THE ASPHALT COLLECTOR AND SOLAR ROAD ON THE A58

Research into the potential of applying the asphalt collector and solar road on the A58

Bachelor thesis

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Preface

The thesis that is situated in front of you is titled 'The asphalt collector and solar road on the A58'. This research has been performed as a graduation assignment for the Bachelor study Civil Engineering at the University of Twente. I have performed this research during an internship at Witteveen+Bos from April 2018 until June 2018.

I would like to thank my attending at Witteveen+Bos, Teun van Breukelen, for giving me advice and feedback whenever I needed it and for always being stand-by when I had a question about the content of my thesis. I would also like to thank my attending from the University of Twente, Andreas Hartmann, for helping me out with the structure of my thesis, giving me feedback and helping me to formulate research questions.

A large amount of information was coming from interviews, e-mails, or phone calls and I would not be able to give a complete answer to the main question without this information. Therefore, I would like to thank everyone that provided this information for cooperating.

Finally, I would like to thank the employees of Witteveen+Bos for the fine cooperation. I have often been able to discuss my research with them in an effective way.

I hope you will enjoy reading this report!

Aron Vossebeld

Enschede, June 27, 2018

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List of abbreviations

°C	Degrees Celsius
$°C(m^{-2}s)^{-1}$	Temperature change in Degrees Celsius per square meter per second
AC	Asphalt Concrete
Cm	Centimetre
DAC	Dense Asphalt Concrete
dB	Decibel
E.g.	For example (exempli gratia)
Et al.	Used to stand in for two or more names in references meaning 'and others'.
Excl.	Excluding
GJ	Giga Joule = 10^9 Joule
ITSR	Indirect Tensile Strength Ratio
km	Kilo meter
kN	Kilo Newton
kW	Kilo Watt
kWh	Kilo Watthour (=0,0036GJ)
m/s^2	Metre per second squared (unit of acceleration)
m^2	Square metre (unit of a surface)
MCA	Multi Criteria Analysis
MV	Medium-Voltage
PIA	Pipes In Asphalt
PIC	Pipes In Concrete
PTC	Network of pipes arranged in a parallel fashion
PV	Photo-Voltaic
Re_D	Reynolds number
RES	Road Energy Systems
RWS	Rijkswaterstaat
Sd	Without a date; in bibliographical enumerations (Latin: Sine dato)
SDE	Stimulering Duurzame Energieproductie (Stimulation Sustainable Energy production)
STAB	Chippings asphalt concrete (Dutch: STeenslag Asfalt Beton)
STC	Network of pipes arranged in a serpentine fashion
VOAC	Very Open-graded Asphalt Concrete (Dutch: ZOAB)
VOWAC	Very Open-graded water-bearing Asphalt Concrete (Dutch: ZOWAB)
VOWAC+	VOWAC with modified bitumen
$W \cdot m^{-1} \cdot K^{-1}$	Watts per meter-kelvin (Unit of thermal conductivity)
W+B	Witteveen+Bos
WKO	Heat Cold Storage (Dutch: Warmte Koude Opslag)

Abstract

Rijkswaterstaat has given Witteveen+Bos the assignment to widen parts of the A58 from two to three lanes and to start the plan elaboration. This must be done in an innovative way and therefore all possible innovative applications that can be implemented at the A58 need to be considered.

Two of these applications are the asphalt collector and the solar road. The aim of this thesis is *to give Witteveen+Bos and Rijkswaterstaat insight in the potential of the asphalt collector and solar road on the A58 in the study area.* To reach the aim, the main question of the thesis is formulated as followed: *What is the potential for applying the asphalt collector and solar road on the A58 within the study area?* The asphalt collector is a way to collect heat out of the asphalt and the solar road is a road covered with photo-voltaic cells.

To give an answer to the main question, information out of literature and several interviews have been used, also geospatial data have been analysed. The technical conditions of the asphalt collector and solar road have been discussed first. The most important findings out of this are that the presence of an aquifer and the distance to the heat consumer is largely determining the potential of the asphalt collector and the costs, efficiency, strength and driving comfort are largely determining the potential of the solar road.

After the technical conditions were discussed, an overview of the pros and cons has been given. The largest pro for both the asphalt collector and the solar road is that when they are implemented, the road has been given an extra function, not only transporting but also generating sustainable energy. The largest cons of the asphalt collector are the possible threat of losing an important heat consumer and that there is always a large number of involved parties what makes it difficult who is going to be in charge of the collector. For the solar road the largest cons are its costs and that it is hard to deal with the decrease in transparency of the top layer.

From the above-mentioned and the effect of the asphalt collector and solar road on the technical conditions of the A58 the best potential implementation for both applications is determined. For the asphalt collector that is to use the Pipes-In-Asphalt collector at 5 lanes of 571 meter on the A58 close to the Sint Elisabeth hospital. The best potential implementation for the solar road on the A58 is to use the application that is used by Pavenergy at 2.1 km of emergency lane.

From this research can be concluded that there is potential for applying the asphalt collector on the A58 within the study area because of the suited location and the ability to give the road two functions. On the other hand, there is not much potential to implement the solar road on a large scale when the A58 will be widened because of its high costs. A pilot project on a small scale to test the performance of the solar road on the Dutch highway has potential when there is support from subsidy.

1. Introduction

Do the asphalt collector and solar road have potential? In this report, research has been done to the potential for applying these innovative applications on the A58. In this section the motive, objective, research questions and methodology of the thesis is discussed. There has also been explained what can be expected in the content of this report.

1.1. Motive

At the end of 2015, almost 200 countries came together during the climate conference in Paris. They voted for a new climate agreement. In that, it has been agreed that global warming needs to be limited to a maximum of 2 degrees Celsius (Dutch Emissions Authority, sd). Therefore, it is important that the emission of CO_2 will decline. One of the main culprits of CO_2-emmision, is the combustion of fossil fuels. That is why the step to sustainable energy is important. In this, there is a big challenge for the densely populated Netherlands because there is a lack of space for sustainable energy. Therefore, the Netherlands needs innovative companies to implement sustainable energy in other spatial functions. Because the road network claims a large part of the Dutch space, it will be a good solution to add the function to generate sustainable energy to the transporting function of the roads.

On the A58 between the nodes Sint-Annabosch and Galder, and Eindhoven and Tilburg there is a large amount of congestion what causes economical damage (Witteveen+Bos, 2018). Therefore, the ministry of Infrastructure and Water Management has instructed Rijkswaterstaat to widen the A58 from two to three lanes at these parts and to start the plan elaboration. From the node Sint-Annabosch to the node Galder, the length is approximately 6 km and the A58 from Eindhoven to Tilburg approximately 19 km (OpenStreetMap, 2018). Together a 25 km part of the A58 will be widened. Rijkswaterstaat awarded the assignment to widen the A58 on these parts to Witteveen+Bos (W+B). The A58 project of Witteveen+Bos is a project that is in the plan phase. It is expected that the design will be finished and submitted for consideration at the end of 2018. Within the design, the project InnovA58 must be considered. This project aims at the widening of the A58 in an innovative way. InnovA58 has set, among other goals, the goal to stimulate the climate adaptation and to get the image of 'example' and 'innovative' in terms of tackling the innovation challenge (Rijkswaterstaat, 2018). Because the project is in the plan phase, the A58 project is a good opportunity to combine the transport function with generating sustainable energy and therefore to lower the CO_2 emission of the Netherlands. Two applications that combine these functions, are the asphalt collector and solar road. In the thesis the potential for applying the asphalt collector and solar road in the study area (Figure 1) at the A58 will be discussed.

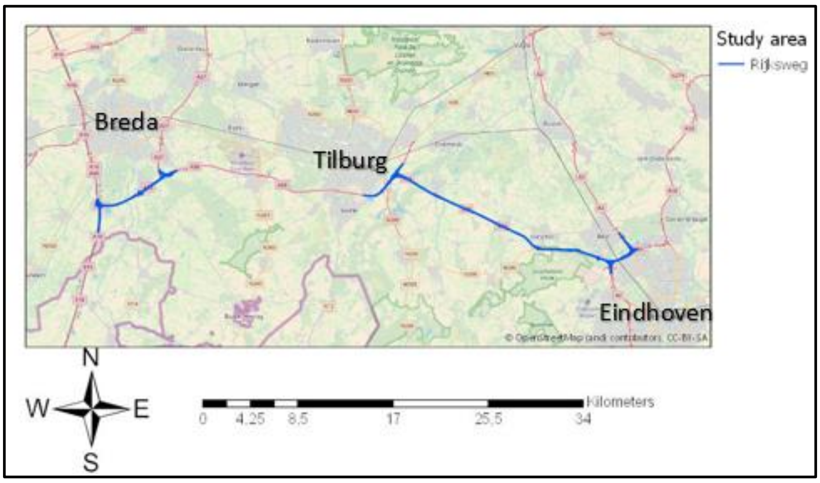

Figure 1: Study area in ArcGIS Pro[1]

[1] ArcGIS Pro is software that can be used to view, edit, create and analyse geospatial data.

1.2. Objective and research questions

Commissioned by Rijkswaterstaat, Witteveen+Bos will widen the A58 within the study area considering the InnovA58 project and they will start the plan elaboration (Witteveen+Bos, 2018). They will make a design and are responsible for the assessment of environmental impact. To consider this project, all kinds of innovative applications can be used. Two of those applications are the asphalt collector and solar road. But it is not known if there is enough potential to apply these applications during the A58 project. This thesis will give insight in if there is potential to apply the asphalt collector and solar road on the A58. Therefore, the aim of the thesis is:

To give Witteveen+Bos and Rijkswaterstaat insight in the potential of applying the asphalt collector and solar road on the A58 in the study area.

To reach the aim, research questions are formulated using the SMART philosophy (Wayne State University, 2017). Each question is Specific, Measurable, Achievable, Relevant and Time-oriented. The main research question of the thesis is as following.

- *What is the potential for applying the asphalt collector and solar road on the A58 within the study area?*

To answer the main research question, the following sub questions are formulated.

1. How does the asphalt collector and solar road work?
2. What are the technical conditions of the asphalt collector and solar road?
3. What are the pros and cons of the asphalt collector and solar road?
4. What is the effect of the asphalt collector and solar road on the technical requirements of the A58 within the study area?
5. What is the best way to implement the asphalt collector and solar road on the A58 within the study area?

1.3. Methodology

For this research, a literature review has been done and geospatial data from the study area has been analysed in ArcGIS Pro. Also, information from experts have been gathered during three interviews. It has been decided to not mention the names of the interviewees. To show what research methods is used for what research question, an overview is given in Table 1.

Table 1: Methodology

Research question	Research methods
1. How does the asphalt collector and solar road work?	• Literature study • Interview with solar energy expert of W+B (Interviewee 1) (Appendix A) • Interview with asphalt collector expert from Ooms (Interviewee 2) (Appendix B)
2. What are the technical conditions of the asphalt collector and solar road?	• Literature study •Interview with asphalt collector expert from Ooms (Interviewee 2) (Appendix B)

3. What are the pros and cons of the asphalt collector and solar road?	• Literature study • Interview with asphalt collector expert from Ooms (Interviewee 2) (Appendix B)
4. What is the effect of the asphalt collector and solar road on the technical requirements of the A58 within the study area?	• Literature study • Interview with asphalt construction expert of W+B (Interviewee 3) (Appendix G) • Analysing traffic intensity in study area using ArcGIS Pro
5. What is the best way to implement the asphalt collector and solar road on the A58 within the study area?	• Multi Criteria Analysis (MCA) (CROW, 2012) • Analysing geospatial data using ArcGIS Pro

1.4. Reading Guide

In chapter 2 the working principle, technical conditions and pros and cons of the asphalt collector are discussed. Chapter 3 focussed on these topics for the solar road. In chapter 4 the effect of the asphalt collector and solar road on the technical requirements of the A58 is shown. With the information from chapter 2 to 4, the best potential implementations for the asphalt collector and solar road on the A58 are determined in chapter 5 and 6. The conclusion follows in chapter 7, where an answer has been given to the main question. Finally, points of discussion are formulated, and recommendations have been made, in chapter 8 and 9 respectively.

2. Asphalt collector

This chapter starts with an explanation of the working principle of the asphalt collector. After the working principle has been described, the technical conditions are discussed. The chapter ends with the pros and cons of the asphalt collector. With this chapter, an answer to the asphalt collector part of the first three research questions has been given.

2.1. Working principle asphalt collector

The asphalt collector is an application for collecting and releasing solar energy with the help of asphalt. Asphalt can get 50 to 60 °C during summer and that heat will be absorbed by water that is transferred via a pipe system or water-bearing asphalt layer, that is applied into the asphalt construction (Weijers & Groot, 2007). The structure of the asphalt collector with a pipe system is shown in Figure 2. The generated heat can be used directly as a source for a heat pump or can be stored in an aquifer[2], so it can be used during the winter. In the summer, the pipe system can be used to cool the asphalt, so rutting will occur significantly less. That results in maintenance reduction and a longer lifespan of the asphalt (Waerdse Energie Circuit, sd). In the winter, the pipe system can be used to heat up the asphalt, so the road will not sustain damage from the weather conditions and less road salt is needed to de-ice the road (Kodi, sd). Concluding, the asphalt collector can have 3 different purposes: heat collection, maintenance reduction and smoothness control (Weijers & Groot, 2007).

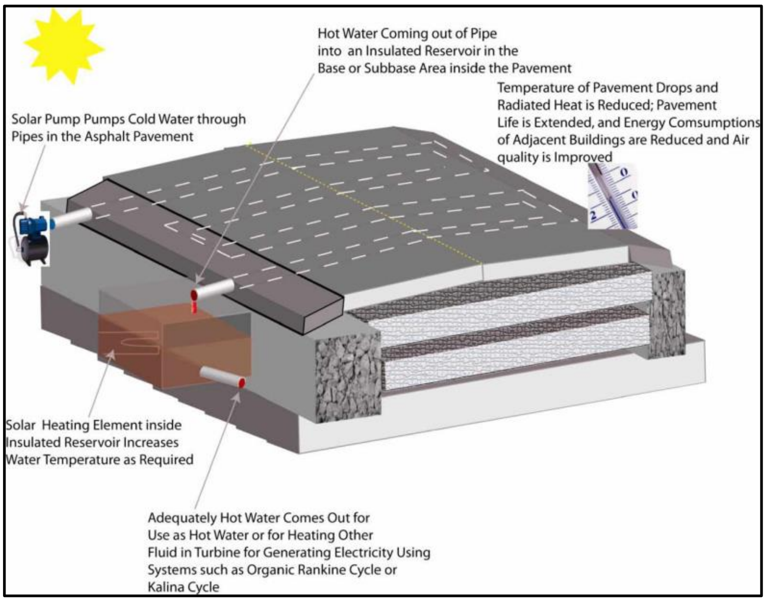

Figure 2: The structure of the asphalt collector with a pipe system (Todd, 2011)

The asphalt collector has been used in three different application types (Weijers & Groot, 2007) that are explained below, namely:

- Pipes In Concrete (PIC-collector)
- Pipes In Asphalt (PIA-collector)
- Water in Very Open-graded Water-bearing Asphalt Concrete (VOWAC-collector)

Pipes In Concrete (PIC-collector)

The asphalt construction is provided with an intermediate layer of steel fiber reinforced concrete, with a closed pipe system integrated. The steel fiber reinforced concrete is laying between two asphalt layers at, at least 13 cm depth beneath the top layer. The cross-section of the asphalt construction with the PIC-collector implemented is shown in Figure 3. The pipes are made of polyethylene and have a diameter of 25 mm. Through the pipes flows a mixture of water and glycol that will absorb the heat of the asphalt. The PIA-collector is developed within a

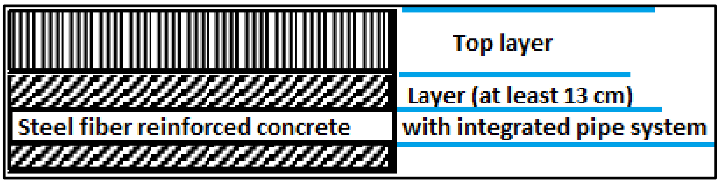

Figure 3: Cross-section asphalt construction with PIC-collector

[2] An aquifer is a water bearing layer in the ground. Aquifers are usually present at a depth between 60 and 120 meters beneath ground level. The water in aquifers is moving only 1 meter in 10 years and therefore, an aquifer is a good possibility to store heat and cold.

collaboration between Van den Boom Wegbouwkundig Bureau BV, ARCADIS Bouw/Infra BV, IF Technology BV en Velta BV and is provided by KWS too. Rijkswaterstaat (RWS) has executed a pilot project with this system, that is called Winnerway, at the N57 above the Haringvlietsluizen. The efficiency was, with 0,6 GJ (Giga Joule) per square meter per year, higher than expected and the extra investments necessary for the implementation of the system earned themselves back in 5 to 10 years. Also, the road has a larger lifespan of approximately 15 years. The costs of the PIC-collector are €25-50 per square meter excluding installation costs. (Weijers & Groot, 2007).

Pipes In Asphalt (PIA-collector)

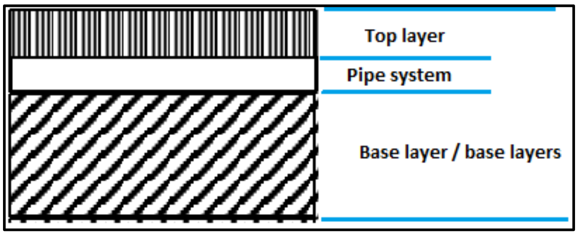

Figure 4: Cross-section asphalt construction with PIA-collector

Within this type of collector, the pipe system is placed directly beneath the top layer of the asphalt. Therefore, the pipes are laying less deep, at 5 to 7 cm beneath ground level. Through the pipes of the PIA-collector only flows water. Apart from the placement and that it is only using water, the system works the same as the PIC-collector. The cross-section of the asphalt construction with the PIA-collector implemented is shown in Figure 4. This application, with, just as the PIC-collector, polyethylene tubes, is used by Ooms Construction in several projects, e.g. Industrial site Westfrisia Oost III in the city of Hoorn (3,350 m²). Ooms is using the name RES (Road Energy Systems) for it. They are constructing it with mats that are pasted to the base layer with an adhesive layer. These mats are used to keep the tubes in place. The construction is finished by applying a special developed asphalt as the top layer (Ooms Construction, 2018). The costs are €50[3] per square meter excluding the installation costs and the efficiency about 0,5 to 0,7 GJ per square meter per year (Weijers & Groot, 2007). The payback time is around 10 years (personal communication, May 31, 2018) and the life span is at least 50 years (Ooms Construction, 2018).

Water in Very Open-graded Water-bearing Asphalt Concrete (VOWAC-collector)

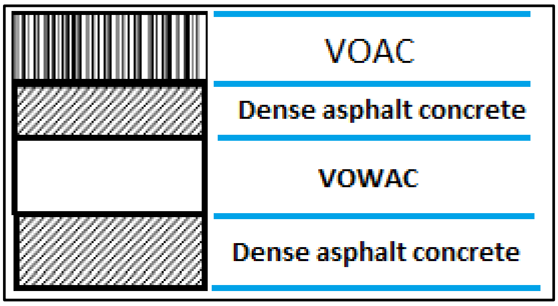

Figure 5: Cross-section asphalt construction with VOWAC-collector

This system, different from the other types, is not using pipes to absorb the heat. Between two layers of Dense Asphalt Concrete (DAC) that must have a width of at least 25 mm (Appendix G), a layer of Very Open-graded water-bearing Asphalt Concrete (VOWAC) is enclosed. On top of the asphalt construction Very Open-graded Asphalt Concrete (VOAC) is used. The cross-section of the asphalt construction with the VOWAC-collector implemented is shown in Figure 5. On the side of the road, pipes will guide ground water through the open structure of the VOWAC. At one side of the road, cold water will be brought in, and on the other side the heated ground water is collected and disposed. This collector type is used in the Zonneweg in Venlo. De Zonneweg is constructed and maintained by, among others, KWS Infra with standard road construction material and fully re-usable material (KWS infra, 2012). Although it is likely that some of the water in the VOWAC layer evaporates and therefore makes it less efficient, the efficiency of the VOWAC-collector, with 0,8 GJ

[3] The costs of €50 per square meter are the costs of the PIA-collector from Ooms (personal communication, May 31, 2018). In Appendix B costs of €75-125 are mentioned, but according to the interviewee the costs of €50 per square meter can be declared because a larger surface will decline the costs (personal communication, June 22, 2018).

per square meter per year, is still higher than that from the the PIC- and PIA-collector (Weijers & Groot, 2007). According to KWS Infra, the costs are about €40 per square meter excluding the installation costs (personal communication, May 28, 2018).

Overview

To give an overview, all relevant information about the three application types of the asphalt collector is shown in Table 2.

Table 2: Overview of application types asphalt collector

Collector type	Provider	Costs (excl. Installation costs)	Efficiency	Particularities	Payback time	Lifespan
PIC	Collaboration	€25-50 per m^2	0,6 $GJ/m^2/year$	Strong structure	5-10 years	Adds about 15 years to lifespan normal construction
PIA	Ooms Construction	€50 per m^2	0,5-0,7 $GJ/m^2/year$	Relatively high laying pipe system	Around 10 years	At least 50 years
VOWAC	Among other, KWS Infra	€40 per m^2	0,8 $GJ/m^2/year$	Is using layer of VOWAC instead of pipes	*Unknown*	*Unknown*

2.2. Technical conditions asphalt collector

To use the asphalt collector in a proper way it must meet certain technical conditions. First, the conditions that count for every application type will be discussed. After that the conditions that only count for the PIC- and PIA-collector and the conditions that only count for the VOWAC-collector will be discussed separately. This section gives an answer to the asphalt collector part of the second research question.

2.2.1. Technical conditions for all type of asphalt collectors

Fluid choice

The fluid that absorbs the heat in the collector must be suited for the asphalt collector. Therefore, the fluid must have a high heat capacity to keep the temperature as high as possible. Also, the fluid must be compatible with the pipes and must be cheap. Water is one of the most common fluids used in asphalt collectors, but sometimes mixtures of water and antifreeze are used (for example in the PIC-collector). This is to keep the solidification temperature of the fluid lower than the minimum temperature expected in the collector. The most commonly used antifreeze is glycol, what is the same antifreeze that is used in the PIC-collector. For most collectors, only water is used in the collectors and for an asphalt collector in the Netherlands, antifreeze is not needed (Bobes-Jesus, Pascual-Muñoz, Castro-Fresno, & Rodriguez-Hernandez, 2013).

The entry- and exit temperature of the cooling medium

The entry- and exit temperature have a large influence on the efficiency of the asphalt collector. If the entry temperature of the water is lower, the temperature in the collector can rise faster and more heat can be collected from the asphalt. That is because with a lower water temperature, the water will hand off less heat to its surrounding.

If the exit temperature is higher, the losses that occur during transportation to the aquifer will increase because of temperature difference with the surrounding.

The choice of the entry- and exit temperature depends on the purpose (smoothness control, maintenance reduction or heat collection) and the other variables of the asphalt collector. Often the temperature of the ground water is used for the entry temperature. The ground water temperature in the Netherlands at 10 meters below ground level is 10°C constantly (TNO, sd). Most of the developers of asphalt collectors strive to an exit temperature between 20 and 25°C, because with temperatures of 30°C or more the density of the stored warm water mass is low enough to create convection flows in the aquifer, what will cause a reduction in efficiency (Weijers & Groot, 2007). The liquid (in most cases water) temperature is based on the purpose of the collector. When the collectors purpose is smoothness control, the temperature must be higher than when its purpose is maintenance reduction or heat collection. The temperature is also based on the value of other variables (e.g. distance between pipes or collector depth). According to research of Bijsterveld et al. (2000), when the temperature increases, the stiffness of the asphalt will decrease. What results in a lower tolerance for peaks in horizontal and vertical stresses.

Flow rate in the collector

The amount of water that flows through the collector (flow rate), has a large influence on the exit temperature. When the flow rate in the collector is higher, the water stays in the collector for a shorter period and therefore it has less time to absorb heat. Also, the higher the temperature of the water, the slower the temperature will rise. So, because a higher flow rate gives the water less time to absorb heat, a higher flow rate and therefore lower water temperature, will cause a higher heat yield (Bobes-Jesus, Pascual-Muñoz, Castro-Fresno, & Rodriguez-Hernandez, 2013). However, the flow rate can't be maximized because the electricity costs of the pump is increasing quadratically with the flow rate (Agentschap NL, 2010). What the optimum is for the ratio between the flow rate and pump capacity, is depending on the entry- and exit temperature of the collector and with that the collector purpose. It is recommended to adjust the flow rate to the collectors' purpose, so the water can get the temperature needed for that.

Collector depth

The depth of the collector is also an important condition to deal with. Because less heat will make it to the lower layers of the construction, the temperature in the collector will be lower. Therefore, the higher the collector, the faster it will absorb heat. However, a larger collector depth results in a more favourable distribution of the stresses in the asphalt construction (Bijsterveld, 2000). Therefore, the collector depth needs to be optimized for its heat collection and the distribution of stresses. The prevention from failure of the asphalt construction must not come too much from a better asphalt mixture, because it will increase the costs. The optima of the discussed collector types are different. For the PIC-collector it has been found at 13 cm underneath the top layer, what comes down to 18 to 20 cm beneath ground level[4]. The PIA-collector has its optimum directly underneath the top layer, so 5 to 7 cm beneath ground level. For the VOWAC-collector it is 7,5 to 9,5 beneath ground level. The collector depth must only be enlarged when the top layer is not able to distribute the stresses. A smaller collector depth for the types can be realized with the use of high thermal conductive material in the asphalt mixture. This will be explained below.

Thermal conductivity of the asphalt pavement

A smaller collector depth can be realized only when the temperature in the lower regions of the asphalt construction is high enough. That can be caused by increasing the thermal conductivity of the asphalt pavement. This can be done by adding high thermal conductive material to the asphalt mixture or exchanging the conventional aggregate in the mixture with high thermal conductive

[4] The top layer width is discussed in section 4.1.2.

aggregate. An example is marble, whose thermal conductivity is about 2,08 to 2,94 $W \cdot m^{-1} \cdot K^{-1}$. Which is significantly larger than the thermal conductivity of conventional stone (1,7 $W \cdot m^{-1} \cdot K^{-1}$) (Wang, Wu, Chen, & Zhang, 2010).

Presence of an aquifer

To store the heat or cold that is collected, there must be an aquifer in the ground underneath the asphalt collector. A geo-technologist must determine if there is an aquifer with enough capacity present. According to a report of Weijers and De Groot (2007), that is the case at almost every location in the Netherlands. They are often located at a depth of 60 to 120 meters. The addition of the aquifer is shown in Figure 6. Interviewee 2 stated that the bigger the asphalt collector is, the bigger the source in the aquifer must be (Appendix B).

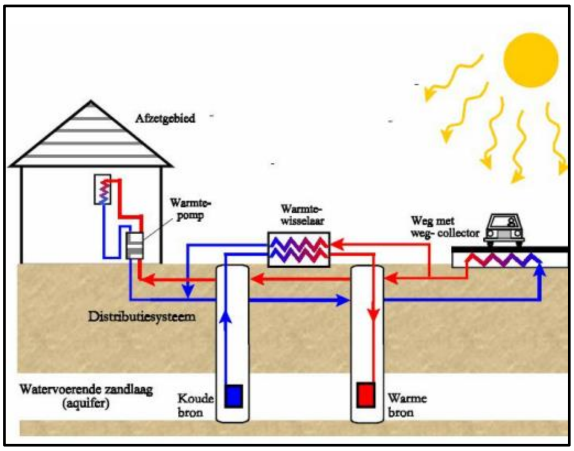

Figure 6: Visualization of heat- and cold transport (Agentschap NL, 2010)

Distance heat consumer to heat source

According to Interviewee 2 (Appendix B), the heat consumer must not be further than 1 km away from the heat source because the isolating layer that is around the pipe that is transporting the heat would be too expensive.

Asphalt colour

Because a darker colour will absorb more light and will therefore become warmer than light colours, it will be logical to strive to dark black asphalt. However, according to interviewee 2 (Appendix B), it is not necessary to experiment with different asphalt mixtures to get darker asphalt colour, because the influence on the efficiency of the collector will be neglectable. Therefore, the colour of original asphalt can be maintained.

Pumping capacity

The pump that is used to pump the water through the collector requires a capacity based on the purpose and surface of the collector. According to research of Siebert and Zacharakis (2010), RES has given a standardization to the dimensions of the pumping capacity. They stated that for example, an office building with a space of 10.000 m^2 requires an asphalt collector with a surface of 4.000 m^2 with a pumping capacity of 110 m^3/h.

Heat pump capacity

When the heat needs to be transported to e.g. a building, a heat pump is needed. This heat pump needs a certain capacity based on the size of the collector and building. For the example of RES with an office building with a space of 10.000 m^2 and an asphalt collector with a surface of 4.000 m^2, a heat pump capacity of 340 kW is needed.

2.2.2. Technical conditions for PIC- and PIA collector only

Distance between pipes

The distance between the pipes in the collector layer has influence on the strength of the asphalt construction and the heat collection of the asphalt collector. A smaller distance results in lower temperatures in the asphalt construction because the heat will be divided over more pipes. The lower temperature leads to higher stiffnesses that will result in a higher resistance to elastic deformation of the construction. Also, according to research of Bijsterveld et al. (2000), a smaller distance between the pipes leads to a larger peak in the vertical stresses. That is because the load must be guided around the hole of the pipe. Smoothness control is easier with a lower distance between the pipes because the flow temperature can be lower. However, the distance cannot be too low because the increase in stresses in the construction that is caused by the pipes can increase due to pipes that influence each other (Bijsterveld, 2000). Wang et al. (2010) tested the influence of the distance between pipes and concluded that the gathering heat's ability is depending on the distance a lot. In Figure 7 is shown that the temperature change rate declines exponentially with the distance between the pipes. Therefore, the distance must be kept as low as possible but there still must be enough space between the pipes for the asphalt to distribute the stresses. With the PIA-collector from Ooms they use a distance between the pipes from 15 cm, what still provides a temperature change rate of 0,65 °C(m^{-2} s)$^{-1}$.

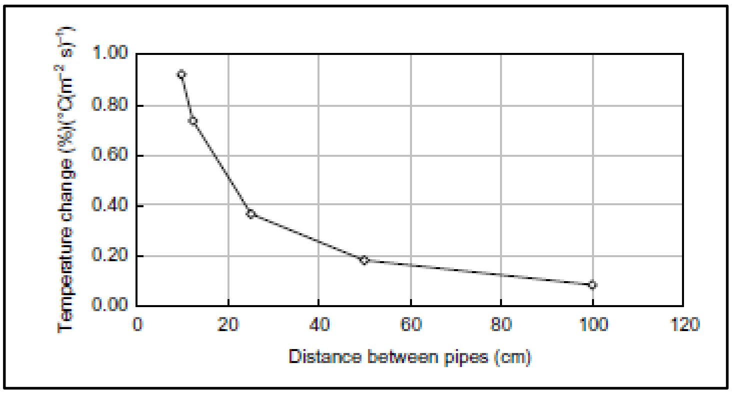

Figure 7: Effect of different distance between pipes on temperature change rate (Wang, Wu, Chen, & Zhang, 2010)

Pipe diameter

According to research of Wang et al. (2010), the effect of the diameter of the pipes on the water temperature is not significant. Although a pipe diameter of 3 cm, compared to a pipe with a diameter of 1 cm, can decrease the surface peak temperature with 5°C. Therefore, when smoothness control is the purpose of the collector, a larger diameter is recommended. However, pipes that are too wide may affect the structural performance of the road system.

Flow regime

To activate maximum heat transfer, the flow regime in the collector must be turbulent. Therefore, the pipe diameter and flow rate must be carefully chosen. Turbulent flow for internal pipe flow starts at a Reynolds number[5] (Re_D) of approximately 2.300, although a fully developed turbulent flow does not occur till approximately $Re_D \approx$ 10.000 (Bobes-Jesus, Pascual-Muñoz, Castro-Fresno, & Rodriguez-Hernandez, 2013).

[5] The Reynolds number determines whether the fluid is in laminar flow or turbulent flow. Laminar flow is when water flows smoothly in a predictable fashion and turbulent flow is when water flows chaotically, making predictions involving its flow difficult (Bergstresser, sd).

Pipe arrangement

There are two types of pipe arrangements for asphalt collectors: a network of pipes arranged in parallel (PTC) and arranged in a serpentine fashion (STC) as shown in Figure 8. Matrawy and Farkas (1997) compared the two arrangements and proved the STC to be more efficient than the PTC. That is because the flow rate along the entire pipe is greater. For maximum efficiency, a uniform flow in the pipes must be maintained, otherwise the efficiency can drop by 2-20% (Chiou, 1982).

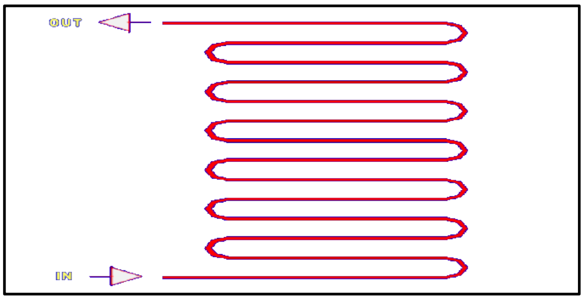

Figure 8: A network of pipes in serpentine fashion (JC Solar Homes, sd)

2.2.3. Technical conditions for VOWAC-collector only

Porosity

The higher the percentage of voids in the VOWAC-layer, the higher the flow rate in the layer is. Pascual-Munoz (2013) tested a VOWAC-collector with 23% and 27% voids in its VOWAC-layer and concluded that the layer with higher porosity (27%) leads to an on average 6 times higher flow rate.

Collector slope

To increase the flow rate, the slope of the road, and therefore the collector slope, can be increased. Pascual-Munoz et al. (2013) concluded in their research, that the flow rate is increasing more when the slope is increased from 0% to 0.5% than from 0.5% to 1%. From that can be concluded that the flow rate is not increasing linear with the collector slope.

2.2.4. Overview of technical conditions

An overview of the technical conditions of the asphalt collector and how is recommended to cope with them when implementing the asphalt collector is shown in Table 3. The collector types for which the technical conditions hold, are marked with an X.

Table 3: Overview of technical conditions of the asphalt collector

Technical condition	Summary	Recommendation	PIC-collector	PIA-collector	VOWAC-collector
Fluid choice	Must have high heat capacity and must be cheap	Water	X	X	X
The entry- and exit temperature of the cooling medium	Entry temperature: low as possible Exit temperature: 20-25 °C	Entry temperature: ground water temperature Exit temperature: 20-25 °C	X	X	X
Flow rate in the collector	Depends on collector purpose	Give water enough time for its purpose	X	X	X

Collector depth	Must be optimized for heat collection and stress distribution, if the collector depth is too large, the thermal conductivity must be broad up	Only be enlarged when top layer is not able to distribute stresses. When collector depth becomes too large add marble to the top layer mixture	X	X	X
Presence of aquifer	Must be present and have enough capacity		X	X	X
Distance heat consumer to heat source	Must be as low as possible	Not more than 1 km	X	X	X
Asphalt colour	Influence of darker colour is neglectable	Asphalt mixture must not be made darker	X	X	X
Pumping capacity	Based on purpose of collector and collector size		X	X	X
Heat pump capacity	Based on collector size and size of building heat consumer		X	X	X
Distance between pipes	Efficiency of collector declines exponentially with increase in distance between pipes	Should be no more than 20 cm to keep a minimum temperature change of 0.5 (%)°C(m^{-2} s)$^{-1}$	X	X	
Pipe diameter	Only when the purpose of the collector is smoothness control a higher diameter has impact	Between 1 and 3 cm	X	X	
Flow regime	Must be turbulent	Pipe diameter and flow rate must cause turbulent flow rate	X	X	
Pipe arrangement	STC better than PTC	STC	X	X	

Porosity	VOWAC-layer with porosity of 27% voids lead to 6 times higher flow rate than with 23% voids	VOWAC-layer must have high porosity			X
Collector slope	Flow rate increases when slope is larger but more from 0 to 0,5% than from 0,5 to 1%	Slope can be added when flow rate is too low			X

The most important results from the technical conditions are that the efficiency is largely depending on the entry- and exit temperature, the flow rate and the collector depth. What can largely determine the potential of applying the asphalt collector is the presence of an aquifer and the distance to the heat consumer that must not be more than 1 km.

2.3. Pros and cons asphalt collector

In this section all the pros and cons of the asphalt collector are discussed. Not all pros and cons have the same importance and therefore, all pros and cons have been ranked from most important to least important.

2.3.1. Pros

Extra function

The strongest point of the asphalt collector is that the road will be given an extra function, not only transporting but also generating heat. The Netherlands is very densely populated and therefore must make good use of its space. It has 5357 km of Rijksweg[6] (CBS, 2017), so when that space can be used for both transport and generating heat by implementing the asphalt collector, that would be a huge advantage.

Sustainable

According to research of Siebert and Zacharakis (2010), the system used in the example discussed in section 2.2.1. under ‘pumping capacity’, can produce 55% less CO_2 than a conventional gas heated and air-conditioned office building and is using 55% less fossil fuels for heating and cooling. So, the asphalt collector could be able to cause a decrease in CO_2 emission. Other factors that make the asphalt collector sustainable are that the lifespan of the asphalt construction enlarges, and it can de-ice the road in an environmental friendly way. This has been explained below.

Lifespan enlarging

When implementing the asphalt collector, the lifespan of the asphalt construction increases. That is because the water in the collector absorbs the heat and therefore, rutting will occur significantly less. Also, according to interviewee 2 (Appendix B), it is normal for RWS to only replace the top layer the first time maintenance work is done. The second time they replace the top layer and the intermediate layer. With RES, the intermediate layer is stronger and therefore, must be replaced within the third time maintenance work has to be executed. So, the lifespan will be enlarged because

[6] A Rijksweg is a road that is managed by RWS. Most highways but also expressways in the Netherlands are managed by RWS (Rijkswaterstaat, sd).

the asphalt has to cope with smaller peak temperatures and because the intermediate layer will be stronger. One of the goals of InnovA58 is to have a decrease in costs during the manage- and maintain phase of 20 percent (InnovA58, 2017). Therefore, the lifespan enlarging asphalt collector is an attractive way to achieve that goal.

Environmental friendly de-icing

Because the heat that is collected and stored in an aquifer during the summer, can be used to warm up the asphalt during winter, the road can be de-iced in an environmental friendly way (Ooms Construction, 2018). However, according to Interviewee 2 (Appendix B), in extreme weather conditions the asphalt collector alone, will not be enough to de-ice the road.

Subsidy

The Waerdse Energy Circuit, a project where the asphalt collector has been implemented, was funded by the European Fund for Regional Development (Waerdse Energie Circuit, sd). Therefore, when implementing the asphalt collector at other places, the costs could be reduced by this fund.

No impact on the landscape

People have an aversion to applications that have a negative impact on the landscape. A strong point of the asphalt collector is that it is almost invisible. Only the pumping station reveals that there is an asphalt collector implemented in the road.

Installable during maintenance work

The asphalt collector can be installed not only during the construction of new infrastructure but also during maintenance work. For example, when a road needs its periodically rebuilt work (Bobes-Jesus, Pascual-Muñoz, Castro-Fresno, & Rodriguez-Hernandez, 2013).

Asphalt ideal for heat yield

The asphalt is a material with high heat capacity and acts as a thermal mass, indicating it can store large amounts of heat (Siebert & Zacharakis, 2010). Also, the heat absorptivity, the amount of heat that is not reflected but absorbed, of asphalt is large. These characteristics makes asphalt an ideal material for heat yield. Because the asphalt stays warm a long time after the sun has gone down, heat can be collected even during the night when, for example solar collectors, do not work.

Space gain for buildings

Another strong point of the asphalt collector is that there is, apart from lower gas uses and therefore lower costs, another advantage for the buildings connected to the collector. Because of the asphalt collectors, radiators do not have to be installed what results in space gain in the buildings (Agentschap NL, 2010).

Traffic safety

Because the asphalt collector can be used to heat up the asphalt during the winter, the road becomes less slippery. Therefore, the traffic safety increases.

Future possibility to convert heat to electricity

When the absorbed heat cannot be used nearby the collector due to falling out of the heat consumer, it can be converted to electricity, so it can be transported without too much losses. Nowadays the efficiency of converting heat to electricity is very low, but in the future, it is likely that this will become more efficient and therefore a benefit for the asphalt collector. Researchers of the American Rice University have already discovered an alternative of the conventional way, by using materials that are not environmental unfriendly or costly, but they cannot produce it in large devices yet (De Ingenieur, 2017).

2.3.2. Cons

Falling out of heat consumer

Interviewee 2 (Appendix B) stated that before implementing the asphalt collector, there must be a plan of where the heat will be transported to and to balance the heat- and cold supply. But a threat is that plans can change. When buildings that are planned to be connected to the asphalt collector are not built, the collector is implemented in the road with no purpose.

Large number of involved parties

A large number of parties is involved in asphalt collector projects. All these parties (e.g. RWS, the province, municipalities and private parties) need to be on one line. A difficulty in this is that the main task of this governments is not providing energy, so they do not want to take the role of energy provider. Therefore, it is hard to determine who is going to be in charge of the collector and its energy production. An example of this problem is that nearby the Gasperdammerweg (A9) in Amsterdam, the project was proved to be technically and financially feasible but nevertheless has never been executed (Weijers & Groot, 2007).

Low-temperature heating-systems required

The buildings that will make use of the heat of the asphalt collector, must have low-temperature heating systems like wall- and underfloor heating (Agentschap NL, 2010). So existing buildings that do not have low-temperature heating systems will be hard to connect to the asphalt collector.

Providing user information

The user of the collected heat, must be provided with information before the first heating season, about using and maintaining the heat pump and underfloor heating. This is because the installation is different in use than the traditional cv-boiler with radiators (Agentschap NL, 2010).

Hard to standardize

To decrease the costs of the asphalt collector, it will be good to standardize the implementation of the collector. However, because all projects differ too much it is hard to do so.

Re-use impeding

Because with the PIC- and PIA-collector, pipes will be used, the later re-use of the asphalt mix will be more complicated.

3. Solar road

This chapter starts with an explanation of the working principle of the solar road. After the working principle has been described, the technical conditions of the solar road are discussed. The chapter ends with the pros and cons of the solar road. With this chapter, an answer to the solar road part of the first three research questions has been given.

3.1. Working principle solar road

The second application is a road covered with solar cells, the solar road. The solar cells are converting solar light to electricity. This is called the photovoltaic (PV) process. Despite criticism about the solar roads angle with the sun, it still has about 85% of the efficiency of the ideal angle with the sun and is therefore worth investigating (Appendix A). The energy can be transported to nearby buildings or can be included in the electricity net. The solar road does not have standard types to implement like the asphalt collector has. Therefore, three examples of application are discussed in this thesis. There are different ways to implement solar cells on a road and all providers are using different names for it. The solar road from Colas, called Wattway, is shown in Figure 9.

Figure 9: The Wattway solar road from Colas (Materia, 2017)

Pavenergy in Jinan, China

The PV-devices on a highway in Jinan are made out of 3 layers and have been built by Pavenergy. The bottom is an insulating layer to prevent moisture from getting to the photovoltaic devices in the middle layer, and the top is the protection layer built by concrete with glass fibers to let light be able to reach the PV-cells (China Daily, 2017). The 3 layers are replacing the top layer of 5.875 square meter of the standard cross-section of the highway. According to a report of Huang (2017), Pavenergy can handle 10 times more pressure than normal asphalt, has a snow-melting system integrated and has a designed lifespan of 20 years. In Jinan, one square meter of the path can generate 170 kWh per year and the constructions costs were €399 per square meter (Yi, 2018).

SolaRoad in Krommenie, the Netherlands

At the SolaRoad in Krommenie, solar collectors are implemented on a bicycle path. In 2014, solar collectors were implemented at 118 square meters of this path and the SolaRoad is enlarged to 144 square meters in 2016. This path consists of concrete modules of 2.5 by 3.5 metres with a hardened and translucent top layer of glass of approximately 1 cm thick, with a rough and transparent coating. The modules replace the top layer of the standard asphalt construction. The solar cells are implemented between protecting layers. This path generates 70 kWh per square meter annually and the costs were €1.000 per square meter. The life span is about 10 to 20 years (Strukton, 2018).

Wattway in Normandy, France

In Normandy, the French company Colas covered a road of 1 km (2.800 square meter) with solar collectors that must generate enough power to provide the street lighting of a village with 3400 inhabitants. According to Colas, that has named their product Wattway, the panels are designed so that they can be installed directly on top of existing roadways and have a lifespan that is able to handle 1 million vehicles or 20 years of normal traffic (The Colas Group, 2018). The panels are made of a thin polycrystalline silicon film and coated in a layer of resin to strengthen them and make them less slippery. Because the panels are so thin, they can adapt to small changes in the surface of the pavement due to temperature shifts and are sealed tightly against the weather (Lewis, 2016). Wattway generates 99 kWh per square meter per year in Normandy and the costs were €1.785 per square meter (Danielo, 2016). Since May 2018, Wattway is tested on the N401 nearby Kockengen on its efficiency and applicability and in Hengelo the Boekelosebrug will be covered with the solar road from Wattway too.

Overview

The three different examples of practice of the solar road are all performing differently. An overview of all relevant information about the different applications is given in Table 4. Because the efficiency depends on the number of hours of sunshine in the area, all the efficiency values are converted to the number of hours of sunshine in the study area. This has been done with statistics of hours of sunshine from Leads2Travel B.V. (2018) and Klimaatinfo (2018).

Table 4: Overview of different applications solar road

Location	Surface	Efficiency	Costs	Particularities	Lifespan
Jinan, China (Pavenergy)	5.875 m^2	170 kWh per m^2 / year = 93 kWh per m^2 / year in Eindhoven	3.000 yuan ≈ €399 per m^2	• Highway • Can handle 10 times more pressure than normal asphalt • Used to power street lights and snow-melting system	20 years
Krommenie, the Netherlands (SolaRoad)	2014: 118 m^2 2016: 144 m^2	70 kWh per m^2 / year = 64 kWh per m^2 / year in Eindhoven	€1.000 per m^2	• Bicycle path • Rough surface due to transparent epoxy resin with glass pearls • Crystalline silicon solar cells in hardened glass	10-20 years
Normandy, France (Wattway)	2.800 m^2	99 kWh per m^2 / year = 80 kWh per m^2 / year in Eindhoven	€1.785 per m^2	• 1 km road	1 million vehicle or 20 years of normal traffic

3.2. Technical conditions solar road

In this section the technical conditions of the solar road are discussed, giving an answer on the solar road part of the second research question.

Transparent top layer

The sunlight must reach the PV-panels in the most efficient way, therefore the glass or concrete above the panels must be transparent and must remain so. When glass is used, to keep it transparent, it must be scratch-resistant. Glass itself is very hard, but quartz (the main component of sand) is harder, so the glass in its normal shape may not be able to deal with the friction of sand with heavily loaded traffic on it. Therefore, relief can be added to the glass. The relief can ensure that only a small part of the glass will be scratched (Rijkswaterstaat, 2012). To make the glass harder, another solution is to give it a coating that is harder than sand (e.g. Aluminium Oxynitride). To keep the glass or concrete transparent, there must be dealt with oil and transmission fluid spills on the road surface too. It is possible to sprinkle titanium dioxide on the surface, which turns oil and grease into a powder that can be blown off by wind or washed away by rain (Engineersaustralia, 2016).

Strength

The solar road must be able to transfer the power of the traffic to the underlying asphalt. It also must be strong enough to manage the point load of falling objects (Heidinga, 2015).

Shrink difference

All 3 applications discussed in section 3.1. are using multiple layers of different materials. These materials have different temperatures at which they shrink and grow. Therefore, when implementing solar cells on a road, this shrink difference must be dealt with. Heidinga (2015) stated in his research, that with the bicycle path in Krommenie, they used a layer of rubber between the concrete and the glass to manage shrink differences, without breaking the glass.

Driving comfort

In most examples the solar road is made of elements that are placed together. The driver must not feel the transition to another element, so the elements need to be placed seamlessly together.

Easy to adjust

Because solar cells are developing fast, the solar road must be able to catch up with this development. Therefore, the solar cells used in the solar road must be easy to adjust.

When using glass

Non-reflecting glass

Because loads of traffic have to pass the solar road each day, the glass must be non-reflecting at every angle it makes with the sun. According to an article of Rijkswaterstaat (2012), scientists are investigating ways to make glass less reflecting and are therefore etching the glass. In that way they managed to get more light in the solar cell and make the glass less reflecting.

Ability to deform

When the road is made of asphalt, the glass layer must be able to deform with the asphalt. According to research of Rijkswaterstaat (2012), one way to manage that is to divide the solar road in small parts with one solar cell each. In this way, the parts can follow the deformation of the road.

Coating

The Solar road must have the skid resistance of the formal top layer of the construction where it is placed. This can be managed with a coating on top of the glass. This coating must be able to keep the skid resistance during the whole lifespan of the solar road.

Overview of technical conditions

An overview of the technical conditions of the solar road and how is recommended to cope with them when implementing the solar road is shown in Table 5.

Table 5: Overview of the technical conditions of the solar road

Technical condition	Summary	Recommendation
Transparent top layer	To keep the glass transparent, it must be scratch resistant	Two options: • add relief • add coating that is harder than sand
Strength	The solar road must be able to transfer the power of the traffic to the underlying asphalt	Enough glass must be used to cover the PV-cells
Able to handle shrink difference	The different materials in the solar road will shrink at different temperatures	A layer of rubber can be added between the asphalt and the glass
Driving comfort	A solar road is in most cases made of multiple elements	The elements must be placed seamlessly together

Easy to adjust	Solar cells are developing fast and the solar road must be able to catch up with this development	The PV-cells must be easy to adjust
Non-reflecting glass	The glass must be non-reflecting at every angle it makes with the sun	The glass can be etched to prevent reflecting
Glass with the ability to deform	The glass must be able to deform with the asphalt	The solar road must be divided into small parts
Skid resistant coating	The solar road must have the skid resistance of the original highway	A coating can be applied to provide skid resistance

From the technical conditions of the solar road the most important findings are that the efficiency of the solar road is largely depending on the transparency of the top layer. The potential of the solar road is largely depending on the strength and driving comfort.

3.3. Pros and cons solar road

In this chapter all the pros and cons of the solar road are discussed. Not all pros and cons have the same importance and therefore, all pros and cons have been ranked from most important to least important.

3.3.1. Pros

Extra function

Just like with the asphalt collector, when implementing the solar road, the road will be given an extra function, not only transporting but also generating sustainable energy.

Sustainable

Because of the climate agreement (Dutch Emissions Authority, sd) the CO_2-emmisions must be declined. However, most of the Dutch electricity is still generated with the use of fossil fuels (CBS, 2016). Because the solar road will generate electricity without emission of CO_2, it helps with reaching the goal to lower the CO_2-emmissions.

Subsidy

According to Interviewee 1 (Appendix A) SDE+ (Stimulering Duurzame Energieproductie) is the subsidy when it comes to large sustainability projects with solar energy. SDE+ gives a certain compensation per kWh to compensate the difference between green and grey energy. However, RWS cannot request this subsidy because it is an authority. But this subsidy can be of relevance when the ground is sold to for example an energy producer like Nuon.

Expansion possibilities

A large benefit of the solar road is that it has many possibilities to be expanded. The road will not only be used to generate electricity and transporting vehicles, but it could be possible to use the road for other futures too. For example, electric cars that drive over the road, could be charged during their ride with the use of induction. A German provider called Solmove has plans to build a road that can do this for the Olympic Games in Beijing of 2022. The road must be able to charge electric busses during their transport of the olympiers to the city (Solmove, 2018). Another possibility is to use the generated power to heat up the road to prevent snow and ice accumulation or to implement signs with LED-lighting into the solar road to warn for e.g. slippery conditions. Solar Roadways, an

American provider of a solar road, has integrated LEDs into their panels that are able to turn up the brightness during dark, foggy or stormy conditions (Engineersaustralia, 2016).

Natural preservation

More and more agricultural ground is used for big solar- or wind parks, but not everyone is content with that (Straver, 2018). Local people are protesting against the parks because of their natural devaluation and the loss of ground for the food industry. A large advantage of the solar road is when it has been implemented on a large scale, these parks are not necessary anymore and the ground can be used for the food industry.

Development of PV-cells

PV-cells are developing fast. The silicon cells are currently used the most, but research to other techniques is done on a large scale. The thin-film solar cell is getting cheaper and more efficient (Solliance, 2018). So, a large advantage of the solar road, is that it will get cheaper to implement it and it will become more efficient too.

Reduction in amount of power lines

The electricity from the solar roads could be used to power nearby houses and buildings. That will reduce the amount of power lines that have to transport electricity over long distances.

3.2.2. Cons

Costs

A large drawback of the solar road are its costs. The solar road with the lowest construction costs of Table 4, is still €399,- per m^2. Assuming that it needs to be replaced every 20 years (max. lifespan in Table 4), the maintenance of the solar road is expensive too, excluding the costs for parts of the solar road that need to be repaired earlier.

The construction and maintenance costs are not the only expensive part of the solar road. The energy generated by the PV-cells must be exported to the electricity network or it must be stored so it can be used for e.g. the lampposts along the highway. However, the costs to connect to the electricity network are high as well, because the network must be (over)dimensioned to cope with the peak moments in the summer. When the energy will be stored, large batteries are needed. As shown in Figure 10, the price of electricity storage is declining but is still \$100/kWh when the goal of 2020 is reached.

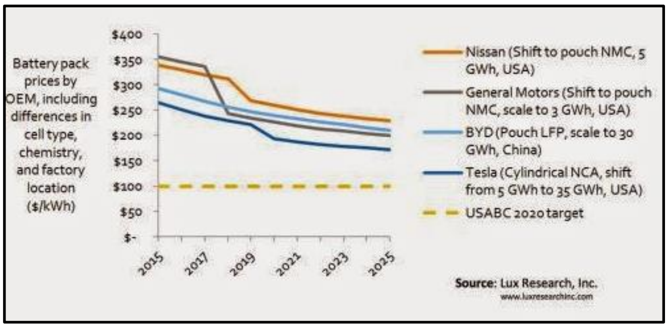

Figure 10: Battery pack prices (Lux Research, 2015)

Designed life cycle not guaranteed

Because the solar road is a relatively new concept, the designed life cycle cannot be guaranteed. For example, the SolaRoad in Krommenie, lost a part of its coating (NH Nieuws, 2014). This shows that the solar road may not be developed enough to implement it on large scale because the unguaranteed life cycle.

Decrease in transparency

Due to the horizontal placement of the panels, the dirt of the traffic (e.g. mud, snow etc.) can easily stick to the surface. The more dirt on the surface, the less light will make it to the solar cells and therefore, the efficiency decreases.

Limitation of electricity net

Nowadays only 13% of the used energy contains of electricity, in a sustainable future probably a lot more will come from electric energy (TU Delft, 2018). The current electricity network has enough capacity to cope with the current amount of energy, but a large incline in the generation of electricity is hazardous. Grid operators Tennet and Enexis are already warning for a capacity shortage of the current electricty network (NOS, 2018). When planning large solar roads, the limitation of the electricity net can be a potential pitfall.

Possible vandalism

According to journalists of the Guardian (2018), after the solar road of Pavenergy in China was open for just 5 days, thieves had stolen a part of the road. Probably they wanted to copy the used technique, because the materials themselves are inexpensive. With this action they damaged adjacent panels too. So, a disadvantage of the solar road is that it is relatively vulnerable for vandalism.

4. Technical requirements A58

Making use of the asphalt collector and solar road results in a change of the system 'road'. To find out what the potential is of the asphalt collector and solar road on the A58, the technical requirements of the road system need to be discussed. This chapter discusses what the technical requirements of the current A58 are, and which of these technical requirements need to be reconsidered when implementing the applications. With this chapter, an answer to research question 4 has been given.

4.1. Technical requirements of current A58

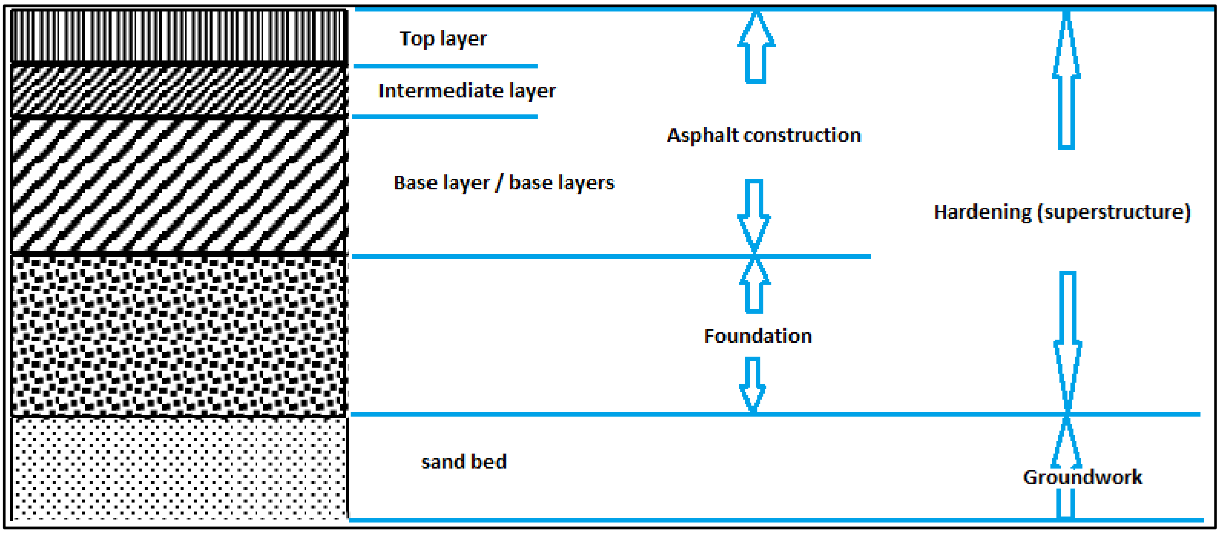

Figure 11: Cross-section of a standard asphalt construction (Erkens, 2015)

A road construction in the Netherlands, and therefore the A58, is built up as shown in Figure 11. What kind of asphalt is used at the A58 will be discussed later. According to Erkens (2015), the functional condition that RWS has set to a road construction is to spread the traffic load to the ground during its lifespan. In addition to the functional condition, Erkens (2015) also mentions a list of categories for technical requirements of a road construction. This list is shown in Table 6.

Table 6: Technical requirements of a road construction (Erkens, 2015)

Main requirements	Sub requirements
Safety	Length profile, cross slope, height differences, skid resistance, brake delay
Reliability	Bearing capacity, stone impact, position of seams, cross slope intermediate layer, drainage
Ambient nuisance	Noise
Maintainability	Removability
Execution	Longitudinal seams, seam damage rollers
Design	Position and design longitudinal seams
Future-proof	Suitable reuse

Because the asphalt collector and solar road will not be implemented in the foundation or base layer of the asphalt construction and therefore are not affecting the technical requirements in these layers, only the asphalt use and requirements of the top layer and intermediate layer are considered in this thesis. The design load that the A58 must cope with and the asphalt use and requirements of the top and intermediate layer are discussed in this section.

4.1.1. Design load

The design load that the asphalt construction must be able to deal with, is expressed in the expected number of truck axles during het design period (Dienst Grote Projecten en Onderhoud, 2013). This is based on the traffic intensity of heavy motor vehicles on the road. The traffic intensity of the study area is directed from statistics of Rijkswaterstaat (2017) and is made visible with ArcGIS Pro as shown in Figure 12 and Figure 13.

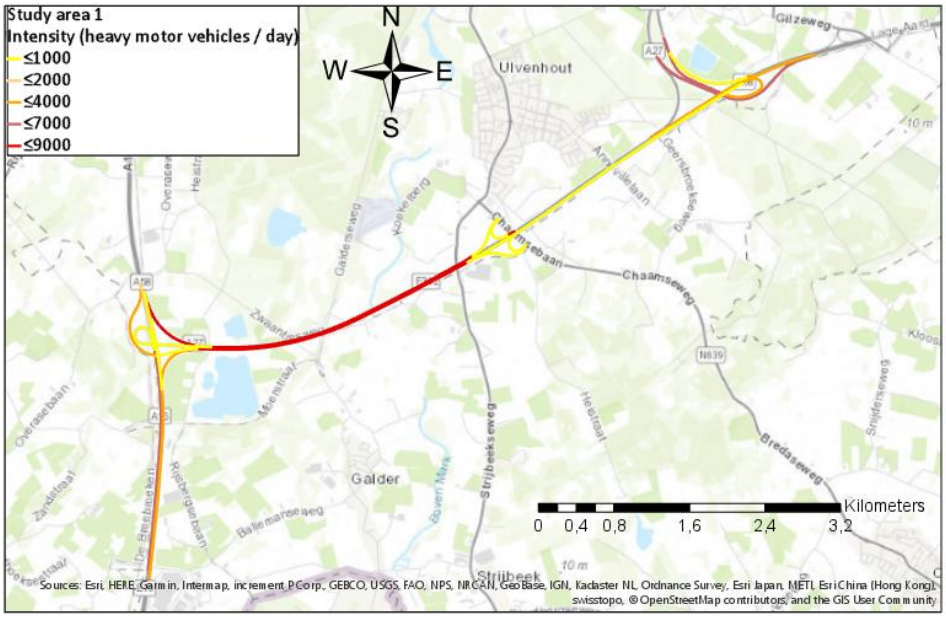

Figure 12: Traffic intensity node Sint-Annabosch - node Galder

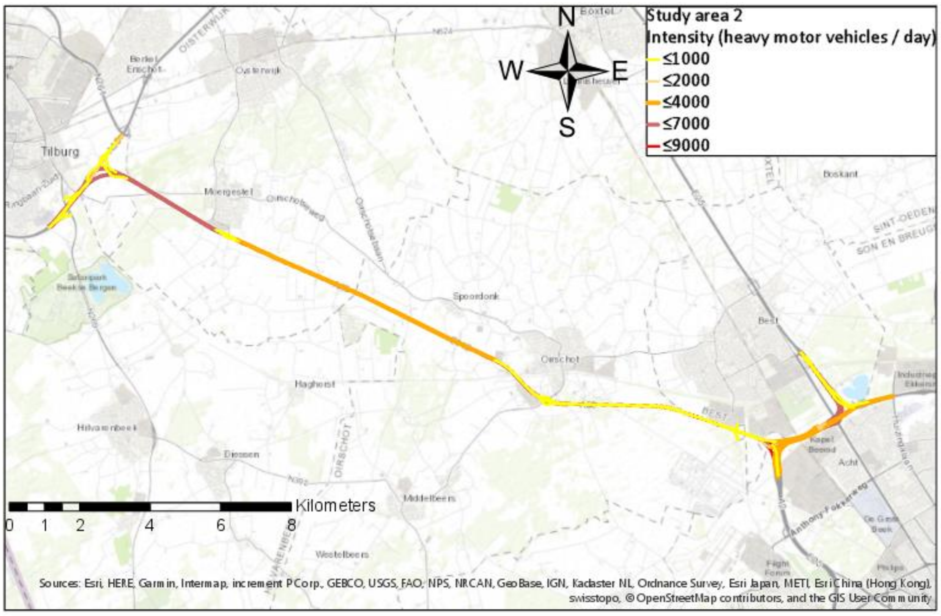

Figure 13: Traffic intensity Eindhoven - Tilburg

With the median of the traffic intensity in the study area, which is 726 heavy vehicles per day, there is calculated that the average asphalt construction in the study area must be able to hold $2{,}2 \times 10^7$ truck axles during its lifespan. The calculation of the design load can be found in Appendix C.

4.1.2. Top layer

The technical advisor of roads of InnovA58 (personal communication, April 30, 2018) stated that the top layer of the A58 consists of VOAC (50mm), VOAC+ (50mm) or double layered VOAC (70mm). For VOAC mixtures only requirements regarding water sensitivity exists. The VOAC mixture must have a minimum water sensitivity of ITSR80 (Indirect Tensile Strength Ratio 80) (CROW, 2010) and of course must be able to hold the in 4.1.1. calculated 2,2 x 10^7 truck axles during its lifespan.

4.1.3. Intermediate layer

According to the technical advisor of roads of InnovA58 (personal communication, April 30, 2018), the intermediate layer of the asphalt construction of the A58 consists of ACBind[7] or STAB VOAC of ca. 80 mm. Interviewee 3 (Appendix G) stated, that STAB is nowadays called AC16[8] or AC20. Depending on the layer, the name base, bind or surf is added.

According to research of Dienst Grote Projecten en Onderhoud (2013), the intermediate layer must be resistant against permanent deformation and must realise a good transmission from shear stresses from the top layer to the ground. Because, according to statistics of Rijkswaterstaat (2017), the A58 has more than 2500 trucks per day per driving direction, the highway is grouped in truck-intensity category C (Dienst Grote Projecten en Onderhoud, 2013). For an asphalt construction with truck-intensity category C, the requirements in Table 7 are set to the intermediate layer. Also, the intermediate layer must be able to hold the in 4.1.1. calculated 2,2x10^7 truck axles during its lifespan.

Table 7: Technical requirements intermediate layer with truck-intensity category C

Characteristic	Condition
Stiffness	5.500-14.000 MPa
Water sensitivity	ITSR70/ITSR80
Deformation resistance	fcmax0,4
Fatigue resistance	80 µm/m

4.2. Changing technical requirements when implementing the asphalt collector or solar road on the A58

Now that the technical requirements of the A58 and technical conditions of the asphalt collector and solar road in general are known, the A58's technical requirements that change when implanting the applications on the A58 can be considered.

4.2.1. Changing technical requirements when implementing the asphalt collector

The asphalt on the A58 must meet a large number of requirements. Most of those requirements do not change when implementing the asphalt collector, but some do. The standard requirements of an asphalt construction are given in section 4.1., the requirements that will change per type will be discussed in this chapter. Every type of asphalt collector has a different effect on the asphalt and therefore, the technical requirements of the A58 that need to be considered per asphalt collector are discussed separately.

[7] AC stands for Asphalt Concrete and is popularly known as 'asphalt'. To the abbreviation AC a name is added depending on the layer of asphalt. 'Base' for the base layer, 'bind' for the intermediate layer and 'surf' for the top layer (Appendix G).

[8] The number behind AC stands for the largest grain size in the aggregate for the asphalt mixture in mm (CROW, 2010).

PIC-collector

The PIC-collector uses an extra steel fiber reinforced concrete layer between two layers (Figure 3). To implement this type of collector, the layer must meet certain technical requirements. The reliability of the asphalt construction can change due to implementation of the new layer. The reliability factors that need to be looked at are: bearing capacity and the cross slope of the upper side of the intermediate layer. Also, one of the factors of maintainability can change due to implementation of the new layer, namely the removability. All technical requirements of the asphalt construction that need to be reconsidered when implementing the PIC-collector can be found in Table 8.

Table 8: Technical requirements of A58 to reconsider when implementing PIC-collector

Factor	Technical requirement
Bearing capacity	The asphalt construction must be able to cope with 2,2 x 10^7 truck axles during its lifespan (section 4.1.1.).
Cross slope of upper side intermediate layer	The cross slope of the upper side of the intermediate layer must be equal to the cross slope of the upper side of the top layer with a tolerance of ±0,2% (Zandberg, 2015).
Removability	The layers must be easy to remove (Erkens, 2015). There are no exact technical requirements for the removability.

PIA-collector

The PIA-collector has its pipe system placed directly beneath the top layer of the asphalt and according to Interviewee 2 (Appendix B), the layer with the pipes, or in the Road Energy Systems' case the tubes, will replace the intermediate layer (Figure 4). This pipe system must meet certain technical requirements to keep the performance of the asphalt intact. The PIA-collector is affecting almost the same requirements of the asphalt construction as the PIC-collector, except that the cross slope of the upper side of the intermediate layer will not change. So, the reliability factors that need to be investigated are the bearing capacity and the removability. All technical requirements of an asphalt construction that need to be reconsidered when implementing the PIA-collector can be found in Table 9. According to Interviewee 2 (personal communication, June 7, 2018), the part that needs to be built into the road of a PIA-collector used by Ooms Construction of max. 10.000 m^2, takes four weeks to implement. The pipe network and sources can be built in during a separate phasing in advance of the road construction. Therefore, the PIA-collector will add four weeks to the phasing of the highway when implementing asphalt collectors of max. 10.000 m^2. The total time needed to mill the top- and intermediate layer and the time needed to apply a new top- and intermediate layer of the current A58, is about 13 days (Appendix D). What comes down to approximately three weeks. So, when implementing the asphalt collector while replacing two layers of the construction, the replacement time will be enlarged from three to seven weeks.

Table 9: Technical requirements of A58 to reconsider when implementing PIA-collector

Factor	Technical requirements
Bearing capacity	The asphalt construction must be able to cope with 2,2 x 10^7 truck axles during its lifespan (section 4.1.1.).
Removability	The layers must be easy to remove (Erkens, 2015). There are no exact technical requirements for the removability.

VOWAC-collector

To implement the VOWAC-collector, a lot of the standard cross-section of the asphalt construction must be changed. Only because of the dense asphalt concrete layers (Figure 5), there is a large number of factors that need to be investigated. The reliability factors that need to be investigated are: bearing capacity, stone impact, cross slope intermediate layer and drainage. The drainage is an important factor for the VOWAC-collector because it may be hard to fit the technical requirements because the DAC layers may not able to cope with extreme weather conditions. Also, the maintainability factor removability needs to be discussed. For the VOWAC layer, the bearing capacity and the cross slope of the upper side of the layer need to be considered. All technical requirements of the asphalt construction that need to be reconsidered when implementing the VOWAC-collector can be found in Table 10.

Table 10: Technical requirements of A58 to reconsider when implementing VOWAC-collector

Factor	Technical requirement
Bearing capacity	The asphalt construction must be able to cope with 2,2 x 10^7 truck axles during its lifespan (section 4.1.1.).
Stone impact	For highways is only 'steenslag 3' allowed (Vos, 2015).
Cross slope intermediate layer	The cross slope of the upper side of the intermediate layer must be equal to the cross slope of the upper side of the top layer with a tolerance of ±0,2% (Zandberg, 2015).
Drainage	The road must have a cross slope of 2,5% and the water must drain per lane separately (Rijkswaterstaat, 2012).
Noise	The noise production must be between the 50 and 65 dB (Rijkswaterstaat, 2016).
Removability	The layers must be easy to remove (Erkens, 2015). There are no exact technical requirements for the removability.

4.2.2. Changing technical requirements when implementing the solar road

The technical requirements of the asphalt construction that will change when implementing the solar road applications in the A58 are discussed in this section. Because all solar road applications are affecting the same technical requirements of the A58, they are discussed together.

The top layer must have the same technical requirements as the top layer of standard asphalt on a highway. Therefore, there are factors that need to be considered. The new top layer of the technique used by Pavenergy, the modules used with the SolaRoad and panels from Wattway all have influence on the same technical requirements. To keep the road safe, the cross slope, skid resistance and brake delay of the new top layer need to be investigated. Also, the reliability factors: bearing capacity and drainage, the ambient nuisance factor noise, and the maintainability factor removability will change when implementing the solar road applications. All technical requirements of the asphalt construction that need to be reconsidered when implementing the solar road applications in the A58, can be found in Table 11.

Table 11: Technical requirements to reconsider when implementing the solar road

Factor	Technical requirement
Skid resistance and Brake delay	The initial brake delay must not be lower than 4,5 m/s^2. After 10 days 5,2 m/s^2. After one year 6,5 m/s^2 (Vos, 2015).
Bearing capacity	The asphalt construction must be able to cope with 2,2 x 10^7 truck axles during its lifespan (section 4.1.1.).
Cross slope and drainage	The road must have a cross slope of 2,5% and the water must drain per lane separately (Rijkswaterstaat, 2012).
Noise	The noise production must be between the 50 and 65 dB (Rijkswaterstaat, 2016).
Removability	The layers must be easy to remove (Erkens, 2015). There are no exact technical requirements for the removability.

5. Potential implementation asphalt collector on A58

Now all technical conditions of the asphalt collector, its pros and cons, and its impact on the technical requirements of the A58 are known, the best way to implement the asphalt collector in the A58 is determined giving an answer to the asphalt collector part of research question 5. This has been done by determining the best application type and best potential location to implement the asphalt collector.

5.1. Best application type for the asphalt collector to implement on the A58

Because the three different types of asphalt collectors have large differences, the best type to implement the asphalt collector on the A58 is picked with an MCA. To pick the best asphalt collector type out of the PIC-, PIA-, and VOWAC-collector, an MCA has been done with the help of six criteria. These criteria and how the collectors score on them are shown in **Fout! Ongeldige bladwijzerverwijzing.**. The explanation of the score of the collectors on the criteria and the sensitivity analysis of the MCA can be found in Appendix E. The scores differ from 1 (bad) to 5 (good) and a weight of 1 to 3 is given to the criteria. The weight and scores are based on the technical conditions of the asphalt collector, its pros and cons, and the impact of the collector on the technical requirements of the A58.

Table 12: MCA best asphalt collector type

Criteria	Weights	PIC-collector	PIA-collector	VOWAC-collector
Innovative [-]	3	1	1	4
Costs [€/m^2]	*2*	*4*[9]	*1*[10]	*3*[11]
Experience [-]	3	2	4	1
Efficiency [GJ/m^2/year]	3	3[12]	3[13]	4[14]
Applicability A58 [-]	3	3	5	2
Re-usability [-]	1	4	4	4
Total score	-	39	45	43

The best asphalt collector type according to the executed MCA is the PIA-collector. This is largely

[9] The costs of one square meter of the pipe system excluding the operating system and further storage according to Weijers & De Groot (2007) are 25-50 €/m^2. Therefore, in the MCA an average of 37.5 €/m^2 is used. In comparison to the cost of the other collectors, a score of 4 is given for the PIC-collector on this criterion.

[10] The costs of one square meter of the PIA-collector of Ooms is 50 €/m^2 for large surfaces according to Interviewee 2 (personal communication, May 31, 2018). In comparison to the cost of the other collectors, a score of 1 is given for this criterion.

[11] According to a telephone conversation (personal communication, May 28, 2018) with a project manager of KWS Infra (provider of the VOWAC-collector), the costs of the asphalt construction of the VOWAC-collector are approximately 40 €/m^2, excluding the installation costs that can differ from €100.000 to €400.000. In comparison to the cost of the other collectors, a score of 3 is given for this criterion.

[12] The efficiency of the PIC-collector according to Weijers & De Groot (2007) is 0.6 GJ/m^2/year. In comparison with the efficiency of the others, the PIC-collector scores a 3 on this criterion.

[13] The efficiency of the PIC-collector according to (Weijers & Groot, 2007) is 0.5-0.7 GJ/m^2/year. Therefore, in the MCA an average of 0.6 GJ/m^2/year is used. In comparison with the efficiency of the others the PIC-collector scores a 3 on this criterion.

[14] According to research of Dijkink (2009), the VOWAC-collector has an efficiency of 0.8 GJ/m^2/year. In comparison with the efficiency of the other the VOWAC-collector scores a 4 on the criteria ‘efficiency’.

because of its applicability on the A58. A provider of the PIA-collector is Ooms Construction B.V. that named the PIA-collector RES.

5.2. Best location to implement the asphalt collector on the A58

In this section the best location in the study area to apply the asphalt collector has been investigated. Important for the location is that the collected heat can be transported max. 1 km away from the asphalt collector to be efficient. Therefore, a location is needed that is not more than 1 km away from the A58 in the study area and that has a high heat demand. To find this location, the gas use around the study area on zip code 4-digit level[15] is directed from statistics of Energie in beeld (2017) and from these statistics a map has been made in ArcGIS Pro with help of the zip code locations from CBS (CBS, 2017). The location is depending on the gas use because heat is mostly generated from gas. In the map, that is show in Figure 14, a boundary is made visible to display the area that is within 1 km of the A58 in the study area. The figure shows three districts within the area where the gas use is, with 3 to 5 m^3/m^2/year, the highest per square meter. Therefore, these districts have the most potential to become the best location for the asphalt collector. In the figure all three districts are marked with an arrow. What points out is that all three best potential locations are positioned in the right part of the study area. That is because the relatively low gas uses around the left area.

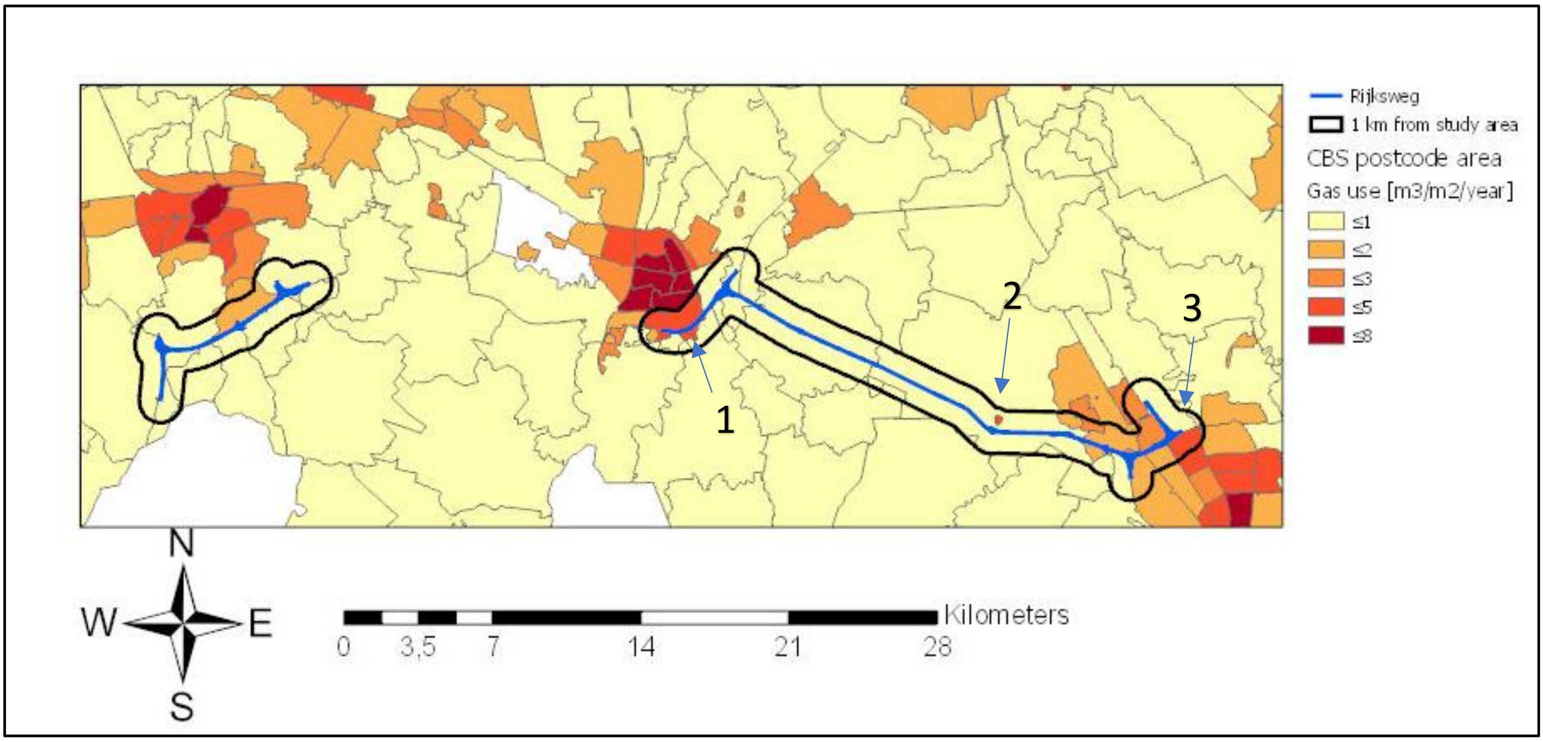

Figure 14: Gas use around the study area

The best location of the three districts

To determine which of the three districts, that are marked with an arrow in Figure 14, is the best, they have been compared to each other. District 2 (the district marked with a two) is probably one of the three districts that has one of the highest gas uses per square meter because there is a gas station in this relatively small district, so the gas is not used to heat up a building. Therefore, this

[15] In the Netherlands the zip code contains of four digits and two letters. The zip code 4-digit level is the zip code excluding the two letters and indicates the region (first two digits) and the district (last two digits) of the concerned area. The zip code 6-digit level contains the four digits and two letters. The letters indicate a range of house numbers, usually on the same street.

district is not a good potential location to implement the asphalt collector. District 1 and 3 are almost equal, with many houses in both districts. However, district 1 contains a large heat consumer (a hospital) with a WKO-system[16] already built into the ground. That means that the connection with the, for the asphalt collector required aquifer, is already there. According to the annual environmental report of the hospital that is called the Sint Elisabeth hospital, it used almost 4 million m^3 of gas in 2015 (Elisabeth-TweeSteden Ziekenhuis, 2015). That comes down to more than 36% of the total gas use in the district (Energie in beeld, 2017). Because this hospital is a large potential consumer of the heat collected by the asphalt collector, district 1 is chosen to be the best location to implement the asphalt collector in the study area.

The best potential location to implement the asphalt collector

The widened part of the A58 that is the closest to the hospital, will contain of 4 lanes and an emergency lane on the road half on the side of the hospital (InnovA58, 2017). Each lane has a width of 3,5 m (CROW, 2016). This means that with a collector surface of 10.000 m^2 (what is the maximum surface according to Interviewee 2 (personal communication, May 31, 2018)), 5 lanes of 571 meter in length must be covered with the asphalt collector. In this way, the distance between the hospital and the asphalt collector is not more than 600 m. A map with the location of the part of the road that is the best location for the asphalt collector is shown in Figure 15. Options with implementing the asphalt collector on less lanes but on a longer part of the road are not preferable because the collector would be further away from the hospital.

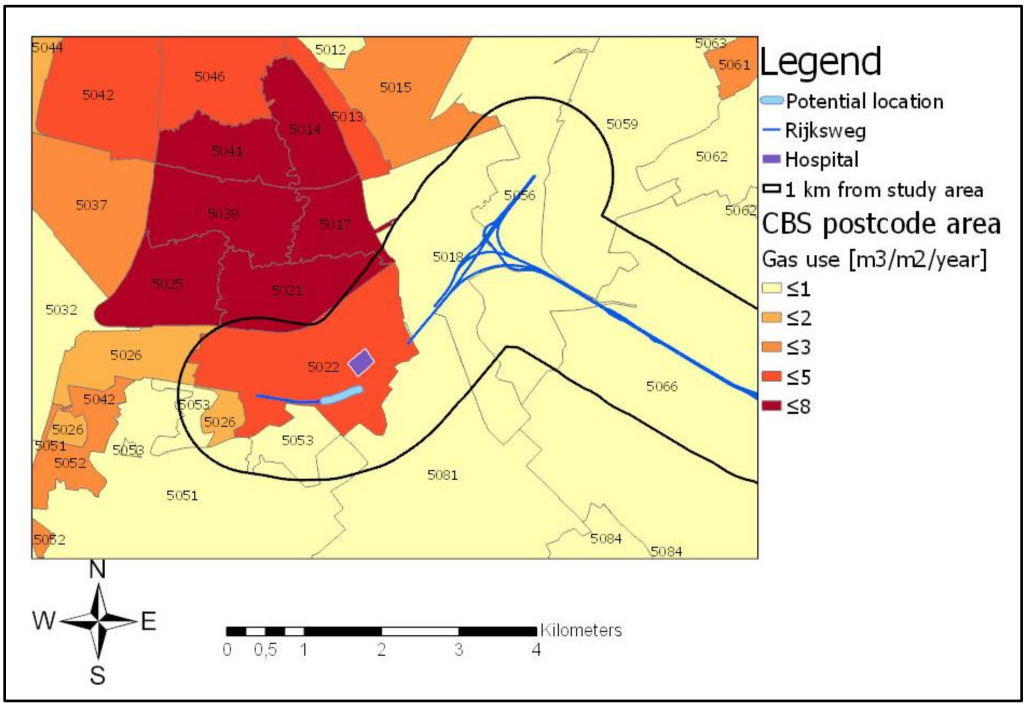

Figure 15: Potential location for the asphalt collector

The total gas use in the hospital in 2015 was almost 4 million m^3, what is equal to more than 14.000 GJ. The WKO-system delivered 747 GJ of heat and 464 GJ of cold in 2015 (Elisabeth-TweeSteden Ziekenhuis, 2015).

[16] In a Heat Cold Storage(WKO)-system, soil energy is used to heat up and cool down buildings. The groundwater in an aquifer is used for this (Geotherm, sd).

An asphalt collector with a surface of 10.000 m^2 will cost around €500.000 and will have a heat yield between 4.000 and 6.000 GJ per year. Because the hospital will safe 4.000 to 6.000 GJ per year and the price of natural gas for bulk consumers like the hospital is €10,843 per GJ (CBS, 2018), the costs of the asphalt collector will be earned back within approximately 8[17] to 12[18] years.

5.3. Best way to implement the asphalt collector on the A58

From section 5.1. and 5.2. can be concluded that the best potential application for the asphalt collector on the A58 in the study area is to implement the PIA-collector at 5 lanes of 571 meter close to the Sint Elisabeth hospital (Figure 15). The WKO-system of the hospital is a good opportunity to store the heat of the asphalt collector. However, the potential of the location is largely depending on the hospital. That it could be unclear who will be in charge of the collector and falling out of the hospital as heat consumer are threats worth considering.

[17] With a heat yield of 6.000 GJ per year.
[18] With a heat yield of 4.000 GJ per year.

6. Potential implementation solar road on A58

In this chapter, the best way to implement the solar road at the A58 in the study area is determined giving an answer to the solar road part of research question 5. This has been done by determining the best solar road application and best potential location to implement the solar road in the study area.

6.1. Best solar road application to implement on the A58

To find out what is the best solar road type to implement on the A58 in the study area, an MCA is done with the help of 5 criteria. These criteria and how the solar road applications discussed in this thesis score on them is shown in Table 13. The explanation of the scores of the collectors on the criteria and the sensitivity analysis of the MCA can be found in Appendix F. Just like in section 5.1., the scores differ from 1 (bad) to 5 (good) and a weight of 1 to 3 is given to the criteria. The weight and scores are based on the technical conditions of the solar road, its pros and cons, and its impact on the technical requirements of the A58.

Table 13: MCA best solar road application

Criteria	Weight	Pavenergy	SolaRoad	Wattway
Costs [€/m^2]	2	5	3	1
Applicability A58 [-]	3	5	1	4
Experience [-]	3	2	2	4
Efficiency [kWh/m^2/year]	3	5	2	4
Life cycle [years]	2	3	3	3
Total score	-	52	27	44

The best solar road application to implement on the A58 in the study area according to the MCA is the Pavenergy technique. This is largely because of its relatively low costs, high efficiency and its applicability on the A58.

6.2. Best location to implement the solar road on the A58

In this section the best location in the study area to apply the solar road has been investigated. Important for this location is that it must be located in an area where the electricity use is high and where connection points to the medium-voltage (MV) network are close. That is because the smaller the distance between the solar road and the nearest electricity network, the lower the resistance losses and construction costs (Arcadis, 2017). The electricity use per zip code 4-digit level and the location of the MV network connection points around the study area are directed from Energie in beeld (2017) and Enexis (2018) respectively. With this information, the map shown in Figure 16 is made in ArcGIS Pro.

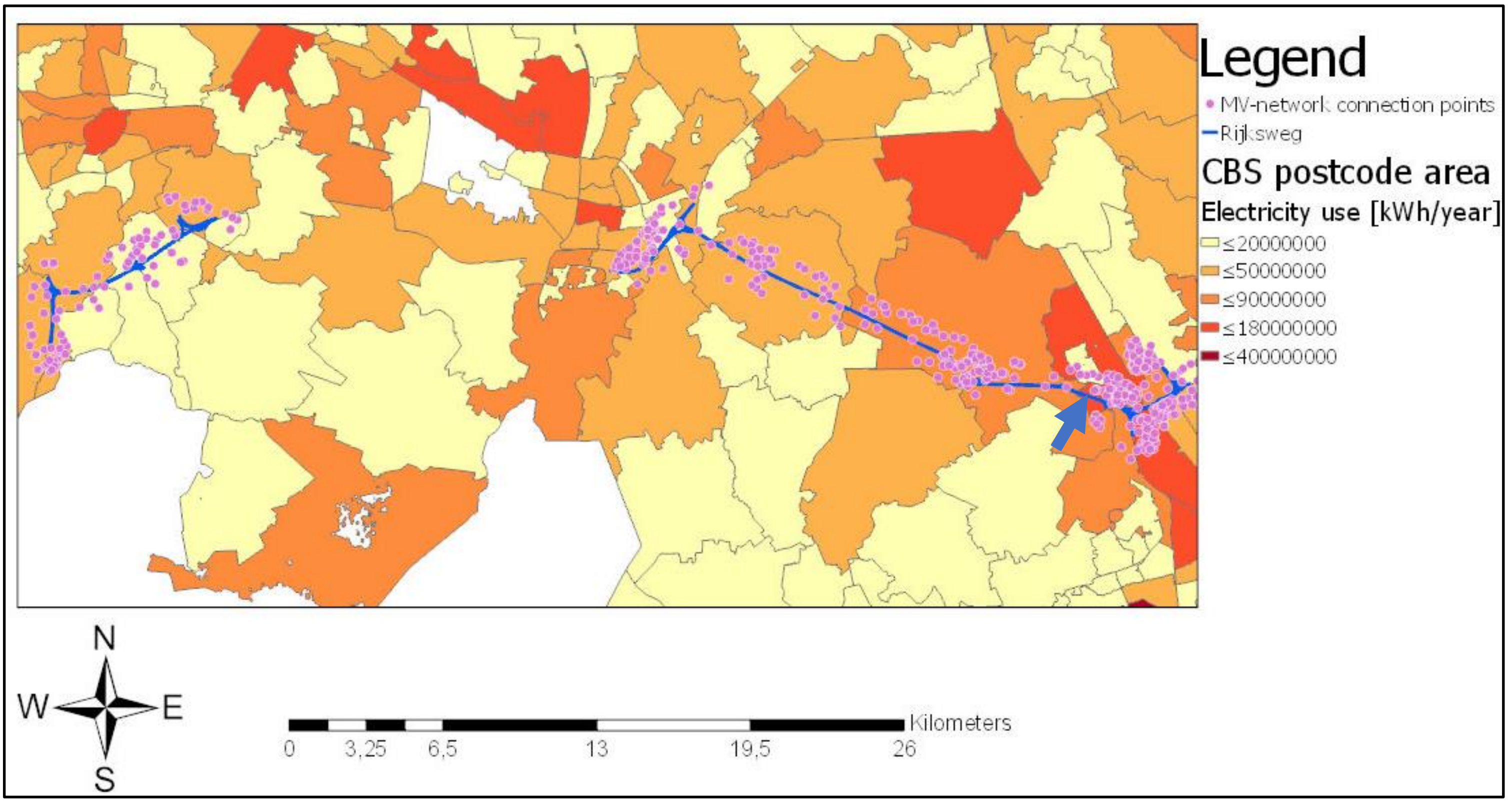

Figure 16: Electricity use and mv-network connection points around the study area

From the figure can be concluded that the part of the A58 in the red district that is marked with an arrow in Figure 16, is the best potential location for the solar road. This is because it is the area with the highest electricity use in the study area and it has a large amount of connection points to the MV-network. In the following section there has been zoomed in on this location.

The best potential location to implement the solar road

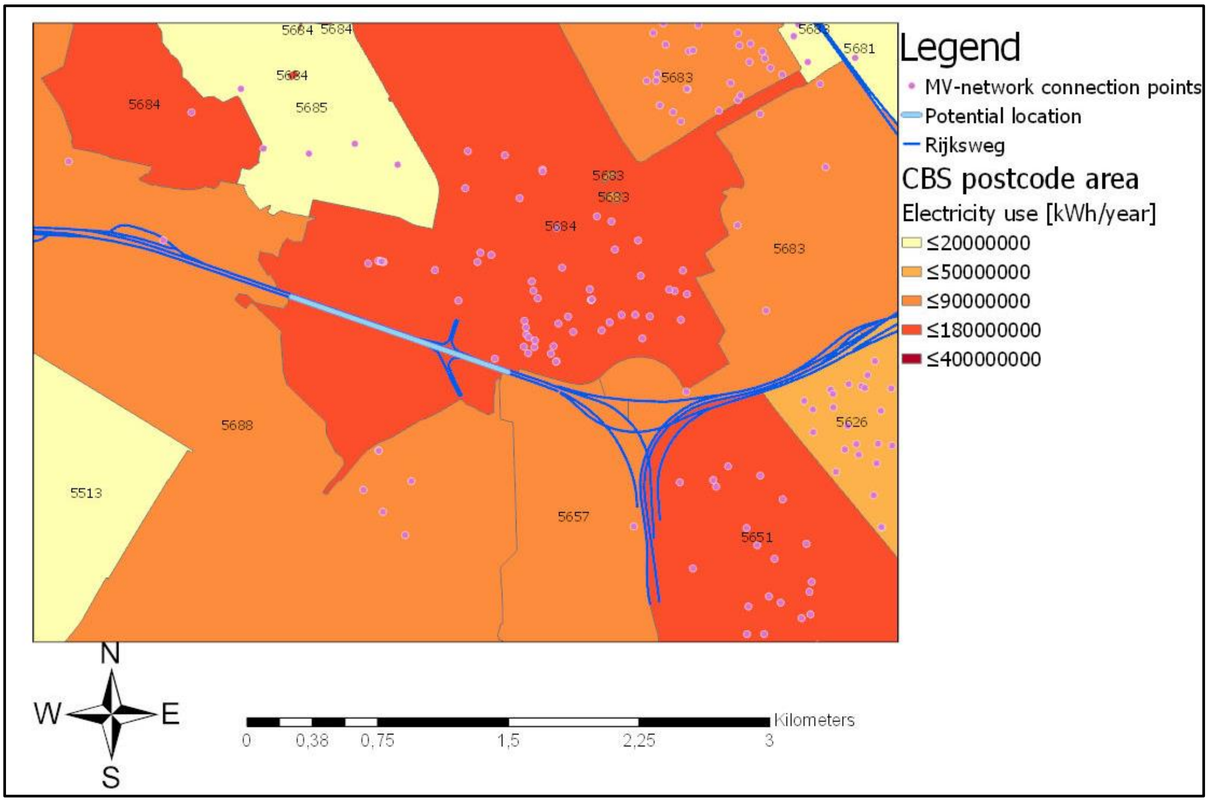

Figure 17: Potential location for the solar road

In Figure 17 the best potential location for the solar road is shown. This potential location contains a 2,1 km part of the A58 that is located within an area with a relatively high electricity use. When covering all lanes there is room for 58.800 m^2 of solar road. The construction costs would be around €23 million, and this solar road could provide 1818 average Dutch households with electricity (Milieu centraal, 2018a). Because of the possible decrease in transparency and unguaranteed life cycle it is not preferable to spend €23 million on the solar road yet. First, the performances of the solar road on a Dutch highway must be tested on a smaller scale.

The largest surface of existing solar roads is 5875 m^2 covered with the Pavenergy project in Jinan. Therefore, when implementing the solar road at the potential location shown in Figure 17, the surface must not outrun the scale of the Pavenergy project. Because 58.800 m^2 would outrun the Pavenergy project with factor 10, there has been looked at implementing the solar road at less lanes or a smaller part of the potential location.

Covering one lane of the A58 at the potential location with the solar road, would create a solar road with a surface of 7350 m^2, what is comparable to the surface of the Pavenergy project. A solar road with this surface could be constructed on 8 lanes of the A58 with a length of 263 m. However, when only implementing one lane the emergency lane can be used. This is preferable because that is the lane with the least vehicles driving on it and therefore it has the most hours of sunshine.

The construction costs to cover 2,1 km of one emergency lane at the potential location on the A58 are €2.9 million and this solar road would generate 684 MWh per year when the transparency is not decreasing over time. 684 MWh can cover the electricity use of 228 average Dutch households (Milieu centraal, 2018a). The €2.9 million can be declined when there will be support of subsidy.

6.3. Best way to implement the solar road on the A58

From section 6.1 and 6.2. follows that the best potential application of the solar road on the A58 is to use the Pavenergy technique at the emergency lane at the potential location shown in Figure 17.
An opportunity for this application is the increase in electric cars. This can be responded to by using the electricity of the solar road for charging the cars by induction while they are driving. Possible threats worth considering are the costs of the solar road. Due to the little experience of Pavenergy the costs can turn out to be higher and there is also a higher chance for unexpected flaws to appear.

7. Conclusion

In this research an answer has been given to the question '*What is the potential for applying the asphalt collector and solar road on the A58 within the study area?'* There can be concluded that there is potential to apply the asphalt collector on the A58 within the study area because of the suited location and the ability to give the road an extra function. On the other hand, there is not much potential to implement the solar road on a large scale when the A58 will be widened because of its high costs and the little experience with the solar road. A pilot project on a small scale to test the performance of the solar road on the Dutch highway has potential when there is support from subsidy. To find the conclusion, the technical conditions of the asphalt collector and solar road, their effect on the A58 and the best potential implementations for the applications have been discussed.

The most important findings that result from the technical conditions are that the efficiency of the asphalt collector is largely depending on the entry- and exit temperature, the flow rate and the collector depth. The presence of an aquifer and the distance to the heat consumer is largely determining the potential of the collector. From the technical conditions of the solar road the most important findings are that the efficiency of the solar road is largely depending on the transparency of the top layer. The costs, efficiency, strength and driving comfort are largely determining the potential of the solar road.

The largest pros of both applications are the addition of a function to the road, its sustainable energy generation and its environmental friendly de-icing. Also, the asphalt collector will enlarge the lifespan of the asphalt construction. The largest cons of the asphalt collector are the threat of falling out of the heat consumer and that there is always a large number of involved parties and therefore the difficulty who is going to be in charge of the collector. For the solar road the largest cons are its costs and that it is hard to deal with the decrease in transparency of the top layer.

The best potential application for the asphalt collector on the A58 is to use the PIA-collector at 5 lanes of 571 meter close to the Sint Elisabeth hospital (Figure 15). This results from the high gas use of the hospital and presence of a WKO-system. The best potential application for the solar road on the A58 is to use the Pavenergy technique at the emergency lane at the location shown in Figure 17. This is the best location because of the high electricity use and multiple close connection points to the MV-network in the area. Because of the high costs, not all lanes must be turned into solar road. The performances of the solar road on the Dutch highway must first be tested.

8. Discussion

There has been concluded that there is potential to apply the asphalt collector on the A58 within the study area and that there is not much potential to apply the solar road on a large scale. However, a pilot project on a small scale has potential when there is subsidy. In this chapter all possible restrictions to this conclusion and remarkable results within the research are discussed. First for the results of the asphalt collector, then for the results of the solar road and finally, for the research in general.

The best potential location to implement the asphalt collector is based on the condition that the location of where the heat that is collected by the asphalt collector is used, must not be more than 1 km away from the collector. A possible restriction is that this maximum distance is not based on calculations, but on experience of the producer of RES. However, this will not influence the result for the best potential location for the asphalt collector because the best potential location (the hospital) is, with not more than 600 m, close to the asphalt collector.

The best solar road application according to the research is the Pavenergy application. A possible restriction of the total construction costs of the application is that the Pavenergy application in China is, compared to the other two applications discussed in this report, remarkable cheap. Therefore, it may be possible that the construction costs when the solar road will be implemented on the A58, turn out to be more than €399 per square meter.

For this research a large amount of information is obtained from the report 'Energiewinning uit weginfrastructuur' of Weijers & De Groot (2007). This report is published 11 years ago and is therefore relatively old. That is why information that is coming from this report may be questioned. Yet, information from the article of Weijers & De Groot (2007) about the asphalt collector has been mentioned by interviewee 2 too and is therefore still relevant. Information from the report has been used because it contains valuable information that is not discussed in other reports. Also, the reports from Chiou (1982), Matrawy & Farkas (1997) and Bijsterveld (2000) are relatively old, but information that is obtained from these reports are all based on experiments that still could be executed and have the same results.

The PIA-collector and Pavenergy application have been picked to be the best applications to use when implementing the asphalt collector and solar road respectively. This has been done with the use of an MCA. An MCA is an effective way to rank all available options, however a small amount of subjectivity is always underlying the results of an MCA. To still obtain a valid result, all scores and weights have been explained and also a sensitivity check is done.

To find the best potential location for the asphalt collector and solar road, the gas- and electricity use in the study area has been used to find the locations with the highest use. A possible restriction is that the gas- and electricity use was only accessible at zip code 4-digit level (explained in section 5.3.). This has resulted in a less accurate result than when the gas- and electricity use at zip code 6-digit level was available.

9. Recommendations

In this chapter is discussed what the project promoter, Witteveen+Bos, is recommended to do with the results of the study and what is recommended what research can be done in a possible follow-up study.

The aim of the study is to give Witteveen+Bos, and with that Rijkswaterstaat, insight in the potential of the asphalt collector and the solar road on the A58 in the study area. The research has shown that there is potential for the asphalt collector to implement it during the widening of the A58. For the solar road there isn't much potential to implement on large scale. That is mainly because of its high costs and the lack of experience. Yet, it could be implemented on a small scale within a pilot project to test its performance on a Dutch highway. For follow-up studies it is recommended to investigate the performances of existing solar roads and to investigate how to bring down the costs.

Because there has been shown that there is potential to apply the asphalt collector, recommended is that the asphalt collector will be implemented in the study area on the location near the Sint-Elisabeth hospital described in section 5.3. Because the hospital is the decisive factor for implementing it or not, it is important that before starting to implement the collector, the hospital wants to participate. Agreements with the hospital must be made about who will be in charge of the collector and who will pay for what. Parties that need to be on one line are Rijkswaterstaat, the municipality of Tilburg and the hospital.

Also important before implementing the asphalt collector is that must be considered if there is enough time to implement the collector. The collector of 10.000 m^2 will add four weeks to the construction phase and compared to replacing 2 layers of road in a normal way, that is more than 2 times as long. It is recommended to consider the achievability of closing lanes for a longer period.

The solar road could be implemented on a small scale on the emergency lane at the location discussed in section 5.4. within a pilot project to test its performance on a Dutch highway. However, this is only recommended when InnovA58 considers its goals 'to stimulate the climate adaptation' and 'to get the image of 'example' and 'innovative' in terms of tackling the innovation challenge', only achievable when doing a pilot project for the solar road. For the generation of electricity, the solar road is not worth the investment.

Finally, in chapter 2 there are given recommendations about how to handle with the technical conditions of the solar road and asphalt collector. When implementing one of the applications, these recommendations must be considered.

10. Bibliography

Agentschap NL. (2010). *RVO*. Opgehaald van Asfaltwarmte, collectieve warmtepompen, collectief warmte/koude netwerk: https://www.rvo.nl/sites/default/files/bijlagen/Concept%20B6%20asfaltwarmte.pdf

Arcadis. (2017). *Ruimtelijke onderbouwing zonnepark.*

Bergstresser, M. (sd). *Reynolds Number: Definition & Equation*. Opgehaald van Study.com: https://study.com/academy/lesson/reynolds-number-definition-equation.html

Bijsterveld, W. v. (2000). *Een modelmatige beschouwing van constructieve en thermische aspecten.* TU Delft.

Bobes-Jesus, V., Pascual-Muñoz, P., Castro-Fresno, D., & Rodriguez-Hernandez, J. (2013). *Asphalt solar collectors: A literature review.*

CBS. (2016). *CBS*. Opgehaald van Elektriciteitsproductie uit steenkool opnieuw hoger: https://www.cbs.nl/nl-nl/nieuws/2016/26/elektriciteitsproductie-uit-steenkool-opnieuw-hoger

CBS. (2017). *Gegevens per postcode*. Opgehaald van CBS: https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische%20data/gegevens-per-postcode

CBS. (2017). *Statline*. Opgehaald van Lengte van wegen; wegkenmerken, regio: http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=70806ned&D1=0-15&D2=0&D3=a&HDR=G2&STB=T,G1&VW=T

CBS. (2018). *Aardgas en elektriciteit, gemiddelde prijzen van eindverbruikers*. Opgehaald van statline.cbs.nl: http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=81309NED&D1=0-1%2C3%2C5%2C7-8%2C11%2C15&D2=0&D3=a&D4=a&HD=121114-1344&HDR=G1%2CG2%2CT&STB=G3

China Daily. (2017). *World's first photovoltaic highway near completion in Jinan*. Opgehaald van usa.chinadaily.com.cn: http://usa.chinadaily.com.cn/a/201712/15/WS5a33346da3108bc8c6734df4_1.html

Chiou, J. (1982). *The effect of nonuniform fluid folow distribution on the termal performance of.*

CROW. (2010). *Deelhoofdstuk 31.2 Asfaltverhardingen.*

CROW. (2010). *Standaard RAW Bepalingen 2010.*

CROW. (2012). *Multicriteria-analyse (MCA)*. Opgehaald van www.crow.nl: https://www.crow.nl/kennis/bibliotheek-verkeer-en-vervoer/kennisdocumenten/multicriteria-analyse-mca

CROW. (2016). *Zijn 80 km/h-wegen te smal?* Opgehaald van CROW: https://www.crow.nl/blog/juli-2016/zijn-80-km-wegen-te-smal

Danielo, O. (2016, november 30). *France's solar road: International solar experts give their analysis*. Opgehaald van PV-magazine: https://www.pv-magazine.com/2016/11/30/frances-solar-roadc2a0international-solar-experts-give-their-analysis_100027057/

De Ingenieur. (2017). *Veilig elektriciteit winnen uit restwarmte*. Opgehaald van deingenieur.nl: https://www.deingenieur.nl/artikel/veilig-elektriciteit-winnen-uit-restwarmte

Dienst Grote Projecten en Onderhoud. (2013). *Specificaties Ontwerp Asfaltverhardingen.*

Dijkink, H. (2009). *Met de Zonneweg een zonnige toekomst.*

Dutch Emissions Authority. (sd). *Klimaatakkoord van Parijs*. Opgehaald van Emissie autoriteit: https://www.emissieautoriteit.nl/onderwerpen/klimaatakkoord-van-parijs

Elisabeth-TweeSteden Ziekenhuis. (2015). *ETZ Milieu Jaarverslag.*

Energie in beeld. (2017). *Rapportages*. Opgehaald van Energie in beeld: http://www.energieinbeeld.nl/inloggen/

Enexis. (2018). *Opend data*. Opgehaald van Enexis: https://www.enexis.nl/over-ons/documenten-en-publicaties/open-data

Engineersaustralia. (2016). *Solar powered roads are now a reality*. Opgehaald van Engineersaustralia.org.au: https://www.engineersaustralia.org.au/News/solar-powered-roads-are-now-reality

Erkens, P. D. (2015). *Infrastructuur: aanleg en beheer.* Opgehaald van Blackboard: https://blackboard.utwente.nl/bbcswebdav/pid-870611-dt-content-rid-1718187_2/courses/2015-201300043-1A/FCE%20Lectures%209%20%26%2010_Sandra%20Erkens_RWS%20and%20TU%20Delft.pdf

Geotherm. (sd). *WARMTE KOUDE OPSLAG (WKO)*. Opgehaald van Geotherm: https://geotherm.nl/wko/

GWW materialen. (2014). *Soortelijk gewicht*. Opgehaald van GWWmaterialen.nl: http://gwwmaterialen.blogspot.com/p/soortelijk-gewicht.html

Heidinga, N. (2015). *Fietsen over zonne panelen: zonnefietspad in Krommenie.*

Huang, E. (2017, december 28). *A new solar highway in China perfectly captures its clean-energy ambitions*. Opgehaald van Quartz: https://qz.com/1166975/a-new-solar-highway-in-china-perfectly-captures-its-clean-energy-ambitions/

InnovA58. (2017). *Innova58*. Opgehaald van Innovatiedoelstellingen InnovA58 zijn haalbaar en uitdagend: https://www.innova58.nl/Nieuws/732770.aspx

JC Solar Homes. (sd). *Solar Collector Flow Dynamics*. Opgehaald van jc-solarhomes.com: http://www.jc-solarhomes.com/collector-flow-dynamics.htm

Klimaatinfo. (2018). *Het klimaat van Jinan*. Opgehaald van Klimaatinfo.nl: https://www.klimaatinfo.nl/china/jinan.htm

Kodi. (sd). *Asfalt als warmtebron*. Opgehaald van Kodi: http://www.kodi.nl/diensten/warmtepomp-systemen/bronsystemen/asfalt/

KWS infra. (2012). *De Zonneweg: de weg als innovatieve energieleverancier.* Opgehaald van www.kws.nl: https://www.kws.nl/dynamics/modules/SFIL0200/view.php?fil_Id=9476

Leads2travel B.V. (2018). *Aantal zonuren in Nederland*. Opgehaald van zonuren.nl: http://www.zonuren.nl/nederland/

Lewis, D. (2016). *France is paving more than 600 miles of road with solar panels*. Opgehaald van www.smithsonianmag.com: https://www.smithsonianmag.com/smart-news/france-paving-more-600-miles-road-solar-panels-180958035/

Lux Research. (2015). *Tesla will extend price advantage, thanks to its Gigafactory - but others see price reductions too.* Opgehaald van www.luxresearchinc.com: http://4.bp.blogspot.com/-jRVF_rqGDk4/VVt3mf_xORI/AAAAAAAAaYo/3_fVcP2Wc5Y/s1600/Electric%2BVehicles%2BMarket.jpg

Materia. (2017). *Wattway: A solar raod to clean energy in normandy*. Opgehaald van Materia.nl: https://materia.nl/article/wattway-solar-road-clean-energy-normandy/

Matrawy, K., & Farkas, I. (1997). *Comparison study for thre types of water collectors for water.*

Milieu centraal. (2018a). *Gemiddeld energieverbruik*. Opgehaald van Milieucentraal: https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/gemiddeld-energieverbruik/

NH Nieuws. (2014). *Wereldberoemd solar-fietspad in Krommenie nu al stuk*. Opgehaald van nhnieuws.nl: https://www.nhnieuws.nl/nieuws/156969/Wereldberoemd-solar-fietspad-in-Krommenie-nu-al-stuk

NOS. (2018). Waarschuwing: geen nieuwe zonneparken, het net kan het niet aan. *NOS*.

Ooms Construction. (2018). *Energie uit asfalt.* Opgehaald van www.ooms.nl: https://ooms.nl/specialismen/energie-uit-asfalt-/

OpenStreetMap. (2018). *OpenStreetMap*. Opgehaald van OpenStreetMap: http://www.openstreetmap.org/directions?engine=osrm_car&route=51.5526%2C4.8351%3B51.5276%2C4.7463#map=11/51.5649/4.8711

P.Pascual-munoz, C.-F. D.-B.-E. (2013). *Thermal and hydraulic analysis of multilayerd asphalt pavements as active solar collectors.*

Rijkswaterstaat. (2012). *Energieke wegen.*

Rijkswaterstaat. (2012). *Richtlijnen Ontwerp Hemelwaterafvoer van wegen en kunstwerken.* Rijkswaterstaat Dienst Infrastructuur.

Rijkswaterstaat. (2016). *Geluid langs rijkswegen.*

Rijkswaterstaat. (2017). *Geluidregister*. Opgehaald van www.rijkswaterstaat.nl: https://www.rijkswaterstaat.nl/kaarten/geluidregister.aspx?cookieload=true

Rijkswaterstaat. (2018). *InnovA58 werkt aan een slimme en duurzame snelweg*. Opgehaald van www.innova58.nl: https://www.innova58.nl/home/default.aspx

Rijkswaterstaat. (sd). *Rijkswaterstaat*. Opgehaald van Wegenoverzicht: https://www.rijkswaterstaat.nl/wegen/wegenoverzicht

Siebert, N., & Zacharakis, E. (2010). *Asphalt Solar Collector and Borehole Storage.*

Solliance. (2018). *Thin-film pv*. Opgehaald van Solliance.eu: https://solliance.eu/thin-film-pv/

Solmove. (2018). *Liquid city #5 Energie für die Stadt*. Opgehaald van solmove.com: http://www.solmove.com/de/

Straver, F. (2018). Stormloop op grond voor zonneparken. *Trouw*.

Strukton. (2018). *SolaRoad*. Opgehaald van www.strukton.nl: https://www.strukton.nl/projecten/solaroad/#tab-02

The Colas Group. (2018). *Wattway: Paving the way to tomorrow's energy*. Opgehaald van www.wattwaybycolas.com: http://www.wattwaybycolas.com/en/

The Guardian. (2018). *Daylight robbery: thieves steal chunk of China's new solar highway*. Opgehaald van theguardian: https://www.theguardian.com/world/2018/jan/09/china-solar-highway-thieves-steal-panels

TNO. (sd). *Aardwarmte*. Opgehaald van Geologie van Nederland: http://www.geologievannederland.nl/ondergrond/afzettingen-en-delfstoffen/aardwarmte

Todd, D. A. (2011). *Buildipedia*. Opgehaald van Asphalt Pavement Solar Collectors: The Future is Now: http://buildipedia.com/aec-pros/engineering-news/asphalt-pavement-solar-collectors-the-future-is-now

TU Delft. (2018). *Op zoek anar beter Li-ion batterijen en alternatieven*. Opgehaald van www.tudelft.nl: https://www.tudelft.nl/2018/tnw/op-zoek-naar-betere-li-ion-batterijen-en-alternatieven/

Vos, E. (2015). *Stoefheid op rijkswegen.* Delft.

Waerdse Energie Circuit. (sd). *Asfaltcollectoren*. Opgehaald van Waerdse-energie: https://www.waerdse-energie.nl/asfaltcollectoren/

Wang, H., Wu, S., Chen, M., & Zhang, Y. (2010). *Numerical simulation on the thermal response of heat-conducting asphalt pavements.*

Wayne State University. (2017). *S.M.A.R.T. Objectives*. Opgehaald van hr.wayne.edu: https://hr.wayne.edu/leads/phase1/smart-objectives

Weijers, E., & Groot, G. d. (2007). *Energiewinning uit weginfrastructuur.*

Witteveen+Bos. (2018). *PvA Verkennend onderzoek - A58 Route du Soleil.*

Witteveen+Bos. (2018). *Witteveen+Bos doet planuitwerking A58*. Opgehaald van www.witteveenenbos.nl: http://www.witteveenbos.nl/nl/nieuws/bericht/51049-witteveenbos-doet-planuitwerking-a58/newspage/

Yi, X. (2018). Road of the future paved with solar panels. *The Telegraph*.

Zandberg, B. (2015). *2e nota van inlichtingen bij contract.*

11. Appendices

Appendix A: Interview solar energy

Date: 12-4-2018

Interviewee number: 1

Interviewer: J.A. Vossebeld

Introduction

Interviewee 1 is part of the group Wind- and solar energy of Witteveen+Bos and is an expert in solar panels and how to integrate them. He is working in the InnovA58 project and therefore knows what this thesis is about. The meeting was held in Dutch and to not detract from Interviewee 1's words, the reporting of the interview is kept in Dutch.

At the start of the meeting I explained what my thesis is about to give Interviewee 1 an insight in what the interview would be about. Interviewee 1 brought a few solar cells to explain what kinds of cells are available and what he is experimenting with. He explained that he is experimenting with epoxy as layer on top of the panel instead of glass. When he was done explaining the working of the panels, the interview started.

Interview

1. Ben je bekend met de zogenoemde Solar Road?

Interviewee 1 vertelt dat hij ervan heeft gehoord en er een paar artikelen over heeft gelezen. Hij zit ook in het InnovA58 project van Witteveen+Bos en daarvoor heeft hij al wat globale resultaten van de Solar Road opgezocht, maar hij zou graag wat specifiekere resultaten zien.

2. Is er al onderzoek gedaan binnen Witteveen+Bos naar iets soortgelijks?

Binnen Witteveen+Bos weten we hier nog niet heel veel van. Wel zal je contact op kunnen nemen met de aanbieders die er wel wat mee hebben gedaan. Via Ingrid Bolier, (gedetacheerd bij Rijkswaterstaat voor het A58 project) zou je misschien nog aan nieuwe contacten kunnen komen.

Ook vertelde hij over Solliance in Eindhoven, daar onderzoeken ze in plaats van glas als toplaag, dunne film. Dit hebben ze ook al toegepast in het fietspad in Krommenie.

Nadat ik vertelde over Wattway (de solar road in Frankrijk), vertelde Interviewee 1 me dat het leuk zou zijn als ik contact met hun op zou nemen. Misschien dat ik dan zelfs wel een bezoek zou kunnen brengen aan Frankrijk om het allemaal in het echt te bekijken.

Ik vroeg me af waarom Wattway hun kennis met mij zouden willen delen terwijl ik mijn opdracht bij Witteveen+Bos doe. Daarop antwoordde Interviewee 1 dat veel bedrijven graag hun kennis delen met studenten, om ze zoveel mogelijk een inkijk te geven in hun bedrijf en te laten zien wat ze allemaal kunnen. Ook zijn wij als Witteveen+Bos geen concurrent van Wattway. Wij zitten in het voortraject van producenten zoals Wattway. Daarvoor hebben we kennis nodig over de toepassing van hun product. Wanneer dan bijvoorbeeld Rijkswaterstaat aan ons vraagt hoe we de A58 duurzamer gaan maken, dan kunnen wij het product van Wattway onder de aandacht brengen. Zij hebben er dus ook veel aan, dat wij zoveel mogelijk van hun product weten.

3. Denkt u dat er potentie zit in de Solar Road?

Ik denk niet dat we in de komende 4 jaar zonnecellen op de snelweg gaan zien. Gewoon omdat de techniek er nog niet ver genoeg voor is. Het TRL (Technological Readiness Level) van de panelen zit waarschijnlijk op 5 of 6 nu. Het TRL van het gebruik van een baksteen is bijvoorbeeld 9. 5 of 6 betekent dat de techniek al wel is toegepast maar nog niet zo ver is dat het marktrijp is en iedereen het makkelijk kan gaan gebruiken en weet hoe er mee om moet worden gegaan. Eerst moet er gekeken worden naar hoe alle zwakke punten eruit kunnen worden gehaald, zoals de afgifte van het water.

4. Hoe belangrijk is de hoek waarin zonnecellen liggen?

Interviewee 1 zegt dat hij het antwoord op deze vraag heel mooi kan laten zien in een figuur (Figure 18). Het rode punt is 100% rendement. Door te kijken naar de 0 graden lijn, zie je hoeveel rendement een zonnepaneel zou hebben wanneer hij plat op de grond ligt. Het rendement van een zonnepaneel die is geïntegreerd in de weg is dus ongeveer 85%. Dat is zeker geen lage waarde, en daarom is het het waard om te onderzoeken of hier potentie in zit.

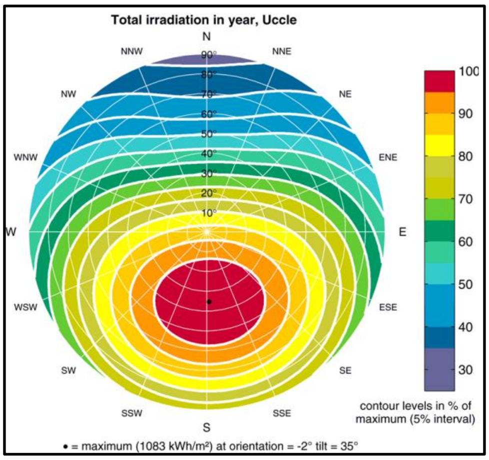

Figure 18: Table Hespul

6. Voor wat voor subsidies zou een Solar Road in aanspraak kunnen komen?

SDE+ is de subsidie als het gaat om grote duurzaamheidsprojecten. Stimulering Duurzame Energieproductie geeft een bepaald bedrag per kWh dat het verschil in kosten met groene en grijze energie compenseert. Echter kan Rijkswaterstaat deze subsidie niet aanvragen want dan zou er geld tussen overheden heen en weer blijven gaan. Wel kan er, door bijvoorbeeld de grond te verkopen aan een energieproducten als Nuon, alsnog een subsidie worden aangevraagd.

Appendix B: Interview Road Energy Systems

Date: 3-5-2018
Interviewee number: 2
Interviewer: Aron Vossebeld

Introduction

Interviewee 2 is working for Ooms Construction BV and is their expert in the asphalt collector. He is working for the company for almost 20 years. For the first 13 years he worked as an executor and after that he went inside to work as a calculator. With his experience from the workplace he knows how things need to be build and what is necessary for it. As an executor he has done a lot of projects with the Road Energy Systems, among others the Vondelingenviaduct in Rotterdam with almost 10.000 square meters of asphalt collectors on a viaduct. The interview is held in Dutch.

Interview

1. Wat zijn u voornaamste werkzaamheden bij Ooms?
Tegenwoordig zit ik bijna alleen maar op kantoor. Enkele keer ben ik bij werkzaamheden op een Rijksweg betrokken. Bij projecten waar asfalt erin, en eruit wordt gehaald word ik nog wel eens ingevlogen als hoofduitvoerder of projectleider. Dat is vooral omdat ik het kunstje met de asfaltcollector al vaak heb gedaan. Het is ook wel fijn om soms nog buiten te zijn. Het is allemaal heel indrukwekkend als je met grote frezen en 4 walsen een wegdek dichtmaakt. Dat geeft wel een kick.

2. Waarom is de asfaltcollector nog niet op een snelweg gerealiseerd?
De techniek heeft met warmte en koude te maken en daarom ben je afhankelijk van een mogelijke afname van warmte. De afnemer moet in een straal van een kilometer van het punt waar je de warmte opwekt zitten anders gaat je rendement verloren. De geïsoleerde laag die om de buis zit die de warmte vervoerd wordt dan zo duur dat het niet meer rendabel is. Ook heb je op een snelweg te maken met het tijdspad. Het vergt best wel wat tijd om het systeem in te bouwen. En de snelweg is natuurlijk de meest belaste soort weg. Maar het voornaamste is dus de afstand tot de warmteafnemer.

Leuk detail is dat de asfaltcollector in de weg voor dit gebouw is aangesloten op dit gebouw. We kunnen straks wel even gaan kijken. Al zie je er natuurlijk weinig van. Je ziet alleen maar het pomphuisje eigenlijk. Dat je er weinig van ziet is natuurlijk 1 van de voordelen van het systeem. Maar het kan natuurlijk ook een nadeel zijn aangezien mensen ook zichtbaar willen maken dat ze op een duurzame manier bezig zijn.

3. Er zijn 3 manieren waarop asfalt collectoren geïmplementeerd worden. Waarom geven jullie de voorkeur aan de buizen-in-asfalt collector boven de buizen-in-beton of zowab-collector?

Die andere zijn inderdaad van concurrerende bedrijven. Maar wij gebruiken de buizen-in-asfalt collector omdat we een asfaltbedrijf zijn met een eigen laboratorium. We zijn groot geworden met een uitvinding met gemodificeerde bitumen. Doordat we dat in huis hebben kunnen wij een bepaald asfaltmengsel samenstellen dat daarvoor geschikt is. Dus uit ons lab komt voort dat wij heel veel asfaltmengsels kunnen mengen. Omdat wij een asfaltbedrijf zijn, zijn wij asfalt gaan gebruiken.

‘Maar de zowab-collector heeft toch ook met asfalt te maken?’

Ja maar die staat nog in de kinderschoenen. Daar hebben wij nog nooit naar gekeken.

4. Wat is eraan gedaan om te zorgen dat de asfaltcollector de asfaltconstructie niet minder sterk maakt?

De slangetjes worden geklikt in een kunststof rooster. Dat rooster fungeert eigenlijk als een soort van asfaltwapening. Dus door dat rooster maak je de weg sterker. Je kan natuurlijk niet bij een klant aan komen en zeggen dat de weg minder sterk wordt door de asfaltcollector. Ook als je hem ergens in legt moet het natuurlijk niet zo zijn dat hij maar 10 jaar mee gaat. De wegen waarbij het toegepast wordt zijn dus eigenlijk nog iets sterker dan normale wegen.

'Komt dat dan doordat het als bewapening werkt of ook doordat er extra asfalt bij komt kijken?'

Meestal wordt de onderlaag waar het op komt een centimetertje dikker gemaakt en de laag met die matjes en slangetje maakt het nog weer extra sterk.

5. Waar wordt de opgewekte energie uit de asfaltcollector die er voor dit gebouw ligt gebruikt?

Alleen in dit gebouw. Er ligt daar ongeveer 1600 m^2. Je slaat die warmte op in de grond waarbij 1 bron de warme bron en 1 de koude bron is. Je bent eigenlijk water aan het rondpompen. Dat water heeft een bepaalde temperatuur en die warmte geeft hij dan weer af aan de bron. Dus in de zomer haal je koud water uit de bodem en dat stroomt door die leidingen en wordt opgewarmd en gaat dan weer de grond in. In de winter zet je de kraan de andere kant op. De warmte die je op hebt geslagen pomp je omhoog, eerst door je gebouw heen en dan door de weg en dan weer de grond in. Als je water op pompt uit de grond dan is het al warm eigenlijk. Want dat water zit dan op, pak hem beet 100 meter diepte, en daar is het altijd al warmer dan boven, door de aardwarmte. Je mag die warmte oppompen maar je moet een vergunning aanvragen want je mag niet te veel warmte uit de grond trekken. Als je dat doet bestaat het gevaar dat je zoveel warmte uit je bron hebt getrokken dat hij bevriest en het niet meer doet. En die asfaltcollector is dus een middel om te zorgen dat je dat systeem in balans krijgt.

'Is het moeilijk om de energie naar dit gebouw te krijgen? Moet er veel isolatiemateriaal aan de buizen zitten?'

Dat gaat met een aardig rendement. Het verlies is miniem. Je hebt wel te maken met drukverlies in je leiding. As je water verder weg moet pompen moet je wel een pomp neerzetten met meer kracht dus dat telt door. Kodi heeft er vooral naar gekeken en de ervaring leert wel dat je je afnamepunt zo dicht mogelijk bij je asfaltcollector wilt hebben. Hoe verder je gaat hoe moeilijker het wordt.

'En hebben jullie die grens van een kilometer echt vastgesteld of gaan jullie voor elke nieuwe situatie kijken of het kan?'

Het is geen vaste waarde maar door ervaring weet ik wel dat het ongeveer tot een kilometer kan.

6. Wanneer de asfaltcollectoren gebruikt worden om gebouwen op te warmen en te verkoelen, is er dan een kritieke grens waarop die gebouwen nog kunnen staan en de techniek nog steeds rendabel is?

Deze vraag was al beantwoordt en daarom niet gesteld.

7. Zit er een verschil in de hoogte van de aquifers voor de warmte- en koudeopslag?

Interviewee 2 schetst twee bronnen 100 meter bij elkaar vandaan. Ze mogen niet te dichtbij elkaar liggen want dan zitten ze in elkaars invloedsfeer. In de ruimte tussen de zandkorreltjes in de aquifer zit het water. Bovenin stroomt het grondwater maar hoe dieper je gaat hoe minder het stroomt. Vandaar dat het water met de warmte ongeveer blijft bij het punt waar je het laat instromen. De bronnen beïnvloeden elkaar dus niet. Dus eerst gaan we kijken d.m.v. een proefboring waar die laag zich bevindt. Een geo-technoloog kijkt er dan naar en bepaald in welke laag je voldoende capaciteit hebt om het te doen. Het hangt ook van het debiet af. De linker bron zou dus een koudebron kunnen zijn en de rechter een warmtebron. Het hangt af van hoe groot de collector is, en het debiet moet afgestemd zijn op het debiet van die bron, want de bron heeft ook een bepaald debiet. Het huis heeft ook een bepaald debiet nodig om het te kunnen verwarmen. Dat is meestal in GJ. Er wordt gekeken hoeveel vierkante meter asfaltcollector er is, en daar komt een bepaald debiet uit. Je snapt wel dat hoe groter de collector, hoe groter de bron. Want je hebt een grotere buffercapaciteit nodig.

'Dus voor je het gaat realiseren kijk je naar wat is de warmtevraag en koudevraag in een gebied?'

Precies, die moeten dan in balans zijn, daar maak je dan een sommetje voor. Een soort haalbaarheidsstudie. Je begint met de potentiele klanten. De een heeft een warmtevraag en de andere een koudevraag en daar speel je mee. Je legt als ware een warmtenet aan en zoekt naar de balans. Je kunt het water er ook sneller of langzamer door laten lopen.

8. Is er iets bekend over met hoeveel jaren de levensduur van het asfalt wordt verlengd door het gebruik van asfalt collectoren?

Interviewee 2 schetst een asfaltconstructie en noemt dat bijvoorbeeld de onderlaag en fundering 50 jaar meegaan en de deklaag 10 of 20 jaar. Het hangt er natuurlijk vanaf hoe de weg wordt belast aangezien het een bitumenproduct is en dat gaat slijten. Dat betekent dat je de deklaag als eerste moet vervangen. De RES (Road Energy Systems) constructie komt op de plaats van de tussenlaag. We hebben getest dat we de deklaag er gewoon af kunnen frezen en er een nieuwe laag opbrengen en dan blijft de RES laag gewoon intact. Normaal gesproken heeft een overheid als onderhoudsstrategie dat je bij de 1^{e} keer onderhoud de deklaag vervangt en bij de 2^{e} keer de deklaag en de tussenlaag. Maar wij maken de tussenlaag sterker en dus hoeft hij pas vervangen te worden bij de 3^{e} doorloopperiode.

'Zijn de kosten dan veel hoger doordat je die laag sterker maakt?'

Natuurlijk kost de asfaltcollector meer dan een normale tussenlaag. De asfaltproductie natuurlijk ook wel iets. We zeggen de RES laag heeft een meerprijs t.o.v. de normale tussenlaag van 75-125 euro per m^2. Als je een groot oppervlakte hebt dan zou het minder zijn dan als je een klein ding hebt. En de kosten voor de bronnen komen er natuurlijk nog bij.

9. Kunnen asfaltcollectoren ervoor zorgen dat er helemaal geen andere manier van sneeuw- en gladheidbestrijding meer nodig is?

Ja dat zou kunnen. We hebben projecten gedaan met een fietstunnel en in Emmen met een oprit. Dan wordt het niet gebruikt om warmte te winnen maar om het sneeuw- en ijsvrij te houden. Het zou ook allebei kunnen maar dan moet je je sommetje iets anders maken. In de weg voor dit gebouw hoeven ze in principe niet te strooien.

'Helemaal niet of in mindere mate?'

Het vergt natuurlijk altijd tijd voordat de sneeuw weg is, want die is niet in 1 keer weg. Maar naar verloop van tijd wel. Je hebt natuurlijk extreme gevallen dus we geven geen honderd procent garantie dat er geen sneeuw meer op de weg ligt.

In Emmen bijvoorbeeld hebben ze dit systeem toegepast omdat ze al stadsverwarming hadden lopen. Ze hebben die asfaltcollector toegepast omdat ze een warmte overschot hadden. Dus dat gebruiken ze om die asfaltcollector op te warmen. Dus zo kun je de collector eigenlijk op meerdere manieren gebruiken.

10. Wat zijn de zwakke punten of risico's van de asfalt collector?

Waar wij eigenlijk tegen aan lopen is dat je een plan moet hebben. Je legt een systeem aan dat heel lang mee gaat. Maar plannen veranderen soms en dat is heel jammer. Je wordt er of te laat bij betrokken of het plan wijzigt zo dat het niet meer rendabel is. Dat er dus afnemers verdwijnen.

Het systeem is doorontwikkeld want we hebben het al 15 jaar dus alle kinderziektes zijn er eigenlijk wel uit. We lopen er ook wel eens tegenaan dat we het in een weg neerleggen en dan zeggen van de rest komt later wel, maar dat komt er dan niet. Dan heb je het probleem dat er slangetjes in het asfalt zitten en die mogen niet bevriezen. Dus dan moet je ze weer leegblazen en met kunst- en vliegwerk in stand houden. Bijvoorbeeld in nieuwbouwwijken wordt het wel eens in de weg gelegd maar in het eerste jaar woont er dan nog niemand dus gebeurt er nog helemaal niks mee. Dus daar moet je wel over nadenken. Het mag natuurlijk niet bevriezen. Dan zou het slangetje op de zwakke punten scheuren en dan gaat het lekken.

'Als er 1 scheurtje in een slangetje zit, is er dan een groot verlies van rendement?'

We kunnen opzich ieder slangetje apart van elkaar dicht zetten. Dus dan zetten we het lekke slangetje dicht en de rest doen het dan nog. Dus het is niet zo dat het hele systeem gelijk platligt als er 1 lekkage optreedt in de weg.

'Zijn er vaak slangetjes kapotgegaan?'

We hebben al best veel asfaltcollectoren neergelegd, maar er is nagenoeg nooit lekkage geweest. 1 keer door een ongeluk met een vrachtwagen, maar dat is overmacht. Door regulier gebruik nog nooit lekkage in de weg. Dus het systeem is wel heel degelijk.

11. Wat kan er gedaan worden wanneer er een onbalans is tussen de warmte- en koude vraag?
Deze vraag was al beantwoordt en daarom niet gesteld.

12. Hoe wordt de optimale afstand tussen de buizen bepaald?

We hebben proefvakken aangelegd met verschillende afstanden en daarmee is de optimale afstand bepaald.

'Aangezien een asfaltconstructie uit 1 pakket moet bestaan. Neem ik aan dat er wel asfalt zit tussen de kunststof constructie?'

Ja, dat asfalt moet wel heel erg smeuïg zijn met een hoog bitumengehalte. Doordat wij die bitumen zelf kunnen maken en het recept aan kunnen passen hebben we dat ook geoptimaliseerd. Dus het is zo verwerkbaar dat het de ruimte tussen de slangetjes ook vult. Want anders wordt je laag niet sterk genoeg.

13. Ik las dat er in de asfaltcollectoren in Scharwoude 200 sensoren zijn geïnstalleerd, gebeurt dat bij alle asfaltcollectoren of is dat gedaan om testen te doen? Wat meten deze sensoren?

Die 200 sensoren zitten er nu niet meer in. Die waren om te monitoren aangezien dit de eerste test was. De toenmalig directeur Jan Dirk Ooms had zoiets van, als ik laat zien dat ik zoveel vertrouwen heb in mijn product dat ik er zelf mijn gebouw op durf aan te sluiten dan geeft dat natuurlijk ook vertrouwen voor de klant. De sensoren hebben de temperatuur gemonitord. Ook kan je met een warmtecamera kijken waar de slangetjes lopen aangezien ze een andere temperatuur hebben.

14. Hebben asfaltcollectoren onderhoud nodig? Is dit goed te doen?
Deze vraag was al beantwoordt en daarom niet gesteld.

15. Aan een asfaltconstructie zit normaal gesproken ook de eis dat het voor onderhoud makkelijk te verwijderen moet zijn. Is dit door het gebruik van de asfaltcollector veel moeilijker?
Deze vraag was al beantwoordt en daarom niet gesteld.

16. Op welk project waar de asfaltcollector is gebruikt zijn jullie het meest trots en waarom?

We zijn natuurlijk op ieder project trots. Maar persoonlijk ben ik heel erg trots op het project in Rotterdam op de Vondelingenbrug. Door het tijdspad en ook omdat we toen nog niet zo lang bezig waren met de asfaltcollector. Dat is ongeveer 10 jaar geleden dus toen waren we nog maar 5 jaar bezig. Wat wel erg jammer is, is dat er naast dat viaduct een grote brandweerkazerne gebouwd zou worden maar die is er nooit gekomen. Daar was wel de collector voor bedacht maar het systeem is daar dus nooit in bedrijf gegaan. Maar ondanks dat, ligt hij er nog steeds wel heel goed in.

'Als een collector niet gebruikt wordt, blijft hij dan langer in een goede staat of zit daar niet zoveel verschil in?'

Maakt niet zoveel verschil. Met deze hebben we hem gewoon leeggehaald en er een andere vloeistof in gedaan zodat we er geen werk meer mee hebben.

17. Zijn er personen waarvan u mij kunt aanraden om ze te spreken voor mijn onderzoek?

Het is wel grappig dat ik en jaar of 3 á 4 geleden ben benaderd door de TU Twente die een zwembad hebben naast een atletiekbaan. Die atletiekbaan moest nieuw asfalt krijgen. Met dat asfalt wilden ze het buitenzwembad gaan verwarmen. Toen ben ik daar geweest. Daardoor weet ik wel hoe lang je hebt moeten reizen om hier te komen. Maar met wie je kan spreken: Kodi is handig voor het installatietechnische deel. En op de N211 is de BAM bezig om een duurzame weg te maken. Dat is misschien ook wel leuk. Ik zal even voor je op schrijven wie je daarvoor kunt bereiken. Daar komt ook een stukje Road Energy bij kijken.

'Is dat via jullie of is BAM zelf bezig met een eigen asfaltcollector?'

BAM is zelf bezig maar wij zijn in onder aanneming. Marcel moet je daarvoor hebben. Hij krijgt ook heel veel publiciteit. Hoe ze dat daar doen is wel leuk voor je scriptie.

'Waarom is het uiteindelijk niet doorgegaan bij de Universiteit?'

Ten eerste kwamen we te laat. Ze waren eigenlijk al bezig met die baan te asfalteren toen ik daar kwam. En er is eigenlijk ook een veel goedkoper alternatief om een zwembad te verwarmen. Dat is heel simpel. Je hebt een soort slakkenhuis met een tyleen buis. Tyleen is een zwarte kunststofbuis en beetje flexibel. Als je die in een piramidevorm omhoog doet en je laat er water doorheen stromen dan wordt het warm. Net als bij het zwarte asfalt. Daar hebben ze uiteindelijk voor gekozen. Ik heb het ook aan hun voorgesteld aangezien ik toen bij een buitenzwembad werkte in Opdam en die techniek had gezien.

'Had het veel uitgemaakt voor het rendement van de asfaltcollector als de atletiekbaan rood zou zijn i.p.v. zwart? '

Niet heel veel. Zwart absorbeert natuurlijk het beste warmte. Maar rood wordt ook wel warm. De verschillen zijn niet heel erg groot.

‘Hebben jullie tijdens het testen ook gekeken hoe het mengsel moet worden om het zo zwart mogelijk te maken of helemaal niet omdat het niet zoveel uitmaakt?’

Nee want zo veel maakt het niet uit. De grond warmt altijd op door de zon.

Appendix C: Calculation design load

The calculation of the design load is based on the method of Dienst Grote Projecten en Onderhoud (2013). The design load is calculated as followed:

$n_{total} = V * a_{vw} * W * F_r * G * t * F_v$

in which:

n_{total} = total number of truck axles with axle load more than 20 kN during the design period;

V = number of trucks per workday per driving direction (-)

a_{vw} = average number of axles with load more than 20 kN per truck (-)

W = number of working days per year (-)

F_r = correction factor for the number of driving lanes per drive direction (-)

G = growth factor (-)

t = design period (years)

F_v = Correction factor for the speed of truck traffic (-)

All variables are directed from Dienst Grote Projecten en Onderhoud (2013), except for the number of trucks per workday per driving direction (V). V is directed from Rijkswaterstaat (2017).

V	=	726
a_{vw}	=	3.5
W	=	270
F_r	=	0.90 (three lanes or more)
G	=	1
t	=	20
F_v	=	1

n_{total} = 12349260

Dienst Grote Projecten en Onderhoud (2013) works with characteristic values. Therefore, n_{total} has to be multiplied by the uncertainty factor $F_{herkomst}$.for the origin of the traffic information. $F_{herkomst}$ for a standard choice of RWS primary roads is 1.75. The characteristic number of truck axles is:

$n_{truck, total} = n_{total} * F_{herkomst}$ = 12349260 * 1.75 = 21611205 ($2,2 \times 10^7$)

Appendix D: Planning replacing top- and intermediate layer

To know how long it takes to replace the top- and intermediate layer the planning in Figure 19 has been created with information from a construction costs expert from W+B (personal communication, June 14, 2018) and experts from GWW materials (GWW materialen, 2014). In the figure is shown that the time to replace the top and intermediate layer of the A58 takes 13 days.

Time to compl	Activity													
1000 m2/day	Milling top layer	1	2	3	4	5	6	7	8	9	10			
1000 m2/day	Milling intermediate layer	0	1	2	3	4	5	6	7	8	9	10		
2000 m2/day	Applying intermediate layer	0	0	0	0	0	0	0	1	2	3	4	5	
2700 m2/day	Applying top layer	0	0	0	0	0	0	0	0	0	1	2	3	4
	Days in total	1	2	3	4	5	6	7	8	9	10	11	12	13

Figure 19: Bar chart planning replacing asphalt construction

Appendix E: Explanation Multi Criteria Analysis best asphalt collector

In this section the reason for the criteria scores that has been given to every collector is discussed. The scores that come from a source has not been given an explanation. The scores differ from 1 (bad) to 5 (good) and a weight of 1 to 3 is given to the criteria. The reason of the weights per criteria is explained first.

Explanation of weights

Innovative (3)

Because innovation plays a large role in the project InnovA58, the best collector for the A58 has to be largely innovative

Costs (2)

The collector must be affordable otherwise it will never be implemented. But because innovative applications are often expensive in its starting phase, the costs are not the reason for not realising an innovative project that fast.

Experience (3)

Because the highway must be built in a short time period, an experienced application type will be preferred. If there is experience with implementing the collector, it will be easier to implement the collector on a highway.

Efficiency (3)

The efficiency of the collector is very important. When the collector does not have enough heat yield, it is not worth implementing it.

Applicability A58 (3)

In section 4.2.1. is discussed what all types would change to the technical requirements of the A58 itself. The collector must be relatively easy to apply in the A58, if it changes too much of the original asphalt construction it will never be implemented. Therefore, this is an important criterion.

Re-usability (1)

If layers of the asphalt construction with the asphalt collector implemented can be reused, that will be good for the sustainability. But because the collector itself has a much larger contribution to the sustainability, the re-usability will not be of that much importance.

Explanation of scores

PIC-collector

Innovativeness (1)

The PIC-collector is not an innovative application because this application comes close to the PIA-collector and the PIA-collector is used for many years and fully developed.

Experience (2)

Although the application is relatively old, it has not been carried out often. Therefore, there is not much experience with this application.

Applicability A58 (3)

As discussed in section 4.2.1., the technical requirements of an original highway that need to be investigated when implementing the PIC-collector, are in comparison to the other types around average.

Maintenance (4)
Because the top layer and 13 cm of the intermediate layer will have the same lifespan as an original asphalt construction of a highway, the PIC-collector does not affect the lifespan in at these parts of the construction. However, the steel fiber concrete layer will probably have a longer lifespan than an original intermediate layer.

PIA-collector

Innovativeness (1)
The PIA-collector is, just like the PIC-collector, not an innovative application because it is used for many years and fully developed.

Experience (4)
Ooms Construction has carried out a large number of projects with the PIA-collector. The reason the PIA-collector does not score 5 on this criterion is because it has never been done on a highway before.

Applicability A58 (5)
As discussed in section 4.2.1., there are not much technical requirements of an original highway that need to be reconsidered when implementing the PIA-collector. So, the PIA-collector is in comparison to the other types relatively easy to apply.

Maintenance (4)
According to Interviewee 2 (Appendix B), the intermediate layer will be replaced the third time instead of the second time maintenance work is done. The top layer can be milled without problems. Therefore, the score of maintenance of the PIA-collector is 4.

VOWAC-collector

Innovativeness (4)
In comparison to the other types of asphalt collectors, the type is relatively new. According to Interviewee 2 (Appendix B), it is still in its infancy.

Experience (1)
There are only a few projects carried out using this type of asphalt collector.

Applicability A58 (2)
A large number of technical requirements of an original highway must be reconsidered when applying the VOWAC-collector. Therefore, this type of collector is relatively hard to apply.

Maintenance (4)
According to Dijkink (2009) de VOWAC-collector is constructed and maintained with standard road construction equipment. Because of this the asphalt can be fully reused.

Sensitivity analysis
To check the robustness of the MCA, a sensitivity analysis has been done. The weights of all criteria have been reduced and increased by 1 to check if the results were the same. The results of the sensitivity analysis are shown in Table 14.

Table 14: Sensitivity analysis of MCA best asphalt collector type

Collector type	**Original score**	**Innovativeness**		**Costs**		**Experience**		**Efficiency**		**Applicability A58**		**Re-usability**	
Weight		-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1
PIC	39	38	40	35	43	37	41	36	42	36	42	35	44
PIA	45	44	**46**	44	**46**	**41**	49	42	48	**40**	50	41	49
VOWAC	43	39	**47**	40	**46**	**42**	44	39	47	**41**	45	39	47

What points out is that the VOWAC-collector turns out to be slightly better than the PIA-collector when the weight of innovativeness is made more important and when the weight of the experience or applicability on A58 is lowered. However, in most cases the PIA-collector is the best collector type and therefore this collector type is picked as the best application type of the asphalt collector.

Appendix F: Explanation Multi Criteria Analysis best application type solar road

In this section the reason for the criteria scores that has been given to every application type of the solar road is discussed. The scores that come from a source has not been given an explanation. The scores differ from 1 (bad) to 5 (good) and a weight of 1 to 3 is given to the criteria. The reason of the weights per criteria is explained first.

Explanation of weights

Costs (2)

The solar road must be affordable otherwise it will not be implemented. But because innovative techniques are always expensive in its starting phase, the costs will not be the reason of not realising an innovative project. The costs of the solar road now do not have to be low, but to have potential for the future, it has to decline largely.

Applicability A58 (3)

The best application for the A58 needs to be determined and the three solar road applications differ from a bicycle path to a highway. It is a large benefit if the application type has already been applied on a highway before because it is comparable to the A58 project.

Experience (3)

Because the highway must be built in a short time period, an experienced application type will be preferred. If there is experience with implementing the solar road application type, it will be easier to implement the collector on a highway, and the road is more reliable.

Efficiency (3)

The efficiency of the solar road has a large importance. The purpose is to collect energy and to reduce the costs, it must be as efficient as possible, otherwise it not worth implementing it.

Life cycle (2)

The life cycle of the solar road application is important because the road is relatively expensive and will never be implemented if the life cycle is short.

Explanation of scores

Pavenergy

Applicability A58 (5)

Pavenergy is implemented on a highway of more than 1 km in length. Therefore, the Pavenergy project comes close to the A58 project and is therefore well applicable.

Experience (2)

The Pavenergy application has, excluding a pilot project, been executed only once. Therefore, there is not much experience with the product. However, because it was a relatively large project, the score is 2.

SolaRoad

Applicability A58 (1)

The SolaRoad is implemented on a bicycle path. To implement the application on the A58, it has to be designed so it can be used on a highway and is therefore relatively hard to apply.

Experience (2)

The SolaRoad only has been applied on the bicycle path in Krommenie. However, they upgraded the path with new techniques two years after the first version was implemented.

Wattway

Applicability A58 (4)

The Wattway application is used on a road for cars and therefore the application comes close to how it will be designed if it would be used on the A58.

Experience (4)

Wattway is implemented on a road for cars in Normandy, and since May 2018, it is tested on the N401 nearby Kockengen on its efficiency and applicability and in Hengelo the Boekelosebrug will be covered with solar panels from Wattway too. Therefore Wattway is relatively experienced with its technique and therefore gets a score of 4.

Sensitivity analysis

To check the robustness of the MCA, a sensitivity analysis has been done. The weights of all criteria have been reduced and increased by 1 to check if the results were the same. The results of the sensitivity analysis are shown in Table 15.

Table 15: Sensitivity analysis of MCA best application type solar road

Application type	Original score	Costs		Applicability		Experience		Efficiency		Life cycle	
Weight		-1	+1	-1	+1	-1	+1	-1	+1	-1	+1
Pavenergy	52	47	57	47	57	50	54	47	57	49	55
SolaRoad	27	24	30	26	28	25	29	25	29	24	30
Wattway	44	43	45	40	48	40	48	40	48	41	47

What points out is that Pavenergy turns out to be the best application type of the solar road for the A58 in all cases. Therefore, it has been picked to be the best solar road implementation on the A58.

Appendix G: Interview asphalt construction

Date: 1-5-2018

Interviewee number: 3

Interviewer: J.A. Vossebeld

Introduction

Interviewee 3 is working for Witteveen+Bos and he is their expert in road design. Therefore, he knows everything about the asphalt construction. The interview was not only about an answer to the questions because more topics were discussed. Therefore, the questions and outcomes are separately reported. The information has been filtered and the useful information is reported. The interview was held in Dutch.

Questions

1. Bent u betrokken bij het A58 project?
    - Wat zijn u werkzaamheden binnen het project?

2. Zijn er ontwerpen van de toekomstige doorsnede van het te verbreden deel van de A58? Of van de huidige A58?

3. Er is een techniek om asfaltcollectoren toe te passen d.m.v. een ZOAB laag tussen twee DAB lagen. Echter wordt op de snelwegen in Nederland vooral ZOAB gebruikt, betekent dat, dat DAB niet toegepast kan worden op snelwegen?

3. Zijn er kwantitatieve eisen waaraan de verharding moet voldoen? Bijv. contracteisen, NEN of CE?
    - Verwijderbaarheid, draagkracht, waterdoorlaatbaarheid bovenlaag

4. Zijn er eisen per asfalt laag? - sterkte, stijfheid

5. Is er nog andere informatie die nuttig kan zijn voor mij om te kijken welke aan welke eisen de technieken moeten voldoen?

Usable information

- Belangrijkste eisen van een weg zijn vlakheid en stroefheid.
- Asfalt constructie ontwerpers maken gebruik van standaardmodellen en gaan van bepaalde constructiedikte uit. Totale dikte van asfalt laag is meestal rond de 25 cm en van de fundering 30 cm.
- STAB wordt tegenwoordig AC (Asphalt Concrete)16 of AC20 genoemd. Daar wordt dan meestal de naam base, bind of surf aan toegevoegd. Base voor de onderlaag, bind voor de tussenlaag en surf voor de deklaag. De dikte van de onderlaag is meestal 8 cm maar daar kunnen er wel 2 of 3 van worden gedraaid.
- RWS gebruikt meestal dubbele ZOAB laag van 7 cm of een enkele van 5 cm.
- Er kan waarschijnlijk niet worden gerekend met koperen buizen in het asfalt. Wel moet er rekening gehouden worden met hoeveel druk zo'n buis kan hebben en hoe dicht de buizen bij elkaar kunnen worden gelegd. Er moeten genoeg bitumen en stenen tussen kunnen liggen. Hele asfalt laag moet wel 1 pakket worden. Anders kan die op de buizen laag scheuren.
- Berekeningen op asfalt worden gedaan met behulp van herhalingen. Niet statisch maar dynamisch. Je kunt asfalt zien als een paperclip die je kunt buigen maar op een gegeven moment dan knapt hij kapot. Zo'n koperen leiding kan dus ook meebewegen.
- Eisen verschillen per snelweg. Er wordt gekeken naar de intensiteiten en percentage vrachtverkeer. Aantal auto's maakt niet zoveel uit. Bij een verhardingsberekening tellen 1.000 auto's grofweg als 1 vrachtwagen. Vrachtverkeer meestal op rechter spoor. RWS wil geen verschil in sporen dus constructie wordt gebaseerd op rechter spoor. De cijfers van verkeersintensiteiten zijn project

specifiek en waarschijnlijk te krijgen bij Jeroen Snijders of Hugo Bakker. Jeroen heeft namelijk de geluidsberekening gemaakt voor de A58. Anders moet je iemand hebben die verkeersmodel heeft doorgerekend. Dat kan Merel zijn die op de 2e etage zit. Of via Robbert Beentjes en Robbert … een website krijgen die alle gegevens over de lussen in het wegdek heeft.
- Voor diepte buizen of laag zou je moeten kijken naar hoe de warmtecurve loopt met de dikte. Als het boven 35 is hoeveel is het dan onderin?
- Ik denk niet dat er hele belangrijke eisen per asfalt laag zijn. De bovenste laag moet duurder zijn de onderste lagen maar de eisen daaraan veranderen niet. Het gaat gewoon om de complete constructie.
- Belangrijk is dat je de normale functie van de weg niet uit het oog verliest.
- In nl 2 hoofdcontractvormen:
RNW-bestek conform standaard: je maakt een boek. Aannemer moet zoveel en asfalt zoveel banden gebruiken etc. Dat gaat allemaal conform bestekstekeningen.
UAV-gc contract: A58 ook. Ontwerp dat ze maken gaat naar opdrachtnemer en RWS heeft een standaardcontract en daarin verwijzen ze naar specificaties. Daarin staan alle functionele eisen waar een aannemer rekening moet houden. Daar kun je ook naar kijken.
- Meeste vuil op wegdek in de winter
- De laag DAB die onder de bovenste ZOAB laag komt moet minimaal 2,5 cm zijn want veel dunner kan denk ik niet.
- ZOAB is constructief sterk genoeg. Door de holle ruimtes hanteren we de vuistregel: 5cm ZOAB net zo sterk als 4 cm normaal asfalt.