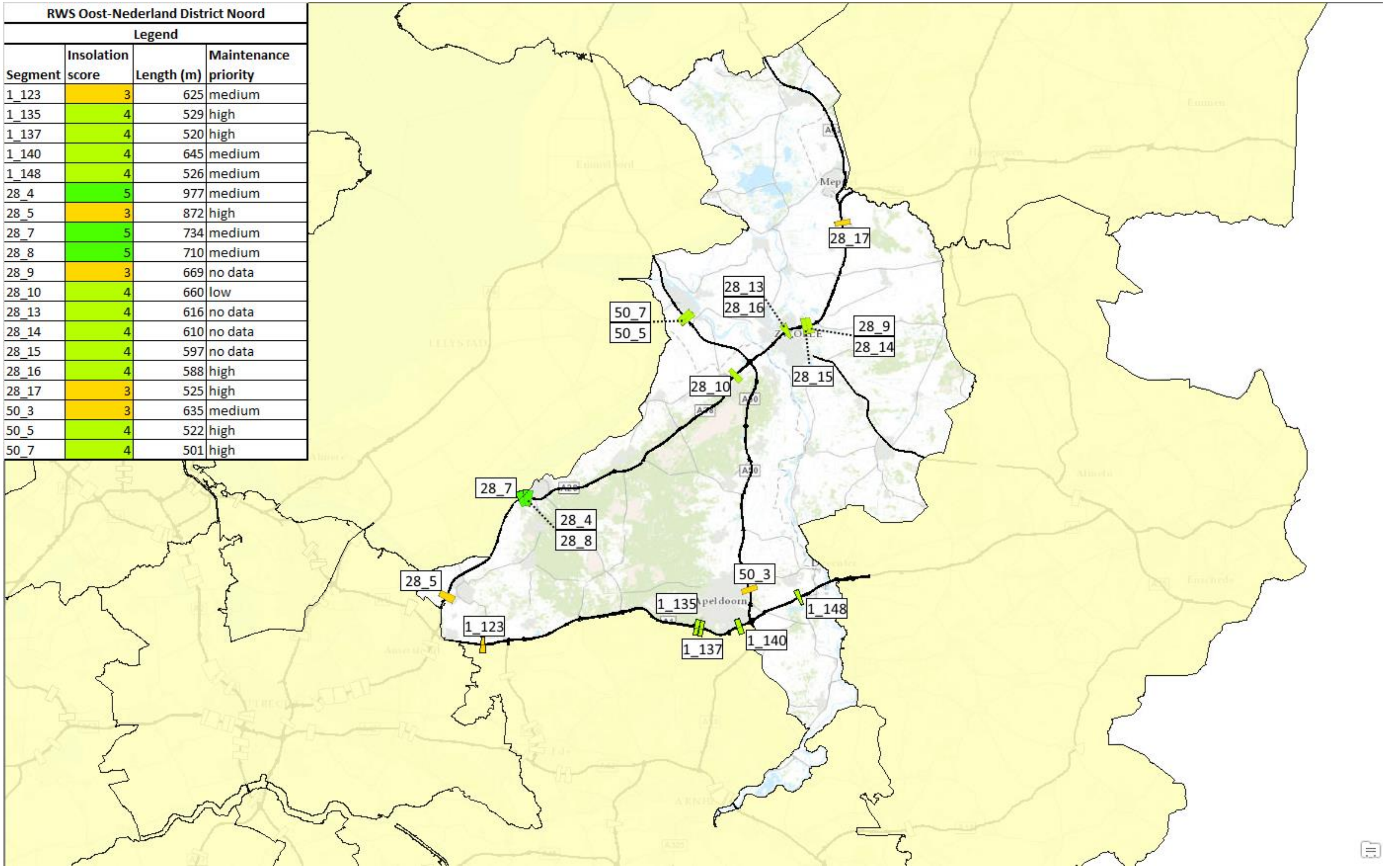
RWS Noord-Nederland District West

RWS Noord-Nederland District West			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
31_1	4	655	high
32_1	3	1786	no data
32_2	3	986	no data
32_3	4	545	high
32_4	2	538	high
32_5	3	526	high



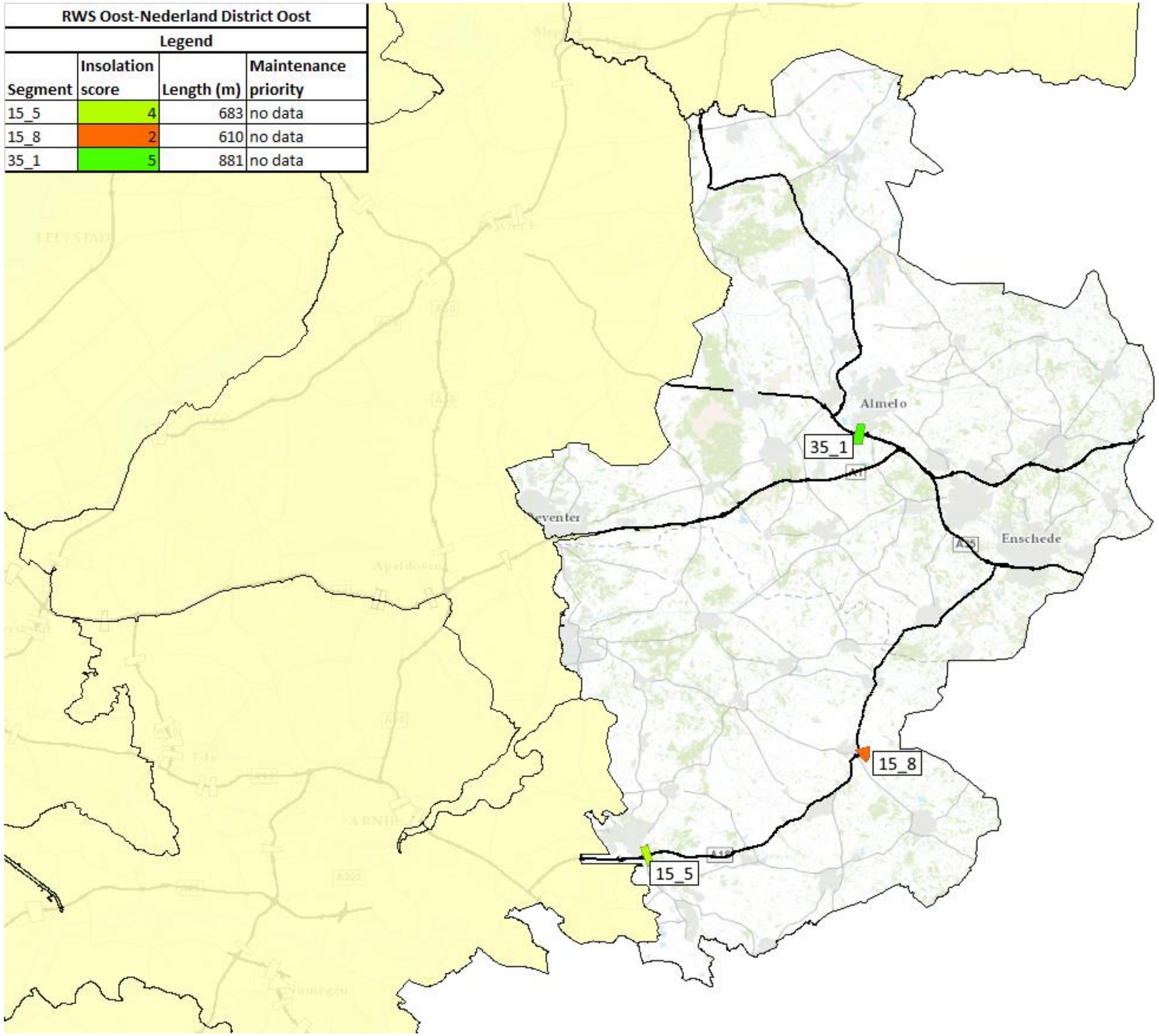
RWS Oost-Nederland District Noord

RWS Oost-Nederland District Noord			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
1_123	3	625	medium
1_135	4	529	high
1_137	4	520	high
1_140	4	645	medium
1_148	4	526	medium
28_4	5	977	medium
28_5	3	872	high
28_7	5	734	medium
28_8	5	710	medium
28_9	3	669	no data
28_10	4	660	low
28_13	4	616	no data
28_14	4	610	no data
28_15	4	597	no data
28_16	4	588	high
28_17	3	525	high
50_3	3	635	medium
50_5	4	522	high
50_7	4	501	high



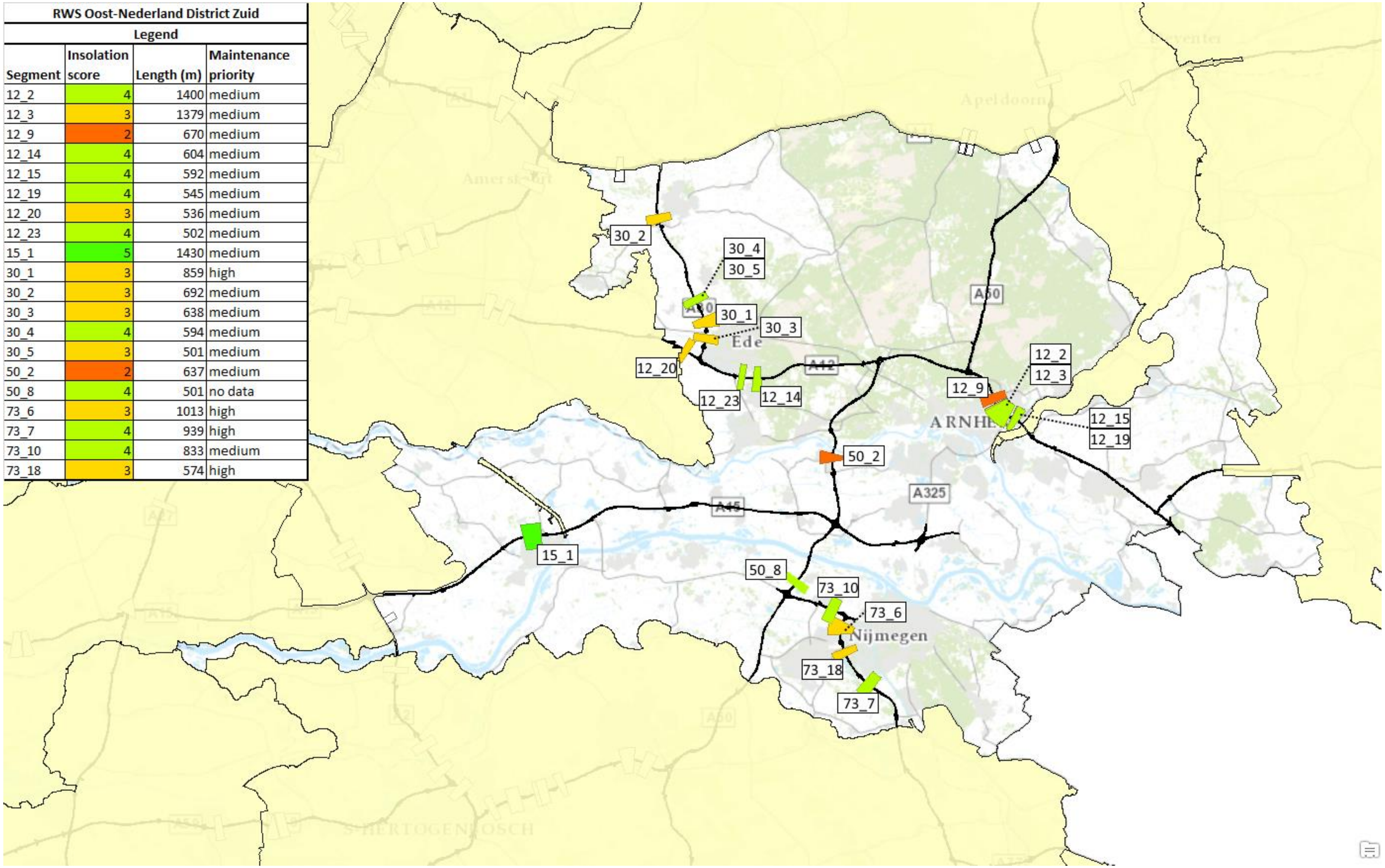
RWS Oost-Nederland District Oost

RWS Oost-Nederland District Oost			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
15_5	4	683	no data
15_8	2	610	no data
35_1	5	881	no data



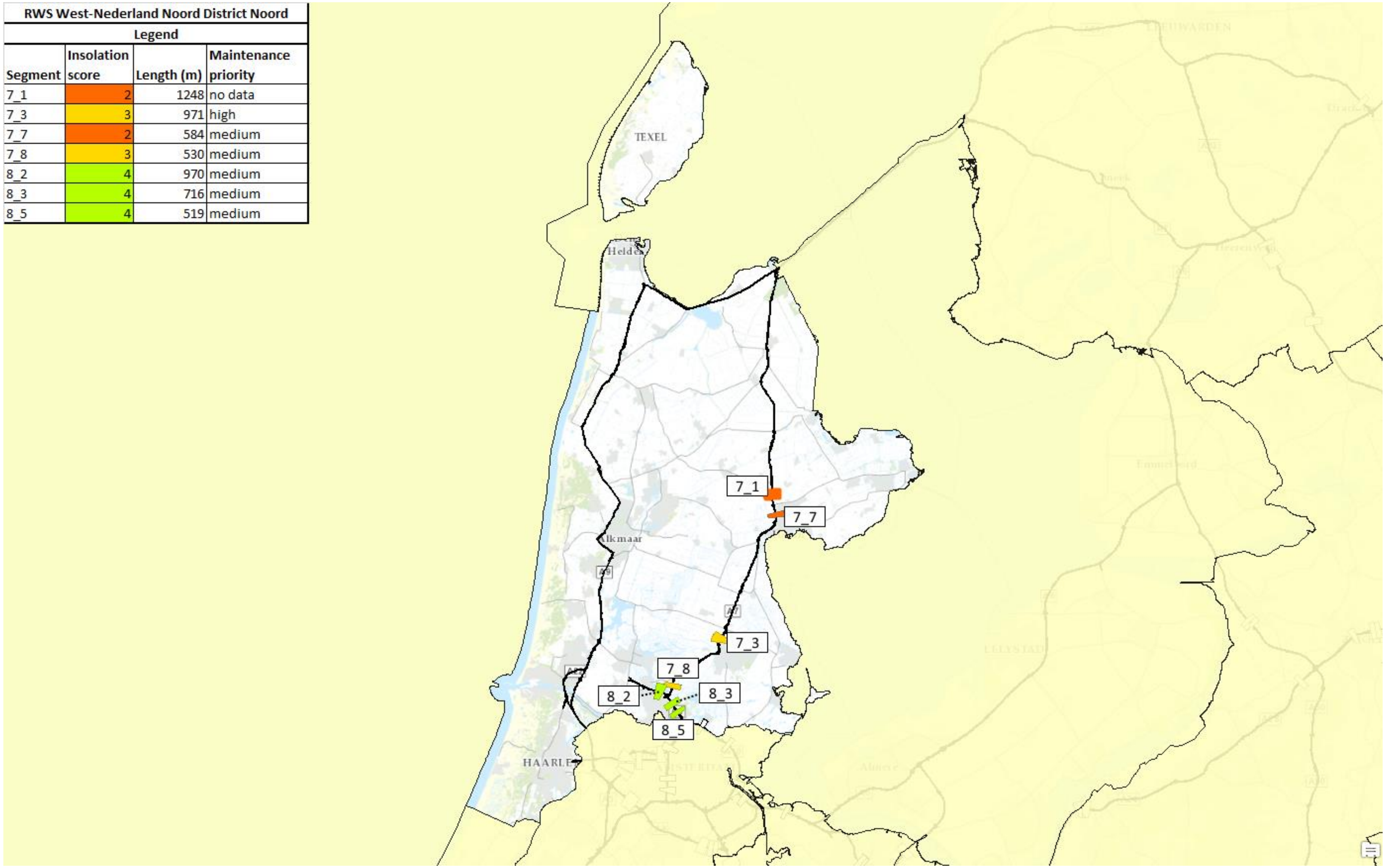
RWS Oost-Nederland District Zuid

RWS Oost-Nederland District Zuid			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
12_2	4	1400	medium
12_3	3	1379	medium
12_9	2	670	medium
12_14	4	604	medium
12_15	4	592	medium
12_19	4	545	medium
12_20	3	536	medium
12_23	4	502	medium
15_1	5	1430	medium
30_1	3	859	high
30_2	3	692	medium
30_3	3	638	medium
30_4	4	594	medium
30_5	3	501	medium
50_2	2	637	medium
50_8	4	501	no data
73_6	3	1013	high
73_7	4	939	high
73_10	4	833	medium
73_18	3	574	high

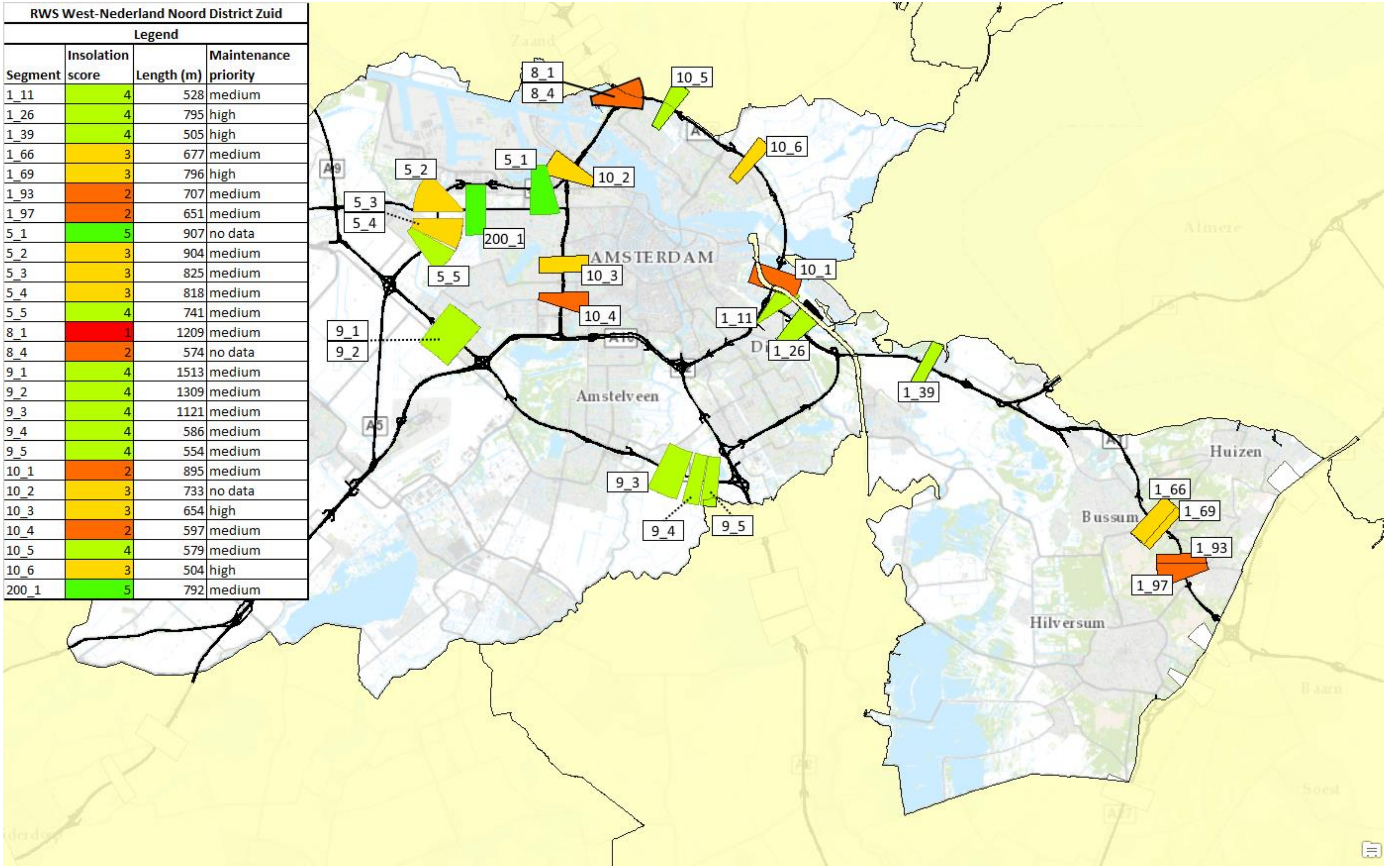


RWS West-Nederland Noord District Noord

RWS West-Nederland Noord District Noord			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
7_1	2	1248	no data
7_3	3	971	high
7_7	2	584	medium
7_8	3	530	medium
8_2	4	970	medium
8_3	4	716	medium
8_5	4	519	medium



RWS West-Nederland Noord District Zuid



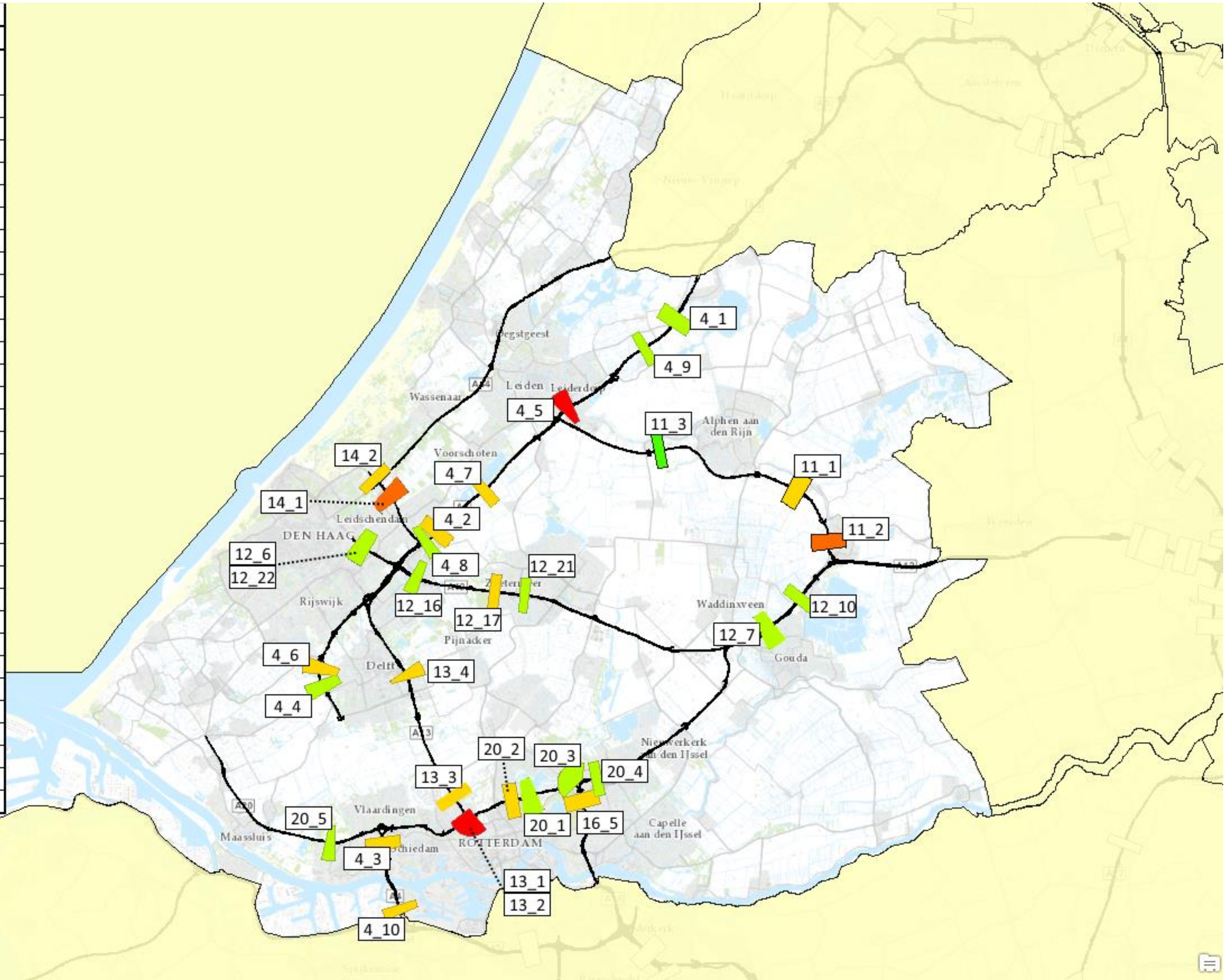
RWS West-Nederland Noord District Zuid

Legend

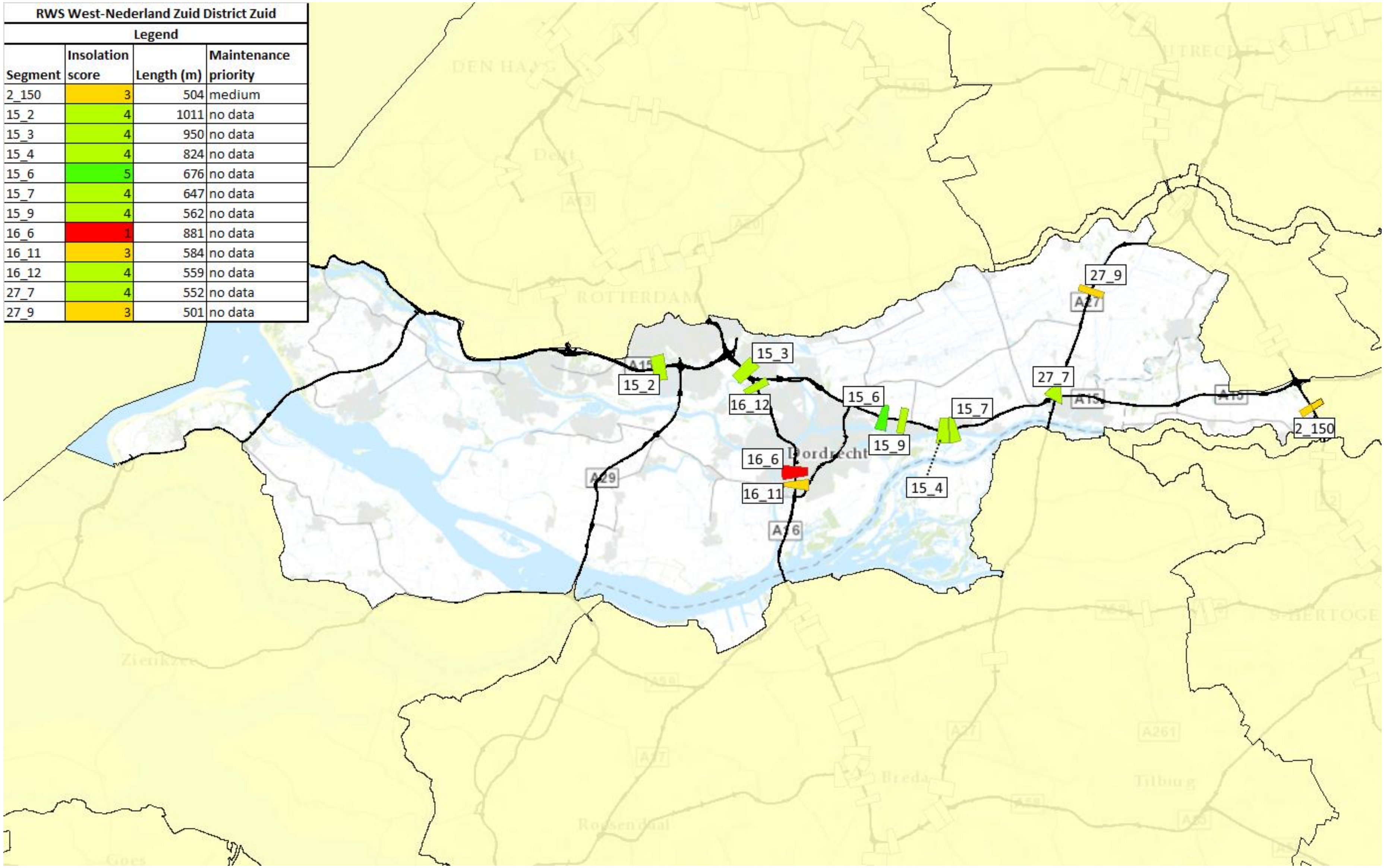
Segment	Insolation score	Length (m)	Maintenance priority
1_11	4	528	medium
1_26	4	795	high
1_39	4	505	high
1_66	3	677	medium
1_69	3	796	high
1_93	2	707	medium
1_97	2	651	medium
5_1	5	907	no data
5_2	3	904	medium
5_3	3	825	medium
5_4	3	818	medium
5_5	4	741	medium
8_1	1	1209	medium
8_4	2	574	no data
9_1	4	1513	medium
9_2	4	1309	medium
9_3	4	1121	medium
9_4	4	586	medium
9_5	4	554	medium
10_1	2	895	medium
10_2	3	733	no data
10_3	3	654	high
10_4	2	597	medium
10_5	4	579	medium
10_6	3	504	high
200_1	5	792	medium

RWS West-Nederland Zuid District Noord

RWS West-Nederland Zuid District Noord			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
4_1	4	894	no data
4_2	3	774	no data
4_3	3	737	no data
4_4	4	723	no data
4_5	1	697	no data
4_6	3	642	no data
4_7	3	598	no data
4_8	4	579	no data
4_9	4	535	no data
4_10	3	522	no data
11_1	3	956	no data
11_2	2	871	no data
11_3	5	571	no data
12_6	4	898	medium
12_7	4	804	no data
12_10	4	646	medium
12_16	4	585	no data
12_17	3	560	low
12_21	4	523	low
12_22	4	511	no data
13_1	1	787	medium
13_2	1	778	no data
13_3	3	563	no data
13_4	3	537	no data
14_1	2	852	no data
14_2	3	568	no data
16_5	3	884	no data
20_1	4	811	no data
20_2	3	762	no data
20_3	4	738	no data
20_4	4	636	no data
20_5	4	540	low



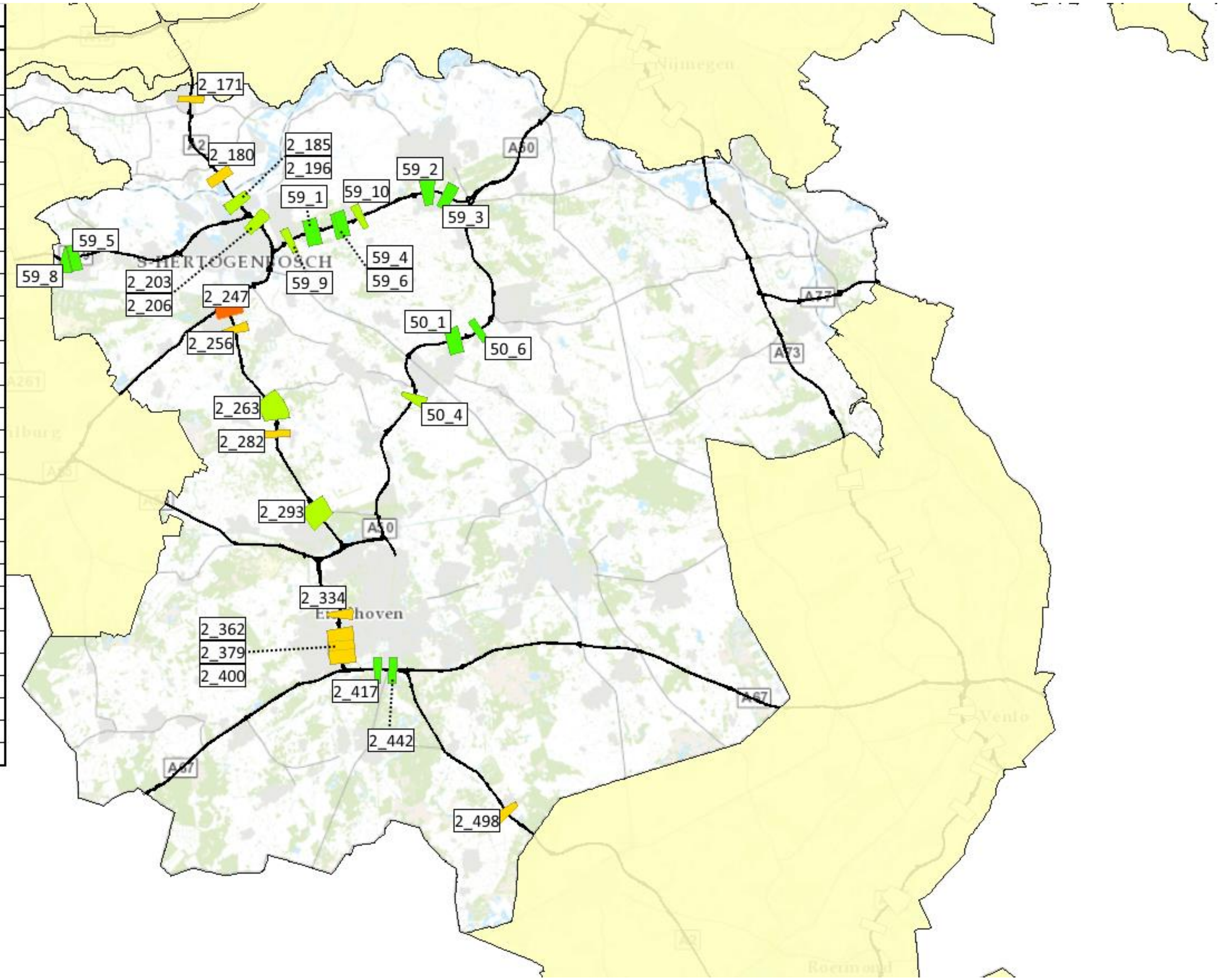
RWS West-Nederland Zuid District Zuid



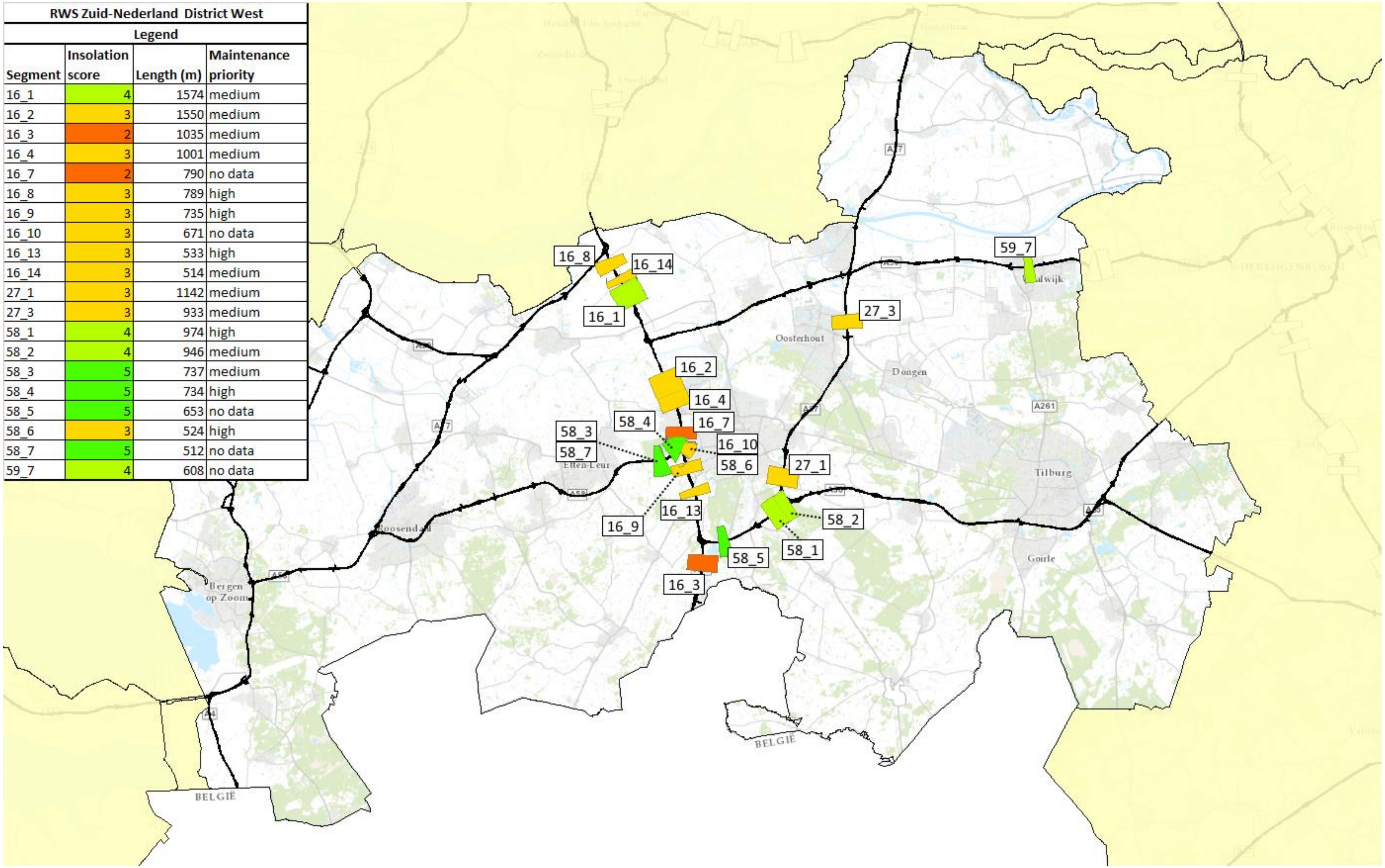
RWS West-Nederland Zuid District Zuid			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
2_150	3	504	medium
15_2	4	1011	no data
15_3	4	950	no data
15_4	4	824	no data
15_6	5	676	no data
15_7	4	647	no data
15_9	4	562	no data
16_6	1	881	no data
16_11	3	584	no data
16_12	4	559	no data
27_7	4	552	no data
27_9	3	501	no data

RWS Zuid-Nederland District Midden

RWS Zuid-Nederland District Midden			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
2_171	3	513	medium
2_180	3	744	no data
2_185	4	799	no data
2_196	4	522	no data
2_203	3	505	no data
2_206	4	808	no data
2_247	2	638	no data
2_256	3	557	no data
2_263	4	1984	no data
2_282	3	511	medium
2_293	4	1722	medium
2_334	3	545	no data
2_362	3	1377	no data
2_379	3	717	no data
2_400	3	1056	no data
2_417	5	507	no data
2_442	5	602	no data
2_498	3	589	no data
50_1	5	1075	no data
50_4	4	627	medium
50_6	5	502	high
59_1	5	1056	no data
59_2	5	962	high
59_3	4	833	high
59_4	5	772	medium
59_5	5	754	no data
59_6	5	636	medium
59_8	5	572	no data
59_9	4	569	medium
59_10	4	547	medium



RWS Zuid-Nederland District West



RWS Zuid-Nederland District West			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
16_1	4	1574	medium
16_2	3	1550	medium
16_3	2	1035	medium
16_4	3	1001	medium
16_7	2	790	no data
16_8	3	789	high
16_9	3	735	high
16_10	3	671	no data
16_13	3	533	high
16_14	3	514	medium
27_1	3	1142	medium
27_3	3	933	medium
58_1	4	974	high
58_2	4	946	medium
58_3	5	737	medium
58_4	5	734	high
58_5	5	653	no data
58_6	3	524	high
58_7	5	512	no data
59_7	4	608	no data

RWS Zuid-Nederland District Zuid-Oost

RWS Zuid-Nederland District Zuid-Oost			
Legend			
Segment	Insolation score	Length (m)	Maintenance priority
73_1	4	1657	high
73_2	4	1502	medium
73_3	3	1218	medium
73_4	4	1064	medium
73_5	3	1049	medium
73_8	5	892	high
73_9	4	874	medium
73_11	3	800	high
73_12	3	731	medium
73_13	3	720	medium
73_14	3	702	medium
73_15	3	672	medium
73_16	3	654	medium
73_17	4	608	medium
73_19	3	537	medium
73_20	4	532	medium
73_21	4	530	medium
73_22	4	510	medium
76_1	5	651	medium
76_2	5	634	medium
76_3	4	548	medium
76_4	3	539	no data