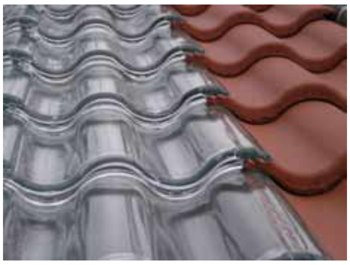

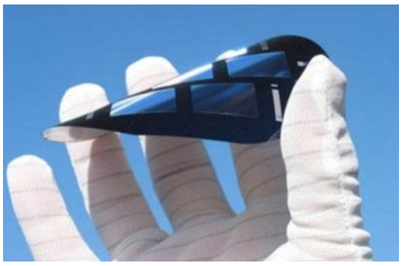

# Sustainable Energy Options in the municipality of Aa en Hunze

21st of June 2013


Group 2

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# Summary

Our project within the course 'Environmental Project Studies' (ETE-20310) was about helping the inhabitants of the Veenkoloniën in the municipality Aa en Hunze to develop village energy plans. The municipality of Aa en Hunze in the Province of Drenthe wants to be more sustainable.

Simultaneously, the EU exerts pressure on the Dutch government to reduce the $CO_2$ emission during their energy production. For the government wind farms are most cost-effective. A wind farm of about 120 -150 MW is planned to be set up in the Veenkoloniën. After the plans were announced the concept of the village energy plan was created as a kind of counterpart by the displeased citizens together with the municipality.

The village energy plans are plans for installing and investing in alternative energy options. Each village decides on them individually via a committee per village. ECO-Oostermoer, a local organisation set up to facilitate local initiatives in the Veenkoloniën and of which the board consists inter alia out of Associations of Village Interests of which a lot of inhabitants are member, is the informal client of our project. The municipality of Aa en Hunze is the formal client. The aim is to let the inhabitants make a more informed choice about what alternative (mix) suits their wishes and possibilities best.

We were part of a learning network consisting of workgroup Veenkoloniën, students of Van Hall Larenstein, students of Rijksuniversiteit Groningen, students of Geo-Information Science of Wageningen University, the entrepreneurial group, inhabitants, ECO-Oostermoer, the municipality and ourselves. Each of this groups provides different knowledge which are put together to reach the overall goal (Kenniswerkplaats, 2013). Our role is to check the technical feasibility of the three energy options SolTech, Thin Film Solar cells and floating PV cells, all based on solar energy, and to investigate the environmental performance of them.

We designed a generic method in the form of a five-step method and an excel model for the solar energy options, which can be used for every village and be adjusted to the wishes and possibilities of the village committees. The five-step method it is also applicable for other alternatives, but we applied it for the three options using a standard house and standard wijk. According to the model Thin Film Solar would produce 94% of the standard house's energy demand and SolTech 86%. For the floating PV cells we referred to a standard wijk which could cover the demand of about 10 houses. The percentages are based on optimal conditions.

To assess the environmental performance we used a Multi Criteria Analysis (MCA). We based it on the greenhouse gas emission during the life cycle, the production of hazardous components and the use of scarce resources. To measure the hazardousness of the components we looked up their $HC_{50}$ values in literature. For the scarcity of resources we used the time to depletion found in various sources. With the standardization step of the MCA the criteria became comparable to get a final score per energy option for their environmental impact. According to the MCA Thin Film Solar Cells perform environmentally best, followed up by SolTech and the floating PVs.

In the last step of the evaluation of the environmental performance we linked the technical standard objects to the MCA, so that the conclusion can be drawn more clearly with the two aspects combined. We calculated the greenhouse gases emission (expressed in $CO_2$-equivalents) per standard house and compared this to the emission of greenhouse gases by fossil fuels when the same amount of energy is produced. The results were that the alternative options emit between 2.6

and 3.5% of the emission that fossil fuels would cause. Further, we determined the amount of hazardous resources that hypothetically could be found in the soil under the standard house. These amounts were compared to the $HC_{50}$ values of the respective resources. The technologies all produced less than these values. The Thin Film Solar cells produced between a factor of 10 and 1,000 less. SolTech and the floating PVs produced between a factor of 10,000 to 100,000 less. We did not quantify the use of scarce resource in regard to the standard house, because we were not able to quantify the level of scarcity.

Overall we concluded that compared to convenient electricity all the three options are better in terms of sustainability. Within these three the MCA nominated Thin Film Solar cells as the best one and it also appeared to be the best options regarding efficiency when used on a roof. However, the floating PVs had the highest production per area per year. Since both options need to be installed in different places, they can be easily used in an energy mix in the village energy plans.

# List of abbreviations and terms

## Abbreviations

- **RUG**: Rijksuniversiteit Groningen
- **GIS:** Geo-Information Science
- **WUR:** Wageningen University and Research Centre
- **VHL:** Van Hall Larenstein
- **GHGs:** Greenhouse gases
- **PV:** Photo-voltaïc
- **$CO_2$-eq:** $CO_2$-equivalent
- **$HC_{50}$:** Hazardous Concentration for 50% of a population
- **MCA:** Multi Criteria Analysis
- **NIMBY:** Not In My Backyard
- **SDE+:** Stimulering Duurzame Energie
- **LSTM:** Local Standard Time Meridian
- **NOCT:** Normal Operating Cell Temperature
- **UTC:** Universal Time Coordinated
-

## Terms and definitions

- **Wijk:** Wijk is the local Dutch term used in the Veenkoloniën for ditches and canals which usually separate fields. We chose the Dutch term because it is a characteristic term for the area.
- **$CO_2$-equivalent:** The carbon dioxide equivalent is a way to express the global warming potential of greenhouse gases. It uses the amount of carbon dioxide that would have the same global warming effect as the respective amount of greenhouse gas (OECD, 2013).
- **MCA:** A Multi Criteria Analysis is a tool to compare the performance of different options taking into account several criteria. It makes it possible to add up values with different units due to putting them on a common scale.
- **NIMBY-syndrome:** *"(...) phenomenon that certain services are in principle considered as beneficial by the majority of the population, but that proposed facilities to provide these services are in practice often strongly opposed by local residents."* ( van der Horst, 2007)
- **Hazardous waste:** "*Hazardous waste is a waste with properties that make it potentially dangerous or harmful to human health or the environment.(...) They can be the by-products of manufacturing processes, discarded used materials, or discarded unused commercial products, such as cleaning fluids (solvents) or pesticides."* (California department of toxic substances control, 2010)
- **Scarce resource:** ''*A resource with an available quantity less than its desired use now and in the future and that thus has a risk of depletion within 200 years.''* (Economic Glossary, 2008).
- **$HC_{50}$ value**: The $HC_{50}$ value expresses the amount of toxin per amount of dry soil that has an toxic effect on 50% of the ecosystem.

## Introduction

The municipality of Aa en Hunze in the Province of Drenthe wants to become sustainable and if possible be even the most sustainable municipality of the Netherlands. This sustainability idea is not just a top-down decision from the municipality. The development towards sustainability has been noticeable amongst the inhabitants in the villages of Aa en Hunze for quite some time, because the municipality regularly got asked for help from inhabitants for the placement of solar panels and placement of bioreactors at farms. This process of development was suddenly quickly speeded up by the national government's decision to place a wind farm in the area of the Veenkoloniën. This wind farm, called wind farm Oostermoer, is to cover an area of around 2800 hectares (Pondera consult, 2011) and is to have an electric capacity of 120-150 MW (Gemeente Aa en Hunze, 2012). Reason for placing it is the European goal of having 20% sustainable energy in 2020. This goal is converted to specific targets for each Member State and for the Netherlands this target is 14%[1]. (Ministerie E.L.I., 2011) To reach this, the Dutch government plans to set up several wind farms of which the Province of Drenthe agreed to take care of a share of 280 MW. (Gedeputeerde Staten, 2012) Thus, the area near Aa en Hunze was pointed out to meet this target.

The wish to move towards sustainability exists on different levels. The EU exerts pressure on Dutch government which decides to set up wind farms. For the government this is a very good solution because wind farms are relatively cost-effective. The broader public is principally in favour of wind farms, but at the same time it is aware that nobody wants to have it in their back yard (the NIMBY-syndrome) (van der Horst, 2007).

We see that on the bottom-level the inhabitants of the municipality Aa en Hunze are strongly opposed to this wind farm plan. Part of the families living in this area have always lived in Drenthe, part of it are originally from other parts of the country and came to live here because of the tranquillity and the grand view of the countryside, of which a part, the Hunzedal, is part of the national ecological network (EHS). On that level the wind farm does not seem attractive at all, because the value of their houses declines, the landscape gets spoiled and they are afraid of negative effects on their stress levels caused by nuisance (Gemeente Aa en Hunze, 2012). In principle many are in favour of renewable energy production in their region, but prefer other options than the wind farm. Some took the initiative and asked the municipality for help to set up an alternative energy system for the villages.

The municipality of Aa en Hunze wants to make the villages more self-reliant and give them more facilities, such as reliable internet connections and community houses, so the area becomes more attractive to live in. As the wind farms will decrease the attractiveness of the region, the municipality also is critical towards the plan. (Gemeente Aa en Hunze, 2012) Goal of the municipality is to have reduced $CO_2$ emissions with 50% in 2025. However, this goal only includes a maximum of 30 MW generated by wind turbines, because the municipality considers a bigger wind farm to disproportionately affect landscape and work and living environment. (Gemeente Aa en Hunze, 2012) Because less wind turbines are wished for by the municipality itself and the inhabitants, the municipality gives the inhabitants space for participation by coming up with an alternative energy plan for the villages. In order to achieve this, and other sustainability goals of the municipality,

[1] In the recently concluded coalition agreement of the Dutch government the 14% sustainable energy is incremented to 16% in 2020.

workgroup Veenkoloniën was created and a learning network was set up to assist the inhabitants in further development of initiatives. The workgroup plans to set up village committees, which will exist out of groups of interested citizens per village, who will decide on an alternative energy plan for their village. At the moment, the main point of contact for interested and active inhabitants is ECO-Oostermoer, a local organisation set up to facilitate local initiatives in Oostermoer and of which the board consists inter alia out of Associations of Village Interests of which a lot inhabitants are member. ECO-Oostermoer is the informal client of our project, the municipality of Aa en Hunze is the formal client.

Besides our group, there are more scientific groups working on the development of the village energy plans. We are part of the learning network which consists out of workgroup Veenkoloniën, students of Van Hall Larenstein (VHL), students of Rijksuniversiteit Groningen (RUG), students of Geo-Information Science (GIS) of Wageningen University, the entrepreneurial group, inhabitants, ECO-Oostermoer, the municipality and ourselves. A learning network consists of different groups with different knowledge. Their knowledge is combined on a common platform to solve a problem (Kenniswerkplaats, 2013). The students of VHL looked at the economic aspects of alternative energy options. The implementation of these energy options per village are taken care of by the GIS students. The students of RUG set up the energy desk within the municipality. They take care of the communication within the network and the contact with the inhabitants. The students of VHL, the students of GIS and ourselves will develop different tools which can be used by the members of the village committees.

We did not look at specific villages in the municipality Aa en Hunze, as the villages for pilots will be picked out in a later stadium of this whole project. We designed a generic method which can be used for every village and be adjusted to the wishes and possibilities of these villages. We used the model to work out three alternative energy options, but the method it is also applicable for other alternatives. We propose that other student groups use the model and fill in the technical requirements of other techniques to get their energy output per house. This is important because it will offer the citizens more options to choose from. The students of VHL already came up with alternative energy options which can be used in a mix in the energy plan. Although all these alternative options produce energy in a sustainable way, we prefer not to call them sustainable energy options yet, because we want to investigate whether the technical systems used for generating energy (like solar panels) are produced in a sustainable way as well. In our point of view, the energy options are only sustainable when both the production process and the energy production are sustainable. Therefore we like to use the term ‘alternative’ instead of ‘sustainable’.

The three energy options we studied are SolTech, Thin Film Solar cells and floating PV cells, all based on solar energy. These three options are chosen by ECO-Oostermoer out of a list of energy that we composed out of the economically feasible options from VHL and some additional options added by us. This list can be found in Appendix I. ECO-Oostermoer made their choice based on what they thought was interesting to do research on for the area of the Veenkoloniën, because for them and the inhabitants not much was known about these three options.

SolTech differs from conventional solar panels in that the photovoltaic layer is integrated in glass roof tiles instead of placed on top of the roof tiles (Burgers et al., 2013). Thin Film Solar cells are very thin solar panels which are flexible and can be shaped according to the curve of the roof (Burgers et al., 2013). The floating PV cells are solar panels placed on water, thereby combining water storage (no need for filling up the waterways, which is a possibility in Aa en Hunze) and energy production. (Conradi et al., 2012) In the municipality of Aa en Hunze they will be placed in 'wijken' (see List of abbreviations and terms).

Based on all the aspects mentioned above our research question is:

*Which of the alternative energy options SolTech, Thin Film Solar cells and floating PV cells are environmentally sustainable and technically feasible in the Veenkoloniën in the municipality Aa en Hunze?*

To investigate the two aspects of our research question, we will use the following sub questions:

*How do the energy options perform technically?*

- *What are the technical requirements for the different technologies?*
- *How much energy does each energy option produce under optimal conditions in the Veenkoloniën?*

*How do the energy options perform environmentally?*

- *What is the emission of greenhouse gases during the life cycle of the different options? (kg $CO_2$-eq /kWh)*
- *What is the use of scarce resources for the production of the different options? (kg/kWh)*
- *How much hazardous resources do the different options contain? (kg/kWh)*

# 1. Technical performance

## 1.1 Introduction

The technical performance will be investigated by the two following questions, also mentioned in the introduction:

- *What are the technical requirements for the different technologies?*
- *How much energy does each energy option produce under optimal conditions in the Veenkoloniën?*

To answer them we looked at the technical requirements and conditions needed for energy production per energy option to see whether or not this option is feasible in this area. The area of the Veenkoloniën has an overall maximum irradiance of sunlight of 980-995 kWh/m$^2$ a year. (Conradi et al., 2012) Although all the three energy options are based on solar energy, they use this irradiance and produce this energy in different ways, with each way having its own advantages and disadvantages.

### 1.1.1 SolTech

The SolTech system is a system that has a photovoltaic layer integrated in glass roof tiles, thus producing electricity in an integrated way. (Burgers et al., 2013) Because glass rooftop cover is used instead of traditional rooftop, the solar light can enter and reach the photovoltaic layer. An advantage of this system is that people like the sights of it better, because it is integrated into the roof. (Burgers et al., 2013) Disadvantages are that the efficiency is smaller, because the camber of the traditional Dutch roof tile causes a shadow, and that all the small panels need to be electrically connected to each other which increases the change that problems occur. (Quest, 2013)

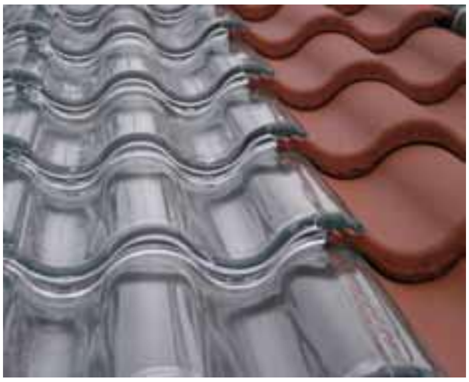

**Figure 1 - SolTech roof tiles.**
**http://www.SolTechenergy.se/document/SolTech_System_2012_eng_web.pdf**

### 1.1.2 Thin Film Solar cells

Thin Film Solar cells are solar cells which are made by depositing thin layers of photovoltaic material on a substrate. (Harris, 2013) The differences with conventional PV panels are that Thin Film Solar cells have less weight, are not influenced by wind, have higher costs and lower efficiency. (Green, 2007)

**Figure 2 - Thin Film Solar cells.**
**http://www.treehugger.com/clean-technology/199-new-thin-film-solar-efficiency-record.html**

### 1.1.3 Floating PV cells

The floating PV cells are solar panels placed on water, thereby combining water storage and energy production. (Conradi et al., 2012) They are not on the market yet, but a pilot[2] has been done in the Veenkoloniën because of the amount of wijken there. Solar energy from the water surface has advantages, since there is a lot of space on the water in the municipality Aa en Hunze, thereby having bigger surface areas of solar panels. Also the water can be used for cooling the solar panels, which is an advantage because the efficiency of solar panels decreases with high temperatures, and the panels can

**Figure 1 - Floating PV cells in a wijk in Valthermond. (Conradi et al., 2012)**

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[2] Graduation project *Veenkoloniën, zonne-energie vanaf een wateropslag.* (Conradi et al., 2012)

move in the direction of the sun. (Burgers et al., 2013)

## 1.2 Methods & means

### 1.2.1 Five-step method

The main method we used is a 5-step plan that we have set up and followed for each option, to make sure every option is treated the same. This 5-step plan is a generic method and can later on be used for other energy options in the overall project. Our 5-step plan consists out of the following steps:

**1. Set the technical requirements for the chosen options.**
(e.g. range of roof angles suitable for PV).

**2. Use an example standard object for the calculations.**
This example standard object can be a standard house or a standard wijk, depending on the energy option. For most energy options these two standard objects can be used, unless for example a bioreactor is used, so no new standard house or standard wijk has to be set: they can be taken from our report. Assumed is that the standard house is suitable for the chosen energy options. For example the roof of the standard house has an angle that is the optimal angle in the range that is suitable for PV panels. The same applies for the standard wijk, which is wide enough to place floating PV cells on it.

**3. Correct the amount of energy produced for a specific house or specific wijk by using a correction factor for the changed variables.**
With the standard house you can for example calculate the amount of energy that can be produced by PV panels, because you have the suitable roof surface. This way you can easily correct the amount of energy produced for a specific house by using a correction factor for the roof surface of this specific house. The same goes for the surface area of a specific wijk. This step will not be included in our results, because of time limitations. The committees of the villages that will make the energy plan for their villages will carry out this step themselves or they will get experts who will look which house in the area is suitable for an option. The roof or water surfaces, roof angles and irradiance can be adjusted in our technical model (which will be explained later on). This model only applies for solar energy options. Step 3 of this generic method can, however, be applied to other technologies. When one chooses for a bioreactor for example, one should correct sizes of the bioreactor compared to a standard bioreactor or if one chooses insulation, then the surfaces of the wall will have to be corrected compared to the surfaces of the walls of the standard house.

**4. Calculate the percentage of the energy use of an average household that can be produced by the sustainable energy production method during its lifetime.**
An average household in the Veenkoloniën uses 1537 kWh of electricity per year.[3] (Pluim, 2011) We calculate the percentage of the energy use that can be produced by the sustainable energy production method during its lifetime. This percentage is an indicator of the feasibility of the technique. Whether a certain percentage is seen as feasible or not is up to the user of the method: ECO-Oostermoer and / or the committees of the villages which will create the energy

[3] For the average household we use the same house(hold) that we use as example for the standard house, so that we remain consistent. The amount of electricity used per year is thus based on the energy consumption of this household.

plan for their village.

Calculation for energy use per lifetime:
energy use per lifetime = energy use household (1537 kWh) * lifetime

Calculation for percentage of energy use:
percentage of energy use = $\frac{\text{output per lifetime}}{\text{energy use per lifetime}}$ * 100%

**5. Calculate the energy production of a certain (mix of) energy production/saving methods per village.**
The energy production by a certain (mix of) energy production/saving methods of a whole village can be calculated by looking at how many houses in the village are suitable for a specific method. Thus a generic method for choosing ways of sustainable energy production at village scale is created. This last step will not be included in de results of our research, simply because this is not our task and impossible for us to calculate considering the time scale.

### 1.2.2 Defining standard objects

#### *1.2.2.1 Standard house*

The standard house was be based on an average house of the region. We asked the Energy Bureau to provide us information about an average house of the region. We received a report of an energy saving plan for a for the region representative house.[4] Based on this document we have set the sizes of our standard house. The roof surface area of the house was known. We assumed that half of the roof was oriented to the south. This assumption could be made because our standard house is suitable for solar energy and has a gabled roof. So we have set the sizes of our house such that we got about the same roof surface area as the house in the document, to make sure that we have a realistic house size. The sizes of the house are not of big importance for solar panels, since then only the roof matters, but they can be of importance for other energy options (like isolation). Therefore we included these sizes, because this standard house may be used further by others who use this generic method.

Roof surface area average house (pitched roof old): 77.9 $m^2$ (Pluim, 2011)
Half of the roof surface area: 77.9/2 = 38.95 $m^2$
This (half) roof surface area can approximately be obtained by a roof of 3.9 m x 10 m. These are the oblique side of the roof (3.9 m) and the longitudinal side of the standard house (10 m).

Because the standard house is suitable for solar panels, the angle of the roof is 36°. Half of the width side of the standard house is than cos(36°)x3.9 = 3.15 m. The total width side is 3.15x2 = 6.30 m. The height of a floor level is usually about 3 m.

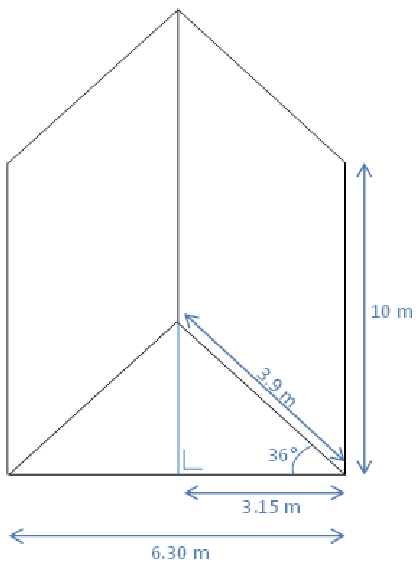

Figure 2 - Standard house.

[4] PLUIM, E. 2011. *Energiebespaarplan. Noordzijde 39, Gasselternijveenschemond.* Veendam: Adviesbureau Ecocert.

So the standard house is 6.30 m x 10 m x 3 m with a roof surface area of 39 m (3.9 m x 10 m).

### *1.2.2.2 Standard wijk*

The width of a wijk is mostly about 4 m. (Huiting, 2013c) So for the width of the standard wijk we took 4 m. For the length of the standard wijk we took a side of one hectare of meadow, because grassland and farmland are usually in this order of magnitude and it is easy to calculate en recalculate with. The length of the wijk is thus 100 m.

We chose to place the frames with panels in the width of the wijk (see figure 3) , because that way you can fit three panels next to each other (frame length with three panels: 3.3 m < 4 m) with a space in between the frames of 3.9 m to fit the reflecting flats. The reflecting panels are mirrors that are placed in such a way that an optimal amount of direct sunlight is reflected towards the solar panels (angle of 14° with water level). (Conradi et al., 2012)

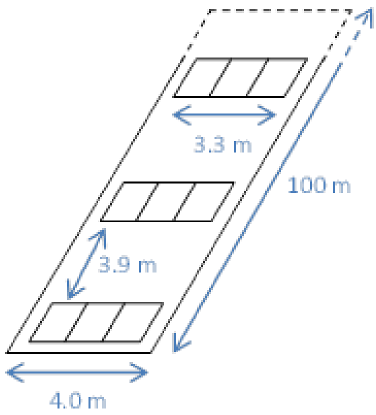


**Figure 3 - Standard wijk with solar panel arrangement.**

The panels themselves take 0.97 m in the length of the wijk: angle of 36° with water level, height of panel 1.65 m (Conradi et al., 2012 so sin 36° * 1.65 = 0.97.
So you can place for example 100 / (0.97 + 3.9 ) = 20.5 = 20 panels in a wijk of 100 m. You cannot place panels in a long row (the width side of the frame parallel with the longitudinal side of the wijk), because 0.97+3.9 > 4m. So this is the most optimal arrangement.

## 1.2.3 Model

### *1.2.3.1 Input data*

The input data (mean radiation on PV panel (W/m$^2$) and mean cell temperature ($^0$C)) we used for our model have been taken from the model of Bierens (Bierens, 2013). This model is based on weather data from the weather station at the Haarweg, Wageningen. This means that not the weather data for Aa en Hunze were used, but since the two municipalities lie in the same global irradiance zone in the Netherlands (980-995 kWh/m$^2$/year, see figure 4) there should be only minor differences. These input data have been calculated based on direct and diffuse irradiance on the solar panel. These depend, inter alia, on:

- Latitude and longitude (of Wageningen as explained above)
- LSTM (local standard time meridian) here taken to be 0 “since the weather station time is in coordinated universal time (UTC)” (Bierens, 2013)

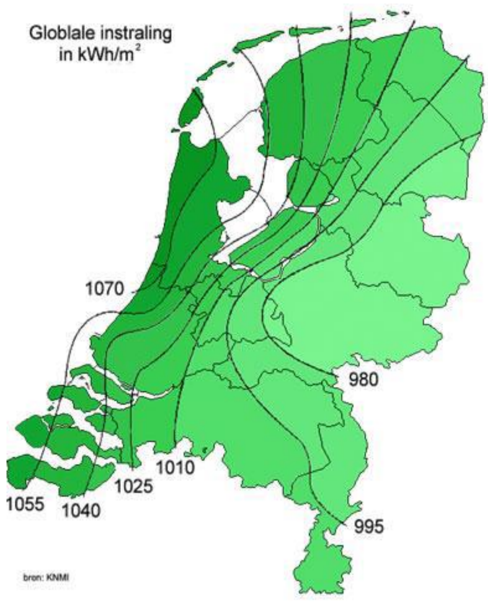


**Figure 4 - Globale instralingskaart van Nederland in kWh/m$^2$. (KNMI, 2012)**

- NOCT (normal operating cell temperature) which is 47 $^{o}$C for poly-crystalline Si PVs (Bierens, 2013).
- Azimuth (angle with the sun) set at 0$^{o}$, to calculate for a PV directed directly at the sun (to the south). Later in the model the production can be adjusted for different angles.
- Module tilt (from now on referred to as roof angle) set at 36$^{o}$, because this is the optimal angle for a solar panel (Conradi et al., 2012). Later, the production can be adjusted in the model by the user to the actual module tilts.

The seasons influence productivity of solar panels, so we have to take them into account. The seasons are based on the following data (Bierens, 2013):

| | |
|---|---|
| Spring | March 1 – May 31 |
| Summer | June 1 – August 31 |
| Autumn | September 1 – November 30 |
| Winter | December 1 – February 28 |

### *1.2.3.2 Model calculations floating PV*

The following calculations are used in the model in Excel:

1. The given maximum panel efficiency (under optimal conditions) is corrected for the roof angle and the roof orientation (azimuth) in the lower table, thereby giving the position efficiency.
2. The actual panel efficiency (including temperature dependency) is calculated (left table) with the following formula:
   IF (logical_test, value_if_true, value_if_false)
   IF (T $\geq$ 25, $(1+(T\text{-}25)*\frac{TD}{100})$*EFF, EFF)
   *T = mean cell temperature*
   *TD = temperature dependency*
   *EFF = position efficiency panel*
   *This formula means that if the temperature is above 25°C (the limit of temperature at which efficiency is optimal (Conradi et al., 2012)) there will be an efficiency decrease following the temperature dependency coefficient. This is the '$(1+(T\text{-}25)*\frac{TD}{100})$*EFF' part. Since the TD is expressed in %, this is converted to a fraction to be able to calculate properly with it. If the temperature is below 25°C, than the efficiency will be optimal for the given irradiance and will equal the position efficiency (the 'EFF' part).*
3. Calculate the production per season (Wh/m$^2$). Production (Wh/m$^2$) = mean radiation on PV panel * actual panel efficiency (right table).
4. This production is converted to kWh/m$^2$/year, because this is the way to compare the options with each other.
   Production kWh/m$^2$/yr = $\Sigma\ (\frac{\text{production (Wh/m}^2)}{1000}$ * no. of days per season$)$.
5. With the surface of PV per unit the output per unit is calculated:
   output per unit = surface unit * production kWh/m$^2$/yr.
6. With the length of the wijk and the length of one unit, the number of units that can be placed in the wijk is calculated. The following formula is used:
   *=ROUNDDOWN((length of wijk/length of unit),0*)

*This round down is to make sure that a number like 20.5 is rounded down to 20 and not 21, because you cannot place half a solar panel.*

7. The output per wijk is calculated. Output per wijk (kWh/year) = output per unit * number of units.
8. Production of the wijk in the lifetime of the panel = *output per wijk* * $\frac{1-\left(1-\frac{ED}{100}\right)^{lifetime}}{1-\left(1-\frac{ED}{100}\right)}$

   *ED = efficiency decrease*

   *This formula is the formula for a geometric series of which the sum equals:* $a\frac{1-r^{n}}{1-r}$.

   *It is necessary to use this formula since there is an efficiency decrease over the years, so the output per wijk is not the same every year. If the production of a wijk during the lifetime of the panels is wished for, then the sum of all the outputs per year (so including the efficiency decrease) has to be taken. The starting value a (here output per wijk) is in our case the amount of energy produced per wijk in the first year. The growth factor r (here* $\frac{ED}{100}$*) represents the efficiency decrease over the years. The power n represents the years of lifetime.*

As mentioned in step 3 of the five-step generic method, adjustments in the model can be made for roof angles and house sizes. The yellow cells are to be filled in by the user of the model, but do not have a direct effect on the calculations. If these two (orientation of roof and roof angle) are known, they can be looked up in Figure 1 of the Excel sheet to estimate the irradiance. This estimation can be done by looking for the values or roof orientation and roof angle on the right axis of the figure and then go to the cross-section of these two lines. The cross-section will be in a certain colour area. The colour of the area represents the amount of irradiance. This irradiance can be filled in in the orange box that is made for it. Oranges boxes in our model represent values that have to be filled in by the user and do effect the calculations. The grey boxes are outputs that are probably interesting for the user.

#### *1.2.3.3. Model calculations SolTech & Thin Film Solar*

The calculations for SolTech and Thin Film Solar are almost the same as for floating PV. The only difference is that for the calculation of the number of units you do not use the wijk length and unit length, but roof surface and unit surface respectively. The roof surface suitable for PV is 1/3 of the part of the total roof that has the best orientation towards the sun (in our case half of the total roof has the best orientation). So the roof surface used is $\frac{1}{3}$ * 38.95 $m^2$ = 13 $m^2$.

We took 1/3, because the lower parts of the roof usually have too much shading from surrounding trees (in Aa en Hunze we observed a lot of houses have trees standing near the house). If there are only a few panels in shadow then the power of the whole arrangement will already be reduced. The power of the arrangement is as high as the worst producing panel. (Conradi et al., 2012)

Thus all panels produce less energy when one of them is in the shade, because they are in series. It is therefore better to place the panels on those parts of the roofs that do not have shadow from trees or other houses in the neighbourhood, to keep the power as high as possible.

## 1.3 Intermediate results

The requirements per energy option are a result of the 5-step generic method (step 1), because they will have to be set for each energy option individually. Part of the requirements will also be used as input data in our model and therefore we consider the requirements intermediate results.

### 1.3.1 Requirements SolTech (KoraSun, 2013)

- **Orientation**: see figure 5.
- **Optimal angle**: Roof tile type Migeon Actua needs a minimal roof angle of 24°; roof tile types Pottelberg Stormpan 44, Migeon Mega and Bisch/Migeon Jura Nova 25°. See figure 5 for optimal angles.
- **Lifetime**: 25 years
- **Dimensions**: Roof surface per PV-module is 0.676 $m^2$ for Actua/Mega/Jura Nova; 0.959 $m^2$ for Stormpan 44
- **Efficiency (no shading):** : 11.4% (Ricaud, 2011)
- **Temperature dependency:** -0.5%/K (De Kooning, 2010)
- **Degradation of efficiency of the years:** 0.8%/year[5]
- **Other:** When placed in an existing roof the useful width should be checked. When placed in combination with Actua, Mega and Jura Nova clay roof tiles a set batten distance of 370 mm should be kept.

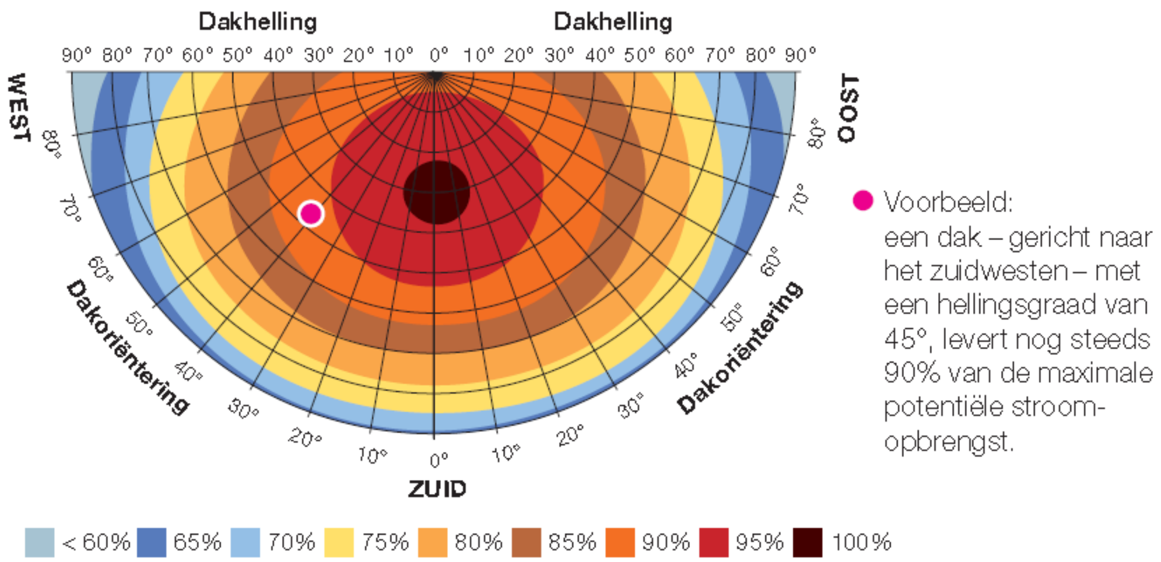


**Figure 5 - Optimal Orientation and Roof Angle for Solar Energy based Techniques in the Netherlands. (KoraSun, 2013)**

### 1.3.2 Requirements Thin Film Solar

- **Orientation**: see figure 5.
- **Optimal angle**: see figure 5.
- **Lifetime**: 25 years (Cheyney, 2010)
- **Dimensions**: Length 1.960 m x width 0.915 m (Nanosolar)
- **Efficiency (no schading):** 12% (CdTe)[6] (Shahan, 2013)

[5] After 12 years efficiency is 90%, after 25 years efficiency is 80%. (KoraSun, 2013) For the first 12 years the degradation of efficiency is then 0.91%/year and for the next 13 years the degradation efficiency 0.77%/year. The mean degradation over lifetime is than 0.8%/year.

- **Temperature dependency**: Temp Coeff Pmax is -0.40 %/K (Nanosolar)
- **Degradation of efficiency of the years:** 1.0%/year[7] (Jordan, 2012)

### 1.3.3 Requirements floating PV cells

- **Orientation**: see figure 5.
- **Optimal angle**: 36° (Conradi et al., 2012)
- **Lifetime**: 30 years[8] (Scheuten Solar, 2013)
- **Dimensions**: 1.65 m x 0.99 m for one panel (Conradi et al., 2012)
- **Efficiency (no schading)**: 16.5%[9] (Conradi et al., 2012)
- **Temperature dependence**: Temp Coeff Pmax is -0,485% /K (Conradi et al., 2012)
- **Degradation of efficiency of the years:** 0.5%/year[7] (Jordan, 2012)
- **Connectable to power grid**: What should be considered is how to panels will be connected to the grid since there are probably no electricity cables running through the meadows near the wijken at the moment. The solar panel produces direct current (DC). When the panel is to be connected to the power grid a converter is needed to change this to alternating current (AC). This converter is called an inverter and exists out of an converter and a MPPT (maximum power point tracker). This actually counts for all PV systems, but usually this is placed inside your house, which is not possible here, so something to take into account a bit extra for floating PV.
- **Distance between frames to prevent shading to occur**: 3.9 m (Conradi et al., 2012)

## 1.4 Results

For optimal conditions our model gives the following results:

**Table 1 - Results of energy production per energy option.**

| | Floating PV cells | SolTech | Thin Film Solar cells |
|---|---|---|---|
| Production (kWh/m$^2$/yr) | 171 | 118 | 125 |
| Output per standard object (kWh/yr) | 16,757 | 1455 | 1627 |
| m$^2$ available per object | 400 | 12 | 12 |
| Output per lifetime (kWh) | 467,901 | 33,093 | 36,142 |
| Energy use per lifetime | 46,110 | 38,425 | 38,425 |
| % of energy use | 1034 | 86 | 94 |

Looking at the production in kWh/m$^2$/yr is the best way to compare the absolute efficiency of the three technologies, since floating PV has much more m$^2$ to be placed at than SolTech and Thin Film Solar (400 m$^2$, 12 m$^2$ and 12 m$^2$ respectively). So floating PV can produce more energy than SolTech and Thin Film because it has a bigger surface with which it can produce energy. When looking at the

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[6] For Thin Film with CdTe: theoretical maximum 29%, best research cell 17.3%, typical module production 12 %. (Shahan, 2013). As can be seen real life solar production with thin film solar cells has a lower efficiency than during research. This is a common phenomenon for solar panels, so the efficiency may vary.

[7] Jordan, 2012: figure 2c and 2b. We took the median instead of the mean, because this is the most frequent degradation factor.

[8] Based on the power warranty of Scheuten Solar for the panel type used for floating PV (Scheuten Solar Multisol® Vitro P6-60 235Wp).

[9] Calculation: 14% efficiency, but efficiency increase by reflecting flats of 18%, so 14*1.18 = 16.5%

production in $kWh/m^2/yr$ in table 1 you can see that floating PV still has the highest production and SolTech the lowest, but the differences are not that big.

In table 1 also the energy uses (per household) during the lifetime of a technique are shown. An average household in the Veenkoloniën uses 1537 kWh of electricity per year.[10] (Pluim, 2011). With that you can calculate the percentage of the used energy that could be produced by each technology. For SolTech and Thin Film Solar these percentages seem quite promising, 86 and 94% respectively. For floating PV it is even better (1034%), which comes down to 10 houses. That energy is produced by only 100 meters of wijk and the amount of wijken for a village may be much more in the area of the Veenkoloniën.

## 1.5 Discussion

There are a few points for discussion of this technical part.
First of all, we use the optimal conditions for the energy options, so the energy production in reality will be lower. The model can be adjusted to other conditions than the standard ones, so for further use this should not be a problem.

Secondly, in the report of Conradi et al. one of the STC (standard test conditions) is the temperature of 25˚C. They did not perform a research on floating PV with temperatures higher than 25˚C. In the report it is stated that there is no influence by cooling of the panels with water on the energy production, although the panels themselves are cooler. This cooling by water could, however, be of importance with temperatures above 25˚C, so the TD (temperature dependency) might differ from the coefficient we used in the technical requirements, which is the same as that of the solar panels not being placed on water. The results of floating PV can therefore be better than pictured now. So further research is needed to see if this is the case.

Thirdly, the conditions of the environment in which the floating PV panels can be placed, can influence the durability and working of the panels negatively. This especially counts for some weather conditions. The sand soils and peat soils in the area of the Veenkoloniën are very susceptible to drought. (Conradi et al., 2012) Sand can be dispersed and the panels will be covered by a layer of sand, which will cause them not to work properly anymore. The panels do have a self-cleaning capacity, because the angle is more than 30 degrees. (Conradi et al., 2012), but we think it would be wise to check the panels should be cleaned once in a while or not. Also, the wijken can freeze over in winter. We do not think this has to be a problem, since the solar panels are placed on frames and not directly on the water. So we think that the chance that the panels will be damaged by freezing is not that big, but perhaps this should be investigated. Of course, when the water is frozen it cannot be used for cooling the PV panels. We do not think that this is a problem, since the cooling of water is not relevant when panels have temperatures up to 25° degrees. In winter, the panels will not exceed this temperature. Another aspect considering the environment is the possibility of animals damaging the panels or even the panels affecting the living environment of animal species. Perhaps, research should be done to this too, before this option can be implemented.

The fifth point is that we use mainly one source for floating PV, namely Conradi et al. 2012. This is because this is the only information available on putting PV panel on the water (in a wijk). So the design of this energy option and most of the data is based on this one research. It could be possible that other researches will have different outcomes, but for now they are simply not

[10] For the average household we use the same house(hold) that we use as example for the standard house, so that we remain consistent. The amount of electricity used per year is thus based on the energy consumption of this household.

available yet.

Last, setting the requirements per energy option might seem a bit irrelevant now, because they are quite similar to each other, since all the options are solar energy options. When having different types of energy options, setting the requirements per option separately is of course of more significance.

# 2. Environmental performance

## 2.1 Introduction

Next to the technical feasibility of the three options the environmental impact is taken into account. A comparison will be made between the environmental performance of the different options using a Multi Criteria Analysis (MCA) and we will have a look at the environmental impact of the options per standard object to make the outcome more clear to the inhabitants.
The MCA will order the options according to how sustainable they are compared to each other. The environmental impact per standard object will point out whether the options can be called sustainable instead of alternative.

Our research questions were as follows:

*How do the energy options perform environmentally?*

- *What is the emission of greenhouse gases during the life cycle of the different options? (kg $CO_2$-eq/kWh)*
- *What is the use of scarce resources for the production of the different options? (kg/kWh)*
- *How much hazardous resources do the different options contain? (kg/kWh)*

## 2.2 Methods & means

To see whether the top 3 alternatives were sustainable a Multi Criteria Analysis was done based on environmental impact, to make the total sustainability picture complete (economic by VHL, social and environmental). The MCA consisted of several steps: Problem analysis, standardization, weighting and ranking.
In the problem analysis the criteria were defined and ordered. Also the units were determined per criterion. The following criteria have been used:

- Emission of greenhouse gases during the production of the systems and during the use of the systems in kg $CO_2$-eq/kWh.
- Use of scarce resources during the production of the systems in kg/kWh and years to depletion.
- Amount of hazardous waste produced during the production of the systems and waste processing of the systems in kg/kWh and mg component/kg dry soil ($HC_{50}$ value).

In our opinion these criteria were important in the evaluation of the environmental performance of the energy options. We would have wanted to consider more criteria, but this was not possible in the amount of time available for the project. We think these three criteria cover parts of the different aspects of sustainability well enough to get a picture of the environmental performance, since we include emissions (climate change and air pollution), scarcity (linked to economy and development) and hazardous waste (effect on ecosystems and humans).

To determine the environmental impact of the three options based on the criteria, data had to be found about the composition of the panels. Based on the data found for Thin Film Solar cells the resources that are considered in the MCA were selected, since for this option it was rather easy to find data about the composition.

There are three types of Thin Film Solar cells: a-Si (amorphous-silicon), CIGS (copper indium gallium deselenide) and Cd-Te (cadmium-telluride). (Harris, 2013)
For this research the CIGS type on metal foil was chosen since this type has the highest cell-efficiency of the three Thin Film Solar types as can be seen in figure 1, Appendix II .

The composition of one CIGS cell is as follows: ''The CIGS cell consists of a layer of ZnO (2 $\mu$m), a layer of CdS (0.05 $\mu$m), a layer of $Cu(In_{.75},Ga_{.25})Se_2$ (2.0 $\mu$m) and a layer of Mo (1.0 $\mu$m).'' (Andersson, 1998)
Not only the materials used for the cell needed to be determined, but also the metal used for the foil. For the used CIGS cells aluminium foil is used. (Harris, 2013)

For the components of a cell, data about the scarcity (years to depletion) and the toxicity ($HC_{50}$ value) had to be determined. The components of which no data could be found have been left out, so the final list is as follows:

**Used resources (list)**

- Aluminium (foil)
- Zinc (Zn-O layer)
- Cadmium(CdS-layer)
- Copper (CIGS-layer)
- Indium (CIGS-layer)
- Gallium (CIGS-layer)
- Selenium (CIGS-layer)
- Silicon
- Phosphorus (semi-conductor) (Harris, 2013)

Silicon is also taken into consideration since this is an important component for the floating PV cells.

For SolTech and floating PV data from a database presented in an Excel sheet (Potting, 2013) was used for the materials above, so this list was used for all options.

### 2.2.1 Multi Criteria Analysis

#### *2.2.1.1 Problem analysis*

#### Emission of greenhouse gases

We obtained the greenhouse gas emissions per technology from literature research. There exists a vast number of Life Cycle Assessments (LCAs) on the environmental performance. They also consider the impacts and emissions during production, transportation, installation and waste treatment of the PVs and resources used. All of them make use of different types of solar panels, different ways of installation, have other values for solar radiations and there are different weather conditions (Peng et al., 2013). The emissions consist of various gases such as for example $CO_2$, $N_2O$ and $SF_6$, but are expressed in $CO_2$-equivalanets per kWh (kg $CO_2$-eq/ kWh) of electricity production.

We selected the articles based on the type of solar cell (multi, mono or CIGS), the year the research was performed and the solar radiation:

- One has to consider that the production and waste treatment [of production processes] became more efficient over time (Alesma, 2000). For this reason it is necessary to choose research that is performed nearly at the same time.
- The amount of solar energy greatly influences the energy yield of a solar panels. This way it has effects on the greenhouse gas emission which is expressed per kWh of electricity production. Therefore, we chose the same average solar radiation for all options.

Based on the criteria mentioned above we selected two articles to obtain the data. For SolTech and the floating PV we referred to the review article of Peng et al. (2013). The authors made use of Fthenakis et al.'s (2011) review on LCAs before 2011. The information for Thin Film Solar cells we got from de Wild-Scholten et al. (2010). The value for the solar radiation for the Thin Film Solar cell we got from Enel (2012).

### Use of scarce resources

For our research we have defined *scarce resource* to make sure that it is clear what we are writing about. This definition can be found in the List of abbreviations and terms.

To determine which scarce resources were used per technology we first had to obtain which materials were used per technology and in what quantity. We made a list of the used resources per alternative and then looked up the scarcity of the used resources (years to depletion). All this data has been obtained from literature research and personal communication with persons that obtained the data from e.g. a database.

We wanted to have a fixed scale for years of depletion to be able to compare the scarcity of resources and score them for the MCA. Therefore it needs to be determined from how many years on the depletion will get a scale factor 1 (see figure 8). In this scale a scale factor of 1 indicates that the resource is least scarce in comparison to the other used resources that have a higher scale factor.

To have an indication of this value for scale factor 1 some literature research about some resources, of which we already knew that they are quite scarce, was done: phosphorus and oil. Beforehand we did not look for a specific relation with the solar alternatives, since when we decided on this, the alternatives were not yet chosen. To be able to set the scale beforehand, it was decided that two scarce resources, phosphorus and oil as mentioned above, would be taken and their years to depletion were looked up to have an indication from what is scarce. It was found that phosphorus will be depleted within 50-100 years (Cordell, 2009) and oil will be depleted within 40-60 years (Vidal, 2005). Based on these data we set the maximum risk of depletion at within 200 years.

To make a fair comparison between the three options in how much scarce resources they use, the years to depletion of the used resources and the used amount of the resources per produced kWh of electricity during the lifetime of a panel need to be known. Therefore we have done some calculations. First the amounts of resources and scarcity of the resources used were scaled and then we calculated a final score per resource, which added up give the total score on scarcity for an energy option used in the MCA.

#### *Scaling*

In figure 8 an example scale of the used amount can be seen. After all data was collected we took the highest amount for a scale factor of 10 and then calculated the step size. Then a scale factor of 10 indicates the worst (highest amount used) and a scale factor of 1 indicates the best (lowest amount used).

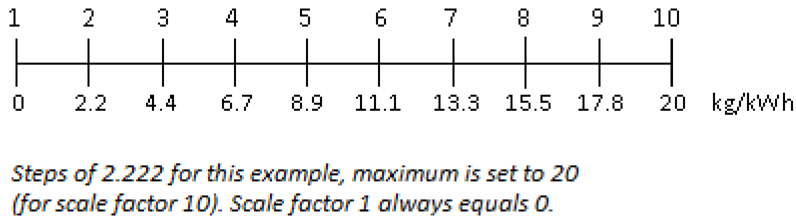


**Figure 6 - Example of scaling the amount of scarce resources used for the energy options.**

The scaling of the amount is different for all three alternative options, since they use different amounts of the resources and therefore have different values of kg/kWh which indicates the score of 10. The scales per energy option can be found in Appendix II.

Next to the scaling of the used amounts the scarcity is scaled, from which an example can be seen in figure 9. Here we used a fixed scale: 200 years to depletion or more get a score of 1 (see definition of scarcity in List of abbreviations and terms). A score of 10 again indicates the worst (scarcest) and a score of 1 indicates the best (least scarce). Since we used a fixed scale, the step size is the same for all three alternatives and we use this scale for all of them.

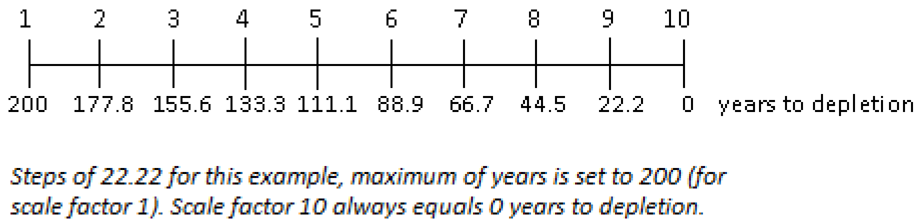


**Figure 7 - Example of scaling the scarcity of resources used for the energy options.**

After the scaling procedure the scale factors per resource are calculated (see table 2):
The scale factor amount is calculated as amount used (kg/kWh)/step size + amount of steps (counted from left to right).
The scale factor depleted is calculated as years of depletion/step size = X
10 – X = scale factor
These scale factors then were multiplied and added up to come to a final scarcity score for each alternative (see table 2).

**Table 2 - Example calculating the environmental impact of the used scarce resources for one energy option.**

| Resource | Amount used (kg/kWh) | Scale factor amount | Depleted (years) | Scale factor depleted | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| **A** | 4 | 2 | 50 | 7.5 | 15 |
| **B** | 8 | 4 | 100 | 5 | 20 |
| **C** | 16 | 8 | 200 | 1 | 8 |
| **D** | 20 | 10 | 50 | 7.5 | 75 |
| | | | | **Total:** | **118** |

### Production of hazardous waste

The toxicity of the hazardous waste that is produced will be expressed by the $HC_{50}$ values per toxic component (during production and waste processing) for an ecosystem. The $HC_{50}$ value expresses the amount of toxin per amount of dry soil that has an toxic effect on 50% of the ecosystem. The exact definition of $HC_{50}$ we use can be found in the List of abbreviations and terms. The $HC_{50}$ values used were obtained by literature research.

We used the same scaling procedure as we did for the resource scarcity. So the highest $HC_{50}$ value got a score of 10 (which indicates the worst) and then the step size was calculated. Also here the $HC_{50}$ scale is fixed since we used the same toxic components for all three alternatives, so the scale could be used for all alternatives.

Next to the scaling of the $HC_{50}$ values we used the produced scale of the amounts again as we did for the scarcity (see figure 8). After scaling we calculated the scale factors amount and scale factors waste and calculated the final score for toxicity per alternative (multiplying the scale factors and add them all up).

### *2.2.1.2 Standardization*

The next step in the MCA is the standardization: ''Given the variety of scales on which attributes can be measured, multi criteria decision analysis requires that the scores of the various criteria are transformed to comparable units. Only if the scales of the criteria are the same, the scores of these criteria can be compared or combined. Making the scores of the criteria comparable is often called standardization or normalization.''(Herwijnen, year unknown)

All the found data will be standardized using the weighted summation method, using the following equation (Groeneveld, 2012):

$$V_{standardized} = \frac{V_{highest} - V_i}{V_{highest} - V_{lowest}}$$

**Equation 1 - Standardization formula used for standardization in the MCA.**

### *2.2.1.3 Weighting*

To determine if the three chosen energy options are environmentally sustainable we have defined the criteria mentioned before. After defining the criteria, weighting has to be done. This was done by ourselves (as environmental scientists) and by ECO-Oostermoer (partly representing the inhabitants of the area of our research). For the outcome of the MCA we used three different weightings: our weighting, the weighting of ECO-Oostermoer and the average weighting of these two. We compared these three outcomes with each other.

#### *Our weighting*

- Emission of greenhouse gases (GHG) during the production of the systems and during the use of the systems in kg $CO_2$/kWh. **40%**
- Amount of hazardous waste produced during the production of the systems and waste processing of the systems in kg/kWh. **20%**
- Use of scarce resources during the production of the systems in kg/kWh. **40%**

We weighed the criterion hazardous waste as least important since this has a local impact while the other criteria have global consequences. The emission of greenhouse gases enhances the greenhouse effect, which leads to a global rise in temperature and sea level. This has a high impact on ecosystems and humans worldwide. The use of scarce resources also has a high impact, especially on humans, since our whole economy is depending of the resources used and these resources are depleting (e.g. metals). The criterion hazardous waste has a high impact on a local scale, e.g. ground water pollution. We do not say this is not important, but in our opinion the global consequences mentioned above are more important than the local consequences that are caused by hazardous waste.

Both emission of GHG's as use of scarce resources have a global impact on ecosystems and humans (e.g. economy). After some discussion we decided that they are equally important, so we have weighted them equally (40%).

#### *Weighting of ECO-Oostermoer*

- Emission of greenhouse gases during the production of the systems and during the use of the systems in kg $CO_2$/kWh. **33.3%**
- Amount of hazardous waste produced during the production of the systems and waste processing of the systems in kg/kWh. **33.3%**
- Use of scarce resources during the production of the systems in kg/kWh. **33.3%**

The board of ECO-Oostermoer could not decide whether they found one criteria more important than another. After some discussion, they decided to weigh the criteria equally. (Ferwerda, 2013b)

#### *2.2.1.4 Ranking*

The final step of the MCA is the ranking. Here, the weighted scores have been multiplied with the standardized scores per criterion and then added up for each alternative energy option. Based on these final scores a ranking of the alternative energy options can be made (highest score gets ranking 1, second highest score gets ranking 2 etc.), which points out which of the three alternative energy option is most sustainable and which one is least sustainable when compared to each other and according to the defined criteria.

### 2.2.2 Environmental impact per standard object

#### *2.2.2.1 Emission of GHGs*

Based on the comparison between the $CO_2$-equivalent of fossil fuels (kg $CO_2$-eq) and the $CO_2$-equivalent of the energy options (kg $CO_2$-eq), it can be said whether the option is sustainable considering this criterion or not. For the $CO_2$-equivalents in kg the following calculations are done:

1. Calculation of the $CO_2$-equivalent for fossil fuels (kg $CO_2$-eq) based on the energy production of the options during their lifetime:
0.85 kg $CO_2$-eq /kWh (Milieu Centraal, year unknown) * output per lifetime of energy option (kWh)

2. Calculation of the $CO_2$-equivalent of the energy options (kg $CO_2$-eq):
$CO_2$-equivalent (kg $CO_2$-eq/kWh) used in MCA * output per lifetime of energy option (kWh)
We used the output per lifetime of the alternative energy options, since we want to make the

comparison with fossil fuels based on the energy production of the alternative energy option. Then you can see how much greenhouse gases fossil fuels would emit when they produce the same amount of energy.

The outputs per lifetime of the energy options are taken from the results of the technical part of this report. The amount of resources used (kg/kWh) can be found in the tables in Appendix II.

#### *2.2.2.2 Use of scarce resources*

For the scarcity we also wanted to calculate the use of scarce resources per standard object, but this calculation cannot be based on a standard object since it is not representative to compare very small amounts of resources used for one standard object with stocks of tonnes.

#### *2.2.2.3 Hazardous waste*

Based on the comparison of $HC_{50}$ (mg/kg dry soil) and concentration of resource used (mg/kg soil) it can be decided that an energy option can be called sustainable instead of alternative or not. To get this concentration of resource used, the following calculation is done:

1. Calculation of the total amount of resource used (kg):
Amount of resource used (kg/kWh) * output per lifetime of energy option (kWh)

2. To make a comparison with the same amounts we used the following information:
Density peat soil: 892 kg/$m^3$
Depth of soil layer: 1 m (this is an assumption for comparison)
Surface area soil beneath standard house: 63 $m^2$ (6.30 m x 10 m, see 2.2.2.1 Standard house)
Surface area soil beneath standard wijk: 400 $m^2$ (4 m x 100 m, see 2.2.2.2 Standard wijk)

3. Calculation of the amount of soil beneath the standard house for SolTech and Thin Film Solar:
892 kg/$m^3$ * 63 $m^2$ * 1 m = 56,196 kg soil
This outcome will be used in further calculations.

4. Calculation of the amount of soil beneath the standard wijk for floating PV:
892 kg/$m^3$ * 400 $m^2$ * 1 m = 356,800 kg soil
This outcome will be used in further calculations.

5. Calculation of the concentration of the resource (mg/kg soil) within a depth of 1 m:
Total amount of resource used (kg) / amount of soil beneath standard object (kg soil)

## 2.3 Results

### 2.3.1 Results Multi Criteria Analysis

In this chapter the results of the Multi Criteria Analysis are presented. For the calculations see Appendix II.

#### *2.3.1.1 Standardization*

##### *Emission of GHGs*

In table 3 the results of the emission of greenhouse gases are presented in kg $CO_2$-eq/kWh. All three technologies were examined under an average solar radiation of 1700 kWh/$m^2$/yr. Under these conditions the $CO_2$-equivalent of SolTech is nearly as much as the $CO_2$-equivalent of floating PV. The Thin Film Solar Cells emit slightly less than the other two options. Overall, for the three options there is not much difference in emission of greenhouse gases during their lifetime.

To compare all criteria with each other, the scores are standardized with the formula in equation 1 (see Methods & Means). The results are presented in table 3, where it can be noticed that the score 1 indicates that this option emits the least greenhouse gases (which is in this case Thin Film Solar) and thus performs best on this criterion.

**Table 3 – Data scores and standardized scores for the emission of GHGs.**

| | Data (kg $CO_2$-eq/kWh) | Standardized scores |
|---|---|---|
| SolTech | 0.028 | 0.14 |
| Thin Film Solar Cells | 0.022 | 1.0 |
| Floating PV | 0.029 | 0.0 |

##### Use of scarce resources

In table 4 the standardized scores of the use of scarce resources (using the scores from tables 2, 3, 4, Appendix II) are presented together with the scaled data. Again for the standardization a score of 1.0 indicates that the option uses the least amount of scarce resources (taking into account the scarcity of the used resources). From table 4 it is clear that Thin Film Solar uses the least amount of scarce resources and floating PV the most, but there is not much difference between SolTech and floating PV.

**Table 4 – Scaled data scores and standardized scores for use of scarce resources.**

| | Data (scaled) | Standardized scores |
|---|---|---|
| SolTech | 59.60 | 8.5E-3 |
| Thin Film Solar Cells | 47.93 | 1.0 |
| Floating PV | 59.70 | 0.0 |

##### Production of hazardous waste

In table 5 the scaled data and the standardized scores of the criterion hazardous waste production (using the scores from tables 7, 8, 9, Appendix II) are presented to be able to make a comparison with the other criteria. Again a score of 1.0 indicates that the options uses the least amount of scarce resources (taking into account the toxicity of the used resources).
It can be seen in table 13 that SolTech scores best and Thin Film Solar scores least best for this criterion.

**Table 5 – Scaled data scores and standardized scores for production of hazardous waste.**

| | Data (scaled) | Hazardous waste scores |
|---|---|---|
| SolTech | 81.58 | 1.0 |
| Thin Film Solar Cells | 111.72 | 0.0 |
| Floating PV | 109.57 | 7.1E-2 |

### *2.3.1.2 Weighting*

#### Separate weighting

In table 6 the final ranking can be seen for our own weighed scores and the standardized scores. Overall it can be seen that Thin Film Solar comes out best with a final score of 0.80 and floating PV comes out least best with a final score of 0.02.

**Table 6 - Final ranking of our weighting and standardized scores.**

| | | GHG's | Scarcity | Hazardous | | |
|---|---|---|---|---|---|---|
| Weighted scores | | 0.4 | 0.4 | 0.2 | | |
| Standardized scores | *SolTech* | 0.14 | 8.5E-03 | 1 | | |
| | *Thin film* | 1 | 1 | 0 | | |
| | *Floating* | 0 | 0 | 7.1E-02 | | |
| | | | | | Final scores | Ranking |
| Multiplied | *SolTech* | 0.056 | 3.40E-03 | 0.3 | 0.36 | 2 |
| | *Thin film* | 0.4 | 0.4 | 0 | **0.80** | **1** |
| | *Floating* | 0 | 0 | 2.1E-02 | 0.02 | 3 |

In table 7 the final ranking can be seen for the weighting of ECO-Oostermoer and the standardized scores. Overall it can be seen that Thin Film Solar comes out best with a final score of 0.67 and floating PV comes out least best with a final score of 0.02.

**Table 7 - Final ranking of ECO-Oostermoer their weighting and standardized scores.**

| | | GHG's | Scarcity | Hazardous | | |
|---|---|---|---|---|---|---|
| Weighted scores | | 0.33 | 0.33 | 0.33 | | |
| Standardized scores | *SolTech* | 0.14 | 8.5E-03 | 1 | | |
| | *Thin film* | 1 | 1 | 0 | | |
| | *Floating* | 0 | 0 | 7.1E-02 | | |
| | | | | | Final scores | Ranking |
| Multiplied | *SolTech* | 4.7E-02 | 2.8E-03 | 0.33 | 0.38 | 2 |
| | *Thin film* | 0.33 | 0.33 | 0 | **0.67** | **1** |
| | *Floating* | 0.00 | 0 | 2.4E-02 | 0.02 | 3 |

#### Combined weighting

In table 8 the final ranking can be seen for the compared weightings of ECO-Oostermoer and ourselves and the standardized scores. Overall it can be seen that Thin Film Solar comes out best with a final score of 0.73 and floating PV comes out least best with a final score of 0.02.

Table 8 - Final ranking of combined weightings and standardized scores.

| | | GHG's | Scarcity | Hazardous | Final scores | Ranking |
|---|---|---|---|---|---|---|
| Weighted scores | | 0.37 | 0.37 | 0.32 | | |
| Standardized scores | *SolTech* | 0.14 | 8.5E-03 | 1 | | |
| | *Thin film* | 1 | 1 | 0 | | |
| | *Floating* | 0 | 0 | 7.1E-02 | | |
| Multiplied | *SolTech* | 5.1E-02 | 3.1E-03 | 0.32 | 0.37 | 2 |
| | *Thin film* | 0.37 | 0.37 | 0 | **0.73** | **1** |
| | *Floating* | 0.00 | 0 | 2.2E-02 | 0.02 | 3 |

## 2.3.2 Results Environmental impact per standard object

### *2.3.2.1 SolTech*

As can be seen in table 9, the concentrations of hazardous waste for SolTech are very low compared to the reference values ($HC_{50}$). This means that virtually no harm is done to the environment.

The emission of greenhouse gases is also small compared to the reference value ($CO_2$-equivalent of fossil fuels): the emission of greenhouse gases for SolTech is 3.3% of that of fossil fuels.

Table 9 - Environmental impact of SolTech. The reference values for hazardous waste are the $HC_{50}$ values, the reference value for the emission of greenhouse gases is the $CO_2$-equivalent of fossil fuels.

| | SolTech value | Reference value |
|---|---|---|
| Hazardous waste (mg/kg soil) Zinc | 2.8E-03 | 210 |
| Cadmium | 1.8E-05 | 12 |
| Copper | 3.8E-03 | 60 |
| Emission of GHGs (kg $CO_2$-eq) | 927 | 2.8E04 |

### *2.3.2.2 Thin Film Solar Cells*

From table 10 it can be seen that the concentrations of hazardous waste for Thin Film Solar are almost nothing compared to the reference values ($HC_{50}$). This means that practically no harm is done to the environment. In comparison to the concentrations of SolTech, the concentrations of hazardous waste of Thin Film Solar are about several dozen bigger in order of magnitude.

The emission of greenhouse gases is small as well compared to the reference value ($CO_2$-equivalent of fossil fuels): the emission of greenhouse gases for Thin Film Solar is 2.6% of that of fossil fuels.

Table 10 - Environmental impact of Thin Film Solar. The reference values for hazardous waste are the $HC_{50}$ values, the reference value for the emission of greenhouse gases is the $CO_2$-equivalent of fossil fuels.

| | Thin Film Solar value | Reference value |
|---|---|---|
| Hazardous waste (mg/kg soil) Zinc | 2.9E-01 | 210 |
| Cadmium | 6.0E-03 | 12 |
| Copper | 5.7E-02 | 60 |
| Emission of GHGs (kg $CO_2$-eq) | 795 | 3.1E04 |

### *2.3.2.3 Floating PV*

Table 11 shows that the concentrations of hazardous waste for floating PV pale into insignificance compared to the reference values ($HC_{50}$). This means that hardly any harm is done to the environment. The concentrations are the same order of magnitude as the concentrations for SolTech.

The emission of greenhouse gases is small compared to the reference value ($CO_2$-equivalent of fossil fuels): the emission of greenhouse gases for floating PV is 3.5% of that of fossil fuels.

**Table 11 - Environmental impact of floating PV. The reference values for hazardous waste are the $HC_{50}$ values, the reference value for the emission of greenhouse gases is the $CO_2$-equivalent of fossil fuels.**

| | | Floating PV value | Reference value |
|---|---|---|---|
| Hazardous waste (mg/kg soil) | Zinc | 4.7E-03 | 210 |
| | Cadmium | 3.0E-05 | 12 |
| | Copper | 6.8E-03 | 60 |
| Emission of GHGs (kg $CO_2$-eq) | | 1.4E04 | 4.0E05 |

## 2.4 Discussion

For the MCA and the environmental impact there are some points for discussion. One of them is the covering of environmental performance by the three criteria. It would have been better for the validity of our conclusions about which option performs best, if we would have included more criteria. We did consider doing an LCA (life cycle assessment), but since our commissioner wanted us to look at the technical feasibility too and due to the time scheduled for this project we decided to do an MCA with only three criteria.

Further, the determination of the time to depletion of the different used resources is a point of discussion. Data from different sources has been used and recycling is not taken into account since it was hard to find appropriate data for all resources to be able to compare them. Probably some of the resources are being recycled, so that will influence the environmental impact for the options and for example their scarcity.

Also the list of resources we have used is based on the resources used for Thin Film Solar cells. It would have been better to consider more resources, also from the other options.

Another issue about the determination of the scarcity of the resources was the fact that a fixed scale is used and set to 200 years (see definition of a scarce resource). This 200 years is an estimation of our interpretation of when you can say that a resource is scarce. To get an indication of scarcity we looked at the scarcity of resources from which we knew beforehand that they are scarce: phosphorus and oil. Although phosphorus is used in the solar panels it would have been better to base the 200 years on the scarce resources from which we knew that they were used for the options (e.g. metals), but the scaling was done before we started to look up data about the options because of time limitations, so therefore we based the scaling on these two resources.

For the scaling we wanted to include some kind of sensitivity analysis about how the resource with the highest amount (e.g. silicon) influences the scaling of the other resources and therefore the MCA results for scarcity and hazardous waste production. Due to lack of time we were not able to include this in our research.

We wanted to take into account the production of hazardous waste during the production of the systems (e.g. processing aids) and during waste processing (potential environmental impact of the most common practice of the waste processing of resources used for the materials of the system, e.g. burning or recycling). Since it was hard to find appropriate data for this we decided to assume that the amounts of resources used are also the (toxic) amounts that will end up in the soil after waste processing of the systems. In reality this will probably not be the case, since the materials of the panels may be reused, but we did not consider this.

Also for the MCA we only looked at the toxicity of the resources zinc, copper and cadmium, because we could only find the $HC_{50}$ values for these three resources. To have a more valid result about the toxicity it would have been better to look at more toxic resources, perhaps by using another indicator than the $HC_{50}$ values for which more data is available. Also the $HC_{50}$ value only says something about the toxicity in the (dry) soil, while some resources may be very mobile in the water phase and have toxic effects there.

Another discussion point is the fact that the MCA makes it look like the differences between environmental performance of the options are quite large (e.g. the one with the lowest score performs bad), while in reality (looking at the hard data for each criterion) these differences are quite small and all options perform environmentally well.

The weighting of the three criteria was done by ourselves and ECO-Oostermoer. The original plan was to let the inhabitants weigh them to include the social factor, but there was not enough time to set up a pilot for this. Also the pilot village, Gasselternijveenschemond, was not picked yet when we started our research. To have a more representative weighting we let ECO-Oostermoer weigh the criteria too, even though they are not fully representing the inhabitants.

Least we did a calculation for the environmental impact for the criteria. For the criterion production of hazardous waste we made the assumption that all the hazardous waste would concentrate under one house, 1 meter deep, so we could compare this concentration with the $HC_{50}$ values. This is not very representative since in reality the waste will probably be processed elsewhere and of course not all waste will accumulate in the first layer of 1 m of the ground. So the impact will be even less in reality.

# Conclusion

Based on the outcomes of the environmental impact it can be stated that SolTech, Thin Film Solar and floating PV each can be called a sustainable energy option (instead of an alternative energy option). So all the three options can be implemented in the villages to become more sustainable if the inhabitants are in favour of these options. All three energy options are also technically feasible if we look at the percentages of the energy use, so they can all be recommended for implementation in the area of the Veenkoloniën.

If people favour to choose the most sustainable energy option of these three, then the choice would be Thin Film Solar, since from the MCA with both ways of weighing it can be concluded that Thin Film Solar is the most sustainable option, followed by SolTech and then floating PV. For implementation on houses Thin Film Solar is also the one that is most technically feasible. It produces more energy per standard house than SolTech.

From the production in $kWh/m^2/yr$, which is perhaps the fairest way to compare the three options technically, it can be concluded that floating PV cells are the best solution, since they produce most. These floating PV cells could be implemented in the wijken and then provide households of energy. This does not mean, however, that floating PV and Thin Film Solar will be competitive. Since they are implemented on different places (roofs and wijken) they can be used in a mix and complement each other.

If, however, SolTech is the most favourable choice of an individual or a village committee, then there is no reason not to choose this option. After all, all the three options are environmentally friendly and technically feasible.

# Discussion

In our research we focussed on alternative ways of energy production. The national government's strategy for dealing with the energy problem gives the following preference order (Root, 2013):

1. saving energy and using it more efficiently
2. developing and investing in alternative ways of energy production
3. more efficient use of fossil fuels

In our research focussed on the alternatives. Thereby we skipped the energy saving. Our choice was based on the wish of our commissioner. ECO-Oostermoer was interested in less popular option and already had information on for example insulation. Further, we had been asked to look into technical feasibility in the initial problem description of the course.

Since the implementation if the alternatives is supposed to be a bottom-up process, it appeared important to us to include the preferences of the inhabitants. Our plan was to investigate the three options which the citizens are most interested in. However, it was not possible to consult them in time. Therefore ECO-Oostermoer provided us with their preference and their weighing for the MCA. With this change in methodology we were no longer able to include the social acceptance of the investigated options.

We offered ECO-Oostermoer a list with energy options (Appendix I) to choose from. The three options to be investigated all happened to be solar technologies.  However, the five steps for creating a model and the standard objects can be used for other types of technology as well. The model we created is not applicable for others than solar technologies, because it is based on solar specific data.

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WINDPARK OOSTERMOER. 2012d. *Hoeveel subsidie wordt door de overheid betaald voor de elektriciteit van de windmolens?* [online]. [Accessed 14th of May 2013] Available from: http://www.windpark-oostermoer.nl/veelgestelde-vragen/item/36-hoeveel-subsidie-wordt-door-de-overheid-betaald-voor-de-elektriciteit-van-de-windmolens

WINDUNIE. 2012. *Development* [online]. [Accessed 14th of May]. Available from: http://www.windunie.nl/development

# Appendix I – Lijst van opties Energieplan Aa en Hunze

## Fotovoltaïsche cel

PV-panelen zijn zonnepanelen die zonlicht omzetten in elektriciteit. Het is gebruikelijk om de panelen aan het lichtnet te koppelen waardoor stroom wordt geleverd aan de energieleverancier wanneer de zon schijnt. ’s Nachts kan dan energie worden gebruikt. De gebruikte en opgewekte energie kan met elkaar worden verrekend als de panelen op een woonhuis zijn geplaatst.

Figure 1 - Fotovoltaïc cells. (Burgers et al., 2013)

## Drijvende fotovoltaïsche cel

Deze vorm van PV-panelen wekken energie op op het water. Zonne-energie vanaf het wateroppervlak brengt veel voordelen met zich mee. Zo is er relatief veel ruimte, kan oppervlaktewater gebruikt worden voor de koeling van de zonnepanelen en kunnen de panelen met de zon mee bewegen.

Figure 2 - Drijvende fotovoltaïsche cel (Burgers et al., 2013)

## Thin film Sci Solar cells

Een ‘thin film Sci Solar cell’ is een zonnecel die wordt gemaakt door het afzetten van een of meerdere dunne lagen van fotovoltaïsch materiaal op een substraat (fotovoltaïsch houdt in dat het (zon)licht direct wordt omgezet in elektriciteit).
Worden in het buitenland al gebruikt (USA, Japan), maar voornamelijk op grote schaal. Zijn ook toepasbaar op lokale schaal (daken etc.).

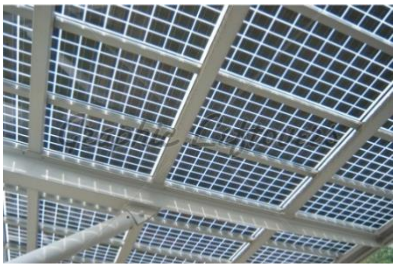


Figure 3 - Thin Film Solar cell. http://en.wikipedia.org/wiki/Thin_film_solar_cell

Verschil met PV: Lichter van gewicht, worden niet beïnvloed door de wind, hogere kosten en lagere efficiëntie.

**Figure 4 - Thin Film Solar cell.** http://science.howstuffworks.com/environmental/green-science/thin-film-solar-cell2.htm

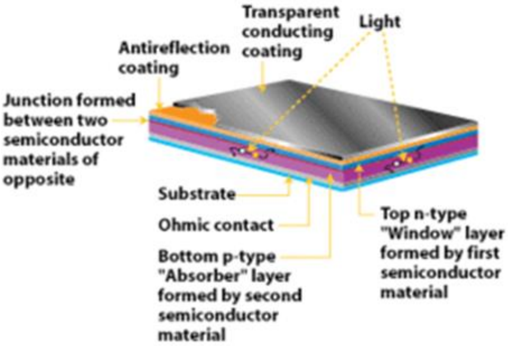



**Figure 5 - Thin Film Solar cell.** http://link.springer.com/content/pdf/10.1007%2Fs10854-007-9177-9.pdf

## V3 solar

Het Amerikaanse concept V3 solar heeft bestaande technieken gecombineerd tot een nieuw soort zonnecollector. Door deze nieuwe techniek haalt de V3 een veel hoger rendement dan conventionele zonnecellen. V3 is echter nog niet op de markt dus de techniek heeft zich in die zin nog niet bewezen, hoewel het veelbelovend is. In 2014 komt V3 op de markt.

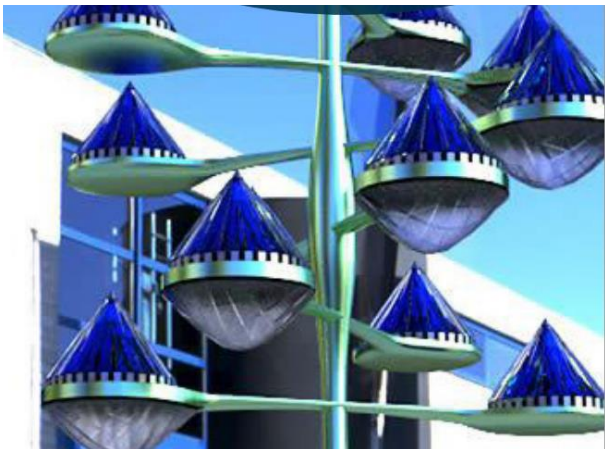


**Figure 6 – V3 Solar (Burgers et al., 2013)**

## SolTech

Het SolTech systeem is een systeem dat op een geïntegreerde manier zonlicht doorlaat en energie opwekt. In plaats van traditionele dakbedekking, wordt er glas gebruikt. Hierdoor kan zonlicht binnentreden en wordt de warmte gebruikt om energie op te wekken. Het systeem werkt ook op dagen dat er minder licht is.

**Figure 7 - SolTech. (Burgers et al., 2013)**

## Zonneboiler

Een zonneboiler is de combinatie van een warmwaterboiler met een zonnecollector. Het is dus een aanvulling op de bestaande verwarmingsketel en kan alleen gebruikt worden voor het verwarmen van tapwater, niet het verwarmen van de woning. Dit laatste kan wel bereikt worden met een zonneboilercombi, maar dan moet dus de bestaande verwarmingsketel vervangen worden.

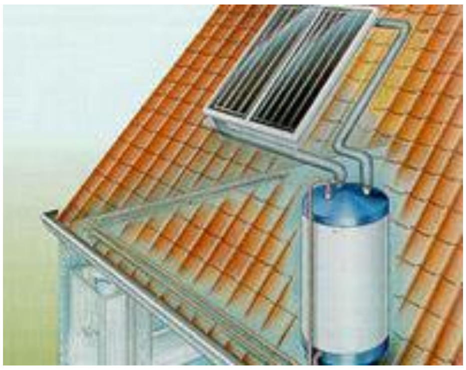


**Figure 8 - Zonneboiler.** http://www.milieucentraal.nl/themas/energie-besparen/energiezuinig-verwarmen-en-warm-water/nieuwe-cv-of-combiketel-kopen/zonneboiler

Meer informatie: http://www.milieucentraal.nl/themas/energie-besparen/energiezuinig-verwarmen-en-warm-water/nieuwe-cv-of-combiketel-kopen/zonneboiler

## Warmtepomp

Een warmtepomp werkt in principe als een koelkast: je verwarmt lucht of water binnen het gebouw en de buitenlucht wordt "gekoeld" door warmte van buiten naar binnen te verplaatsen (het kan ook bij –graden). Ten opzichten van verwarmen met gas levert deze techniek nauwelijks economische voordelen (natuurlijk hangt dat van de grootte van het huis, de gewenste temperatuur en de mate van isolatie af). Als in de regio voornamelijk met gas verwarmd wordt dan lijkt ons deze optie niet waard  verder te onderzoeken. Anders is het wel goed om daarnaar te kijken omdat het per huis geïnstalleerd kan worden en omdat het makkelijk in staat te houden is.

**Figure 9 – Warmtepomp.** http://www.aaaheatingac.com/how-air-source-heat-pumps-work/

Meer informatie:
http://energy.gov/energysaver/articles/air-source-heat-pumps
http://www.which.co.uk/energy/creating-an-energy-saving-home/guides/air-source-heat-pumps-explained/

## Micro-WKK

Micro WarmteKrachtKoppelings installaties, ook wel HRe-ketels, zijn ter vervanging van de bestaande verwarmingsketel. Ze produceren elektriciteit en warmte met een input van aardgas. Het voordeel van micro-WKK's is dat ze de warmte die in principe een reststroom is op een efficiënte manier inzetten voor de verwarming. Deze decentrale energieopwekking is praktischer, omdat het voor grote elektriciteitscentrales moeilijker is de restwarmte te gebruiken.
De micro-WKK is efficiënter dan een normale CV- of HR-ketel. Er wordt daardoor zowel op de elektriciteits- als gasrekening bespaard.

Leverancier NL: http://www.remeha.nl/

***Figure 10 – Micro-WKK.*** *http://www.remeha.nl/intelligentenergy/index.php/remeha_evita_hre_ketel/*

## Isolatie

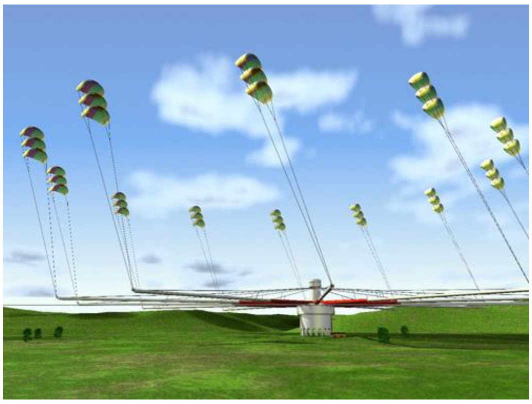
Isoleren helpt om het energieverbruik terug te dringen. Wanneer een gebouw goed is geisoleerd levert dit veel op in energiereductie en comfort, in die zin is het een van de meest rendabele vormen van energiebesparing. Bijkomende voordelen naast energiebesparing en comfort zijn dat isoleren in bijna elke woning financieel rendabel is, veel werkgelegenheid geeft op lokale schaal en niet gelijk zichtbaar is.

*Informatie van VHL*

## Kitepower

KiteGen ® is een nieuwe manier van windenergie productie. De belangrijkste innovatie is dat KiteGen over een onbenutte en vrijwel eindeloos energie vermogen kan benutten: wind op grote hoogte. Hierdoor kan er veel energie geproduceerd worden dan met conventionele windmolens. De grootte van het systeem is variabel. Power kites geven weinig tot geen schaduw. Het geluid van het deel in de lucht is verwaarloosbaar, het geluid van het systeem op de grond kan worden vergeleken met een spoorweg voor lage snelheden met goede geluidsisolatie (50 dB op 200m afstand).

*Meer informatie:* www.kitegen.com/en



# Appendix II – Tables, figures and calculations for environmental performance

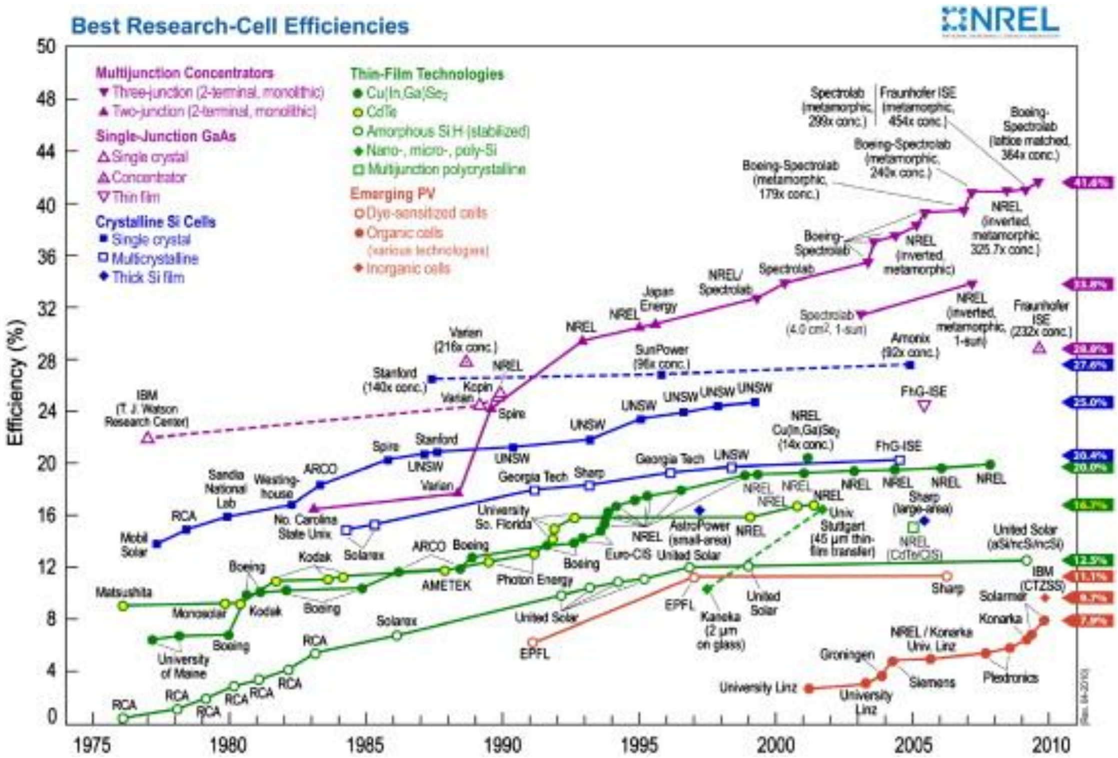



Figure 8 - Cell efficiencies of different solar energy technologies, including the different thin film types (Coby, 2011)

## Calculation of results MCA

### Emission of greenhouse gases

Table 1 –Data for emission of greenhouse gases expressed in $CO_2$ equivalents for all three alternatives

| | SolTech[11] | Thin Film Solar cells[12] | Floating PV[13] |
|---|---|---|---|
| Average solar radiation ($kWh/m^2/yr$) | 1700 | 1700 | 1700 |
| $CO_2$- equivalent (kg $CO_2$-eq/ kWh) | 0.028 | 0.022 | 0.029 |

### Use of scarce resources

In figure 2 the scale of the scarcity of resources is presented. This scale is used for all three options since we have looked at the same used resources and has a step size of 200/9 = 22.2. For each option we made separate scales for the used amounts of these resources.

11 Data from Peng, 2011
12 Data from de Wild-Scholten, 2010
Data from Enel Group, 2012
13 Data from Peng, 2011

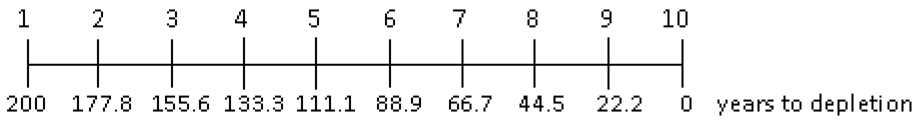



Figure 2 - Scaling of scarcity for used resources.

### *Data*

### *SolTech*

In figure 3 the scale of the amount of resources for SolTech can be seen. The step size is 3.4E-6 / 9 = 3.8E-7.

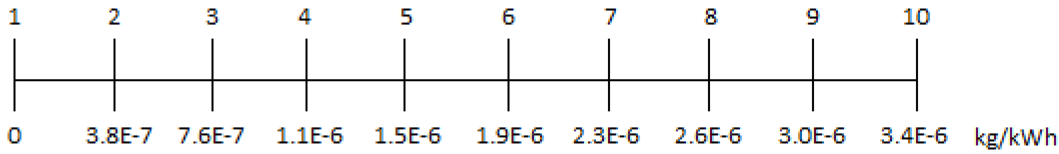



Figure 3 - Scaling of amount of scarce resources. (SolTech)

In table 2 the final scarcity score for SolTech is presented together with the scale factors, amounts and years to depletion.

Table 2 - Calculation of scores (use of scarce resource, SolTech)

| Resource | Amount used (kg/kWh)[14] | Scale factor amount | Depleted (years) [15] | Scale factor depleted | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| Bauxite | 1.4E-07 | 1.37 | 60 | 7.30 | 10.00 |
| Zinc | 4.8E-09 | 1.01 | 100 | 5.50 | 5.56 |
| Cadmium | 3.0E-11 | 1.00 | 200 | 1.00 | 1.00 |
| Copper | 6.5E-09 | 1.02 | 60 | 7.30 | 7.45 |
| Indium | 3.9E-11 | 1.00 | 30 | 8.65 | 8.65 |
| Gallium | 4.2E-14 | 1.00 | 25 | 8.88 | 8.88 |
| Selenium | 1.4E-07 | 1.37 | >200 | 1.00 | 1.37 |
| Silicon (mono) | 3.4E-06 | 10.00 | >200 | 1.00 | 10.0 |
| Phosphorus | 5.5E-09 | 1.01 | 75 | 6.62 | 6.69 |
| | | | | **Total:** | **59.60** |

[14] Data from Potting, 2013

[15] Data from Roper, 2013
Data from Coby, 2011
Data from Guineé 2001
Data from Cordell, 2009
Data from Vidal, 2005

### *Thin Film Solar*

In figure 4 the scale of the amount of resources for Thin Film Solar can be seen. The step size is 5.6E-5 / 9 = 6.2E-6.

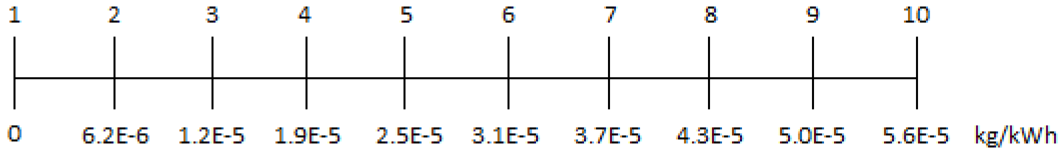



Figure 4 - Scaling of amount of scarce resources. (Thin Film Solar cells)

In table 3 the final scarcity score for Thin Film Solar is presented together with the scale factors, amounts and years to depletion.

Table 3 - Calculation of scores (use of scarce resource, Thin Film Solar)

| Resource | Amount used (kg/kWh)[16] | Scale factor amount | Depleted (years) | Scale factor depleted | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| Bauxite | 5.6E-05 | 10.00 | 60 | 7.30 | 7.30 |
| Zinc | 4.5E-07 | 1.07 | ±100 | 5.50 | 5.89 |
| Cadmium | 9.4E-09 | 1.00 | ±200 | 1.00 | 1.00 |
| Copper | 8.9E-08 | 1.01 | ±60 | 7.30 | 7.37 |
| Indium | 1.4E-07 | 1.02 | ±30 | 8.65 | 8.83 |
| Gallium | 2.6E-08 | 1.00 | ±25 | 8.88 | 8.88 |
| Selenium | 2.4E-07 | 1.04 | >200 | 1.00 | 1.04 |
| Silicon (mono) | 2.7E-10 | 1.00 | >200 | 1.00 | 1.00 |
| Phosphorus | 3.5E-11 | 1.00 | 75 | 6.62 | 6.62 |
| | | | | **Total:** | **47.93** |

### *Floating PV*

In figure 5 the scale of the amount of resources for floating PV can be seen. The step size is 2.4E6 / 9 = 2.7E-7.

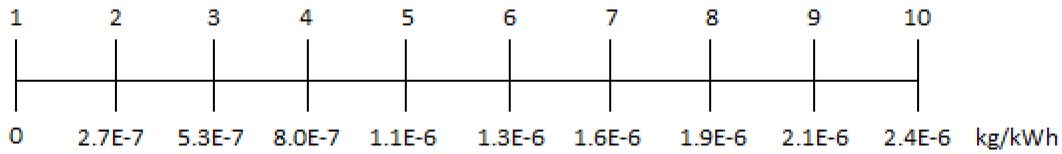



Figure 5 - Scaling of amount scarce resources. (floating PV)

[16] Data from Andersson, 1998
Data from Potting, 2013
Data from European Aluminium Association, 2009

In table 4 the final scarcity score for floating PV is presented together with the scale factors, amounts and years to depletion.

**Table 4 - Calculation of scores (use of scarce resource, floating PV)**

| Resource | Amount used (kg/kWh)[17] | Scale factor amount | Depleted (years) | Scale factor depleted | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| **Bauxite** | 1.0E-07 | 1.37 | 60 | 7.30 | 10.0 |
| **Zinc** | 3.6E-09 | 1.01 | ±100 | 5.50 | 5.56 |
| **Cadmium** | 2.3E-11 | 1.00 | ±200 | 1.00 | 1.00 |
| **Copper** | 5.2E-09 | 1.02 | ±60 | 7.30 | 7.45 |
| **Indium** | 2.85E-11 | 1.00 | ±30 | 8.65 | 8.65 |
| **Gallium** | 4.7E-14 | 1.00 | ±25 | 8.88 | 8.88 |
| **Selenium** | 1.1E-07 | 1.41 | >200 | 1.00 | 1.41 |
| **Silicon (mono)** | 2.4E-06 | 10.00 | >200 | 1.00 | 10.0 |
| **Phosphorus** | 4.8E-09 | 1.02 | 75 | 6.62 | 6.75 |
| | | | | **Total:** | **59.70** |

## Final scores

In table 6 the standardized scores (using the scores from table 2, 3, 4) are to be able to make a comparison with the other criteria. Again a score of 1.0 indicates that the options uses the least amount of scarce resources (taking into account the scarcity of the used resources).

**Table 6 - Overview of standardized scarcity scores.**

| | Data (scaled) | Standardized scores |
|---|---|---|
| **SolTech** | 59.60 | 8.5E-3 |
| **Thin Film Solar cells** | 47.93 | 1.0 |
| **Floating PV** | 59.70 | 0.0 |

### *Production of hazardous waste*

In figure 6 the scale of the toxicity (expressed as the $HC_{50}$ value) is presented. This scale is used for all three options since we have looked at the same used toxic compounds and has a step size of 210/9 = 23.3. For each option we made separate scales for the used amounts of these toxic compounds.

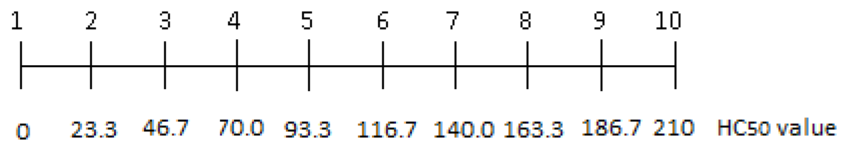



**Figure 6 - Scaling of $HC_{50}$ values.**

[17] Data from Potting, 2013

## SolTech

In figure 7 the scale of the amount of hazardous waste for SolTech can be seen. The step size is 6.5E-09 / 9= 7.2E-10.

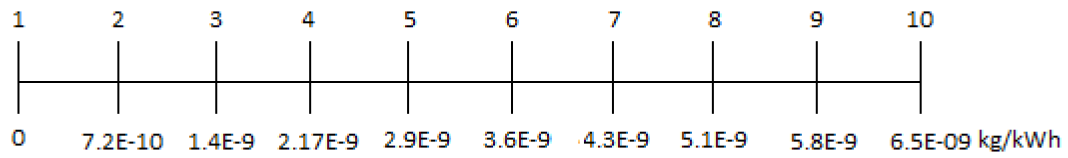



**Figure 7 - Scaling of amount hazardous waste. (SolTech)**

In table 7 the final hazardous score for SolTech is presented together with the scale factors, amounts and $HC_{50}$ values.

**Table 7 - Hazardous waste production and $HC_{50}$ values. (SolTech)**

| Resource | Amount (kg/kWh) | Scale factor amount | $HC_{50}$ value (mg component/kg dry soil) | Scale factor waste | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| **Zinc** | 4.8E-09 | 7.65 | 210 | 10.00 | 76.50 |
| **Cadmium** | 3.0E-11 | 1.00 | 12 | 1.51 | 1.51 |
| **Copper** | 6.5E-09 | 10.00 | 60 | 3.57 | 3.57 |
| | | | | **Total:** | **81.58** |

## Thin Film Solar cells

In figure 8 the scale of the amount of hazardous waste for Thin Film Solar can be seen. The step size is 4.5E-7 / 9 = 5.0E-8.

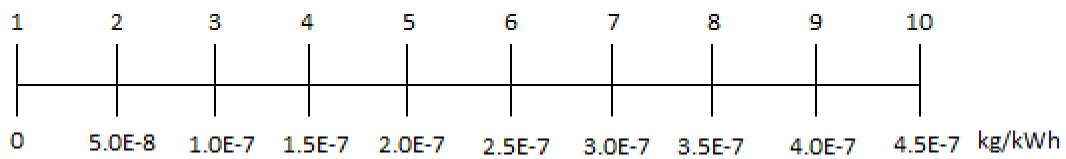



**Figure 8 - Scaling of amount hazardous waste. (Thin Film Solar cells)**

In table 8 the final hazardous score for Thin Film Solar is presented together with the scale factors, amounts and $HC_{50}$ values.

Table 8 - Hazardous waste production and $HC_{50}$ values. (Thin Film Solar cells)

| Resource | Amount (kg/kWh) | Scale factor amount | HC50 value (mg component/kg dry soil) | Scale factor waste | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| Zinc | 4.5E-07 | 10.00 | 210 | 10.00 | 100.00 |
| Cadmium | 9.4E-09 | 1.19 | 12 | 1.51 | 1.80 |
| Copper | 8.9E-08 | 2.78 | 60 | 3.57 | 9.92 |
| | | | | **Total:** | **111.72** |

## Floating PV

In figure 9 the scale of the amount of hazardous waste for floating PV can be seen. The step size is 5.2E-09 / 9 = 5.8E-10

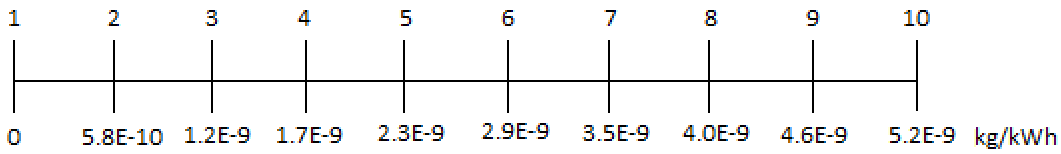



Figure 9 - Scaling of amount hazardous waste. (floating PV)

In table 9 the final hazardous score for floating PV is presented together with the scale factors, amounts and $HC_{50}$ values.

Table 3 - Hazardous waste production and $HC_{50}$ values. (floating PV)

| Resource | Amount (kg/kWh) | Scale factor waste | $HC_{50}$ value (mg component/kg dry soil) | Scale factor waste | Score (scale factors multiplied) |
|---|---|---|---|---|---|
| Zinc | 3.6E-09 | 7.23 | 210 | 10.00 | 72.30 |
| Cadmium | 2.3E-11 | 1.04 | 12 | 1.51 | 1.57 |
| Copper | 5.2E-09 | 10.00 | 60 | 3.57 | 35.70 |
| | | | | **Total:** | **109.57** |

## Final scores

In table 10 an overview of the hazardous scores is presented. Here it can be seen that SolTech performs best for the criterion and Thin Film Solar performs least best.

Table 40 - Overview of final hazardous waste scores

| | Hazardous waste scores |
|---|---|
| SolTech | 81.58 |
| Thin Film Solar cells | 111.72 |
| Floating PV | 109.57 |

### *Standardization*

In table 11 the standardized scores (using the scores from table 12) are calculated to be able to make a comparison with the other criteria. Again a score of 1.0 indicates that the options uses the least amount of scarce resources (taking into account the toxicity of the used resources).

**Table 5 - Overview of standardized hazardous waste scores.**

| | Data (scaled) | Hazardous waste scores |
|---|---|---|
| **SolTech** | 81.58 | 1.0 |
| **Thin Film Solar cells** | 111.72 | 0.0 |
| **Floating PV** | 109.57 | 7.1E-2 |

## Disclaimer

This paper is the result of the work of a student-group working with a course given by the department of Environmental Technology, WUR. However, the paper does not purport to represent the views or the official policy of any member of the department of Environmental Technology and/or the WUR.

Due to strong competition in the solar panel branch many companies producing solar panels go bankrupt and their websites are being taken offline. We are not responsible for parts of our literature list not being available anymore due to this phenomenon, or any other reason.