Decommissioning, recycling and reuse of solar farms

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1 INTRODUCTION

As part of the energy transition solar farms are built all around the world and in the last five years there has been a growth of the number of solar farms in the Netherlands. Albeit the clear purpose of solar farms, the society and governmental organisations remain with questions regarding the environmental impact of solar farms. This report addresses several topics where these questions are present. The topics discussed consider leaching of materials into the environment, decommissioning and removal of a solar farm, and recycling and reuse.

In the next chapter an overview is provided of the components and materials of a solar farm. Solar modules are described next to the other components of a solar farm which is referred to as the balance of system (BoS). For a typical solar farm of 8 MWp a bill of materials (BoM) is drafted including number of components and their weight. This will be input for an assessment of the environmental impact in CO_2 equivalents.

In Chapter 3 we assess the potential leaching of harmful materials into the environment by solar farms, including the differences in material impact and the mitigation options against leaching.

Chapter 4 continues with a description of the common steps and activities for decommissioning, including expected machinery required and number of workers present per MWp of installed capacity. Decommissioning activities include disconnection, excavation (cable), dismantling, fencing removal, site clean-up. Finally, conditions and methods to restore the land back into its original state are discussed.

An assessment of CO_2 impact related to an 8 MWp solar farm case study is conducted using a combination of literature, market knowledge and Environmental Product Declarations (EPDs) in chapter 5. EPDs are International Organization for Standardization (ISO) certificates of a specific product which determine the environmental impact of its life cycle. A Life Cycle Assessment (LCA) is at the basis of the EPDs.

Recycling and reuse are treated in Chapter 6. An assessment is made of the different carbon scores of a reuse option or a recycling option of solar farms.

2 COMPONENTS AND MATERIALS

This chapter provides a short overview of the components and materials used in a solar farm in order to facilitate the assessment of decommissioning and recycling of solar farms. A solar farm can be designed according to a few different topologies which basically all contain similar components and materials. A solar farm typically contains the following main components:

- Mounting structures and foundations
- Solar modules
- Cabling and combiner boxes
- Inverters
- Transformers
- Switchgear
- Fences, access gates and internal roads
- Other components: monitoring and control, security system, buildings

Figure 1 and Figure 2 provide a graphic and schematic overview of the electrical components of a solar farm.

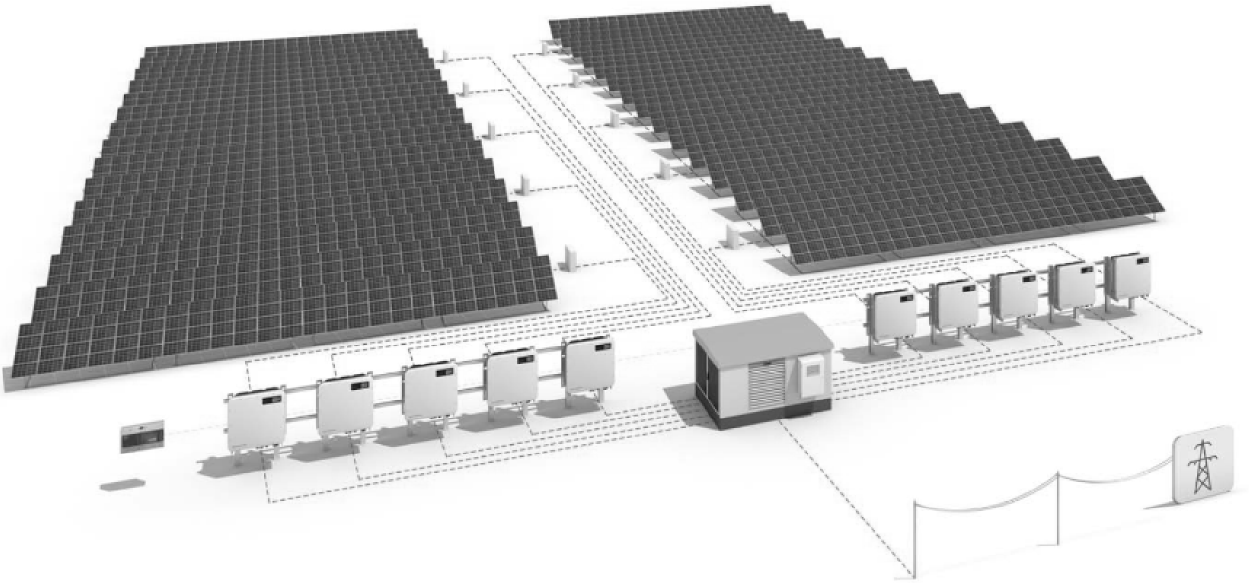


Figure 1. Graphic overview of the electrical components of a solar farm. Source: SMA /1/

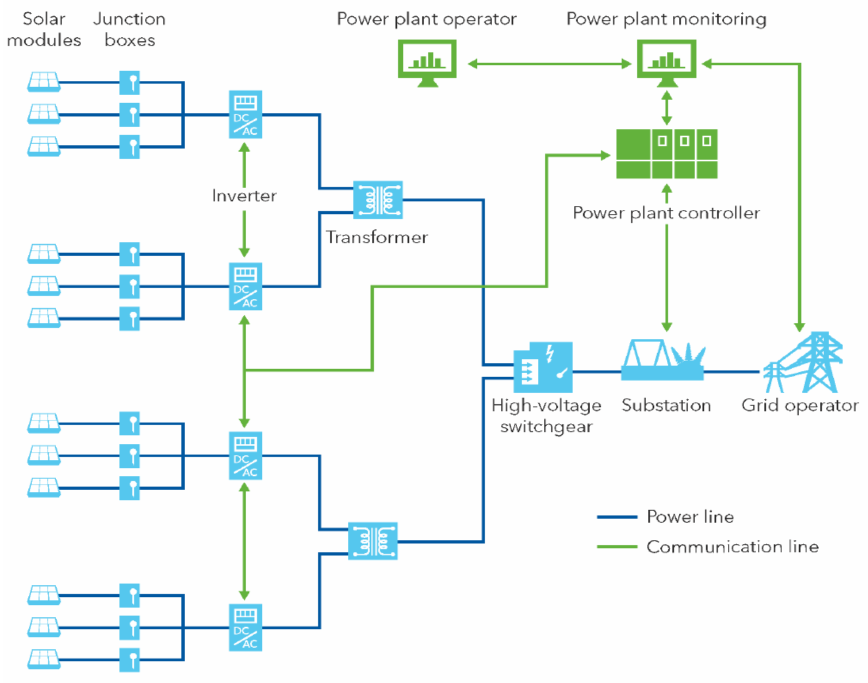


Figure 2. Schematic overview of the electrical components of a solar farm. Source: DNV /2/

2.1 Solar modules

In most of today's ground-mounted solar farms, solar modules with crystalline silicon PV technology are used. A distinction is made between monocrystalline and polycrystalline (also known as multi crystalline) technology, see Figure 3. Primary differences between these types are their cost and efficiency. For this study monocrystalline modules are assumed to be used as these are Statkraft's preferred choice based on aesthetics and the balance between costs and efficiency.

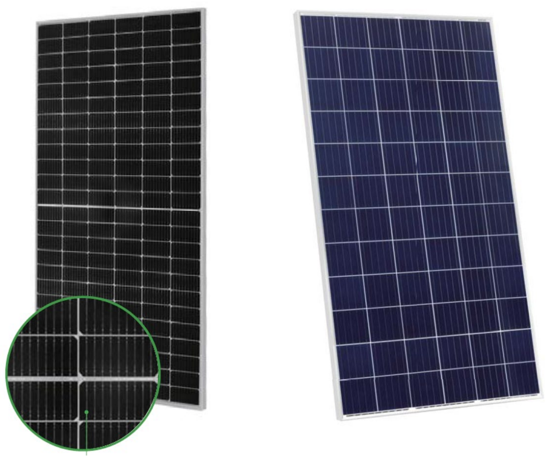


Figure 3. Pictures of a monocrystalline (left) and polycrystalline (right) solar module. The round corners of the monocrystalline cell show that the monocrystalline cells are made from monocrystalline wafers. In the monocrystalline module 'half cut cell' technology is applied. Source: Jinko Solar /3/ /4/.

Monocrystalline technology

Monocrystalline solar modules have a uniform crystal structure across the entire panel PV cell. They have a higher efficiency rating compared to polycrystalline technology and perform better than other types of modules in low-light conditions. The efficiency also decreases more slowly over time. Monocrystalline PV cells are produced from silicon ingots and wafers and are relatively expensive to manufacture. Monocrystalline modules have the highest initial cost; however, the higher energy production over time make the cost worthwhile.

Polycrystalline technology

Polycrystalline silicon solar modules have a speckled blue color that varies in shade with different areas of the module. As they are not made of silicon ingots and wafers but from solidified silicon, the crystal structure in these modules is not homogenous, which means that the crystal structure is different in various areas of the PV cell. As a result, polycrystalline solar modules are less efficient than monocrystalline ones. They are less efficient at their operating temperature due to their larger temperature coefficient compared to monocrystalline solar modules. Due to the reduced power conversion efficiency, a greater number of modules are required to generate the same power. Polycrystalline silicon solar modules are less expensive than monocrystalline silicon solar modules which can make them economically attractive in projects.

2.2 Balance of system

In a solar farm, all components apart from the modules are referred to as the balance of system (BoS). These system components consist mainly of glass, steel, aluminum, plastics, copper, concrete and wood. Figure 4 provides an overview of the materials breakdown of a typical 8 MWp solar farm. The cumulative weight of this typical solar farm is about 1250 tons. Internal roads are not included in the figure as their application differ greatly per solar farm (concrete roads, gravel roads, sand roads or no roads may be permitted). Further details are provided in Chapter 5.

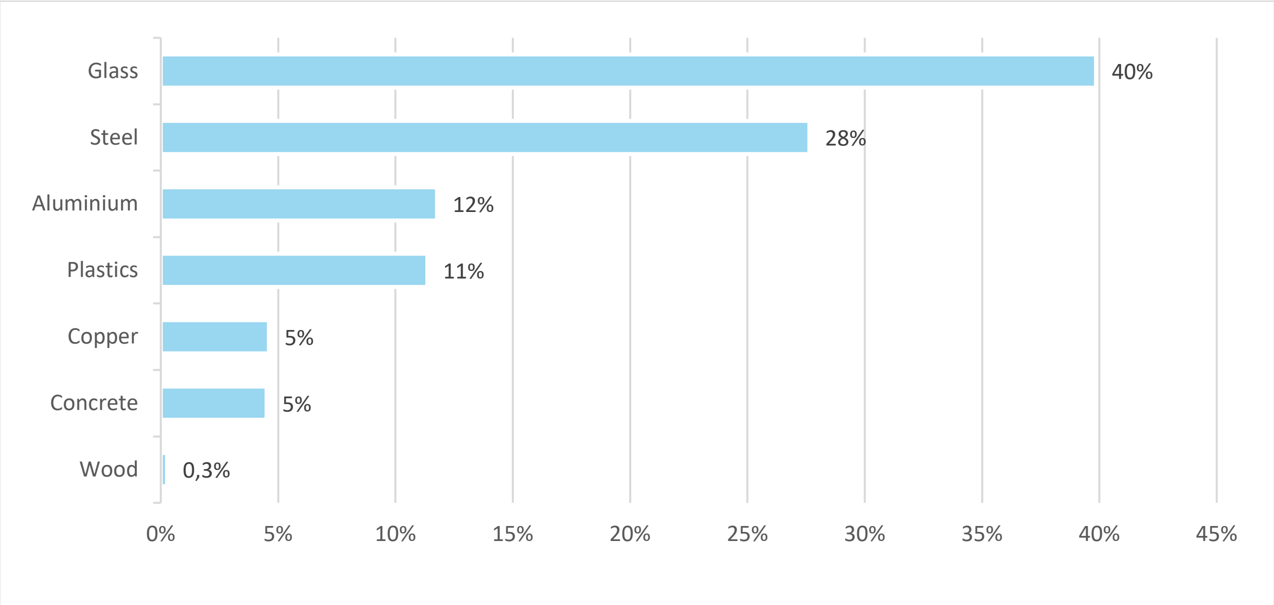


Figure 4. Materials mass breakdown for a typical 8 MWp solar farm (excluding internal roads).

3 LEACHING INTO THE ENVIRONMENT

This section discusses the risk of pollution of the soil and the environment, with glass, polymers and/or metals, as well as the mitigating actions that can prevent any leaching. It can be concluded that the risk of leaching is neglectable and may only occur under specific circumstances which are not expected.

3.1 Solar modules

Figure 5 shows the main components of a typical silicon monocrystalline solar module. The basic solar module construction has not changed much over the years. Most solar modules are made up of a series of silicon crystalline cells sandwiched between a front glass plate and a rear polymer plastic back-sheet or glass plate, often supported by an aluminium frame. Recently the 'half cut cell' technology was introduced. Here all cells are cut in half, which changes the appearance of the cells in the module slightly, see also Figure 3.

Although no specific number is known, it can be assumed that up to 5% of the solar modules require replacement during the lifetime of 25 years. The share of physically broken panels however is smaller as often modules are replaced due to defects ascribed to delamination and cracked cell isolation in which case exposure to the environment is often limited.

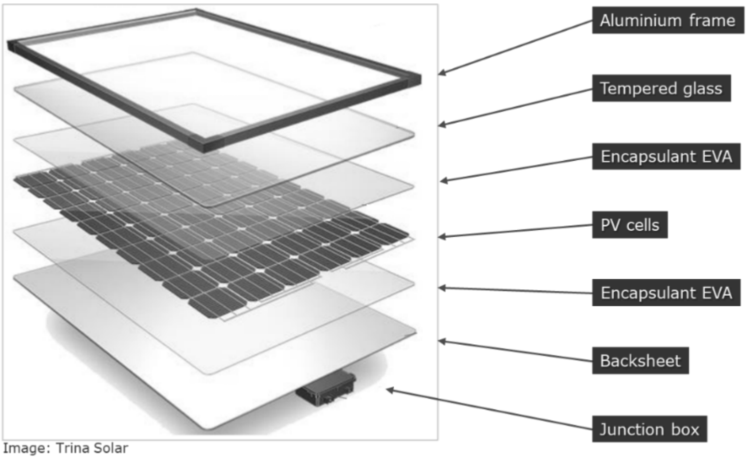


Image: Trina Solar

Figure 5. Main components of a solar module. Source: Trina Solar, adapted from /5/

Studies on the leaching of solar modules have shown that leaching does not occur when the modules are intact. Leaching however can occur when modules are crushed and disposed over longer periods of time (e.g. in landfills) /7/. Laboratory tests showed that if pieces (5x5 cm) of crystalline Si modules were put in water-based solutions for a period of 18 months, after 8 days the first traces of metals could be detected within the water solutions /8/. After 18 months, under normal environmental circumstances (pH 7), these metals remained below the tolerable limit. Results also showed that the highest contaminating values occurred in more acidic environments (e.g. pH 3) and when the modules were delaminated. Those circumstances do not occur in a normal outdoor environment.

DNV concludes therefore, that the risk of leaching of (harmful) substances into the environment from crystalline silicon solar modules, under outdoors environmental conditions, is very low. Even though the modules contain certain harmful materials, they are not expected to be released into the environment when the modules are intact. In case solar modules are damaged, automated alarms will be triggered and defect solar modules will be replaced. Monitoring and replacement of broken modules will ensure that no leaching occurs in case of severe damage to the modules.

3.2 Balance of system

The other components of a solar farm can also be expected to have very little risk of leaching of materials into the environment. All components and materials used contain standardised materials applied throughout electrical installations in many industries. The following materials could possibly be a source for leaching if not considered according to industry best practice:

- PVC is used as insulator around cables. PVC can be susceptible to leaching, but this depends on the type of plasticizer used. Plasticizers like DOP are not allowed anymore. PVC is used in many applications (e.g. water proofing layers) and can be considered safe to use.
- Zinc coating is generally applied on support structures of solar farms. The amounts used are very limited and leaching is not expected and if any will be very limited and of short duration.
- Copper is used in cables and is a material that can be susceptible to leaching. Still leaching is not expected as the copper cables are protected by a cover which should be intact during the lifetime of the project. At the end-of-life the copper cables will be removed from the project location.

4 DECOMMISSIONING AND REMOVAL

In the following section the steps and the resources required for decommissioning and removal of a solar farm are explained. The European Community Directive on Waste Electrical and Electronic Equipment (WEEE) represents the first example worldwide of regulation on solar waste. This directive pushes for higher resource efficiency in recycling and better design-for-recycling for new modules.

4.1 Decommissioning

Decommissioning will start soon after the end of the project's operating life (assumed to be 25 years for purposes of this study), and all decommissioning work is performed in generally conducive weather conditions. DNV expects that the decommissioning of an 8 MWp solar farm can be done in 2-3 months. Decommissioning includes the full removal of modules, support system, piles, cabling, electrical components and buildings, roads, and any other associated facilities.

Table 1. Typical activities to be conducted for decommissioning of a solar farm.

Decommissioning item	Decommissioning considerations
Solar modules	Dismantling and collection by a recycling/ treatment facility.
Aboveground electrical cables	Dismantling and collection high voltage cable, low voltage AC cable, earthing copper, DC cable, communications cable.
Underground electrical cables	Majority of the cabling onsite is trenched, and hence excavation is required. Scrap metal could be resold.
Structures	Disassembly and removal of support posts and racking system
Inverters, switchgear and transformers.	Disconnection and removal of each item. Electronic waste will need to be disposed of/recycled responsibly and in accordance with relevant current regulations. Salvage costs are considered unlikely. Any hazardous substances will need to be disposed of safely. Transformers typically have a life >25 years, and hence resale of equipment may be possible.
Concrete blocks (transformers, inverters)	Excavation of concrete pads Concrete to be crushed and recycled as granular material.
CCTV system	Dismantling and removal of cameras, power cable, communication cable. CCTV cameras mounted on freestanding poles next to the boundary fence. Cables are trenched and require excavation. Scrap metal from cables could be resold. Electronic waste from CCTV system will need to be disposed of/recycled responsibly.
Fences and gates	Fences and gates to be removed and recycled. Recycling of wooden posts and scrap metal meshed fence.

4.2 Land restoration

A permit requirement may be that the project location shall be reinstated into the original state as it was prior to the solar farm. Permit conditions may apply to vegetation types, soil quality and rainwater run-off trenches, which may be due for discharge by the competent authority. All project roads and laydown area may be removed and reclaimed.

A benchmark measurement study shall be performed before the project was granted an environmental permit, to later confirm that the original land qualities have been restored after decommissioning.

Table 2 describes items and considerations with respect to land restoration.

Table 2. Typical activities to be conducted for land restoration of a solar farm

Land restoration item	Land restoration considerations
Underground materials	Excavation and removal of all underground materials.
Aboveground materials	Collect and dispose of waste left throughout the site during the decommissioning process.
Leave no trace – principle	Collect and dispose of waste left throughout the site during the decommissioning process.
Land reinstatement	Seeding or planting vegetation according to permit requirements
Biodiversity land survey	Species diversity measurement after decommissioning is completed.

5 ASSESSMENT OF CARBON IMPACT: 8 MWP SOLAR FARM

DNV has assessed the carbon impact of a typical 8 MWp solar farm in the Netherlands. A combination of EPDs, literature review, LCA software and expert knowledge have led to the calculation of the carbon impact. The input values are based on the expected BoM for the total of all main solar farm components. The values are provided in Table 3. DNV recognises that the values of the complex components (e.g. switchgears and inverters) contain a relative high uncertainty as assumptions were made on the type of components, their weight, and their mass breakdown. We have assessed the carbon impact of the main components, which weigh more than 1% of the total weight of the solar farm, with the exception of the inverter which weighs less than 1% of the total weight of the solar farm but inverters are considered key components of a solar farm. The carbon impact is an indicative number as no full LCA was performed. Additionally, for some components not the full life cycle is assessed in terms of carbon impact as some information was missing. Per component in section 5.2 DNV has indicated the scope of carbon impact in terms of life cycle stages and uncertainties. In this chapter the methods used for the carbon impact assessment, the components, and the carbon impact of the components are discussed.

5.1 Sources of information

The following sections describe the sources of information that were used.

5.1.1 Environmental Product Declarations

EPDs are reports which describes how a product is made, the materials needed to produce the product and the environmental impact of its life cycle. EPDs are based on international ISO standards (e.g. ISO 14044, ISO 14025 and ISO 21930). EPDs can be verified by independent organisations. The basis of an EPD is an LCA.

5.1.2 Literature review

Scientific articles are used as a basis for the report. DNV has conducted literature research on topics such as LCAs for solar farm and its components, carbon impact of a solar farm, recycling and reuse stages, and the carbon impact of other energy producing units as a reference (e.g. coal plant, nuclear plant).

5.1.3 Life Cycle Assessments

An LCA can be used to determine the expected environmental impact of an 8 MWp solar farm, based on ISO-14040 and ISO-14067 for greenhouse gas (GHG) emission modelling. An LCA is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. This assessment can include the Global Warming Potential (GWP), ozone depletion and water consumption. SimaPro is the world’s leading LCA software and is compliant with ISO 14040 for LCAs and ISO 14067 for GHG emission modelling. SimaPro uses scientific databases for emission factors such as EcoInvent or the European Life Cycle Database. For the purpose of this study, the GWP is used.

5.1.4 Expert knowledge

Expert knowledge has been used throughout the report to fill in gaps of information which could not be provided by other sources of information or in making decisions in how to use available information. An example is the expert input regarding listing the bill of materials of an 8 MWp solar farm in the Netherlands. It has enabled determining the items relevant for the carbon impact assessment.

Table 3. High-level breakdown of materials used in a typical 8 MWp solar farm.

Category	Unit	Quantity	Unit weight from datasheet [kg]	Weight [tons]	%Aluminum	%Steel	%Glass	%Copper	%Plastic	%Wood	%Concrete
PV Modules	pc.	20,000	22	440	15%		67%	3%	15%		
Inverters	pc.	3	3400	10.2	10%	60%		10%	10%		10%
Transformers	pc.	3	4500	13.5	15%	75%			10%		
Switchgears	pc.	3	1500	4.5		80%		10%	10%		
Support & mounting structures	pc.	mix	mix	185		100%					
String boxes	pc.	50	25	1.25		40%		20%	40%		
Cables	m	135,000	0.3	40.5	45%			45%	10%		
Connectors	pc.	4,000	0.1	0.4				30%	70%		
Ducts	m	10,000	1	10					100%		
Earthing	m	1,000	1	1				100%			
Monitoring system	pc.	1	750	0.75	10%	10%		10%	10%		60%
Security system	pc.	1	2000	2	10%	10%		10%	10%		60%
Fences - 3 m height	m^2	3,000	1.67	5.01		50%			10%	40%	
Other buildings	pc.	3	10800	32.4		3%					97%
Total for 8 MWp equivalent				**747**	**11.7%**	**28.0%**	**39.5%**	**4.6%**	**11.3%**	**0.3%**	**4.6%**

*** Materials for internal roads in solar farms are excluded from the percentage breakdown as they can vary greatly per project (sand, concrete, gravel) and in some cases internal roads are not permitted.**

5.2 Components and carbon impact

This chapter indicates which methods are used to determine the carbon impact per component listed in Table 3. The components are modelled to cover the Netherlands but are not specifically aimed at production, construction, use and decommissioning in the Netherlands. For solar modules, the irradiation is adjusted to fit the irradiation rate for the Netherlands. For the rest of the components, average numbers for either global or European (depending on the information available) standards have been assumed. As of such, the carbon impact and materials described are indicative and represent information and values which are estimated.

5.2.1 Solar modules

For solar modules, the EPD of the Trina solar module TSM-DE15M(II) is assumed /8/. The solar module has the following characteristics:

Type	144 half-cut mono crystalline cells
Power output range	390-415 Wattpeak
Maximum efficiency	20.7%
Dimensions	2015 x 996 x 35 mm
Weight	22 kg
Lifetime	30 years
Markets of applicability	Europe, North America, Global
EPD scope	Cradle-to-grave

SimaPro 9 and the EcoInvent database were used. The TSM-DE15M(II) modules are comparable to the preferred solar modules for the 8 MWp solar farm in terms of type, power output range, efficiency, dimensions and weight. Table 4 shows the different life cycle stages which are included in the EPD.

Table 4 Life cycle stages included in the carbon impact score, table from /8/

	PRODUCT STAGE			CONSTRUCT-ION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw material supply	Transport	Manufacturing	Transport from gate to site	Assembly/Install	Use	Maintenance	Repair	Replacement	Refurbishment	Building Operational Energy Use During Product Use	Building Operational Water Use During Product Use	Deconstruction	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling Potential
EPD Type: cradle-to-grave	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MND

MND* = module not defined. Reuse, recovery and recycling potential is not included in the analysis.

The impact results are calculated based on 1 kWh electricity generated by the solar farm.

As the case study is for the Netherlands, several changes to the carbon impact have been made. Firstly, the EPD assumed a lifetime of 30 years, whereas DNV assumes a lifetime of 25 years. As of such, the carbon score has been adapted to fit 25 years. Secondly, the irradiation is based on Mongolia. The Netherlands has a lower irradiation rate (approximately 1 050 kWh/m^2/year instead of 1 660 kWh/m^2/year for Mongolia). DNV has adjusted the carbon impact to fit the irradiation conditions in the Netherlands. The resulting carbon impact per produced kWh is 0.024 kg CO_2.

In line with the Dutch subsidy scheme for solar modules, the flat annual energy production of 950 kWh/kWp/year is assumed for the first 15 years and for years 16-25 this is 870 kWh/kWp/year for the 8 MWp solar farm. In total, for 25 years, the 8 MWp solar farm will produce 184 GWh. In total, the carbon footprint of the solar modules during the lifetime of the farm is assumed to be approximately 4,424 tons CO_2 equivalents.

5.2.2 Inverter

Simapro includes the option of an inverter for a photovoltaic grid-connected system with a capacity of 500 kW. For the 8 MWp solar farm, three inverters of 2 MW each are assumed. The inverter in SimaPro weighs approximately 3,000 kg and has an efficiency of 95.4%. The market of applicability is Europe. The 500 kW inverter includes materials, packaging and electricity use for the production of an inverse rectifier and the disposal of the product after use.

DNV has assumed a number of inverters to match the expected inverter capacity. For the case study, 6 MW inverter capacity is assumed. As of such, 12 inverters of 500 kW are modelled to reach the same capacity.

The impact results are calculated based on the number of inverters. The average assumed lifetime of the inverter is 15 years, which means DNV has calculated the results for 20 inverters instead of 12 units to reach the assumed lifetime of 25 years.

The carbon impact for one 500 kW inverter is 13 990 kg CO_2. For 20 inverters, the total CO_2 impact is assumed to be 279.8 tons kg CO_2 eq.

5.2.3 Transformer

The 8 MWp solar farm will contain three transformers of 2 MVA each, for a total apparent power of 6 MVA. Due to information constraints, DNV has used the EPD of a Schneider Trihal transformer with a 20 MVA power rating (25 MVA air forced) and 36 kV maximum operating voltage /9/. A lifetime of 30 years is assumed. DNV has not adjusted the carbon impact as transformers usually have a long lifetime. The EPD assumes the transformer to be operational 100% of the time. For solar farms, the transformer will not be running 100% of the time (e.g. not during the night). As of such, DNV assumed a 50% operational time and has adjusted the carbon impact accordingly.

The stages which are included are manufacturing, distribution, installation, use and end-of-life. The transformer has a recycling potential of 85%.

The carbon impact for one transformer (including the adjusted operational time) is 364 tons CO_2 eq. The total carbon impact for three transformers is assumed to be 1,092 tons CO_2 eq.

5.2.4 Support and mounting structure

The 8 MWp solar farm will use steel support and mounting structures to support the solar modules. DNV has used an EPD of different types of structural steel and assumes 50% of the structural steel for heavy-duty applications and 50% of the structural steel for medium-duty applications /10/. Heavy-duty applications include e.g. columns, beams and plates. Medium-duty applications include e.g. lintels, sheet piles and crash barriers. The carbon score includes production from raw materials, transport to site, fabrication and erection, removal from the structure and waste disposal. Use, maintenance and replacements are not included. The steel structure is assumed to have a lifetime of 25 years.

The carbon score of the EPD is calculated per ton structural steel. For heavy-duty applications and medium-duty applications the carbon score is respectively 480 kg CO_2 and 940 kg CO_2. The assumed amount of steel used for the structures is 185 tons. As of such, 92.5 tons steel is assumed for both types of steel (heavy-duty and medium-duty). The total carbon impact is assumed to be 131.4 tons CO2 eq.

5.2.5 Cables

For cables, the following standard items from SimaPro version 9 are used:

- Three-conductor cable
- Excavation by hydraulic digger
- Market for waste, electrical and electronic cables.

The three-conductor cable consists of around 50% copper and 50% polyethylene. The modelled impacts include materials, production of the cable and infrastructure for a cable produced by a Swiss producer. Installation, use and end of life phases are not included.

The carbon impact of the cable is 5.9 kg CO_2 per meter cable and the length of cables needed for an 8 MWp solar farm is about 135,000 meters.

During the installation phase, parts of the length of the cable will be underground. A hydraulic digger will be necessary to transform the land to be able to bury the cables. DNV has modelled the excavation of 250 m^3 of soil (500 m length and 0,5 m deep) for the 8 MWp solar plant. The carbon impact of excavation is 0.53 kg CO_2 eq per m^3.

The waste scenario is modelled by using the market for waste, electrical and electronic cables per kg in Europe. The LCA includes infrastructure, energy consumption to dispose of the cables and transportation efforts from the construction site to the waste treatment facility. The carbon impact is 0.90 kg CO_2 per kg of treated cable and the modelled weight of the cables are 40,500 kg for 135,000 meters of cable.

The total carbon impact for cables is assumed to be 841 tons CO_2 eq.

5.2.6 Buildings

Three buildings are expected to be on the 8 MWp solar farm site which will hold electrical equipment, security systems and monitoring systems. The buildings are assumed to consist mainly of concrete and reinforced concrete and weigh approximately 10.8 tons per building. For the calculation of the carbon impact, the following standard components from SimaPro are used:

- Reinforced concrete production
- Concrete blocks production
- Reinforced concrete waste
- Concrete gravel waste.

Reinforced concrete is modelled for floors and consists of the following ingredients for 1 m^3: 357 kg cement, 200 kg water, 913 kg gravel, 724 kg sand, 3.57 kg polyfunctional admixture, 25 kg steel long fibre. The ingredients add up to approximately 2 tons of reinforced concrete per m^3. The stages which the LCA includes is the reception of raw materials at the ready-mix plant gate to the delivery of concrete at the construction site. There is no installation, use or end-of-life phase included in the LCA. The carbon impact is 399.7 kg CO_2 eq per m^3. DNV has assumed 2.5 m^3 of reinforced concrete.

The process of concrete blocks includes the production of the raw materials, transport and production of the concrete blocks and packaging in Germany. There is no installation, use or end-of-life phase included in the LCA. DNV has assumed the use of 27.4 tons of concrete for the rest of the buildings (excluding floors). The carbon impact is 0.13 kg CO_2 per kg concrete blocks.

For the waste scenario, DNV has assumed a scenario for the reinforced concrete and the treatment of waste concrete gravel. The treatment of reinforced concrete waste in Europe for final disposal includes energy for dismantling, particulate matter emissions, transport to dismantling facilities, and final disposal of waste material. The carbon impact is 0.014 kg CO_2 eq per kg reinforced concrete waste (approximately 5 tons for 2.5 m^3). Regarding the treatment of waste concrete gravel, the LCA includes energy for dismantling, handling, transport to dismantling facilities, and final disposal of waste material. The carbon impact is 0.012 kg CO_2 eq per kg treated concrete waste (approximately 27.4 tons).

The total carbon impact is assumed to be 5 tons CO_2 eq.

5.2.7 Roads

Material of internal roads in solar farms can vary greatly per project (sand, concrete, gravel) and in some cases internal roads are not permitted. Approximately 500 meters of road is modelled for the 8 MWp solar farm. DNV has used the following standard components in SimaPro to model the carbon impact:

- Crushed gravel production
- Concrete gravel waste

The process of crushed gravel production includes the whole manufacturing process, internal processes and infrastructure. There is no installation, use or end-of-life phase included in the LCA. DNV has assumed the use of 500 tons of concrete for the construction of 500 m of roads. The carbon impact is 0.008 kg CO_2 per kg crushed gravel.

For the waste scenario, DNV has assumed a scenario for the treatment of waste concrete gravel. Regarding the treatment of waste concrete gravel, the LCA includes energy for dismantling, handling, transport to dismantling facilities, and final disposal of waste material. The carbon impact is 0.012 kg CO_2 eq per kg treated concrete waste (approximately 500 tons).

The total carbon impact is assumed to be 10.4 tons CO_2 eq.

5.3 Accumulated carbon impact

The different components from section 5.2 and their carbon impact are accumulated. The total carbon impact is assumed to be 6 784.6 tons CO_2 over the lifetime of the solar farm. The results of the relative carbon score per component is shown in Figure 6.

The relative impact of the solar modules in comparison to the rest of the components is high (see Figure 6). For other LCAs of PV systems, the relative impact of solar modules were calculated to be 77% /11/. The LCAs of solar systems include the solar modules and the inverters. DNV has drafted a carbon impact assessment which includes a very comprehensive BoS/BoM compared to other LCAs which DNV has considered in the literature. As of such, the carbon impact compared to the LCAs is higher, but is more comprehensive and includes approximately 98% of the components of a solar farm. The missing items are the switchgears, string boxes, connectors, ducts, earthing, monitoring system, security system and fences. These components account for approximately 2% of the total weight of the solar farm and are not included.

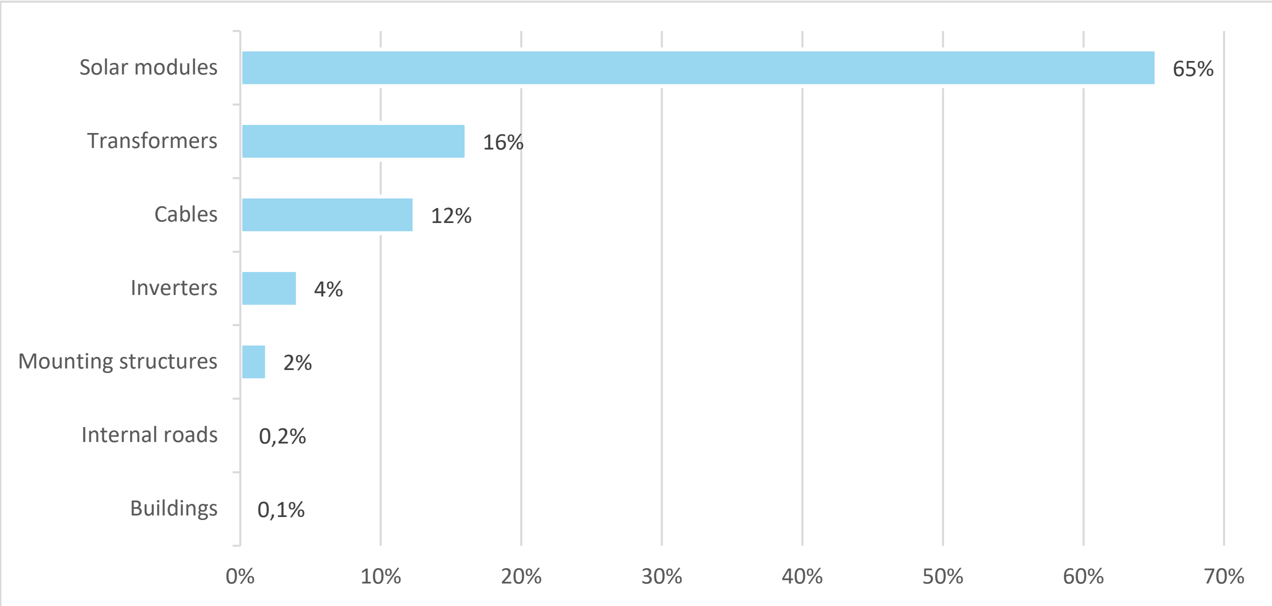


Figure 6 Relative carbon impact of typical components of an 8 MWp solar farm.

5.3.1 Carbon impact relative to other energy sources

The relative carbon impact of the 8 MWp solar farm is compared to other energy sources to show the relative carbon footprint compared to other renewable and non-renewable energy sources (see Figure 7).

	Carbon Footprint [g CO_2-eq/kWh] *
a-Si PV	26–60
CIS PV	
mc-Si PV	
sc-Si PV	
Flat plate collector	20–45
Vacuum tube collector	
Wind	9–35
Geothermal plant	6–79
Hydroelectric	1–24
Nuclear	4–110
Natural gas	410–650
Oil	778
Coal	740–1050

Figure 7. Comparative life cycle carbon footprint results for the studied renewable energy systems (adapted from /11/)

The carbon footprint of fossil fuel-based energy producing technologies per kWh produced is multiple times higher compared to PV systems. The carbon footprint of the modelled 8 MWp solar farm is 36.9 g CO_2 eq/kWh.

5.3.2 Energy payback time

For mono crystalline silicon solar modules, the carbon cost to produce the modules are generally higher compared to other type of solar modules. However, the mono crystalline silicon solar modules are also higher in efficiency and offer a greater yield compared to other types of solar modules /11/ /12/. For the case study of the 8 MWp solar farm DNV has not calculated the energy payback time (EPBT) due to information constraints. Nevertheless, academic literature shows that for mono crystalline silicon solar modules the EPBT ranged between 1.4 and 7.3 years (studies between 1990 and 2016) /12/. As the technology for the modules keeps developing and is becoming more efficient over the years, as well as the cleaner technologies to produce the solar modules (taking into account the greening of the energy mix and creating higher efficiencies), the EPBT is expected to be lowered as technologies improve. Energy demand from the solar modules has declined over the years (more than 8050 MJ/m^2 in 2000s to less than 1000 MJ/m^2 in 2016) /12/ due to improvements in conversion efficiency and cell production. DNV assumes that the energy payback time of a new 8 MWp solar farm will be lower than or comparable to the values found in the literature.

6 RECYCLING AND REUSE

6.1 End-of-life options

There is, currently, not much experience in the market regarding reuse and recycling. Around the year 2035, however, the first photovoltaic systems will reach their end-of-life (EoL) on a large scale. Project developers have several options to meet the economic and ecological challenges of the EoL of solar farms. The following sections contain indicative conclusions from peer reviewed literature on EoL options of solar modules, such as reuse and recycling, and expert knowledge.

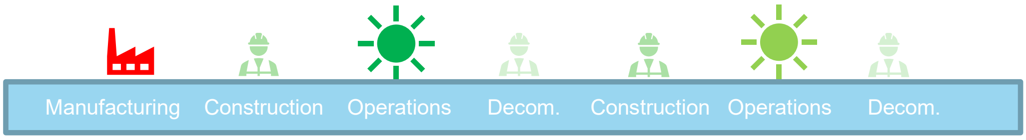
6.1.1 Reuse

The lifetime of solar modules is generally longer than the typical 25 years of the project lifetime. Depending on possible extensions of the runtime of the environmental permit, a project may be extended after 25 years at the same location.

An EoL option is to reuse the solar modules at a different location, after the project has been decommissioned. The indicative scenario of reuse is visualised in Figure 8, including solar farm lifetime phases of manufacturing, (engineering, procurement and) construction, and decommissioning. The expected carbon emissions for each phase are represented with a red score. The green carbon scores represent the expected energy production by the solar farm during the two operational phases, compared to their avoided CO_2 emissions (if the same amount of energy had to be generated with fossil fuels). Raw material production and manufacturing is assumed to have a higher carbon impact compared to construction and decommissioning phase. The first operational phase will have a higher energy yield compared to the second operational phase, as the solar modules lose some of their efficiency due to degradation.

The energy production of the solar farm is based on assumptions by DNV on the degradation rate of the modules. It is assumed that the entire solar farm (modules + BoS) is subject to an annual degradation of 0.64%[1]. For LCA purposes and in line with the Dutch subsidy scheme for the first 15 years a flat annual energy production of 950 kWh/kWp/year is assumed and for years 16-25 this is 870 kWh/kWp/year.

[1] DNV observes that the degradation rate may vary significantly between different module suppliers. In certain cases an annual degradation rate of for example 0.5% may be possible. Based on research DNV's default value for linear annual degradation is 0.64%.



Lifetime phase	Steps included	Emissions considered	Expected carbon score
Manufacturing (1)	Raw materials procurement	Mining, Transport	
	Manufacturing	Industry	
Construction (1)	Components procurement	Transport	
	Construction/installation	Light and heavy machinery	
Operations (1)	Solar energy production	Renewable energy yield	
Decom. (1)	Dissassembly	Light and heavy machinery	
Construction (2)	Components procurement	Transport	
	Construction/installation	Light and heavy machinery	
Operations (2)	Solar energy production	Renewable energy yield	
Decom. (2)	Dissassembly	Light and heavy machinery	
Total net carbon score	All		

Figure 8. Indicative scenario and visualisation for reuse (one manufacturing phase, two EPC phases, two operational phases and two decommissioning phases)

6.1.2 Recycling

Another EoL option is the recycling of the solar modules, by means of an industrial recycling treatment of the materials involving high energy processes such as smelting. Recycling is currently unprofitable, due to lower prices for raw materials and low incentives for non-virgin material procurement, but recycling is likely to be mandated in more jurisdictions.

The European Commission recognised the need for actions to foster resource-efficient solutions to recover silicon and other materials from solar farms, to reduce its criticality and overall to improve the circularity of the European economy /13/ /14/.Base-case recycling of solar modules has a low efficiency and, in some cases, cannot even reach legislative targets. Conversely, high-efficient recycling can meet these targets and allows to recover high quality materials (as silicon, glass and silver) that are generally lost in base-case recycling /15/.

The benefits due to the recovery of these materials counterbalance the larger impacts of the high-efficiency recycling process. Considering the full life cycle of the module, the energy produced by the module grants the most significant environmental benefits. Raw material production, manufacturing and recycling are assumed to have a higher carbon impact compared to construction and decommissioning phase. The first operational phase is expected to have a lower energy yield compared to the second operational phase, as the solar modules are expected to gain efficiency due to technological progress.

The indicative carbon score for recycling is assumed to include the transportation (of components) to a recycling facility, a high-efficiency recycling process with an 80% recuperation rate. The carbon score for manufacturing is expected to decrease by 30% after 25 years due to a low-carbon energy mix /16/.

Lifetime phase	Steps included	Emissions considered	Expected carbon score
Manufacturing (1)	Raw Materials procurement	Mining, Transport	
	Manufacturing	Industry	
Construction (1)	Components procurement	Transport	
	Construction/installation	Light and heavy machinery	
Operations (1)	Solar energy production	Renewable energy yield	
Decom. (1)	Decomissioning	Light and heavy machinery	
Recycling	Secondary Raw Materials	Industry	
Manufacturing (2)	Raw materials procurement	Transport	
	Manufacturing	Industry	
Construction (2)	Components procurement	Transport	
	Construction/installation	Light and heavy machinery	
Operations (2)	Solar energy production	Renewable energy yield	
Decom. (2)	Decomissioning	Light and heavy machinery	
Total net carbon score			

Figure 9. Indicative scenario and visualisation for recycling (one recycling phase and one manufacturing phase are added, compared to the reuse scenario)

7 CONCLUSIONS AND RECOMMENDATIONS

In this report several items regarding the environmental impact of solar farms are assessed.

7.1 Leaching

First, the risk of leaching of materials into the environment is assessed. It is concluded that the risk of leaching of (harmful) substances into the environment from crystalline silicon solar modules, under outdoors environmental conditions, is very low. Also, other components of a solar farm can be expected to have very little risk of leaching of materials into the environment. To ensure that no leaching occurs, the following mitigating actions can be taken:

- Daily remote monitoring of defective modules by means of automated alarm systems.
- Effective detection of broken modules and quick replacement minimising the risk of solar modules leaching into the environment.
- Careful removal of components during decommissioning to prevent modules from breaking.
- Recycling or reuse of the solar modules to prevent modules being disposed into landfills.

7.2 Decommissioning and removal

A list of typical decommissioning and land restoration activities is presented. DNV expects that the decommissioning of an 8 MWp solar farm can be done in 2-3 months.

7.3 Carbon impact assessment: 8 MWp solar farm

The carbon impact assessment in this case study looks at the *entire* solar farm, including auxiliary buildings, road construction, cabling, inverters and transformers. Around 98% of the solar farm is included in the case study. These are normally not found in carbon impact assessments of a solar farm, which shows the comprehensiveness of Statkraft's understanding of their project impact.

7.4 Recycling and reuse

Based on expert judgement it can be said that both EoL scenarios, recycling and reuse, are expected to have a positive carbon impact during the solar farm's lifetime. In the reuse scenario, less CO_2 emissions are expected compared to the recycle scenario as the reuse scenario does not include a second manufacturing process nor a recycling process. But in the recycling scenario, a higher energy yield is expected compared to the reuse scenario due to the increased efficiency in the solar modules. At this point in time, it is hard to determine which scenario will be most favourable as it depends on factors like the development of the solar module efficiency and the CO_2 emissions of the processes needed after 25 years. Both scenarios, reuse and recycling, will be viable options and based on the evolution of technology in the next decades it will become clear whether one scenario will be more attractive than the other.

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APPENDIX A
Carbon impact per component

Component	Carbon score per unit	Number of units	Carbon score with a lifetime of 25 years (tons CO_2 eq)	Relative carbon score per component (%)
Solar module	0,024 kg CO_2 eq per kWh electricity generated (corrected for lifetime and irradiation)	114 GWh for the first 15 years and 69.6 GWh for the last 10 years	4,424.3	65.2
Inverter	13 990 kg CO_2 eq per 500 kW inverter	20 units*	279.8	4.1
Transformer	364 tons CO_2 eq per transformer produced (corrected for 50% capacity during the use phase)	3 units	1,092	16.1
Mounting structure	480 kg CO_2 eq per ton heavy application steel 940 kg CO_2 eq per ton medium application steel	92,5 tons 92,5 tons	131.4	1.9
Cables	5.9 kg CO_2 eq per m, (production) and 0.53 kg CO_2 per m^3 excavation (installation) 0.90 kg CO_2 eq per kg (decommissioning/waste)	135.000 m 250 m^3 40.500 kg	841.7	12.4
Buildings	399.7 kg CO_2 eq per m^3 reinforced concrete 0.13 kg CO_2 eq per kg concrete blocks 0.014 kg CO_2 eq per kg reinforced concrete waste 0.012 kg CO_2 eq per kg treatment of waste concrete gravel	2,5 m^3 27.4 tons 5 tons 27.4 tons	5	0.1
Roads	0.008 kg CO_2 eq per kg crushed gravel (production) 0.012 kg CO_2 eq per kg treatment of waste concrete gravel	500 tons 500 tons	10.4	0.2
Total	-	-	6,784.6	100%

*20 units refer to 4 x 500 kW inverters = 2 MW inverter capacity. An 8 MWp solar farm uses 3 x 2 MW inverters (thus in total 12 x 500 kW inverters). The lifetime of an inverter is assumed to be 15 years, and thus to model the carbon impact of 25 years, 2/3 of the number of inverters is added. As of such, 20 x 500 kW inverters are modelled for their carbon impact.

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