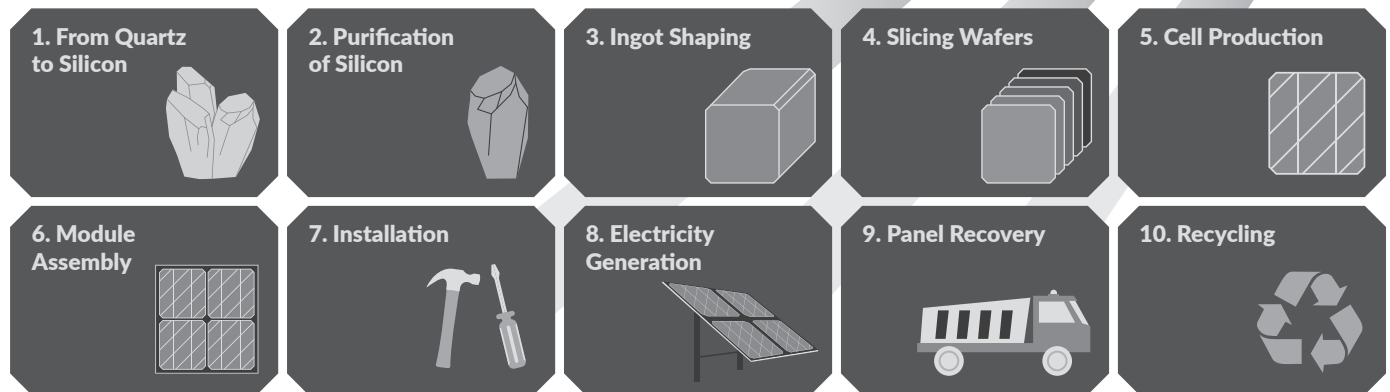


The Ten Steps in the Life cycle of a Photovoltaic Panel



METHODOLOGY



1

The Life Cycle Analysis (LCA) serves to evaluate and compare, based on common criteria, the environmental impact of a product throughout its lifetime, from manufacturing to recycling, using quantitative, standardized indicators. This method is governed at international level by standards ISO 14040 and ISO 14044.

2

In this infographic, we have chosen a **photovoltaic panel manufactured in China** for reference. In 2024, China accounted for 90% of the European market. The Chinese electricity mix, based mainly on coal, increases the carbon footprint of panel production.

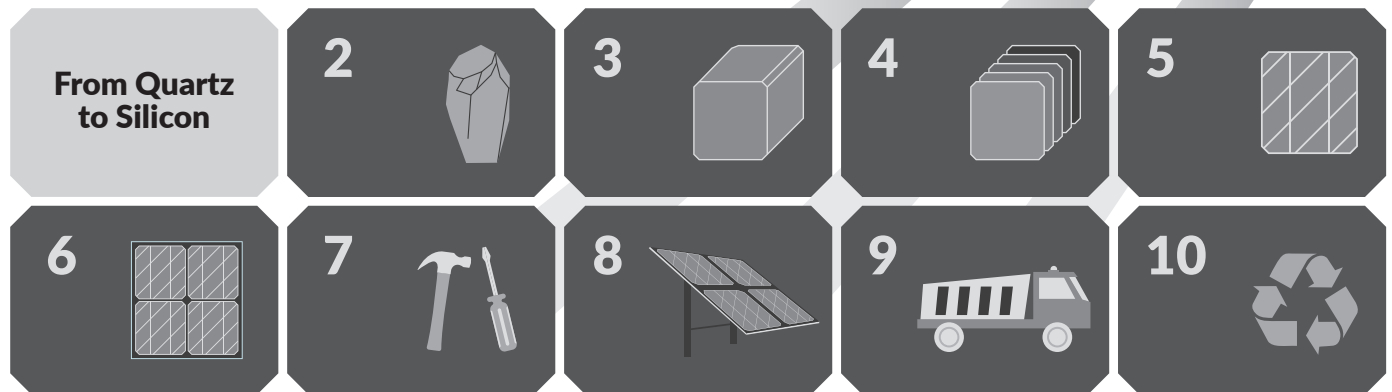
3

We have chosen two **widespread industrial processes**: the chemical method ('Siemens process') for the production of solar-grade silicon (step 2) and the 'Czochralski' process for the fabrication of monocrystalline silicon (step 3).

4

France has been chosen as the place of use, which influences the energy required to transport, install and recycle the panel. This choice particularly impacts the quantity of electricity produced, related to local sunshine levels. The more electricity a panel produces, the faster it offsets the embodied energy used for its production.

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 1 - FROM QUARTZ TO SILICON

OBJECTIVES

- Obtain silicon from the silica (SiO_2) present in quartz or sand
- Extract the oxygen from the silica to obtain metallurgical grade silicon (MG-Si)

PROCESSES

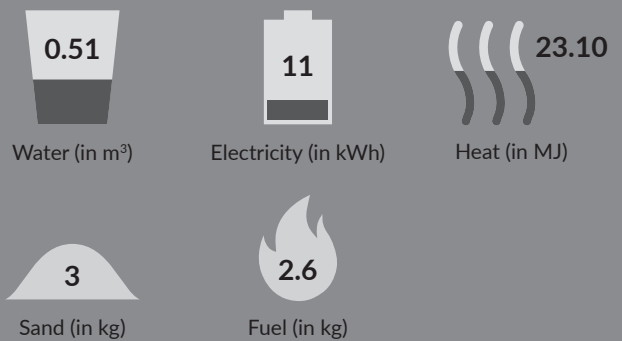
- Heat a mixture of quartz and carbon-based fuel (coke, coal and wood)
- Carbon and oxygen combine to produce CO_2
- This leaves 98-99% pure metallurgical silicon

IMPACTS

- Energy and water consumption, and CO_2 emissions

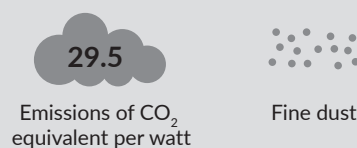
INPUTS

To produce 1kg of MG-Si

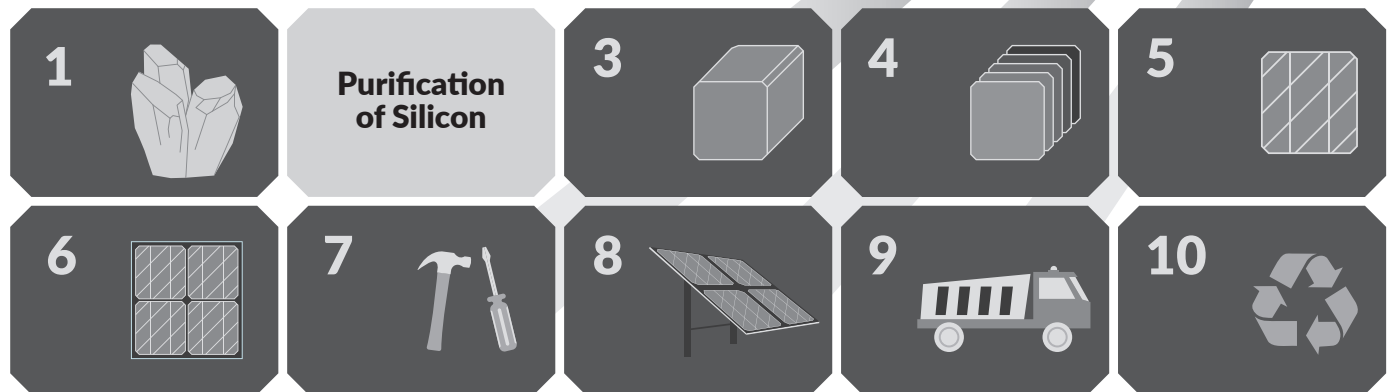


N.B.: one kWh equals 3.6 megajoules (MJ)

OUTPUTS



The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 2 - PURIFICATION OF SILICON

OBJECTIVES

- Purify metallurgical silicon to obtain 99.9999% pure polycrystalline solar-grade silicon (SoG-Si).

PROCESSES

- Chemical or metallurgical
- Mainly chemical at present, as this process produces a purer material, but consumes more energy and has inherent risks owing to the use of chlorinated products

IMPACTS

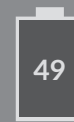
- These first two steps combined represent 40% of the energy consumed in the entire production cycle of a photovoltaic panel

INPUTS

To produce 1kg of SoG-Si



Water (in m³)



Electricity (in kWh)



Heat (in MJ)



MG-Si (in kg)



Chemicals (in kg)

OUTPUTS

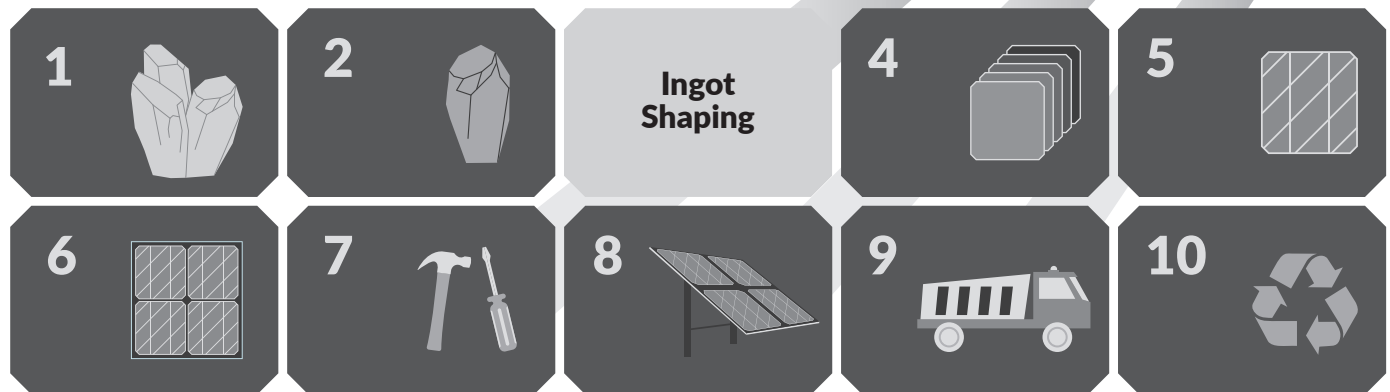


Emissions of CO₂ equivalent per watt (in g)



Chlorinated products

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 3 - INGOT SHAPING

OBJECTIVES

- Transform polycrystalline solar-grade silicon, whose atoms are randomly distributed, into monocrystalline silicon, where they are organized and aligned
- Shape silicon into ingots

PROCESSES

- Melt down and gradually resolidify the solar-grade silicon by adding boron, a doping element

IMPACTS

- High gas consumption

INPUTS

To produce a single 1kg ingot

5.09

Water (in m³)
including 4.8 m³
to be retreated

32

Electricity (in kWh)

68.20

Natural gas for
the burner (in MJ)

1.02

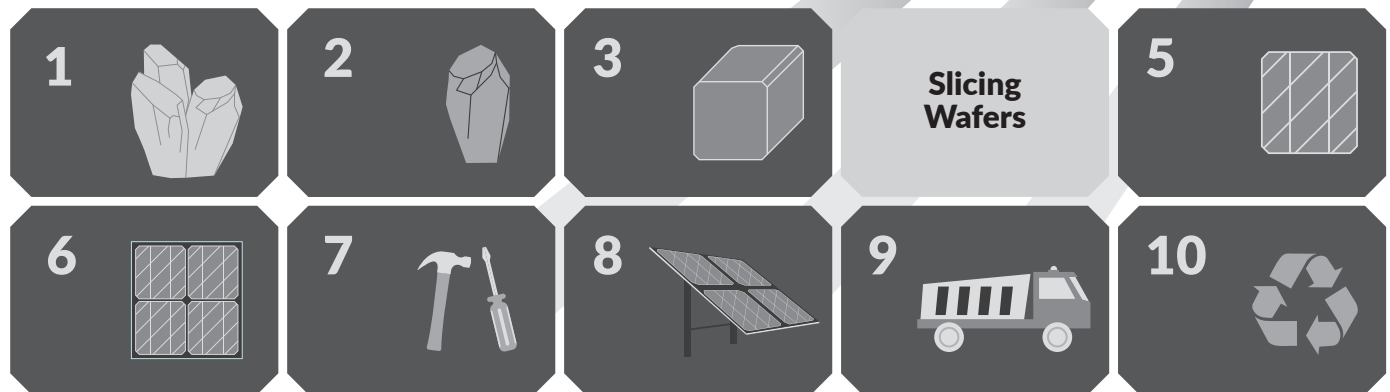
SoG-Si (in kg)

OUTPUTS

26.5

Emissions of CO₂
equivalent per watt (in g)

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 4 - SLICING WAFERS

OBJECTIVES

- Slice the **monocrystalline ingots** into thin slices - wafers - 250 micrometers (μm) thick

PROCESSES

- Use a **wire saw** with an abrasive solution (slurry)

IMPACTS

- Significant loss of 30-40% of the material when sawing
- Potential for recycling the powder in other industrial sectors

INPUTS

To produce 1 m² of wafers

0.056

Water (in m³)

4.76

Electricity (in kWh)

4

Natural gas for the burner (in MJ)

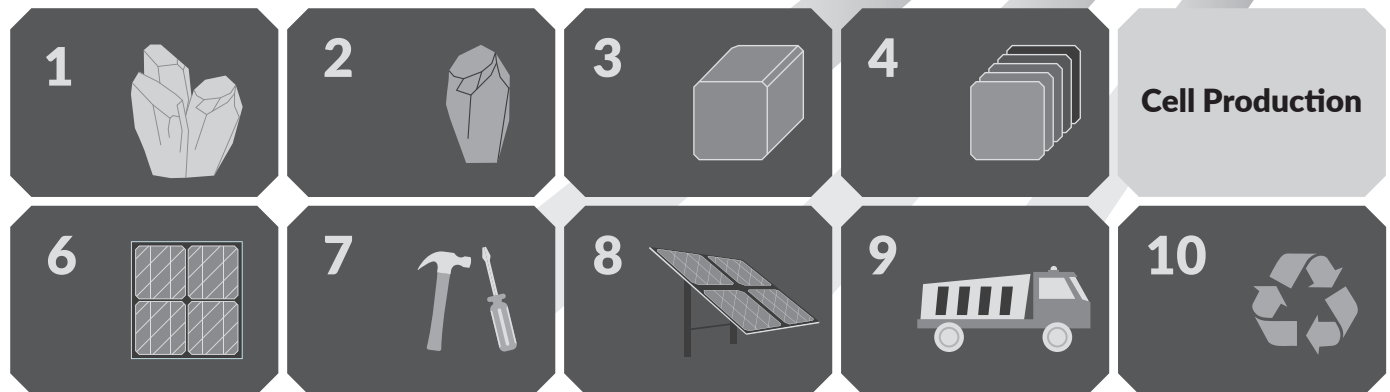
OUTPUTS

8.19

Emissions of CO₂ equivalent per watt (in g)

Silicon powder, slurry

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 5 - CELL PRODUCTION

OBJECTIVES

- **Manufacture cells** that convert light energy into electrical energy
- The cells can be **square or rectangular** (15-20 cm)

PROCESSES

- **Doping silicon** exposed to a gas cloud containing phosphorous
- **Deposition of a thin layer of aluminum**
- **Engraving of electric contact wires** (aluminum and silver)
- **Anti-reflection films and treatments** in acid or alkaline baths

IMPACTS

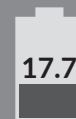
- **Use of electric furnaces** and many irritant, corrosive and toxic chemical compounds

INPUTS

To produce **1 m²** of cells:



Water (in m³)



Electricity (in kWh)



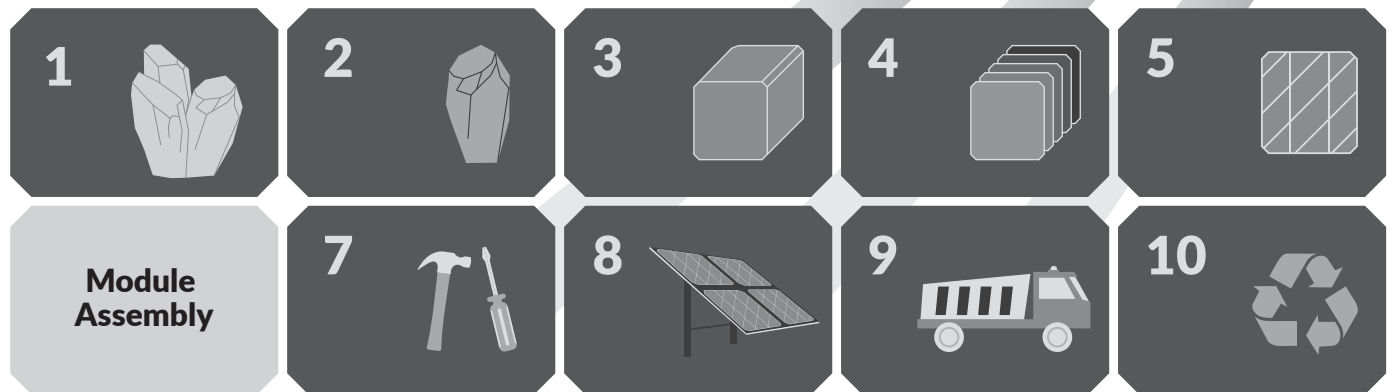
Various chemical elements (in kg)

OUTPUTS

73.6

Emissions of CO₂ equivalent per watt (in g)

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 6 - MODULE ASSEMBLY

OBJECTIVES

- **Protect the cells from the outside environment** by assembling them in modules of 60 to 72 cells (1.7 m x 1m, surface area: 1.7 m²)

PROCESSES

- **Connect the cells**
- **Encapsulation in an Ethylene-Vinyl Acetate (EVA)**, envelope which, once heated, forms a layer of glue around the cells
- **Protection using a solar glass pane** and a rigid plastic sheet (backsheet)
- **Fitting of an aluminum frame**
- **Addition of a junction box, wiring, and an inverter** (to convert direct current into alternating current)

IMPACTS

- **Handling of numerous chemical compounds** that require the implementation of safety and discharge prevention measures
- **The production of aluminum uses a lot of energy**, and the process emits sulfur hexafluoride (SF₆), a greenhouse gas with a high global warming potential (GWP)

INPUTS

To produce 1 m² of modules

0.005

Water (in m³)

14

Electricity (in kWh)

17.62

Solar glass
(in kg)

2.13

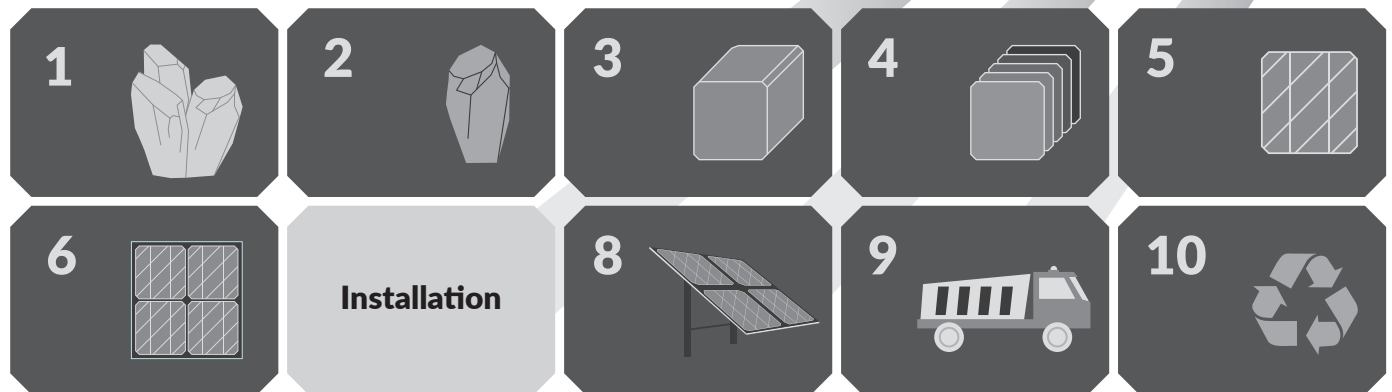
Aluminum (in kg)

OUTPUTS

226

Emissions of CO₂
equivalent per watt (in g)

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 7 - INSTALLATION

OBJECTIVES

- Panel transport, site preparation and installation on the ground

PROCESSES

- Transport by sea/road, installation of structures for the solar farm

IMPACTS

- Carbon footprint of transport
- Forest clearing
- Loss of animal habitats
- Social acceptability of large facilities

INPUTS

- Lifting and handling, civil engineering and construction materials

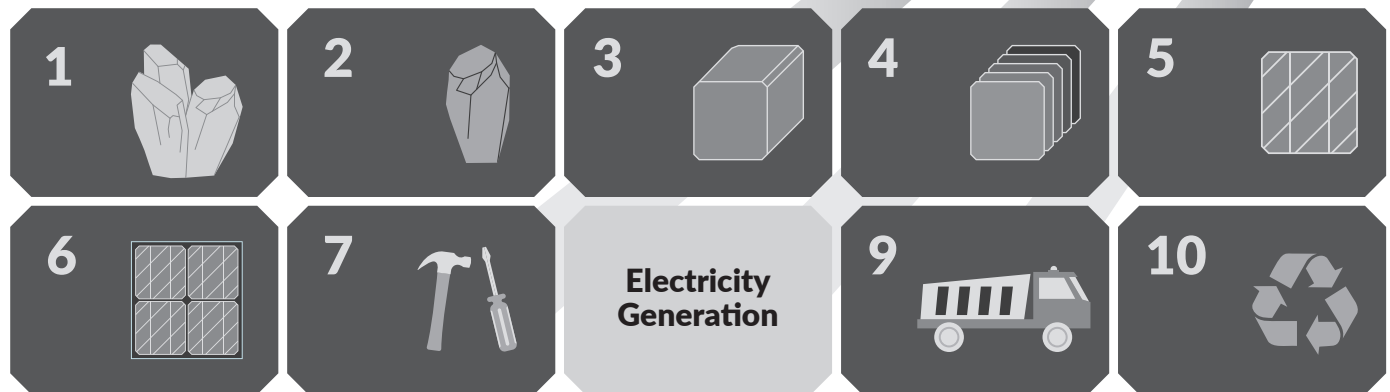


OUTPUTS

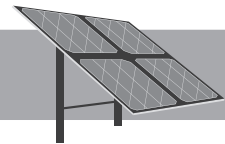
606

Emissions of CO₂
equivalent per watt (in g)

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 8 - ELECTRICITY GENERATION



OBJECTIVES

- Ensure auto-consumption or export of generated electricity into the grid
- Average lifetime of a solar panel: 30 years

INPUTS

- Consumes very little energy (except for maintenance)

PROCESSES

- Suitable electric connections
- Maintenance of facilities

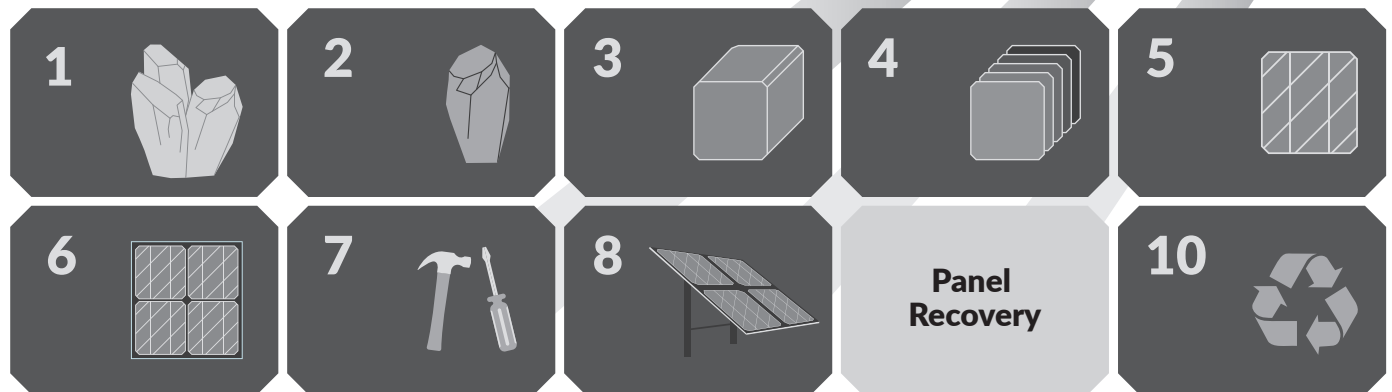
OUTPUTS

- No CO₂ emissions

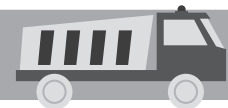
IMPACTS

- Impacts **under** the panels in the case of agrivoltaics: reduces light exposure but improves water retention
- Incidence **on** the panels: heat island effect
- Disrupts the movement of large mammals

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 9 - PANEL RECOVERY



OBJECTIVES

- Recover panels at the end of their useful life and take them to collection points

PROCESSES

- Disassembly and transport by truck, optimizing journey times as much as possible

IMPACTS

- Risk of a high number of truck journeys generating a carbon footprint

OUTPUTS

Emissions of CO₂ equivalent per watt for the last two steps 9 and 10:

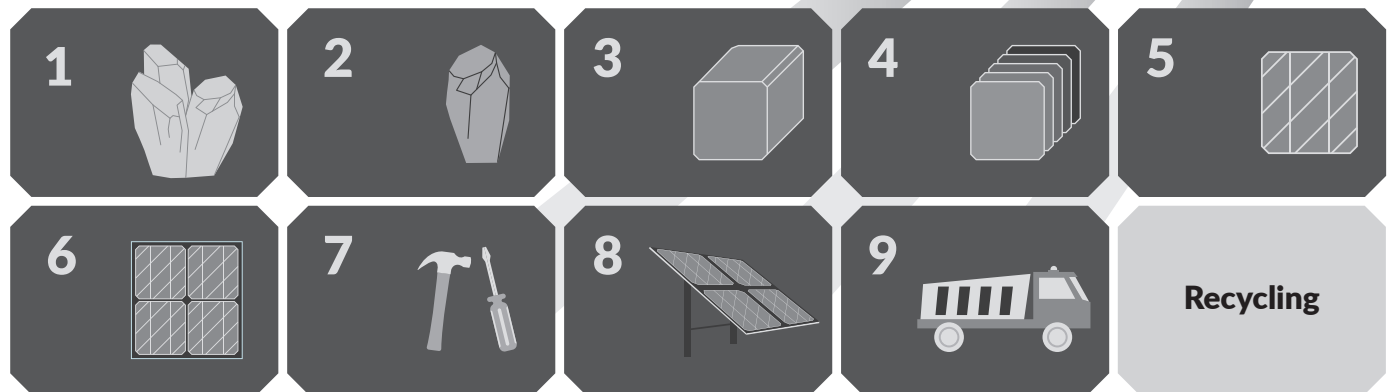
- Collection and recycling of used panels

382

Emissions of CO₂ equivalent per watt (in g)

- Recovery of 94% of the materials means that emissions estimated at -124 g CO₂eq/W can be deducted from the final energy balance

The Ten Steps in the Life cycle of a Photovoltaic Panel



STEP 10 - RECYCLING



OBJECTIVES

- **Separate the fractions a panel comprises:** 68% glass, 12% aluminum, 9% plastic, 4% silicon, 1% tinned copper (tin-plated), 1% copper, 6% scrap material
- **In total: 94% of a panel can be recycled and reused**

PROCESSES

- **Separation of junction boxes, wiring and the aluminum frame** to be melted down in a foundry
- **Grinding: the recovered particles are sorted by air-separation** (an air jet separates the glass, copper and fine particles), floating (plastics, traces of silver), eddy current (tinned copper, aluminum residues)
- **Delamination: separation of the glass plate and photovoltaic cells** using a hot knife (300°C)

IMPACTS

- **Consumption of electricity and gas** for machines and furnaces
- **Scrap materials**

INPUTS

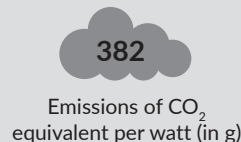


- The quantities of electricity and chemical products are not specified, as they vary greatly and account for only 6% of the panel's total composition

OUTPUTS

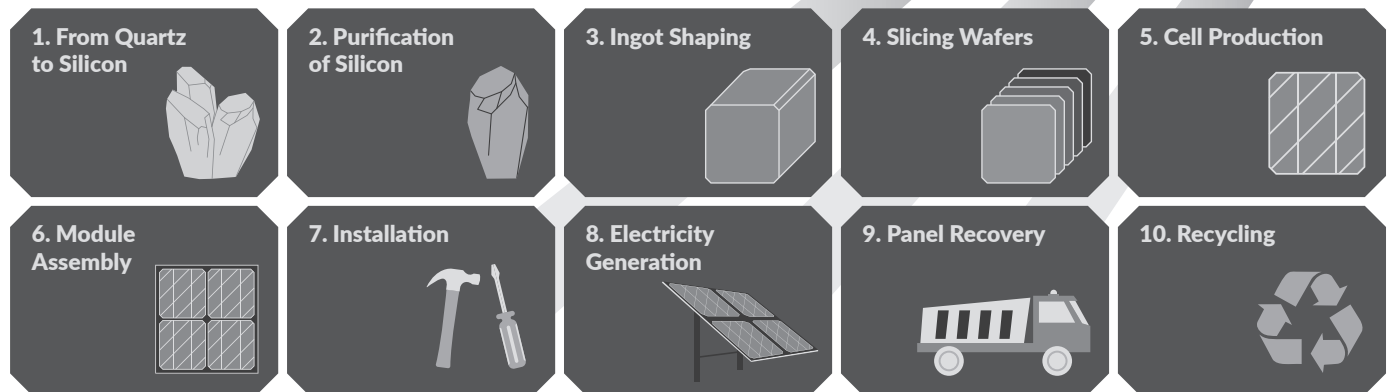
Emissions of CO₂ equivalent per watt for the last two steps 9 and 10:

- **Collection and recycling of used panels**



- **Recovery of 94% of the materials** means that emissions estimated at -124 g CO₂eq/W can be deducted from the final energy balance

The Ten Steps in the Life cycle of a Photovoltaic Panel



THE ENERGY BALANCE

1

It reveals the “energy payback time”, i.e. the time required for the photovoltaic system to produce the same amount of energy that it has consumed throughout its lifecycle.

2

The energy consumed to produce, transport, install and recycle the panel is called “embodied energy”. On average, the panel manufacturing process represents over 60% of this gray energy. The installation of inverters, wiring and structures represents about a third, and transport represents the smallest share. 94% of a module can be recycled and reused, which reduces the overall impact.

3

Electricity yield depends on geographic location: a solar panel produces more power in the Sahara desert than in Scandinavia, so its location determines the time it takes to compensate for the gray energy used to produce it.

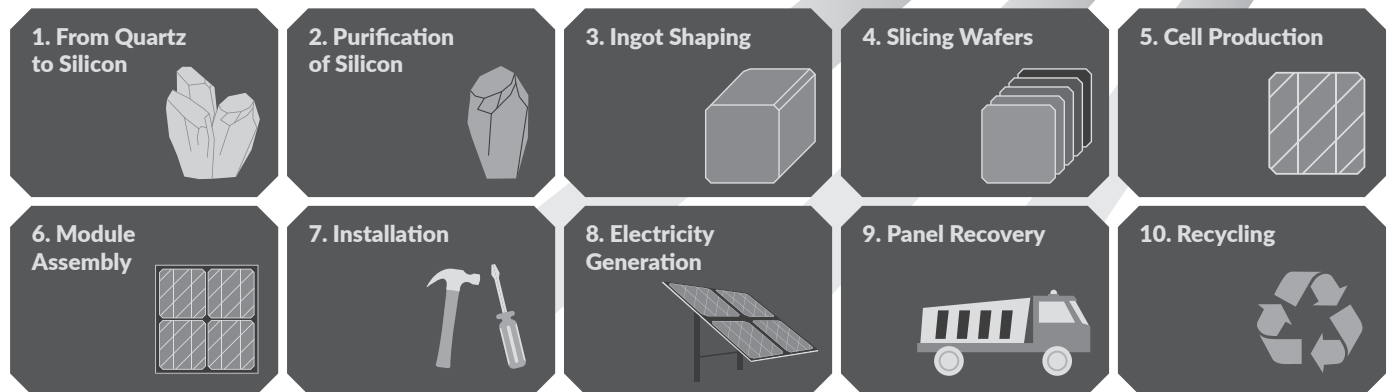
4

In France, the energy return time is estimated at 1 to 1.5 years depending on the sunshine and installation conditions (in particular how panels are oriented). Over its lifetime, a panel can generate between 17 and 35 times the embodied energy used in its production.

5

Over the past 30 years, the energy payback time has been divided by three thanks to technological advances.

The Ten Steps in the Life cycle of a Photovoltaic Panel



THE CARBON FOOTPRINT

1

The carbon footprint corresponds to the amount of greenhouse gases emitted during the lifecycle of a product and expressed as CO₂ equivalent (gCO₂eq).

2

In France, for systems fitted with Chinese photovoltaic panels, the standard value is **43.9 gCO₂eq/kWh produced**. By way of comparison, a gas power station emits almost 500gCO₂eq/kWh. The figure drops to 32.3 gCO₂eq/kWh for European panels, and to 25.2 gCO₂eq/kWh for panels made in France.

3

The difference can be explained by the **electricity mix in different countries**: producing a solar panel consumes a lot of electricity. A country that uses mainly coal to generate electricity will have a higher carbon balance than a country who uses renewable or nuclear energy.

4

Finally, **transport by container ship from China**, though a long journey, has a **low carbon footprint per panel**, as each shipment comprises a very large quantity of panels.