The vulnerability of solar panels to hail

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Climate-KIC project: '*1 million near-zero energy homes in 2023*'

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Summary

This research is linked to the EIT Climate-KIC programme: ‘1-million near-zero energy homes in 2023’. Solar panels play an important role in the transition to a carbon-neutral society. However, due to hailstorms and other weather extremes, solar panels can be damaged and slow down this transition process. Especially, with the expectation of increasing hailstorms due to climate change in most regions in Europe, the relation between hail and damage to Near-Zero Emission measures is becoming even more interesting.

In this study, we explore, and make a first attempt to quantify the vulnerability of solar panels to hailstorms. Literature reviews and expert interviews are used to give an overview of damage from hailstorms in Europe and in the Netherlands and of solar panels and their potential damage, standards and rules, and insurance. To make a first attempt on quantifying the vulnerability, a case study is done for the most severe hailstorm in the Netherlands on 23 June 2016. In this case study, we have done an assessment on the relation between the damage of solar panels, hailstone sizes and solar panel characteristics using insurance damage data and modelled hailstone sizes.

The study shows that the frequency of hailstorms is increasing, as well as damage from hailstorms in Europe and in the Netherlands. Indicating that exposed objects, such as solar panels might become more vulnerable. The solar panel market is a relatively new market, as a result, standards and rules around the quality and installation of solar panels are not well regulated. This can result in damage to solar panels during installation, but also in increased fire hazard (Achmea, 2019b), and can make solar panels more vulnerable to extreme events, such as hailstorms. There is room for improvement in the insurance of solar panels as well, as there is no overall consensus between insurance companies on how solar panels should be insured in the Netherlands and in Europe.

Solar panels are vulnerable objects, of which different factors may affect the performance: (i) environmental factors, (ii) installation factors, and (iii) production factors. These factors can result in cracks in the front glass of a solar panel, which are directly visible and will result in a lower yield. However, smaller cracks (micro-cracks) can form as well, which are not formed in the front glass layer but in the more fragile silicon. Micro-cracks usually do not result in a lower yield initially. However, after a few months, the damaged areas can start to show a rapid decline of power output and after around one year the micro-cracks become visible on the outside of the panel as well. All damages are expected to shorten the lifespan of a solar panel.

The case study shows the relation between solar panels and hail:

- The damage to solar panels is mostly occurring with a maximum hailstone size of 3 cm or more. Larger hailstones (more than 4 cm) cause on average more damage than smaller hailstones, but also show a wider variety in the amount of damage to solar panels.
- The claims with no damage, half of the claims, show most variety in hail sizes. Indicating that more claims on various locations can indicate a wider range of hail sizes.
- Both invisible and visible damage can occur as from 3 cm, but from 4 cm onwards the share of visible damage increases substantially.

- The orientation of the roof in respect of the direction of the hailstorm (and with-it prevailing winds) can considerably affect hail damage to solar panels, and even become more determining than the hail size itself (with direction away from the hailstorm reducing damage considerably).
- There are indicators that also the angle at which the solar panel stands (represented by low-angle on flat roofs and higher angle on pitched roofs) can affect the damage to solar panels (with low-angle having more damage), but the results are not strongly significant.
- Increasing hailstone size increase the amount of damage, however with increasing hail sizes the extra increases in damage are declining.

Several options can be considered to decrease this vulnerability by looking at the characteristics of the solar panels, but also by improving (the enforcement of) standards, regulations and insurance of solar panels. The development of specific measures, such as a cover for the solar panels, may also help to decrease this vulnerability. More research must be done on the vulnerability of other NZE measures to other types of extreme weather and on the effects of micro-cracks using different data sources. Lastly, hail risk and the vulnerability of solar panels to hail should be included into risk models and climate adaptation strategies.

1 Introduction

Late July 2013, the low-pressure system Andreas caused insured damage of € 2.8 billion in Germany, the costliest insured loss event worldwide in that year (Punge & Kunz, 2016). In June 2016, the Netherlands experienced a hailstorm leading to the highest damage ever measured in the country due to hail. In 2017, extreme weather resulted in a total of € 2.9 billion damage of which € 1.13 billion due to hail to the residential building sector in Germany. Hail is not only causing large amounts of damage in Germany and in the Netherlands but has an impact worldwide, causing billions of dollars of damage annually (Pucik, et al., 2019).

This damage is caused by hail risk that is a combination of the hazard, exposure, and vulnerability. It is expected that the hazard of hailstorms will increase, as a result of an increasing frequency of hail events due to climate change (MunichRe, 2019). Not only the hazard is growing but also the elements that are exposed to hail. To decrease the hail risk and damage from this risk, the vulnerability of these exposed elements has to be reduced.

1.1 1-Million near-zero energy homes in 2023

The presented analysis in this report is linked to the programme: '*1 million near-zero energy/carbon homes in 2023'*. This programme is part of EIT Climate-KIC, which is a European public-private partnership focused to tackle climate change and building resilient, net zero-carbon societies. To limit global warming to 1.5°C, emissions will need to be 80-90% lower in 2050 than today. To reach this goal, all new buildings are required to be carbon neutral and the existing ones being adjusted at an annual rate of at least 4%. This has led to the goal of creating one million Near-Zero Energy (NZE) homes within five years (EIT Climate-KIC, 2018).

Measures that can be taken to create NZE buildings are installing external wall insulation or solar panels for example. However, due to the impacts of weather extremes, such as hail, these measures can be damaged or even destroyed (MunichRe, 2019). With the expectation of increasing hail hazards due to climate change together with an increase of exposure of these vulnerable measures (Achmea, 2019a) an increase in hail risk to NZE measures can be expected. This increasing risk may result in a decline in the uptake of such measures, hampering the transition towards a climate neutral society.

1.2 Vulnerability of solar panels to hail

The aim of this study is to determine how vulnerable solar panels are to hail. Solar panels are currently one of the most common measures taken to realize the energy transition. At the same time, there is only limited information available in Europe about the potential hail damage to these panels. A situation in which many solar panels were damaged due to hail was during the hailstorm on the 23rd of June 2016 in the southeast of the Netherlands. Leading to total damage of more than 700 million Euros, of which 500 million was insured damage (Nationaal kennis- en innovatieprogramma: Water & Klimaat, 2019). Due to its widespread impacts, this event is chosen as a case study to further our understanding of the different vulnerability aspects of solar panels to hail.

Some research has been done on the effects of solar panel damage, and on hail risk in general, but only little on the combination of hail damage and solar panels. Two studies from the seventies are available on testing solar modules in an experimental setting (Moore & Wilson, 1978; Hoffman, Arnet & Ross, 1978). However, with the constant development of new solar panels, these studies are outdated. More recently, Muehleisen et al. (2018) show how invisible damage to a panel, can be detected. Gupta et al. (2019) reviews the more recent work on the impact of hail on the performance of solar panels, showing the formation of hailstorms and that the impact of a hailstorm reduces the output power and the life of a solar panel. The International Energy Agency did an impact and a lab-controlled test on the impact of hail on photo-voltaic (PV) modules (Mathiak, et al., 2015). Valuable aspects from these studies will be combined with the results of this study. However, no other recent academic research is available on the relation of hail and damage to solar panels. Therefore, this research is trying to find the relationship between damage to solar panels, their characteristics, and hail.

1.3 Report outline

This study is taking a first attempt on analysing the relation between insurance damage data of solar panels, solar panel characteristics, and hailstone sizes, with the goal to determine the vulnerability of solar panels to hail. The remainder of this report is structured as follows. Chapter 2 describes the applied methods. Chapter 3 presents an analysis of hailstorms and damage in Europe and in the Netherlands. Chapter 4 provides an overview of the fundamentals of solar panels and damage to solar panels, using literature and information obtained from interviews with experts. Chapter 5 presents the results of the case study showing the relation between hail and damage to solar panels. Chapter 6 is discussing the results and advising on a way forward to decrease the risk of damage to solar panels. Finally, chapter 7 concludes the report by highlighting the key findings.

2 Method

This chapter describes the applied methods in this research, divided into three parts. The first part describes how information on the damage from hailstorms in Europe and the Netherlands is obtained. The second part describes how information on solar panels is collected. The third part is explaining how the case study is done and what methods are used in combining and analysing the acquired data and information.

2.1 Damage from hailstorms in Europe

Firstly, literature on damage from hailstorms in Europe is gathered and combined with insurance claim data from Achmea on damage due to hail and severe weather in the Netherlands. The insurance claim data records range over the period 1990 to 2017. Due to the sensitive nature of this data, we only obtained the amount of insured damage due to hail, relative to the total amount of insured damage due to all severe weather. With this data, we perform an analysis on the average share of damage due to hail from the total damage due to severe weather per month, per year and per province. The dataset is also used to create a top ten of days with most damage due to hail and the areas in the Netherlands where most of the damage occurred, also corrected for the market share of Achmea.

2.2 Solar panels

In the second part of this study, we focus on the fundamentals of solar panels and their potential damages. To do so, various meetings and interviews with solar panel experts are conducted. Talks are held with various people from Achmea (re-)insurance, who are experts in the area of solar panels. Other interviews are conducted with a supplier of solar panels, a company that does tests on the quality of solar panels, and an organization that focusses on the recycling of solar panels. All interviews are semi-structured, with a set of prepared questions, but an open mind to obtain new information and to add questions during the interviews where relevant (Bryman, 2012). From every stakeholder, at least three different individuals are interviewed, resulting in a total of 18 individuals (see reference interviewee list, Appendix A) to ensure a broad understanding of the current situation.

The interviews are used to gather information on current processes and guidelines that are in place and for more information on damage to solar panels. Relevant aspects included in the interview are production quality, guarantee measures, transportation measures, installation measures and damage determination methods. Information from literature is added to complement the overview of the fundamentals, types, standards, insurance of and damage to solar panels.

2.3 Case study: hailstorms 23 June 2016

The next step is to dive into the vulnerability of solar panels through a case study. In this case study, we use the hailstorm on 23 June 2016 as it was the hailstorm with the largest damage in recent history. Through this case study, we will look at the relation between damage to the solar panels and characteristics of the hailstorm and the angle and direction of the roof.

Hail data

The hailstorm data consists of hailstone sizes for the whole of the Netherlands, obtained from using radar data supplemented with data from a numerical weather model (Hirlam) from the KNMI (KNMI, 2019) and acquired from Wouters et al., (2019). Wouters et al., (2019) can be consulted for more information on the dataset. For this case study, we have used the maximum hail size per postcode (PC4) per day from this dataset.

Claim data

These maximum hail sizes per postcode are coupled to damage to solar panels in each postcode area. The claim data on solar panels is acquired from Achmea (Achmea data, 2019). These claims are obtained from two different filing systems that Achmea uses. Because the filing systems do not save specific information on damage to solar panels, the textboxes in these claims are manually searched for the term solar panel, solar panels, panels, etc. Claims that include one of these words but indicate damage by other causes than hail are removed from the dataset. This approach results in a dataset of 249 claims with information on the address, the type of damage (no damage, visual damage, invisible damage, or both), number of solar panels that are damaged, and the type of building (agricultural, commercial, or private).

Roof characteristics

This dataset is supplemented with the maximum hailstone sizes and characteristics of the roofs. The characteristics of the solar panels are obtained with a manual analysis of aerial photos. The aerial photo used for this analysis is an orthophoto from 2016 with a resolution of 25 cm (PDOK, 2016). For each claim, the number of solar panels, the orientation of the panels (E, SE, S, SW, W, NW, N, NE), and the roof type (pitched or flat) are acquired. For the roof type, it is assumed that solar panels on a flat roof have on average a lower angle than on a pitched roof. For each of the characteristics, the average damage is determined and hypotheses on the difference in damage between the different groups are tested for using t-tests.

Statistical analysis

To determine the relationship between the maximum hailstone size, damage to solar panels, type of damage and characteristics of the solar panels, a multiple regression analysis is conducted, using ordinary least squares (OLS). The dependent variable that is tested is the damaged solar panels as a percentage of the total number of solar panels. This dependent variable is chosen because a percentage can be easier translated to roofs with other numbers of total solar panels instead of using the absolute number of damaged solar panels.

One of the independent variables is the Maximum Estimated Hail Size (MEHS). A first step in the data preparation is removing the three observations where the MEHS is zero, as including these observations would result in possible outcomes where no hail is observed, but with damage greater than zero. Two of these observations are from the commercial portfolio and one from the agricultural portfolio. The damage in combination with a hail size of zero might be caused by a mismatch of the address of the insured and the location of the damage or simply because the model did not capture the hail in that area.

To be able to take the other variables into account, some variables have to be converted into dummy variables. Firstly, a dummy variable is created to take the angle of the roof into account. Two categories are distinguished: non-pitched roofs and pitched roofs. Secondly, the orientation of the roofs is also taken into account. This results in four additional dummy variables, for each of the observed orientation (southeast, south, southwest, and west). For the flat roofs, we assume that the orientation of the solar panels is optimal regarding solar radiation; an orientation to the south.

An intercept is omitted because damage can only occur when the hail size is greater than zero. This means that we want our models to pass through the origin. In order to take non-linearities into account, the square of the MEHS and the natural logarithm of the MEHS are used as independent variables as well. In order to see if hail damage to solar panels only occurred from a certain hail size onwards, regressions are also done using only the variables with a MEHS of 2 cm and higher. In the regression, interaction effects were also included. This means that a new interaction variable is used, which is (in our research) a dummy multiplied with a continuous variable. This gives us information on the extra influence of the continuous variable, given that the dummy variable is one. This way we can, for example, account for the fact that MEHS has a bigger impact on pitched roofs than on flat roofs. The standard errors in the regression are heteroscedasticity robust, this is indicated with the HC3 in the table with the results of the regression[1].

In order to compare the different models, information criteria are used: the R^2, the adjusted R^2, the log-likelihood value, the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) are included. The R^2 value shows how good the regression fits the data[2]. This is a simple criterion for comparing regressions, however it does not correct for the number of regressors, the independent variables. The more regressors in a regression, the better the regression fits. However, including a high number of additional regressors would result in overfitting, but a relatively high R^2 value. In order to prevent a high R^2 when many regressors are added, the adjusted R^2 is used, which penalises the number of regressors in a regression[3]. For both the R^2 and the adjusted R^2, the higher the value, the "better" the model performs. Furthermore, the log-likelihood value in the regression output is included[4]. The higher the relative value of this criterion, the better the model performs. Lastly, two information criteria were used

[1] The MEHS data cannot directly be assumed to be homoscedastic, the variance in damage might not be the same for all estimated hail sizes. This can usually be attributed to outliers in the data but would violate the OLS assumption where the variance of the conditional distribution of the residuals is constant for every observation. If heteroskedasticity is the case, the standard errors should be adjusted accordingly, and heteroskedasticity robust standard errors can be computed using the robust covariance matrix as discussed in MacKinnon and White (1985). This covariance matrix is preferred over the covariance matrix discussed in White (1980) because it performs better in smaller samples.

[2] The R^2 criterion penalises the regression based on the remaining sum of squared residuals (SSres), scaled by the total sum of squares (SStot). It is defined as: $R^2 = 1 - (SS_{res}/SS_{tot})$. The better the regression fits the data, the smaller the sum of squared residuals and the higher the total R^2 value. This is a simple criterion for comparing regressions.

[3] $\bar{R}^2 = 1 - \frac{(1-R^2)(n-1)}{n-k-1}$

n denotes the number of observations and *k* denotes the number of regressors in the model. For both the R^2 and the adjusted R^2, the higher the value, the "better" the model performs.

[4] Besides using OLS, a linear regression can also be estimated using Maximum Likelihood. As the name says, this estimator tries to maximise the probability that the true model can be explained by the estimated model. The likelihood value that results from estimating a model using maximum likelihood is also included in the regression output.

that try to give an idea of the prediction error, the AIC and BIC[5]. Just like the adjusted R^2, this criterion penalises models for having many regressors. The BIC penalises the number of regressors even further, scaled by the number of observations used to fit the model. For both the AIC and the BIC, the smallest (relative) value indicates that that model is the best model.

It is not expected that all those criteria to unanimously point to one regression as the best performing regression, but we might be able to have a majority of the criteria indicating that one regression performs the best. The results of the used methods can be found in section 3, 4, and 5.

[5] $AIC = 2k - 2LL \qquad BIC = 2k\ln(n) - 2LL$ LL denotes the log-likelihood value of the regression.

3 Damage from hailstorms in Europe

This chapter provides a literature review on damage from hailstorms in Europe (3.1) and a more specific damage data analysis in the Netherlands (3.2).

3.1 Damage from hailstorms in Europe

3.1.1 Research on hail in Europe

The availability of hail reports is limited within Europe. Weather stations mostly do not record hail sizes and information about hail frequency and intensity is hard to obtain due to the low occurrence probability of hailstorms at specific locations (Punge & Kunz, 2016).

Data that is available comes from empirical, crowd-sourced, observation databases, like the European Severe Weather Database (ESWD, 2019) or from networks of hail pads in areas that are prone to hail (Pucik, et al., 2019). In these databases, the largest hailstones, might be missing as they might be partly melted before someone finds and reports them. Also, these databases might be biased towards population dense areas and the availability of “hail spotters” within any given area. However, it can be used to validate hail proxies from radar observations (Punge & Kunz, 2016). This is also done for the Netherlands by Wouters et al. (2019), more information on this type of data can be found in that research.

Other sources of information about hail can be found in hail climatology researches for individual countries. Punge & Kunz (2016) reviewed most of these studies. In 2019, Pucik et al. performed a new study on large hail and the economic and societal impacts across Europe. Pucik et al. (2019) shows an overview, based on the European Severe Weather Database, on areas with the highest hail frequency as shown in the section below.

3.1.2 Hail characteristics in Europe

Pucik et al. (2019) shows that large hail (>= 2 cm) occurs in similar spatial patterns but less frequent than very large hail (>= 5 cm), as can be seen in Figure 1. The highest frequencies can be found in the southeast of Austria. This area experiences large hail around three to four days a year and very large hail every two years. Other areas with a high frequency of hail are in southwestern Germany, the Po Valley in Italy, over the Ore Mountains on the border of the Czech Republic and Germany, and on the border of the Czech Republic and Poland. (Pucik, et al., 2019). Punge & Kunz (2016) also show an overview of hail event frequency in Europe. According to that study, central Europe, like Germany, Switzerland, and Austria, are highly exposed to hail hazard.

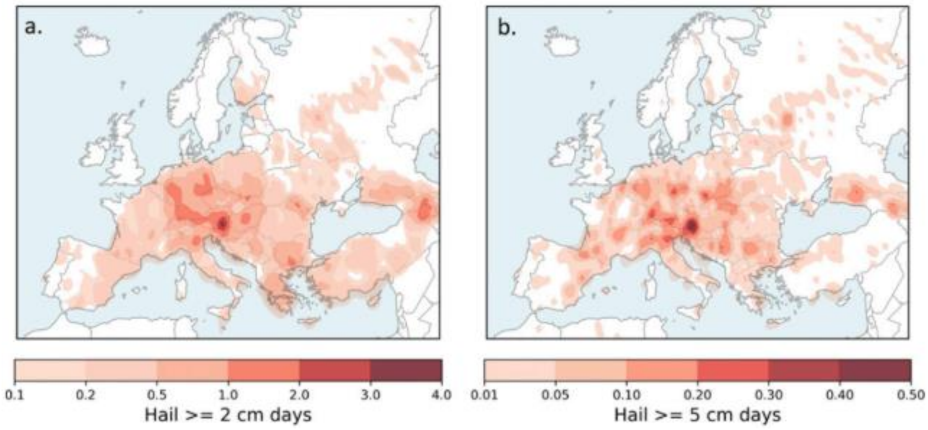

Figure 1: Mean annual number of days with (a) large & (b) very large hail (from the research of Pucik et al. (2019)).

The results of these studies are in agreement with the study of Suwala & Bednorz (2013) on hail in Central Europe, stating mountainous areas, like the southern part of Germany have the highest frequency of hail, probably due to the topography. In Austria, the frequency and intensity of hail events are also influenced by the topography of the Alps. The strongest hailstorms, with the largest damage, are located along the foothills of the Alps, close to the Hungarian border, and along the hilly regions close to the lowlands (Svabik et al., 2013). Figure 2a, obtained from Punge & Kunz (2016) shows the occurrence of maximum hailstone sizes reported in the European Severe Weather Database until September 2015. Despite a possible reporting bias, a maximum is found in Central Europe and a decreasing maximum towards the SW, NE, and SE.

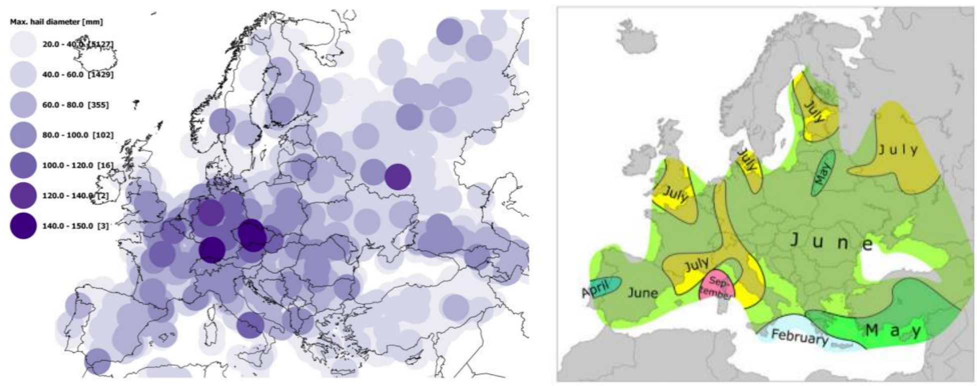

Figure 2: (a) Maximum size (mm) hailstones reported by ESWD until Sep. 2015 (from the research of Punge & Kunz (2016)). (b) The month with the most frequent large hail occurrence (from the research of Pucik et al. (2019)).

Pucik et al. (2019) confirms that large hail is mostly reported in the summer months, with June or July as the peak in most areas of Europe as can be seen in Figure 2b. In the Southern regions, the peak months differ from April in Portugal to February in the South of Italy and Greece. This is because continental areas experience the peak thunderstorm season and thus large hail, in the months with peak heating. The coastal maritime areas, such as in Italy and Greece, experience their peak in autumn to winter months as the Atlantic subtropical ridge shifts southward and deep low-pressure systems develop over the Mediterranean Sea (Pucik, et al., 2019). Suwala & Bednorz (2013) mentioned that in Central Europe most hail events occur during the first half of the warm season (April to

June), with May as peak month, contrary to the month June according to Pucik et al. (2019).

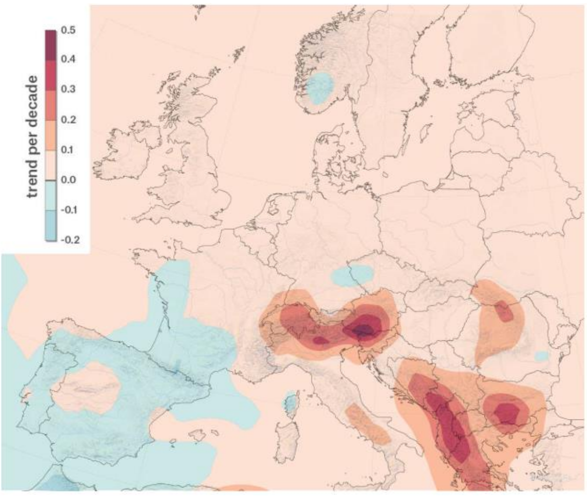

Figure 3: Trend of change in hail events from 1979 to 2015 (from the research of MunichRe (2019)).

The number of hail events increased significantly in a period of 37 years from 1979 to 2015 in Europe (MunichRe, 2019). However, these changes are not homogeneous all over Europe. The number of hail events increased the most in areas with mountains and in pre-Alpine regions (EEA, 2017). The largest increases are observed in northern Italy and on the Adriatic coast, as can be seen in Figure 3. In central Europe, in France, the Benelux and Germany smaller increases were seen. In the southwest of France and parts of the Iberian Peninsula a slight decrease is found (MunichRe, 2019).

Future projects of hail events have large uncertainties, because large scale storms are rare and small-scale storms are hard to be represented in global and regional climate models. However, central Europe will have an increasing hailstorm frequency according to most model-based studies (EEA, 2017). The KNMI (2016) explains this is also the prediction for the Netherlands. Due to warmer weather, the air can hold more water, this can lead to increasing vertical movements in the air, resulting in a higher change of thunderstorms with strong winds and large hail.

3.1.3 Damage of hailstorms in Europe

Hail events are among the costliest extreme weather events in several regions in Europe, leading to damage to crops, vehicles, buildings and infrastructure (EEA, 2017). Together with exposure and vulnerability, patterns of increasing hazards in some regions are leading to a higher risk of hailstorms and related damages. Pucik et al. (2019) looks at the societal and economic impacts of large hail across Europe and the relationship between hail size and damage. They use archived hail reports, hail loss insurance data and a probabilistic hail model. Pucik et al. (2019) finds 669 loss events involving hail between 1980 and 2018 across Europe. Most of the loss events are located in Germany, Austria, and Switzerland. Table 1 presents the highest (normalized) losses that have occurred in Europe due to hail, together with the location that experienced the highest loss during the event. The events show an average maximum hail size of 8.5 cm. Eight events show losses exceeding $1 billion (USD). Six of the events out of this list occurred in Germany. The loss database might be underestimating a number of events in countries where the incidence of very large hail events is similar to southern Germany, but the number of loss events is much smaller. This is because the reporting of hail reports may not be equally distributed, and some areas might be underreported.

Table 1: Ten highest hail-related loss events across Europe (from the research of Pucik et al. (2019))

Date	Country	Location	Loss (in millions USD)	Maximum hail size (cm)
27–28 Jul 2013	Germany	Reultingen	4689	8
12 Jul 1984	Germany	Munich	4330	10
7–10 Jun 2014	France/Belgium	Île de France	2301	11
28 May–2 Jun 2008	Germany	Krefeld	1987	8
23–24 Jul 2009	Switzerland/Austria	Romont	1856	10
22–24 Jun 2016	Netherlands	Someren	1783	10
19–21 Jun 2013	Germany	Lohmar	1295	7
4 Jul 1994	Germany	Köln	1032	5
19–24 Jun 2002	Germany	Hochstetten	834	10
11 Jul 1984	France	Epinal	782	6

The event in July 2009 in Switzerland caused widespread damage to property, motor and crop damage. This event caused the largest losses due to hail in recent history in Switzerland. Severe hailstorms occur regularly during the summer months in the country (GCcapitalideas, 2009). Pucik et al. (2019) showed that the annual trend in hail losses in Germany seems positive, but is not statistically significant. From 1990 to 1999 the average annual hail loss was $527.7 million (USD) and from 2006 to 2018 this was 1398.24 million (USD). This upward trend of hail losses can be attributed to changes in exposure, vulnerability, and hazard. Increasing populations in cities and the increasing vulnerability of assets has increased potential hail risk.

3.2 Historic hailstorms & damage in the Netherlands

The Netherlands is one of the countries in Europe that deals with damage due to hailstorms as well. Figure 4 shows an overview of the share of insured damage in the Netherlands due to hail from the total insured damage caused by severe weather (Achmea data, 2019). It can be seen that there are several years that the damage due to hail plays a large role in the total damage. For example, in 2016, 73% of all insured damage caused by extreme weather is caused by hail, but on average it makes up 19% of the total damage by severe weather. However, it must be kept in mind that the data before 2007 does not include all the damage data from the insurance company. So, the graph gives an overview of the share of hail damage, also before 2007, but it does not give the exact shares of damage.

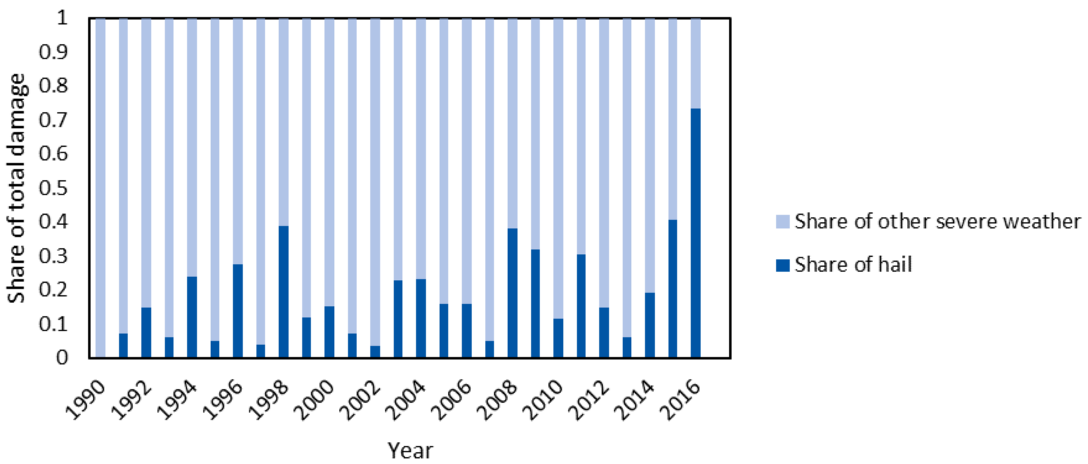

Figure 4: Average share of insured damage due to hail from all insured damage by severe weather per year from 1990 to 2016 (data from Achmea data (2019)).

Figure 5 shows the largest share of insured damage due to hail per month, averaged over the years 1990 to 2017. Hail damage occurs the most in the summer months from May to August. This is also in agreement with the findings of Pucik et al. (2019) who show that the Netherlands experiences most hailstorms in June and July. This indicates that damage is in relation to hailstone sizes, as the largest hailstones are found is summer as well, as can be read in the research of Wouters et al. (2019)).

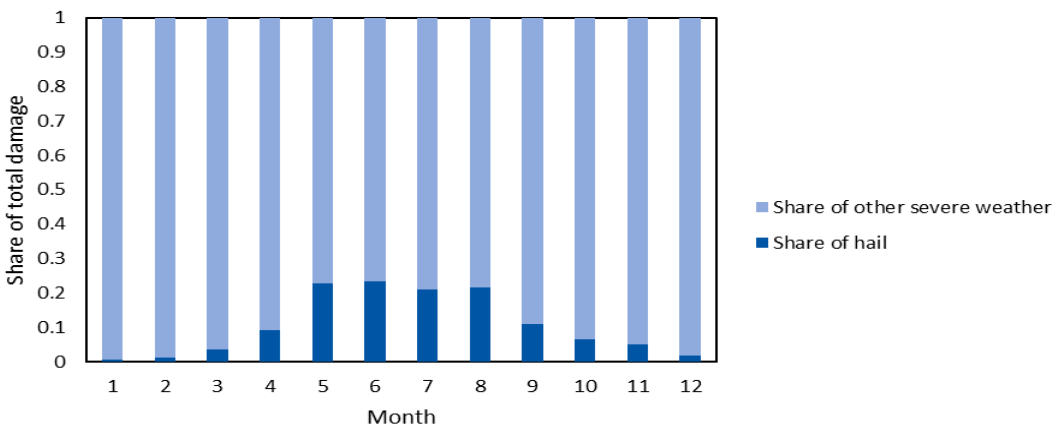

Figure 5: Average share of damage due to hail from all damage by severe weather per month from 1990 to 2016 (data from Achmea data (2019)).

The data also shows that the damage due to hail from the total damage from severe weather over a period from 2007 to 2016 is the largest is the south-east of the Netherlands and smallest in the north-west of the country. This is in agreement with the research of Wouters et al. (2019): the largest hail sizes are also observed in the south-east of the Netherlands.

Table 2 shows the ten hail events on which most insured damage has occurred due to hail, together with the areas that show the highest recorded damage on that date. Figure 7 shows a map of the Netherlands with the postcode level one numbers divided into north, east, south, west to indicate the areas of the table. Table 2 shows that the top event contribute to more than half of the amount of damage caused by this top 10 events, making it the largest hail event from 1990 till 2017. The sum of the damage in the top 10 explains 70% of all the insured damage due to hail in this period. It can also be seen that the top three of hail events occurred in the south of the Netherlands (postcode 5 and 6) and caused 59.3% of the total hail damage. These events all happened in the south or west of the country.

Table 2: Top 10 hail events with the most damage in the Netherlands from 1990 to 2017 (data from Achmea (2019)).

Top 10	Date	Relative damage /event (%)	Relative damage per area (%)			
			N	E	S	W
1	23-6-2016	62.56	0	0	**98**	2
2	30/31-8-2015	14.68	1	1	**70**	28
3	22-6-2008	7.42	16	16	**55**	13
4	6-6-1998	3.00	20	3	4	**73**
5	26-5-2009	2.66	17	1	4	**78**
6	28-6-2011	2.47	1	1	8	**90**
7	24-6-2016	2.38	1	1	**95**	3
8	10-9-2011	2.28	4	1	1	**94**
9	10-7-2010	1.55	1	0	**93**	6
10	2-7-2015	1.00	0	1	**78**	21

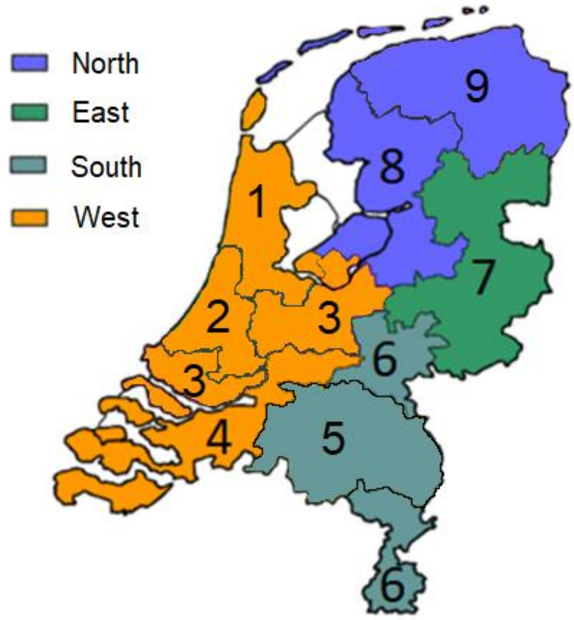

Figure 6: Numbers postcode in the Netherlands (adjusted from (Geoinformatie bronnen op internet, 2009)).

Due to increasing frequency and intensity of hailstorms, exposed elements are at higher risk of being damaged by hailstorms in the future. As explained in the introduction one of these exposed elements is solar panels. They are vulnerable to hail and getting more and more exposed due to the increasing number of solar panels. Together with an expected increase in hail events in Europe, the risk of damage to solar panels is increasing as well. The next chapter will give a description of solar panels and their potential damage.

4 Solar panels

This chapter will give a short description of solar panels, types of solar panels, standards and guidelines of solar panels and the insurance of solar panels.

4.1 Fundamentals of solar panels

Solar panels are boards of solar cells. The solar cells use light energy to generate electrical energy. The mechanism behind this conversion is called photovoltaic energy conversion (Soga, 2006). While the materials used in solar cells differ, the structure of solar cells remains the same (Fonash, Ashok, & Fonash, 2018). The structure of a solar panel and cell can be seen in Figure 8 (Fonash et al., 2018).

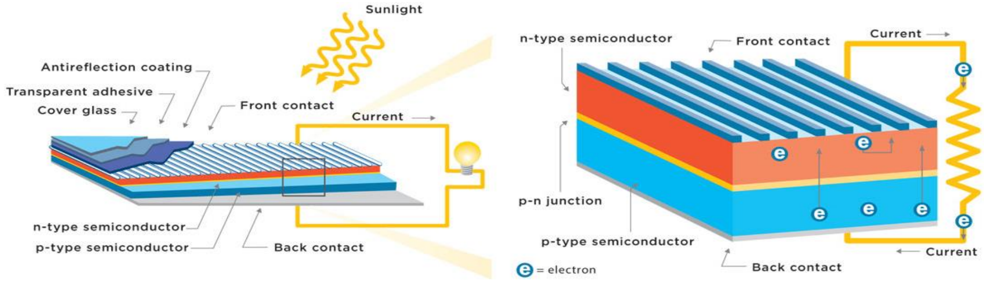

Figure 7: Fundamentals of a solar panel and solar cell (Alpine Solar, 2019).

Sunlight first encounters the antireflection layer. This layer has an optical coating, which is made to minimise the loss of light and retain the light as best as possible. In order to do this, the transmission of the light to subsequent layers is promoted. Those subsequent layers convert energy. They consist of a top-junction layer, an absorber layer, and a back-junction layer. These three layers, together with the antireflection layer, are situated between two electrical contact layers. The front electrical contact layer consists of very thin and widely spaced grid lines. Those grid lines are made to be as small as possible, in order to minimise the blockage of light. The back electrical contact layer does not have any restrictions on its surface area and therefore covers the entire back of the solar cell (Fonash et al., 2018).

The absorber layer of the solar cell tries to absorb as much radiation from the visible range of the spectrum because this range contains most of the energy of sunlight and artificial light. The sunlight is absorbed by semiconductors. Electrons in the absorbing layer are excited as soon as radiation hits the solar cell. Those electrons are excited from their ground state (where they are bound to atoms in the solid) to a higher excited state. In this state, they can move around. The two junction layers induce an electric field that generates the photovoltaic effect. This allows the electrons to be passed on, to an external circuit. The electrical energy can be stored in electrochemical storage batteries (Fonash et al., 2018).

Solar panels are subsequently put together in a chain. They are connected in a string of panels. This means that if one of the solar panels in the string has a lower output (for example due to shadow), the entire string of solar panels suffers from this reduction. A solution to this problem is microinverters (Consumentenbond, 2019a). Microinverters handle the output of single panels, which means that a reduction in output for one panel does not lead to a reduction in output for all the panels. Another benefit of microinverters is the fact that you can monitor the output of your solar panels

(Consumentenbond, 2019a). This means that damages in the solar panels are easier to locate. However, the downside is that these microinverters are relatively expensive, and not every roof has the inverters.

4.2 Types of solar panels

Solar panels can be divided into a few categories: monocrystalline solar panels, polycrystalline solar panels, and thin-film solar panels. The first two are silicon-based solar cells (Hussain, 2018). They are named after the material of the semiconductor and currently hold the largest market share in the Netherlands (Consumentenbond, 2019b). Monocrystalline solar panels are currently the most efficient type of solar panels (Consumentenbond, 2019b). Polycrystalline solar panels are less efficient than monocrystalline solar panels but are also less expensive. Monocrystalline panels can also be made into all-black solar panels. Those panels are aesthetically well designed and have an all-black appearance. However, all-black panels absorb more heat on the parts around the antireflection layer, which lowers the efficiency of the panel.

Figure 8: Three different types of solar panels (Solarmarket.com.au, 2019).

Another type of solar cell are thin-film solar cells. Those cells are not made from crystalline silicon, but from amorphous silicon (Burgess, 2018). While the efficiency of this type of solar cell still lags behind the crystalline cells, the cost of thin-film panels is lower than that of the crystalline types. Thin-film solar cells can be flexible and can, therefore, be installed on curved surfaces. This is an advantage of the thin-film solar cells and might be a reason that the thin-film solar cells overtake the crystalline cells, combined with the lower production costs (Ramanujam et al., 2019).

4.3 Standards, guidelines and certification related to solar panels

As the solar panel market is a relatively new market there are not a lot of enforced laws and rules regarding solar panels. However, there are some standards, certifications and warranties being used.

4.3.1 Guidelines

The international IEC-standards are the foundation of European and national standards and guidelines concerning solar panels (VKG, 2019). The IEC-standards indicates a solar panel must be able to resist a hail stone with a diameter of 25 mm (Mathiak, et al., 2015). The International Electrotechnical Commission (IEC) is a global organization that publishes consensus-based international standards and also manages conformity assessment systems for the sector of electrotechnology (IEC, 2019). The adoption of these International Standards is voluntary, although national laws or regulations often refer to them.

In the Netherlands, the standards based on the IEC International Standards are called the NEN-standards. Such a NEN-standard is a voluntary agreement between market parties which has no legal status, but is generally applicable (Roofs, 2019; KSN, 2019). The NEN-standards concerning photovoltaic systems can be divided into four categories: the general and building standards, the product standards, the installation standards, and the practical guidelines and technical agreements (Castenmiller, 2019). An overview of the most important standards concerning solar panels applied in the Netherlands is given in Appendix C1.

4.3.2 Certification

In the Netherlands, all solar panels on the market should follow the standards of IEC and NEN, but since these standards are not mandatory, manufacturers of solar panels can decide for themselves whether they meet these requirements (Achmea, 2019a). Despite the fact that these standards are not mandatory, there are multiple hallmarks and certifications in the Netherlands to guarantee the quality and safety of the components of photovoltaic systems and the installation of these systems (Zonnekeur, 2013; Stichting Garantiefonds Zonzeker 2019b; Achmea, 2019a). The Kwaliteitsborging Installatiesector (Kiwa) administers a register with valid and reliable photovoltaic components (NEN, 2013a). Even though the technical standards are trusted, the monitoring of the compliance of these standards is insufficient.

The most common hallmarks on the Dutch market are the CE-hallmark, the TÜV hallmark, the RoHS-certificate, and the IEC-hallmark (Stichting Garantiefonds Zonzeker, 2019b; Zonnepanelengids.com, 2019). The CE-hallmark (Conformité Européenne) is a mandatory hallmark for photovoltaic systems and demonstrates that the solar panels meet the standards of the (European) law related to safety, health and environment (Stichting Garantiefonds ZonZeker, 2019a; Zonnepanelengids.com, 2019; RVO, 2019a; European Commission, 2019). However, other hallmarks are not mandatory (NVWA, 2019). Besides the hallmarks intended for the photovoltaic system itself, also different certifications and hallmarks concerning installation companies and producers of solar panels are present. Installers of these systems can get certified by Cito to guarantee their expertise (NEN, 2013a). The ISO-certificate (International Organization for Standardization) is another example of a certificate that guarantees that the producer of solar panels meets certain requirements regarding safety, reliability and quality (Zonnepanelengids.com, 2019; Stichting Garantiefonds ZonZeker, 2019b). More information on other hallmarks used in the Netherlands can be read in Appendix C2. In conclusion, certification and hallmarks are not uncommon in The Netherlands. However, as for the IEC and NEN standards, most of these certifications and hallmarks are not mandatory and therefore not used a lot in practice (Achmea, 2019a).

The Netherlands is not the only country that does not have mandatory certifications and hallmarks since the same applies to Germany. In Germany, there is also no real certification process in place, but an international testing procedure according to the earlier mentioned IEC-standards is present (GDV, 2019). Moreover, the German engineering association possesses a publication concerning the installation of photovoltaic systems. This publication consists of technical guidance which describes the requirements solar panels have to meet to resist certain wind speeds and hail and provides a guideline for the requirements of installing photovoltaic systems. Despite the existence of this publication, these requirements are also not mandatory.

4.3.3 Warranties

The average lifespan of solar panels, not regarding film panels, is estimated to be 25 to 30 years depending on the material of the system and the installation conditions (Atama Solar Energy, 2016; Energysage, 2019; Green Coast, 2019; Verbond van Verzekeraars, 2019; Sungevity, 2019). As for many technical products or installations with relatively longer lifespans, there is also a warranty on photovoltaic systems (Consumentenbond, 2019c). The warranties concerning photovoltaic systems can be divided into several categories: product warranty, power warranty, warranty on installation, system warranty, and power yield warranty (Consumentenbond, 2019c; Sungevity, 2019). More information about these specific types of warranties can be read in Appendix C3.

The lack of guidelines and certifications can lead to poorly installed solar panels or even damaged panels during the production or installation. This can, in the end, lead to the solar panels being more vulnerable to other causes of damage, such as after a hailstorm for example (Achmea, 2019a).

4.4 Insurance of solar panels & hail

To be able to financially protect an owner of solar panels from damage, insurance plays an important role. In general, in the Netherlands solar panels are insured against fire, induction, and damage caused by nature like lightning and hailstorms (Verbond van Verzekeraars, 2019). The insurance differs for the agricultural, commercial and private sectors.

In the private sector, there is no separate insurance for solar panels, they are automatically insured in the home insurances. This means that a solar panel is insured in the same way as a roof tile. As a consequence, at some insurance companies, individuals do not have to let insurance know whether they are in possession of solar panels (Achmea, 2019b). As shown in Appendix B, this insurance of solar panels differs among different insurance companies (Solar Magazine, 2019). Most insurers in the Netherlands pay out the visible damage caused by hail. Whether the invisible damage (micro-cracks) is insured differs per insurance company. At some companies, this damage is not insured, whereas, in others, micro-cracks are only insured if it can be proven that the damage is caused by the hail and not by other causes (like during the installation or production). These rules were set after the hailstorm in 2016, which damaged many solar panels, for the first time at such a scale, and caused a lot of problems during the handling of the claims (Solar Magazine, 2019).

Problems that were noticed by insurance companies when handling the claims after the hailstorm of June 2016 (Achmea, 2019a; Achmea, 2019b):

- No specific rules were available on how to handle invisible damage.
- A large number of panels were damaged due to micro-cracks; however, this cannot be seen in the output production directly.
- There is no rule that indicates that the customer must actually replace the broken solar panels, so in theory damaged solar panels can get back on the market again and insurance companies could have to pay for the same panel multiple times.
- There was not always consensus in the determination of paying claims after invisible damage.

- Solar panel suppliers and testers sent letters to solar panel owners to point out they should let their solar panels be tested by them on micro-cracks. This led to unreasonable claims for insurance companies.

In the commercial sector, it is not yet determined how the policy must be changed regarding hail and invisible damage. Before the hailstorm in 2016, the amount of money paid out by Achmea to companies with damaged solar panels was based on the reconstruction value/repair costs or the reduced market value of the solar panels (Achmea, 2019d). Another difference in handling claims of private policyholders and companies is that in the case of companies, Achmea always checks if solar panels are damaged by sending an expert to the policyholder who claimed damage. With private policyholders, this does not happen for every damage claim. After it has been determined that a solar panel has been damaged, it is intended that the damaged solar panels are being replaced by new panels. However, it is not checked whether this is actually done.

In the agricultural sector, customers can sometimes choose in the policy whether to include damage caused by hail or not. So, depending on what type of insurance they have, the hail damage is or is not insured. Overall there is not really a consensus between insurance companies in the Netherlands on how solar panels should be insured (Achmea, 2019a; Achmea, 2019b).

For other countries in Europe, no specific information is available on the insurance of solar panels. Comparing the Netherlands with insurance of solar panels in Germany, it can be said that the general arrangements are the same. In Germany, there is also not separate insurance for solar panels present (Gothaer, 2019), as these are also included in the construction insurance contract (GDV, 2019). There has not been a great focus on hail risk and damage concerning insurance in Germany since not a lot of money is earned with the insurance of solar panels ((GDV, 2019); (Gothaer, 2019)). Consequently, no specific law is in place that regulates the insurance of solar panels (GDV, 2019). However, discussions have also started in Germany if hail risk should be incorporated in the insurance as a separate policy.

4.5 Damage to solar panels

Solar panels can get damaged in various ways leading to various problems. To make sure solar panels produce energy with the highest efficiency it is important to find out how the panels can be damaged and what the effects are of the damage. This section will discuss these topics.

4.5.1 Factors that can lead to damage of solar panels

As proposed by Gupta et al. (2019) the current factors that are expected to affect the performance of solar panels are divided into two categories, environmental factors, and installation factors. In this study, all interviewed stakeholders stated that currently the supply chain from producing the cells until the installation is poorly regulated (Achmea, 2019a; Achmea, 2019b; SolarClarity, 2019). This is leading to damages that can occur somewhere in the supply chain, leading to the third category of damage factors, the production factors. Figure 10 shows these three categories with the corresponding factors. This shows that many factors can damage the solar panels which are not only happening due to environmental factors like hail but can already happen during the production and installation process.

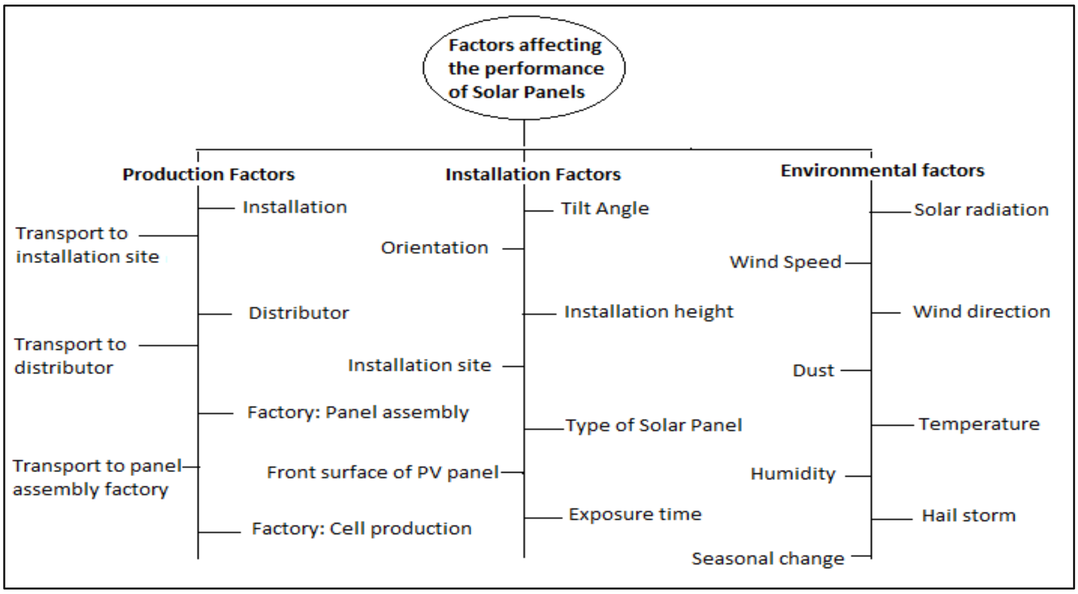

Figure 9: Factors affecting performance of solar panels, adapted from the research of Gupta et al. (2019)

Figure 10 shows an overview of these three categories. During the production solar panels can get damaged during transport, installation or already at the factory. Installation factors can affect the performance of the panels as well, by the choice in type of solar panel, the orientation, and the tilt angle of the panel for example. Environmental factors can affect the performance after the panel is installed due to wind, dust, and hail for example.

4.5.2 Effects of damaged solar panels

The above factors can potentially cause damage to the solar panels which can occur in different forms. The front glass surface of a solar panel can crack after the impact of an object. This type of crack is directly visible. The crack reduces the solar insolation to enter straight to the solar cell which consequently results in a lower yield (Gupta et al., 2019). Smaller cracks that are not formed in the front glass layer but in the more fragile silicon layer are called micro-cracks (Solar Tester, 2019). These micro-cracks can only be seen using special tests, an Electro Luminescence test for example. In this test, the light output increases with the voltage so areas with cracks appear as dark spots. Therefore, the test can show the shape of the cracks and can indicate the cause of the crack. For example, a star-shaped micro-crack can indicate the impact of a small object, like a hailstone. Micro-cracks usually do not show a lower yield initially, but will after a few months (Solar Tester, 2019). In Figure 11 a simple example of visible and invisible damage is given. Other methods that can inspect the damage to installed solar panel modules in the field are thermography technique and the UV-fluorescence imaging method. The thermography technique is most commonly used in the field, using a portable camera that can detect thermal hot spots indicating disconnection between modules or strings for example (Gupta et al., 2019).

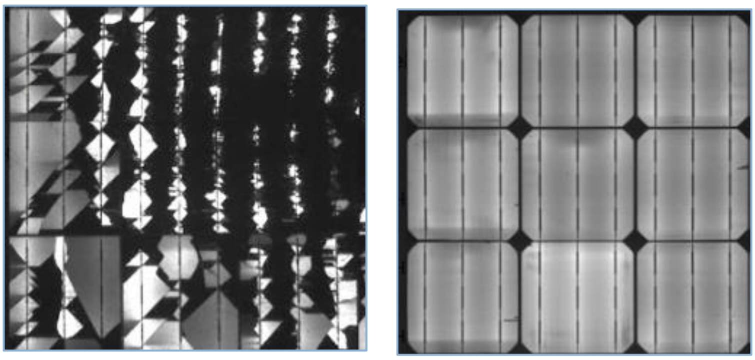

Figure 10: Results of electroluminescence of (a) visible and (b) invisible (micro-cracks) damage to a solar panel (provided by Solar Tester Nederland (2019)).

Several studies (Gupta et al., 2019; Moore & Wilson, 1978; Berardone et al., 2014; Dimish et al, 2017; Kajari-Schroeder et al, 2012; Morlier et al., 2015; Paggi et al., 2013) have proposed empirical methods to quantify the effects of damage on the performance of solar panels. It is very complicated to measure the effects of the damage, because of the complicated nature of the development of damage on solar panels.

As stated by Solar Tester (2019), micro-cracks do not result in lower energy yield initially. Because of temperature changes, the cracks can grow (Achmea, 2019a). After a few months, depending on the number and size of cracks, the orientation and the type of panel, the damaged areas start to show a rapid decline of power output and after around one year the micro-cracks become visible on the outside of the panel as well. When these micro-cracks become visible on the outside of the panel they are often referred to as snail trails and are discolorations on parts of the solar cell surface (Meyer, et al., 2013). All damages are expected to shorten the lifespan of a solar panel (Gupta et al., 2019)

Currently, scientific research is lacking knowledge on the actual quantitative effects of different damages on the shortening of the lifespan. However, by combining existing academic literature (Mathiak et al., 2019; Gupta et al., 2019; Dimish et al, 2017), grey literature (Solar Edge, 2017; Solar Tester, 2019) and interview results (Achmea, 2019a; Solar Tester, 2019; SolarClarity, 2019), an overview of current knowledge on the effects of damaged solar panels was made, as can be seen in table 3.

Table 3: Type of damage to solar panels and their effect on the output power (from multiple researchers as explained in the text).

Damage	Type of crack	Damage area required to significantly affect output power (per panel)	Scientific literature (1)	Grey Literature (2)
Visible damage	Diagonal break (+45°)	>85.85 mm^2	x	
	Diagonal break (-45°)	>85.85 mm^2	x	
	Parallel to bus bars break	>82.00 mm^2	x	
	Perpendicular to bus bars break	>79.40 mm^2	x	
	Multiple direction break	>46.20 mm^2	x	
Invisible damage	Micro-cracks	>1 % cells disconnected (>20 % very critical effects)		x

The table shows for visible- and invisible (micro-cracks) damage, the type of breaks and their minimum sizes to significantly impact the output power of a panel. For a micro-crack to be critical, at least 1% of the cells need to be disconnected by the crack. The last two columns indicate what sources were used. The studies that contributed to the results of this table all used different methods to test the required damages to significantly impact the power output. Appendix D gives an overview of the methods used in these studies.

4.5.3 Hail impact on solar panels

Pucik et al. (2019) showed that damage to vegetation (crops and trees) occurs the most with a hail of 3 cm. Damage to vehicle bodies, house windows and roofs most frequently occurred with a hail of 5 cm and vehicle windows with a hail of 7 cm. Injuries were mostly reported with a hail of 5 cm, but in some cases injuries were recorded at smaller hail sizes. Even though not a lot of research has been done on the impact of hail to solar panels specifically, some lab studies have been done as described below.

The International Energy Agency (Mathiak, et al., 2015), did research on a setup of two roofs impacted by hail. They find that hail-typical cell damages are star cracks and that the power of just the cracked cells is mostly unchanged. On the roof hit by hailstones of 6 cm in diameter, 42% of the modules were showing visible damages. On the other roof hit by hailstones with a diameter of 4 cm, only around 3% of the panels showed visible damages, but 90% star-shaped micro-cracks. This research described the same factors that could lead to damage as was described in Figure 10. However, their lab tests also specified on some factors that can make a panel more resilient to hail:

- A glass-glass panel instead of a glass-foil panel.
- Thicker glass (3.2 mm glasses can be destroyed by 5 cm ice balls; 4.0 mm glasses only show micro-cracks).
- No earlier cracks by transport or snow.
- Stronger clamps that attach the panel.

The experiments of Moore & Wilson (1978) demonstrated that the impact of hailstorms on the solar panel mainly depends on the material utilized for the front layer. Utilizing clear silicone potting as front layer demonstrated it could not withstand 1-inch (around 2.5 cm) simulated hailstones without cell breaking. Anneal glass as the front layer was fit for withstanding up to 1-inch, to 1-1/4-inch (2.5-3.2 cm) hailstones. Using tempered glass could withstand 1-1/2-inch (3.8 cm) ice balls, but broke under the effect of 2-inch (5 cm) ice balls. The research of Moore and Wilson (1978) did the same type of research where silicon potting as the front surface was the weakest, then annealed glass and tempered glass could withstand hail the best.

Damage to solar panels can have many different causes. Especially for micro-cracks that are not directly visible, it is hard to determine what it was caused by unless special tests are used. Micro-cracks can lead to a decline in power output in the longer term. The next chapter will try to relate the damage to solar panels with hail sizes and solar panel characteristics.

5 Vulnerability of solar panels to hail (case study: 23 June 2016)

5.1 Damage caused by the hailstorm

On the 23rd of June 2016, heavy thunderstorms led to large amounts of water, wind and hail damage. Especially the southeast of the Netherlands was hit by the hailstorm. The 23rd of June was a hot day with maximum temperatures of 30 degrees Celsius or higher, with an extremely moist air leading to the highest dew point temperature ever measured in the Netherlands (Sluijter, 2016). Just before 8pm, heavy hailstorms reached Noord-Brabant, in the south of the Netherlands. In the Southeast of Noord-Brabant, one of the storms developed into a supercell. This supercell travelled into north-north-eastern direction leading to a large amount of damage due to large hail stones. On various locations, hailstone sizes with a diameter of 4 to 6 cm were observed. Locally, even hail of 7 to 10 cm was observed, making it the largest hail observed in the last 25 years in the Netherlands (Sluijter, 2016).

This can also be seen in Figure 12, which shows the maximum estimated hailstone sizes per postcode (PC4) in centimetres. It can indeed be seen that in the southeast of the Netherlands, in Noord-Brabant and Limburg, the largest hail occurred according to a dataset from Wouters et al. (2019). The map on the right shows the damage as a share of damaged houses of the total houses in the postcode (Achmea data, 2019). In general, the same area where the largest hail was observed also shows the highest damage, leading to areas where more than 20% of the houses were damaged by the hailstorm. However, it can also be seen that in some areas where hail sizes were large, the damage is not that large. This could be explained for example by agricultural areas that are sparsely populated, or because hail is a very local phenomenon, so even if in some postal code areas, the maximum hail size was very large this does not directly mean it was that big in the whole area.

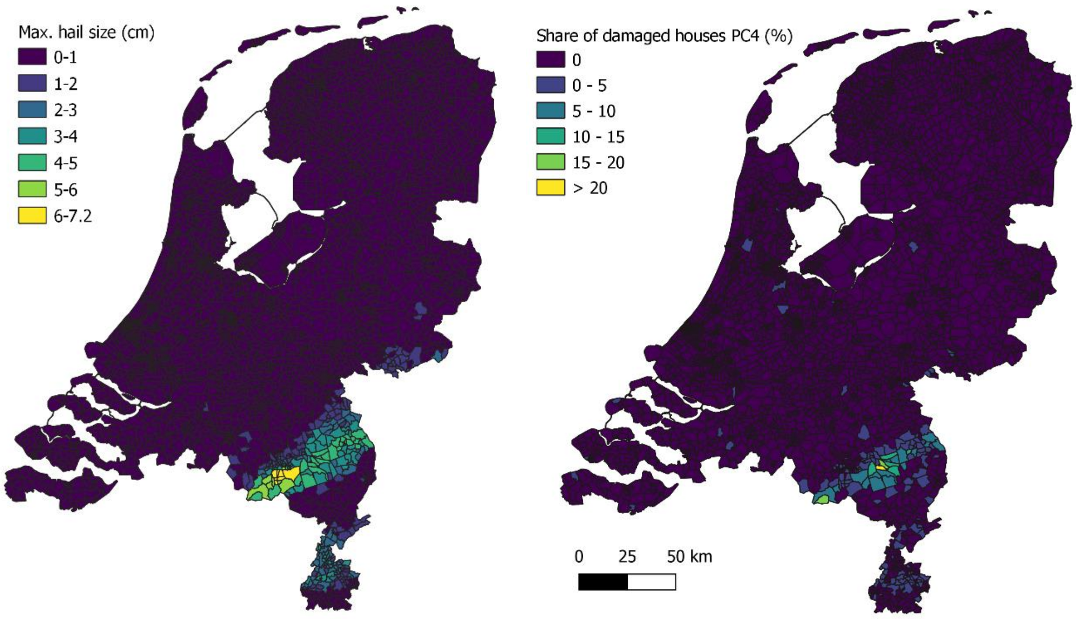

Figure 11: Hailstorm 23 June 2016 in the Netherlands (a) Max. hailstone size (cm) in postcode (KNMI (2019)). (b) Share of damaged houses of total insured houses in postcode (based on data from Achmea (2019)).

Figure 13 shows a plot of the number of damaged houses from the total number of insured houses in a postal code in relation to the maximum hailstone size in that postal code. The numbers on the y-axis are left out of the figure, as this data contains sensitive information. The figure shows that even from small hailstones damage can occur, but from a hail size of 3 cm, the damage to property is increasing substantially. It can also be seen that for larger hailstone sizes it seems that the damage is decreasing again. However, this could also be the case because there are only very few areas where these large hailstones occurred, where maybe no buildings were located.

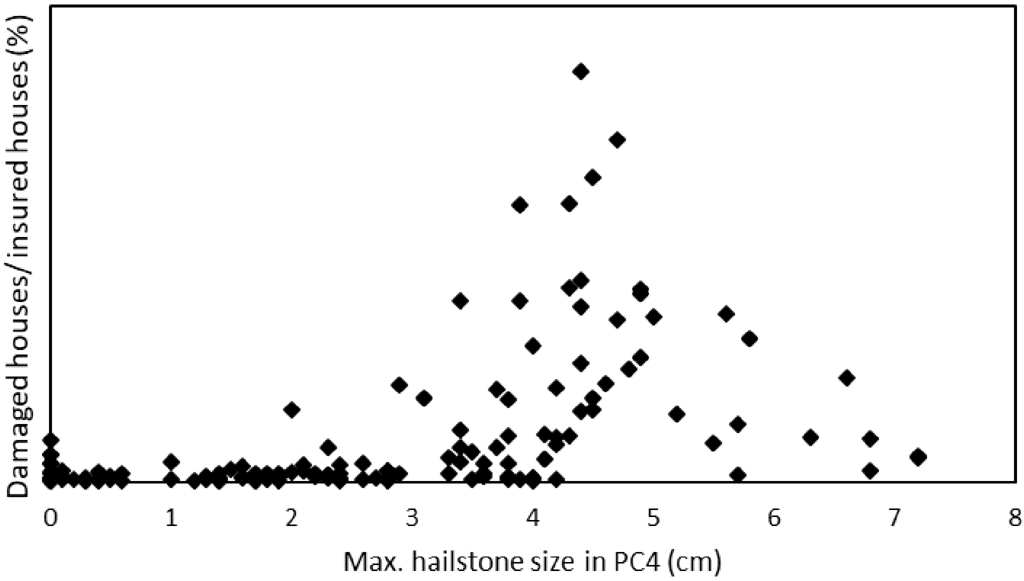

Figure 12: Share of damaged houses of total insured houses to max. hail sizes in corresponding postcode (based on data from Achmea (2019) and KNMI (2019)).

5.2 Damage to solar panels by hail

The damage specifically to solar panels caused by the hailstorm on the 23rd of June is also analysed. In this case study, 249 insurance claims are used that included damage to solar panels caused by hail (Achmea data, 2019). These claims are divided into no damage, invisible damage, visible damage, or both types. Figure 14 shows per type of damage the maximum hailstone sizes in the postcode the claim was located in. On the locations of the claims with no damage, the largest variety in hail sizes is observed. This might be caused by the fact that, more than half of all the claims, had no damage to the solar panels. So, more claims on various locations can indicate a wider range of hail sizes. It can also be seen that in the damage categories, the hail sizes of 2 and 3 cm are decreasing from invisible damage to visible damage and that the hail sizes of 4 cm are increasing. However, it can also be seen that the larger hail sizes are decreasing a bit as well. This can again be caused by the fact that hail is very local and a maximum hail size in a postcode does not mean that this was also the exact hail size on the location of the claim. This indicates that the impact of hail stones of 4 cm or larger can make solar panels more vulnerable to become visibly damaged.

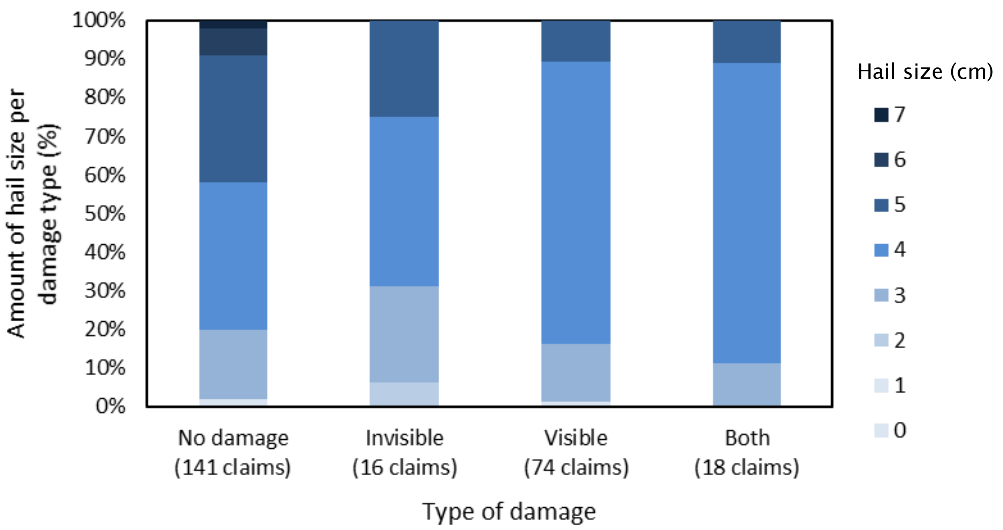

Figure 13: Share of max. hail sizes (cm) per type of damage (based on data from Achmea (2019) and KNMI (2019)).

Figure 15 shows the share of damaged solar panels from the total number of solar panels on a building, in relation to the maximum hailstone size in the postcode where the claim was located. Most damage to solar panels starts from a maximum hail size of 3 cm or more. It can also be seen that there are two claims where the detected hail size by the radar was 0 cm, but there was some damage, this is probably related to uncertainties in the hail stone size estimation (i.e. the radar imagery augmented numerical weather model data). Larger maximum hail sizes than 3 cm, are causing more damage. The hail can cause only a few percent of the solar panels to be damaged or can lead to all the panels on a roof to be damaged. There are not many claims in postal code areas with hail with a maximum size of 6 cm or larger, so the low damage percentage factors should not be considered indicative for the overall vulnerability.

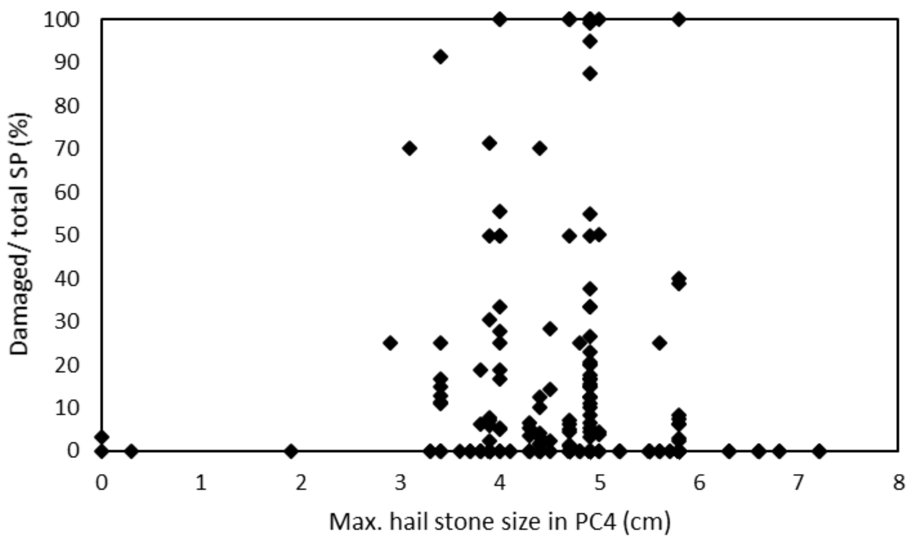

Figure 14: Share of damaged solar panels of the total number of solar panels per claim in relation to the max. hail size (cm) (based on data from Achmea (2019) and KNMI (2019)).

Figure 16 presents three boxplots for claims with damage with a maximum hail size of 3-4 cm, 4-5 cm and 5-6 cm. The lower hailstone sizes are not taken into account as these were only two claims. Hailstones of 4-5 cm cause on average more damage than hailstones of 3-4 cm, but also show a wider range of damage. The hypothesis is tested that solar panels that were hit by hailstones of 4-5 cm have more damage than solar panels that were hit wit hailstones of 3-4 cm. The results of a t-test (one-tailed) showed that this was indeed the case (p-value = 0.063, one-tail). However, the figure also shows that hailstones of 5-6 cm show a lower average damage. This might be due to more variety in hailstones in an area with high maximum hailstone sizes. The chance that a solar panel was actually hit by such a large hailstone is not very high. A t-test shows there is no significant difference between these two groups (p-value = 0.250, one-tail).

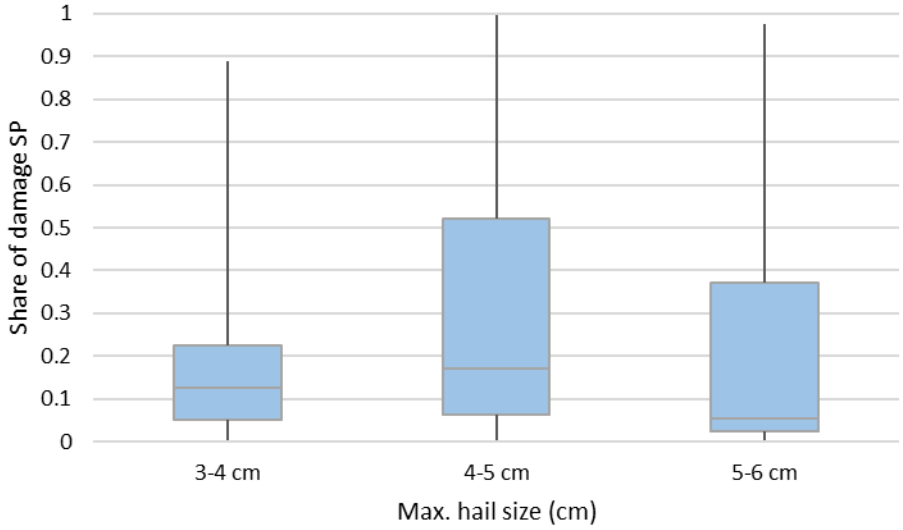

Figure 15: Share of damaged SP per claim in relation to max. hail size (cm) for 3-4 cm and 5-6+ cm

Damage might not only be dependent on the hailstone size but can also depend on the characteristics of the solar panels on the roofs as was explained in the section on factors leading to damage. In this research, a difference was made between pitched and flat roofs, where it is assumed that the solar panels on flat roofs have a smaller tilt angle than on a pitched roof. The optimal angle for solar panels in the Netherlands is 36 degrees, so it is assumed that solar panels on a flat roof have an angle of around 36 degrees (Zonnepanelen.net, 2019c). On average, most pitched roofs have an angle of 45 degrees in the Netherlands (Demalux, 2019). Table 4 shows the average damage for claims with flat and pitched roofs, indicating that buildings with flat roofs have on average higher damage to solar panels (18.1% of the solar panels was damaged on average), than pitched roofs (12.6%). The hail size in both groups was on average almost the same, respectably 4.8 and 4.7 cm. The hypothesis was tested that flat roofs have higher average damage than pitched roofs. This was tested and led to a p-value (one-tail) of 0.059, indicating that the results are significant with 94%.

Table 4: Average damaged solar panels of the total number of solar panels per roof type (based on data from Achmea (2019) and aerial photos from PDOK (2016)).

	Average damaged / total SP (%)	Average mean hail size (cm)	% of claims
Flat	18.1	4.8	29
Pitched	12.6	4.7	71

Another characteristic taken into account is the orientation of the solar panels. The roofs are categorized into eight groups: N, NE, E, SE, S, SW, W, NW. However, there are no claims found where the solar panels had an N or NE orientation and only four claims had an E orientation and only two an NW orientation. So, these directions are not taken into account in Table 5. However, the other four orientations show the average share of damaged solar panels per claim for each group. If can be seen that the SE orientation has a lower share of damaged solar panels than the other directions, even though the average hail size was not lower. This might be caused by the fact that the hailstorm came from a SW direction (Buienradar, 2019), making the solar panels with the other three orientations more vulnerable to hail. This led to the hypothesis that solar panels orientated in SE direction have lower damage than solar panels in other orientations. There is no significant difference in the damage of one orientation being higher than the other, except between the damage of an S and SE orientation. The damage to solar panels on a roof with S orientation is significantly higher than solar panels with a SE orientation (p-value = 0.014, one-tail). If the damage of SE is compared with the damage of S, SW and W combined there is a significant difference between the two categories as well (p-value = 0.016, one-tail).

Table 5: Average damaged solar panels of the total number of solar panels per orientation (based on data from Achmea (2019) and aerial photos from PDOK (2016)).

	Average damaged / total SP (%)	Average mean hail size (cm)	% of claims
S	17.0	4.7	48
SE	8.4	4.9	18
SW	13.6	4.5	25
W	15.7	4.9	9
S,SW,W	15.8	4.7	81

Lastly, the total number of solar panels on a roof is taken into account. We hypothesize that roofs with a higher number of solar panels have on average higher damage. This was expected due to the possible bouncing effects of hailstones from one panel to the other (Achmea, 2019a). However, no clear trend is seen in an increasing number of solar panels on the roof. For the smallest category, the average share of damaged solar panels is high (39.6%), but for the largest category with more than 100 solar panels (SP) on one roof, the damage is also relatively high (25.7%). All of the groups are significantly different from each other with a significance ranging from 95% to 99%, except between the first (1-6 SP) and the last (>100 SP) group and between the second (7-15 SP) and third (16-50 SP) group the difference was not significant. Overall, no trend is found in the total number of solar panels.

Table 6: Average damaged solar panels of the total number of solar panels per total number of solar panels (based on data from Achmea (2019) and aerial photos from PDOK (2016)).

	Average damaged/ total SP (%)	Average mean hail size (cm)	% of claims
1-6 SP	39.6	4.6	4
7-15 SP	13.6	5.0	29
16-50 SP	10.6	4.7	50
50-100 SP	3.5	4.3	6
>100 SP	25.7	4.6	11

Even though these tables give a first impression of what might influence the damage to solar panels, it does not link the variables together. Because it is also important to know what variables have the largest influence on the damage, a regression is done. The results of that can be read in the next section.

5.3 Regression of variables influencing damage to solar panels

In this section, we present the most interesting outcomes of the eight regression analyses. Table 7 on the next page shows the regression output for the different regressions. The dependent variable is the number of damaged solar panels, expressed as percentages of the total number of solar panels per individual claim. Multiple criteria are used to choose the best performing regression as explained in the method.

Regression 1 is a basic model, which only includes the MEHS and the dummy variable for a pitched roof. Looking at the criteria, this regression has one of the lowest performances. Judging by the R^2, the adjusted $R^{2,}$ and the log-likelihood, regression 6, with the solar panel orientation and no transformation of MEHS, performs third-best. This regression indicates that, when including the solar panel orientation, hail size has no effect on the damage to solar panels. This regression also shows that the damage to solar panels is the highest when the solar panels are orientated towards a southern, south-western or southern direction. This might be explained by the fact that the storm on June 23rd of 2016 had a southwestern wind direction and mostly impacted the roofs at a southwestern angle. The speed with which hailstones hit the roofs pointed at a south-eastern direction is expected to be much lower than the speed with which the hailstones hit the roofs pointed at a southwestern direction. This means that the direction of the storm, and therefore the wind, has a significant effect on the damage to solar panels according to this regression.

In contrast to the R^2, the adjusted $R^{2,}$ and the log-likelihood, the AIC and BIC do not point towards this regression as one of the best regressions. Those criteria penalise the extra regressors introduced in this regression more. For the AIC, this regression (6) still performs relatively well, but for the BIC, this regression performs the worst. The BIC indicates that the regressions with the squared MEHS (regressions 4, 7 and 8) perform the best. The BIC favours regression 4 due to the fact that this regression only includes three regressors, as compared to respectively seven and five in regressions 6 and 8. Regression 4 does not take any interaction variables into account.

Looking at regression 2, including the logarithmically transformed MEHS, this regression performs well when looking at the AIC and relatively well when looking at the BIC. The R^2, the adjusted $R^{2,}$ and the log-likelihood indicate that this model performs average. The logarithmic transformation intuitively makes sense as it is not expected that damage is linearly correlated to hail size. However, small hailstones are expected to not damage to solar panels.

On the other hand, models can also be dominated by the fact that after a certain threshold, increases in hail size have a less and less relative impact on damage. This is modelled by the regressions including the squared MEHS, regression 4, 5, 7, and 8. Regression 5 does not perform very well, as it does not include the normal MEHS. This might be due to the fact that in this situation the coefficient of MEHS is set to zero, which does not make sense. The other three models perform the best when looking at the R^2, the adjusted R^2, the log-likelihood and the AIC.

The model with just the MEHS, the squared MEHS (regression 4) and the pitched variable performs also relatively well when looking at the BIC. The BIC heavily penalises regression 7 for having many regressors. In this regression, it is seen that all coefficients for roof orientation are estimated to be zero. Inclusion of all these regressors, while they have no significant effect, is penalised by the adjusted R^2, the AIC, and the BIC. While this model has the best R^2, the other criteria indicate that this only happens because of the additional regressors. Lastly, the interaction variable is included, combined with the squared MEHS (regression 8). This has no additional explanatory power compared to the models without the interaction variable.

Table 7: Regression damaged solar panels and various variables with their coefficients & standard-errors.

	% damaged solar panels							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
MEHS	0.031***			0.124***		-0.015	0.089***	0.137***
	(0.007)			(0.022)		(0.011)	(0.024)	(0.032)
Pitched roof	-0.022	-0.035	0.150	-0.067	0.027	-0.019	-0.048	-0.144
	(0.041)	(0.041)	(0.138)	(0.042)	(0.036)	(0.042)	(0.045)	(0.251)
MEHS * pitched								0.011 (0.108)
Log(MEHS)		0.103***	0.112***					
		(0.024)	(0.025)					
Log(MEHS) * pitched			-0.130 (0.091)					
$MEHS^2$				-0.017***	0.004***		-0.014***	-0.020***
				(0.003)	(0.001)		0.003	(0.005)
$MEHS^2$ * pitched								0.001 (0.012)
SE						0.042***	0.029	
						(0.058)	(0.046)	
S						0.253***	0.093**	
						(0.058)	(0.049)	
SW						0.221***	0.069	
						(0.058)	(0.045)	
W						0.217**	0.077	
						(0.085)	(0.073)	
Covariance type	HC3	HC3	HC3	HC3	HC3	HC3	HC3	HC3
Observations	249	249	249	249	249	249	249	249
R^2	0.185	0.196	0.205	<u>0.232</u>	0.154	0.222	<u>0.239</u>	<u>0.233</u>
Adjusted R^2	0.178	0.189	0.195	0.223	0.148	0.203	0.216	0.217
Log likelihood	-36.387	-34.718	-33.354	-29.038	-40.921	-30.652	-27.980	-28.865
AIC	76.77	73.44	72.71	<u>64.08</u>	85.84	73.30	69.96	67.73
BIC	83.79	80.46	83.24	<u>74.60</u>	92.86	94.36	94.53	85.28
Note:						*p<0.1(*)*; p<0.05(**); p<0.01(***)		

Conclusions that can be drawn from all regression in the table are:

- In all regressions the MEHS is strongly significant and has a positive impact on the damage. Except in regression 6, where it has a negative impact on the damage, but is also not significant. In this situation the orientation of solar panels does play a significant role in the damage.
- The dummy variable pitched roof has no significant influence on the damage, but has in all regressions (except for one) a negative impact on the damage.
- Adding a log MEHS, does not lead to increasing regression results. However, adding a squared MEHS, does increase the regression results and also shows a significant relationship with the damage.
- The interaction variables do not show any significant effect on the damage.
- The orientation can have a strongly significant effect on the damage, however in a situation where the squared MEHS is taken into account the effect is no longer significant.

Combining the five comparative criteria, it can be stated that regression 4 performs the best. This is the model with the MEHS and the squared MEHS. This model is outperformed by the model that also adds the direction of the roofs (regression 7), however only if the criteria that do not penalise additional regressors are taken into account. This allows for diminishing damage when the hail size decreases. This makes sense: the smaller a hailstone, the smaller the damage. In this situation, the variable pitched roofs has no significant influence and the orientation is not taken into account. Table 8 shows how much of the solar panels are expected to be damaged from the total number of solar panels according to regression 4. This also shows that the increase in damage diminishes with bigger hailstones, but at smaller sizes steeply increases. Because in reality solar panels only show damage from hailstones of 2 cm or larger, the row with 1 cm hailstones is between brackets.

Table 8: Expected damage from regression 5

Max. hailstone size (cm)	Expected damaged solar panels of total panels on the roof
(1 cm)	(8.8%)
2 cm	15.4%
3 cm	19.8%
4 cm	22.0%
5 cm	22.0%

Overall, in most situations the maximum hail size is most important in causing damage, however the orientation can be even more important than the hail size in some of the regressions. Whether a roof is pitched or not has only very little influence on the damage, in contrast to earlier hypotheses. According to regression 4, a quadratic function describes the relationship between the damage and the variables the best, indicating that the increases in damage with larger hail stones decline.

6 Discussion: the way forward

In the previous chapters, we have explored the characteristics of solar panels and their vulnerability to hail. To decrease the risk of solar panels being damaged, this chapter will give an overview of adaption options that could be implemented to decrease the vulnerability of the panels. It will also advice on doing more research to get more detailed information on how hail damages solar panels.

6.1 Necessary policy changes

As can be read in chapter 4, there are some basic requirements regarding the quality of solar panels. However, much can be improved in the installation and quality requirements of the panels and in the insurance.

The adoption of the International Standards, the foundation of standards and guidelines concerning photovoltaic systems established by the IEC, has a voluntary basis (IEC, 2019). The same applies to the NEN-standards, the implementation of the IEC-standards in the Netherlands, which are voluntary agreements between market parties that have no legal status ((Roofs, 2019); (KSN, 2019)). Producers of solar panels can decide for themselves whether they meet these standards (Achmea, 2019a).

As a result of this, it could be that photovoltaic systems do not always meet the IEC- and NEN-standards and guidelines which entail risks in terms of quality and safety. Lack of clarity about which standards and guidelines concerning photovoltaic systems apply and lack of its uniformly mandatory nature also complicates policy-making and confuses the stakeholders involved in this sector. For example, an insurance company cannot demand that a photovoltaic system has to meet certain standards before damage can be claimed by the policyholder since those requirements are not mandatory. An insurance policy based on mandatory requirements would give more clarity to both the insurance company and the insured party. Which makes matters concerning this issue even more complicated in the Netherlands, is the free market of the insurance sector. If one insurance company adjusts its policy concerning photovoltaic systems by demanding that the system has to meet standards conform the IEC- and NEN-guidelines, this will lead to a loss of clients since it becomes more difficult for the policyholder to get paid compensation if the system does not meet the standards (Achmea, 2019a). Consequently, the insurance company will not change its policy to keep its clients. Another option for the insurance might be increasing their premium, which might lead to less solar panels. A solution to this problem would be the implementation of mandatory IEC- and NEN-standards by an independent organization (Achmea, 2019a). It is therefore recommended that the government obliges that photovoltaic systems meet the IEC- and NEN-standards.

There are multiple hallmarks and certifications in the Netherlands to guarantee the quality is not mandatory. One of the reasons for this might be the quite weak market of solar panels and the fact that most solar panels are imported from Asia (GDV, 2019). An inspection is not mandatory, so not all solar panels are inspected after they are installed. This leads to some problems in the market of photovoltaic systems. First of all, it is not always guaranteed that the solar panels consist of valid and reliable components. Furthermore, it could be that some solar panels are unsafely and not correctly installed. Moreover, the lack of mandatory hallmarks could result in the resale of second-hand solar panels (Achmea, 2019b). In this way, solar panels that are already damaged could be resold, which might lead to unsafe situations like causing a fire.

The same problem holds for the voluntary principle of certification of the installation of the panels. The expertise of the installers is unknown since it is not mandatory to be a certified installation company. On top of that, it is stated that the installation of the solar panels can be done without an installation company, resulting in the self-installation of photovoltaic systems ((Sun-solar, 2012); (Duurzame zonnepanelen, 2019); (Essent, 2019); (Zonnepanelen.net, 2019a)). As a consequence, the installation can be done by people without experience concerning the installation of solar panels, which then again might lead to unsafe situations when the installation is done insufficiently. To tackle problems regarding the consequences of the voluntary nature of quality hallmarks and certification, it is recommended to implement mandatory quality hallmarks and certifications by an independent body, like the government.

6.1.1 Insurance

Currently, no separate insurance policy exists concerning solar panels (Achmea, 2019b). However, discussions have recently started in Germany whether hail risk should be a separate policy (GDV, 2019). Similar discussions have started in the Netherlands, where improvements regarding the registration of damage to solar panels are being made. At Achmea, for example, there was no specific claim registration of damage to solar panels (GDV, 2019). Since 2019, this has been changed and nowadays claims concerning damage to solar panels have been separately registered. This is a first step in separating damage of solar panels from damage to buildings, but a separate policy related to photovoltaic systems would be even more beneficial for the insurance company (Achmea, 2019a).

As there is no separate insurance policy yet, private individuals do not have to let insurance companies know whether they possess solar panels (Achmea, 2019b). From the perspective of the policyholder, incorporating solar panels automatically in the home insurance is beneficial since they do not have to take out a separate insurance policy. As for insurance companies, it might be more beneficial to introduce a separate policy regarding photovoltaic systems (Achmea, 2019a). When such a policy exists, the policyholder has to provide the insurance company with information about the photovoltaic system. In this way, the insurance company has notification of the possession of solar panels by its clients. A separate policy concerning photovoltaic systems gives more transparency between the insurance company and the policyholder and could provide the insurance company with insight in which clients are in the possession of solar panels, how many solar panels are installed and the type of solar panels installed. This is valuable information for estimating the risk of damaged solar panels and for calculating its insurance premium.

The lack of good regulation of the installation of solar panels can be a problem for insurance companies as well. There are no official quality labels that can indicate whether solar panels are of good quality and correctly installed. This can lead to problems when handling claims with solar panels that are being damaged by micro-cracks. There are no conclusive rules on how to handle micro-cracks (Solar Magazine, 2019). Even if micro-cracks can be visualized with tests, the cracks do not directly indicate power loss (Koentges, Kunze, Kajari-Schroeder, Breitenmoser, & Bjorneklett, 2011). So, even if multiple panels on a roof have micro-cracks this does not mean that every panel has to be removed. Insurers are not always sure how these micro-cracks were caused, this could also have happened during the installation of the panels. This would mean that the damage is refundable as part of the guarantee offered by the supplier and not damage that is included in the policy.

This all leads to situations in which clients make unrealistic claims. Insurers are not able to estimate how many solar panels are insured, and therefore they are not able to estimate their risk during a large hail event.

Another issue is that insurance companies do not always check if solar panels are replaced after damage is registered. This complicates matters for the insurance company when the panels are hit by another hailstorm. In theory, someone could claim damage again, while still having the same solar panels (Achmea, 2019d). If the company then claims damage again, the insurance company pays out twice for the same solar panels.

6.2 Recycling of solar panels

The lifecycle of the first generation of solar panels will almost come to an end, which may result in a large amount of waste coming from solar panels. After installation, solar panels have a service life which is estimated at 25 years, resulting in low concerns about the waste of panels. Currently, however, the first batch of solar panels is being retired and waste management is becoming an important environmental issue (Aman, et al., 2015). Since February 2014, solar panels are included in the AEEA law in the Netherlands, coming from the European version of the law: ‘Waste Electrical and Electronic Equipment (WEEE) law’. This law makes parties who put solar panels on the market, referred to as *producers*, responsible for the collection and recycling of solar panels at the end of their life (Staatscourant, 2014).

The AEEA legislation is difficult to enforce due to the complicated market structure, which requires a lot of in-depth knowledge that is only present with market parties. In addition, the Dutch authorities have only limited resources available. This means the overall enforcement is insufficient to get the required level playing field. This results in a heterogeneous market in which there are too many producers that do not participate in the collection and recycling of solar panels (ZRN, 2019). There is a growing urgency of the situation although this is still a rough indication due to the lack of a sufficient database on the exact numbers of solar panels. This lack of registration is probably due to the lack of governmental enforcement. In 2018 the total number of panels entering the market is way larger than registered at (W)EEE revealing the sheer size of the potential future problem (Nationaal WEEE register, 2019). The number of solar panels that are being recycled is much smaller, however, this can also be partly due to the fact that more solar panels are entering the market than leaving the market.

The long-term sustainability of solar panels will depend both on how successful the enforcement of the (W)EEE register is, as well as the effectiveness of the process solutions adopted to recycle the anticipated high number of solar panels in the future (Flavia, Altimari, & Pagnanelli, 2019). The (W)EEE register indicates that 77% of the registered solar panels are being recycled in the Netherlands. Research by Santos et al. (2018) expects that in 2050 75% of the raw materials required to manufacture the solar panels will be recoverable. Economically, an extra incentive is provided because the manufacturing of silicon takes three times more energy and costs than recovering silicon from solar panels (Choi & Fthenakis, 2013). Several explorative academic studies (Fiandra, Sannino, Andreozzi, & Graditi, 2018; Nevalaa, et al., 2019; Flavia, Altimari, & Pagnanelli, 2019) have assessed mechanical, thermal and chemical waste recycling techniques from an environmental point of view and selected the best available technology in terms of optimized circular economy of metals. Even though recycling techniques keep being optimized, there are some very valuable recycling methods already. Because of this, it is necessary to regulate and enforce the process of recycling, not only in the Netherlands but globally.

6.3 Measures to protect solar panels

With an increasing risk in hail and related damage, it is important to decrease the vulnerability of the solar panels. Per location, it has to be determined what measures are most suitable. One of the simplest measures that can be taken is by choosing solar panels that are most resistant to hail. This is the glass-glass panel, where the front and back surfaces of the panel are made out of (tempered) glass (Mathiak, et al., 2015). However, this type of solar panel is heavier and more expensive. This means that in areas with heavy snowfall these types of panels might be too heavy for the roof to additionally carry in combination with thick packs of snow on the roof. In other areas, that do not experience large amounts of snow, the use of glass-glass panels can be a simple method to decrease the hail risk. Even though the panels are more expensive in general, their lifespan might be longer due to less damage, which eventually may balance out the higher price.

Another aspect that should be considered when installing solar panels is the orientation and roof type they are placed on. Solar panels on a flat roof experience on average more damage than on a pitched roof, presumably due to their angle and orientation. The orientation of the panels can have an effect on the damage as well. Placing the panels to the direction where most (hail)storms are coming from can indicate more damage.

In areas where heavy snowfall is occurring and hail is an issue as well, for example in Austria and Switzerland, other measures must be considered. This also applies to buildings that do not have strong constructions like sheds. One measure that could make a big change, but is not widely developed yet is the solution of covers for the solar panels. By using a cover, lighter solar panels can still be protected against hail. After literature research, one text was found of an idea of a cover for solar panels that was applied for a patent (North, 2011). The proposed cover provides protection for the solar panel from weather impacts such as snow, hail, windblown debris, but also against overheating of a solar panel during periods of extremely high and long solar radiation. As this protective cover was not found to be developed yet, we propose that it would be useful if these covers could be controlled from a distance, so no unnecessary climbs on the roof have to be made. Another idea is to automatically link it to weather forecasts, so if hail is forecasted or no solar radiation is measured, the covers get automatically activated. Unfortunately, this solution is not developed yet, but with an eye on increasing hail frequency, other weather events, and the number of solar panels such a development could make a big difference. It has to be considered whether the costs of such a protective cover weigh up to the costs of the damage that is saved with it. However, during this research it was noticed that often all solar panels on a roof are replaced, even if only a couple panels have damage, therefore the costs of replacing damaged panels can be very high.

6.4 Future research

Even though the case study in this report gave a good first indication of how many solar panels are damaged due to hail in a field case study, it is just done for one hail event with a limited number of claims. To improve the study, it must be extended with other hail events and more claims data, so the differences in vulnerability of various characteristics of solar panels can be made more reliable.

An additional source of data for future research of damage to solar panels could be the output of solar panels measured by micro-inverters. Often, an inverter measures the output of all the panels on the roof, but there are inverters that measure the output per panel (such as the inverters of Solar Edge). Measuring the output before and after a hailstorm could create a much larger dataset, with very valuable data in which the invisible damage can also be taken into account. This can give more insights in the quantification of the effects of micro-cracks on the performance of a panel and therefore its vulnerability.

It must be kept in mind that, in this case study, a limited number of claims was available, but data on the type of solar panel was lacking as well. To be able to include this in future research, it is important that insurance companies systematically keep track of damage data of individual objects like solar panels. This would help them as well to be able to estimate the risk of these objects more accurately in the future. Another limitation of this research was the hail size data which was available in the form of the mean or maximum value in a postcode (PC4) coming from model raster data with a 1 x 1 km grid. However, as hail can be very local it might be the case the in some areas the mean or maximum hail size can be very high even though there might have been not hail on another location in the same postal code area.

These limitations are also observed in the regression analysis. The regression would be more reliable when more claims were available and hail size data was more detailed. Especially for the smaller hail sizes, fewer claims are available. This made it impossible to determine whether there is a certain threshold before damage occurs in the regression. However, the assumption can be made that, as there were almost no claims for hailstone sizes of lower than 2 cm, (almost) no damage occurs below that size. Choosing the best regression from all the regressions is dependent on what is considered as the most important criteria, therefore the result can differ depending on what criteria are used. It must be kept in mind that all regressions must be considered and that there is no one correct answer.

This study has only been done for solar panels, however, there are more NZE measures that could get damaged by extreme weather events. So, to increase the speed of the transition to a carbon-neutral society, the vulnerability of other NZE measures to weather extremes should be researched as well. However, the method used in this case study could be used to perform similar studies for different objects and different types of weather extremes.

There are many initiatives to map risks of extreme weather, however, this is not widely done for the risk of hail. This study showed that hail can contribute significantly to damage as part of the total damage due to extreme weather, therefore hail risk must be incorporated into climate risk models and strategies. Next to the describing the risk of hail, the vulnerability of objects to extreme weather, such as solar panels in this study, can be incorporated into risk models as well. By including more detailed information on the vulnerability of solar panels, the risk of hail can be estimated more accurately. This can be beneficial for insurance companies and banks, but can also be used in local adaptation strategies for example.

Next to more research on the vulnerability of NZE measures to weather extremes, it is also important to do research on methods to protect the NZE measures and make them less vulnerable. For example, solar panels have to keep being developed to make them more resistant to weather extremes under changing environmental conditions.

6.5 Future risk on damage solar panels

As the results of the case study showed, solar panels get on general damaged by hailstones with a size of 2 cm or more. Larger hailstones can lead to more damage. It is expected that due to higher temperatures due to climate changes hail events will occur more frequently and therefore more damage to solar panels is expected. In 2018 compared to the year before, the power of solar panels has more than doubled with an increase from 1500 to 4400 megawatt in the Netherlands (CBS, 2019). It is expected that this number will increase more in the coming years. Therefore, it is important to be aware of the vulnerability of solar panels to hail and other types of extreme weather and to try to minimise this vulnerability to realize the transition to a carbon-neutral society.

7 Conclusion

Hail occurs in large parts of Europe and a single hail event may lead to billions of losses. The hail events have increased over the past 37 years in most areas in Europe and are expected to increase even more (MunichRe, 2019). Large hail is occurring mostly during summer. In the Netherlands, the largest amounts of damage due to hail are found in June. The southeast of the Netherlands experiences most of the damage due to hail. The largest hail event in the Netherlands was on 23 June 2016, leading to 73% of all insured damage caused by extreme weather was caused by hail in that year. Hail hazard has the potential to damage vulnerable exposed elements, like solar panels even though solar panels might play a key role in the transition to a carbon-neutral society.

Solar panels can be split up into three categories: monocrystalline, polycrystalline, and thin-film solar panels. Monocrystalline solar panels are currently the most efficient type of solar panels (Consumentenbond, 2019b). Polycrystalline solar panels are less efficient than monocrystalline solar panels but are also less expensive. Thin-films are less efficient but can be flexible and installed on curved surfaces. As the solar panel market is a relatively new market there is no sufficient legislation and enforced rules regarding solar panels. There are some (inter-)national standards, but the adoption is voluntary, although national laws or regulations often refer to them. This lack of standards and rules is leading to issues with the quality and installation of solar panels, resulting in potentially dangerous situations, but also make solar panels more vulnerable to other causes of damage like hail. Also, in the insurance of solar panels, there is no overall consensus between insurance companies in the Netherlands on how solar panels should be insured. There are also differences in insurance for different types of customers in one insurance company. However, after the hailstorm in 2016, insurers noticed that solar panels can play a large role in damage due to hail.

Solar panels are vulnerable objects, different factors can affect the performance of a solar panel, these factors can be split up into three categories: environmental factors, installation factors, and production factors. These factors can lead to cracks in the front glass of a solar panel, which is directly visible and can reduce the solar insolation to enter straight into the solar cell which consequently results in a lower yield. However, smaller cracks (micro-cracks) can form as well, which are not formed in the front glass layer but in the more fragile silicon. Micro-cracks usually do not result in a lower yield initially. However, after a few months, the damaged areas can start to show a rapid decline of power output and after around one year the micro-cracks become visible on the outside of the panel as well. A star-shaped micro-crack can indicate the impact of a small object, like a hailstone. All damages are expected to shorten the lifespan of a solar panel.

To test how these cracks occur with what hail size, the vulnerability of solar panels is explored with a case study. During the hailstorm on the 23rd of June in 2016, a large hailstorm moved over the southeast of the Netherlands with hailstones larger than 7 cm. In the areas with large hailstones obtained from a model, also the large amounts of insured damages were found. Hail sizes from about 3 cm start damaging property more and more.

Looking at the vulnerability of solar panels to hail, according to the case study we find that:

- The claims with no damage, half of the claims, show most variety in hail sizes. Indicating that more claims on various locations can indicate a wider range of hail sizes.
- Both invisible and visible damage can occur as from 3 cm, but from 4 cm onwards the share of visible damage increases substantially.
- The orientation of the roof in respect of the direction of the hailstorm (and with-it prevailing winds) can considerably affect hail damage to solar panels, and even become more determining than the hail size itself (with direction away from the hailstorm reducing damage considerably).
- There are indicators that also the angle at which the solar panel stands (represented by low-angle on flat roofs and higher angle on pitched roofs) can affect the damage to solar panels (with low-angle having more damage), but the results are not strongly significant.
- Increasing hailstone size increase the amount of damage, however with increasing hail sizes the extra increases in damage are declining.

Overall, solar panels are vulnerable to hail and the vulnerability is mostly dependent on the hailstone size. There are several options to decrease this vulnerability, such as taking the characteristics of solar panels into account when installing them. Improvements can be made in (the enforcement of) standards, regulations, and insurance of solar panels. The development of specific measures, such as a cover for the solar panels, may also help to decrease this vulnerability. More research must be done on the vulnerability of other NZE measures, their relation to other types of extreme weather, and on the effects of micro-cracks using different data sources. Lastly, hail risk and the vulnerability of solar panels to hail should be included into risk models and climate adaptation strategies.

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Appendix

Appendix A Interviewee list

Table 9: List of conducted interviews.

Organisation	Date	Topic interview
Achmea 1	17 September 2019	Product management fire insurance
Achmea 2	24 September 2019	Achmea insurances
GDV	27 September 2019	Data solar panels insurance Germany
Achmea 3	1 October 2019	Data solar panels damage insurance Achmea
SCOR	1 October 2019	Data solar panel damage insurance Europe
Solar Tester	11 October 2019	Testing damage to solar panels
Solar Clarity	11 October 2019	Damage solar panels during production and installation process
Gothaer	15 October 2019	Data solar panel damage insurance Europe
Achmea 4	15 October 2019	Claim data solar panels case study
Stichting Zonne-energie Recycling Nederland	26 November 2019	Recycling solar panels

Appendix B Insurance of solar panels in the Netherlands

Table 10: Overview of the insurance of solar panels of different insurance companies (translated from Solar Magazine, 2019)

Insurance company	Insurance	Amount of reimbursement	Standard insured?	Invisible damage insured?	Investigation costs insured?
Centraal Beheer (part of Achmea)	Housing insurance (Building and Glass; and Household effects)	Purchase price until the current value is less than 40 percent	Yes	No	Not applicable
Interpolis (part of Achmea)	All in one policy / residential building	Purchase price until the current value is less than 40 percent	Yes	No	Not applicable
FBTO (part of Achmea)	Home insurance	Purchase price until the current value is less than 40 percent	Yes	Yes	Yes, provided damage is demonstrated by an insured cause
Avéro Achmea (part of Achmea)	Residential building – Extended Extra and Household effects	Purchase price until the current value is less than 40 percent	Yes	No	Not applicable
Nationale Nederlanden (Delta Lloyd)	Residential building (Home insurance Basic + Home insurance All-in)	Current value	Yes	Yes	Yes, provided damage is demonstrated by an insured cause
Aegon	Home insurance	Purchase price until the current value is less than 40 percent	Yes	Yes	Yes, provided damage is demonstrated by an insured cause
ASR	Home insurance Basic + All-risk	Purchase price until the current value is less than 40 percent	No (must be reported and stated on the policy schedule)	Yes	Yes, provided damage is demonstrated by an insured cause
Reaal (Vivat)	Home insurance	Only the reduced energy yield	Yes	Partially	Yes, provided damage is demonstrated by an insured cause
nowGo (Vivat)	Home insurance Aware + / Home insurance Aware	Only the reduced energy yield	Yes	Partially	Yes, provided damage is demonstrated by an insured cause
Univé	Housing insurance	Purchase price	Yes	Yes	Yes, provided damage is demonstrated by an insured cause
ABN Amro	Home insurance	Purchase price until the current value is less than 40 percent	Yes	Yes	Yes, provided damage is demonstrated by an insured cause
Noordhollandsche van 1816 Schade (Nh1816)	Home insurance Optimal / Home insurance Extra Expanded	Purchase price until the current value is less than 40 percent	Yes	No	Not applicable

Unigarant (ANWB/UVM)	Housing package Plus +	Reconstruction value / repair costs	Yes	Yes	Yes, provided damage is demonstrated by an insured cause
OHRA	Home insurance	Purchase price until the current value is less than 40 percent	Yes	Yes	Yes, provided damage is demonstrated by an insured cause

Appendix C Additional information standards & guidelines solar panels in the Netherlands

C.1 Standards

Table 11: Overview of standards concerning solar panels in The Netherlands (VKG, n.d.)

Standard concerning	Standard	Description
Panel	NEN-EN-IEC 61215	Crystalline silicon photovoltaic modules for terrestrial applications – Design classification and type approval.
	EN-EN-IEC 61646	Thin-film photovoltaic (PV) modules for terrestrial applications – Design qualification and type approval.
	NEN-EN-IEC 61730-1	Safety qualification of photovoltaic (PV) modules – Part 1: Requirements for construction.
Inverter	NEN-EN-IEC 62109-1	Safety of power inverters used in photoelectric power systems – Part 1: General requirements.
Public power grid	NEN 11727	Photoelectric systems – Features of the user interface.
Installation	NEN 1010	Safety provisions for low voltage installations.
	NTA 8493	Small photovoltaic systems connected to the grid.
	NPR-IEC/TS 62257-1	Renewable energy recommendations – Part 1: General introduction for decentralized electricity networks.
	NPR-IEC/TS 62257-7-1	Recommendations for renewable energy – Part 7-1: Generators – Photovoltaic generators

Another important NEN-standard is the NEN 7250, which concerns the technical requirements and determination methods regarding architectural aspects of the installation of photovoltaic systems in the building envelope of a construction (Installatie Journaal, 2018). More specifically, the NEN 7250 standard is about the photovoltaic system in its architectural application, testing methods regarding wind resistance and fire, and assessment aspects (Kiwa BDA, 2019). The assessment aspects consist of structural safety, water resistance, internal condensation, air resistance, temperature influence, sound/acoustics, fire resistance, fire spread, sustainability, and roof suitability. The current NEN 7250 has to be revised and expanded because of the developments of photovoltaic systems, like the development of east-west oriented systems, full roof systems and integrated systems (BIPV) (Kiwa BDA, 2019; Roofs, 2019).

C.2 Hallmarks in the Netherlands

The TÜV-hallmark is a German hallmark which is also applicable in the Netherlands (Zonnepanelengids.com, 2017; Stichting Garantiefonds ZonZeker, 2016-2019; TÜV Rheinland, 2019). The corresponding inspection concerns all aspects of the solar panels like its lifespan, safety, performance, and power yield. These inspections are performed in accordance with IEC-standards and national standards (TÜV Rheinland, 2019). The RoHS-certificate (Restriction of Hazardous Substances) can be obtained if the use of hazardous substances with solar panels is limited (Zonnepanelengids.com, 2017; Stichting Garantiefonds ZonZeker, 2016-2019; RVO, n.d.-b). This guideline has been implemented by the European Union (Zonnepanelen.com, 2017; RVO, n.d.-b). The IEC-hallmark guarantees that solar panels meet the IEC-standards (Zonnepanelengids.com, 2017; Stichting Garantiefonds ZonZeker, 2016-2019). The inspection includes the reliability, efficiency over time, sustainability and the resistance of the solar panel to weather conditions like hail and wind. The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System) issues these certifications (IEC-IECRE, 2019).

Hallmarks like the ones described above can only be obtained when the photovoltaic system meets all the requirements of the corresponding hallmark (Stichting Garantiefonds ZonZeker, 2016-2019; KSN, n.d.; Omega, n.d.). Independent inspection companies can carry out the inspections needed to check whether the solar panels meet the requirements of a hallmark. Examples of such companies working in the Netherlands are TÜV Rheinland, Keuring Service Nederland (KSN) and Omega (Achmea, 2019a; TÜV Rheinland, 2019; KSN, n.d.; Omega, n.d.). KSN and Omega perform their inspections of photovoltaic systems based on the NEN 1010, NTA 8013 and NEN-EN-IEC 62446-1:2016 standards (KSN, n.d.; Omega, n.d.). The NEN 1010 describes the general inspection of low voltage installations (Atama Solar Energy, 2016; Verbond van Verzekeraars, 2019). The NTA 8013 is an addition to the NEN 1010 and describes the procedure of the inspection of grid-connected photovoltaic installations (Atama Solar Energy, 2016). The inspection according to the NTA 8013 consists of a check of the documents of the system, a building inspection, and delivery inspection. The NEN-EN-IEC 624456-1:2016 standard provides additional guidelines including requirements concerning commissioning tests, inspection criteria, and defines documentation that verifies the safe installation and correct operation of the photovoltaic system (NEN, 2016; Verbond van Verzekeraars, 2019). This standard is intended for producers and installers of photovoltaic systems and also provides guidelines for periodic retesting.

Besides the hallmarks intended for the photovoltaic system itself, also different certifications and hallmarks concerning installation companies and producers of solar panels are present. Installers of these systems can get certified by Cito to guarantee their expertise (NEN, 2013). The ISO-certificate (International Organization for Standardization) is another example of a certificate that guarantees that the producer of solar panels meets certain requirements regarding safety, reliability, and quality (Zonnepanelengids.com, 2017; Stichting Garantiefonds ZonZeker, 2016-2019). ISO itself only develops International standards and does not issue the certification of these standards (ISO, n.d.), this is done by an external company, the Certificate Institution (Kader-advies, 2017a; ISO Register, 2019). The ISO 9001 and ISO 14001 especially apply to photovoltaic systems (Zonnepanelengids.com, 2017). The ISO 9001 certificate concerns the quality of the management system and the ISO 14001 is about requirements regarding environmental management systems (Kader-advies, 2017b, c; Zonnepanelengids.com, 2017). A type of certification meant for inspection companies is the SCIOS certification. The KSN and Omega are SCIOS certified (SCIOS, 2019a; KSN, n.d.). The SCIOS certification arrangement concerns the inspection and maintenance activities of technical, electrical and combustion installations (SCIOS, 2019b; KSN, n.d.). These arrangements consist of requirements with respect to the education and experience of the installation and inspection companies (SCIOS, 2019b).

C.3 Warranties

The product warranty includes both the solar panels itself and the inverters (Zonne-energie gids, 2017-2019; Consumentenbond – Van der Wilt, 2019a). The supplier or producer of the photovoltaic system issues the product warranties, which are covered by the company selling the photovoltaic systems or the wholesale/importer (Sungevity Nederland, n.d.). The product warranty only concerns damaged solar panels and/or inverters; it offers no guarantee for the gradual reduction in power yield. The number of years the product warranty applies to the system differs among different suppliers. The most common product warranty period is 10 years (Consumentenbond – Van der Wilt, 2019a; Sungevity Nederland, n.d.; Zonnepanelen.net, n.d.-a; Zonneplan, n.d.;), but some suppliers offer product warranties of 30 years (Consumentenbond – Van der Wilt, 2019a). As for the inverters, the number of years of warranty is somewhat lower and generally differs from a minimum of 5 years to 10 years (Zonneplan, n.d.; Consumentenbond – Van der Wilt, 2019a).

The power warranty concerns the loss of revenue due to a gradual reduction in power yield (Consumentenbond – Van der Wilt, 2019a). In general, the power yield or capacity of a photovoltaic system reduces with time (Interview Solar Clarity, 2019; Sungevity Nederland, n.d.). To compensate for extreme reductions in power yield with time, and thus extreme losses of revenue, the power warranty is in place. This type of warranty ensures that the power yield of the photovoltaic system is 80% of its original performance 20 to 25 years after its installation (Zonne-energie gids, 2017-2019; Interview Solar Clarity, 2019; Verbond van Verzekeraars, 2019; Consumentenbond – Van der Wilt, 2019a; Sungevity Nederland, n.d.; Zonneplan, n.d). Another common form of power warranty is a power yield of 90% 10 years after the installation of the system (Zonne-energie gids, 2017-2019; Sungevity Nederland, n.d.). According to the power warranty, the repair/reconstruction costs and losses in revenue are covered if the power yield is less than 90% after 10 years or less than 80% after 25 years (Zonne-energie gids, 2017-2019; Interview Solar Clarity, 2019; Sungevity Nederland, n.d.).

The warranty on installation covers the defects of the installation of photovoltaic systems (Zonne-energie gids, 2017-2019; Consumentenbond – Van der Wilt, 2019a; Sungevity Nederland, n.d.; Zonnepanelen.net, n.d.-a). The warranty period is at least 2 years, but a warranty period of 5 or 10 years is becoming more conventional.

The system warranty is about the installation and mounting materials (Consumentenbond – Van der Wilt, 2019a). It guarantees that the installation has been done properly and that the combination of mounting parts, solar panels and inverters are aligned well with each other. If not, the supplier is responsible for fixing the problem and paying the repair and transport costs. It depends on the supplier of the photovoltaic system if this type of warranty applies to the system.

The granting of the power yield warranty also depends on the supplier (Sungevity Nederland, n.d.). Many factors affect the performance of solar panels (Fouad et al., 2017). These factors can be classified into four main categories: environmental factors, installation factors, factors directly related to the photovoltaic system, and cost factors. These four main categories can then be divided into subcategories. Subcategories of the environmental factors include, for instance: solar irradiance, module temperature, dust accumulation, and shading. Cable characteristics and the angle of inclination are some examples of the subcategories of the installation factors. As for factors related to the photovoltaic system, panel and battery efficiencies, inverter, and panel material influence the performance of the photovoltaic system. As a result of these factors affecting the power yield, the performance of the same type of photovoltaic system differs per location (Sungevity Nederland, n.d.). Some suppliers, therefore, calculate the expected performance of the solar panels installed. The power yield warranty makes sure that if the power yield is less than the expected performance, this difference is compensated. The warranty period is 2 years (Interview Solar Clarity, 2019).

Appendix D Methods used in earlier researchers to detect damage to solar panels and their effect on the output power (described in Table 3)

For **visible damage (Table 3)** the following methods were used:

1. The impact of a 2-inch ice ball traveling at 70 mph was compared for three different solar panels. Each having a different material (e.g. Acrylic sheet, Silicon rubber sheet, Annealed glass sheet) serving as a front layer. In the report, qualitative observations were supported by quantitative power estimations before and after the effect of testing (Moore & Wilson, 1978).
2. Using performance indicators to measure the effect of diagonal breaks (+45, -45), parallel to bus bar breaks, perpendicular to bus bar breaks and multiple direction breaks on the output power of a 10-poly crystalline module (220Wp) and a 35 polycrystalline (130Wp)s (Dhimish, Holmes, Mehrdadi, & Dales, 2017).
3. Research comparing damage formed under known circumstances in the field with regards to hail sizes and recreating these circumstances in the lab to examine how they were formed exactly (Mathiak, et al., 2015).

For **invisible damage (Table 3)** the results of the following were used:

1. Analysis of critical sizes and orientations of micro-crack breaks in the silicon layer of the solar panel. Electroluminescent tests utilized to locate damage and determine if this reduces power output significant (Solar Tester, 2019)).