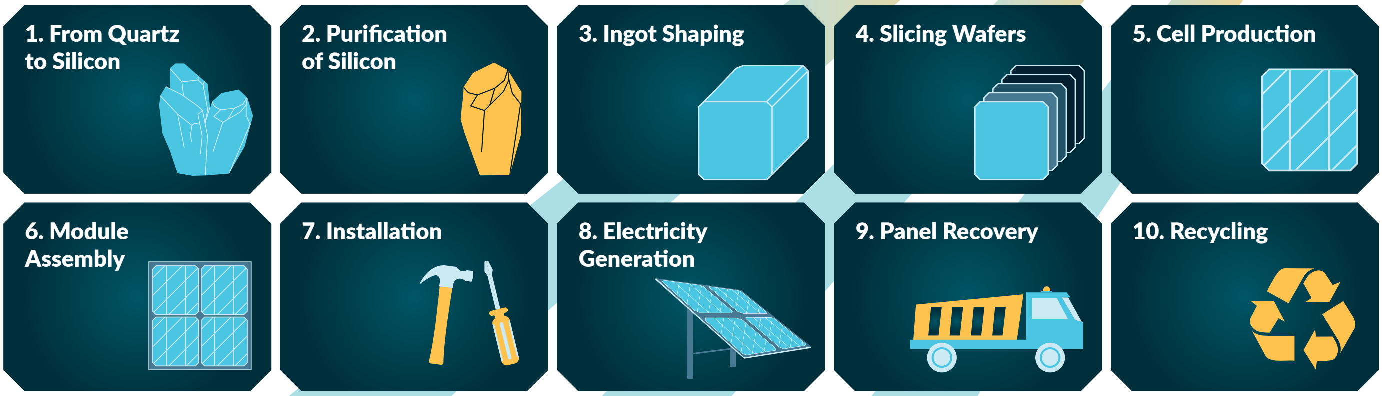
The Ten Steps in the Life cycle of a Photovoltaic Panel



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.

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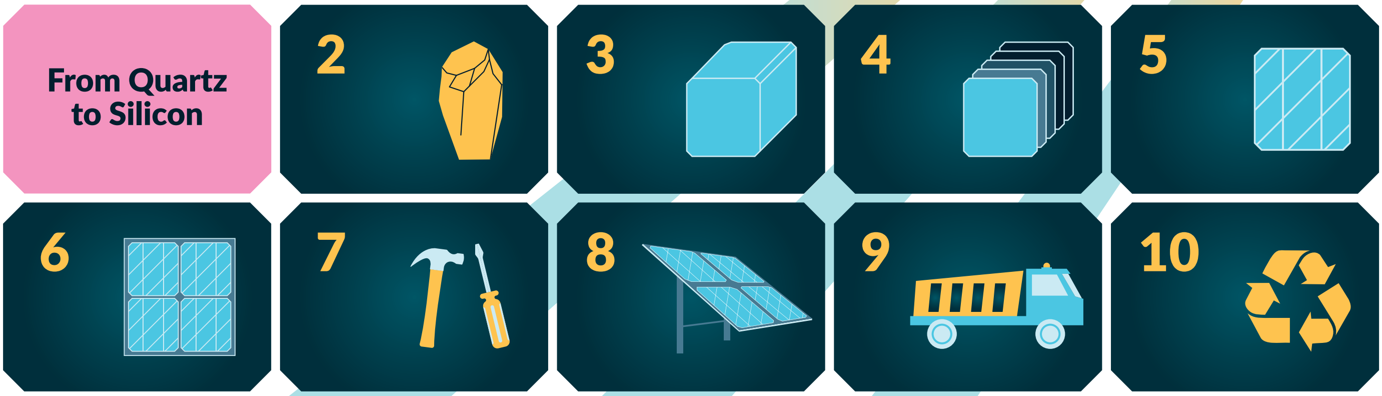

STEP 1 - FROM QUARTZ TO SILICON

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**

0.51	Water (in m^3)
11	Electricity (in kWh)
23.10	Heat (in MJ)
3	Sand (in kg)
2.6	Fuel (in kg)

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

OUTPUTS

29.5	Emissions of CO_2 equivalent per watt
	Fine dust

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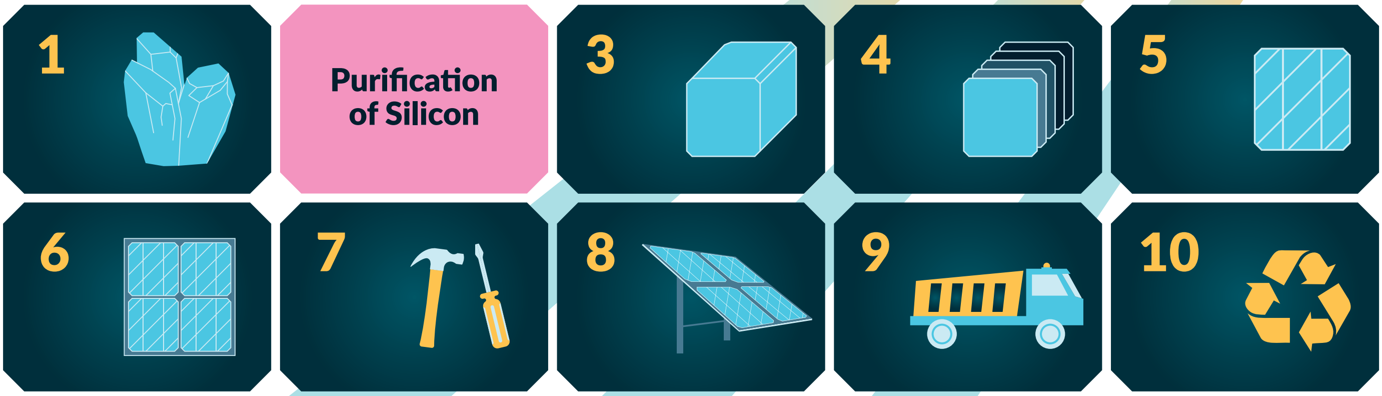

STEP 2 - PURIFICATION OF SILICON

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**

0.35
Water (in m^3)

49
Electricity (in kWh)

28.80
Heat (in MJ)

1.13
MG-Si (in kg)

2
Chemicals (in kg)

OUTPUTS

88.1
Emissions of CO_2 equivalent per watt (in g)

Chlorinated products

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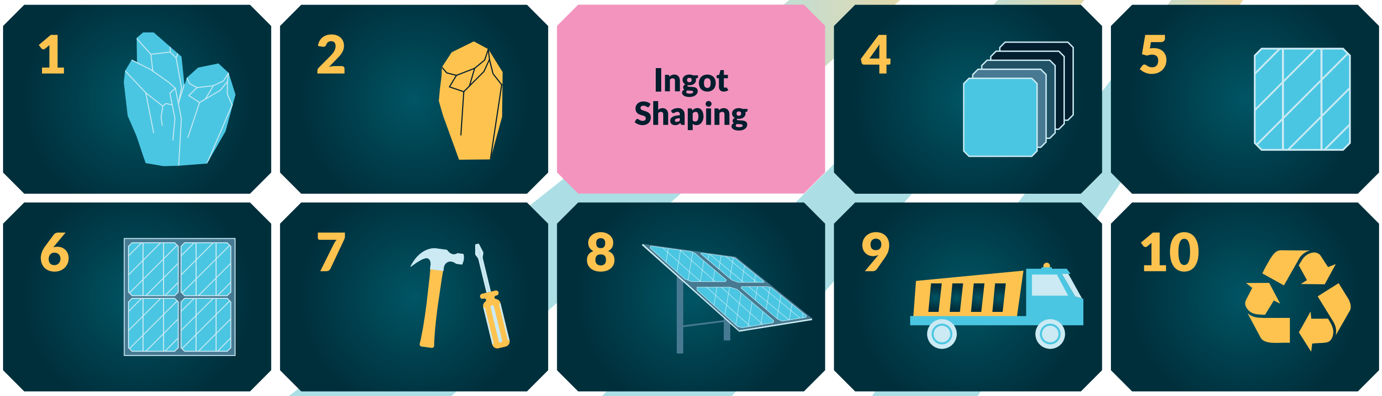

STEP 3 - INGOT SHAPING

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 CO_2 equivalent per watt (in g)

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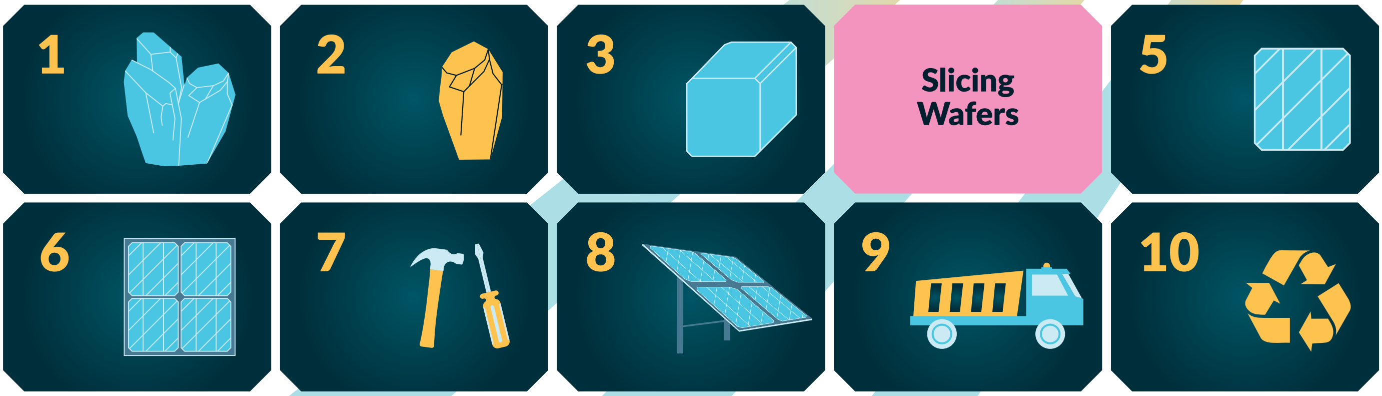

STEP 4 - SLICING WAFERS

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 CO_2 equivalent per watt (in g)

Silicon powder, slurry

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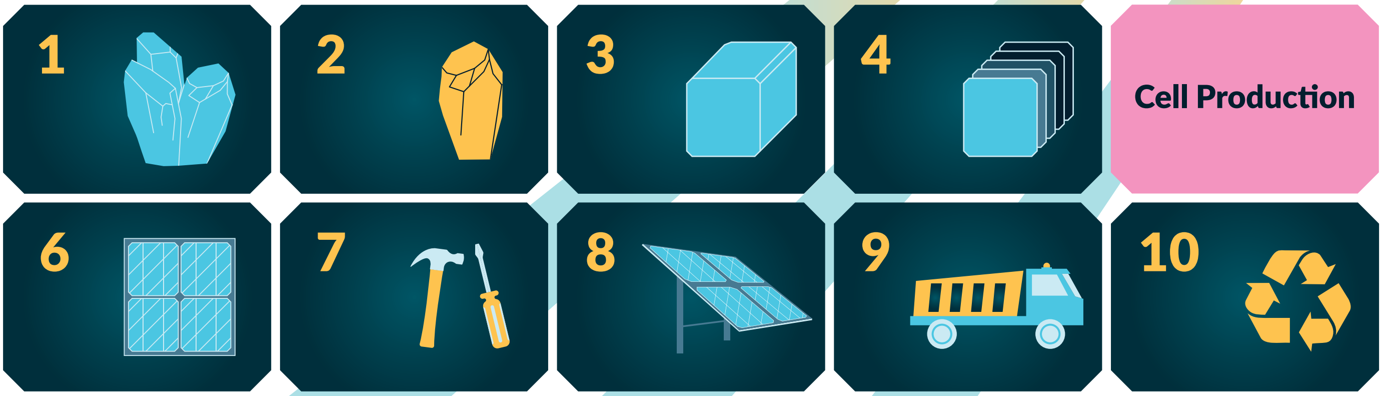

STEP 5 - CELL PRODUCTION

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:**

0.17
Water (in m³)

17.7
Electricity (in kWh)

1.86
Various chemical elements (in kg)

OUTPUTS

73.6
Emissions of CO_2 equivalent per watt (in g)

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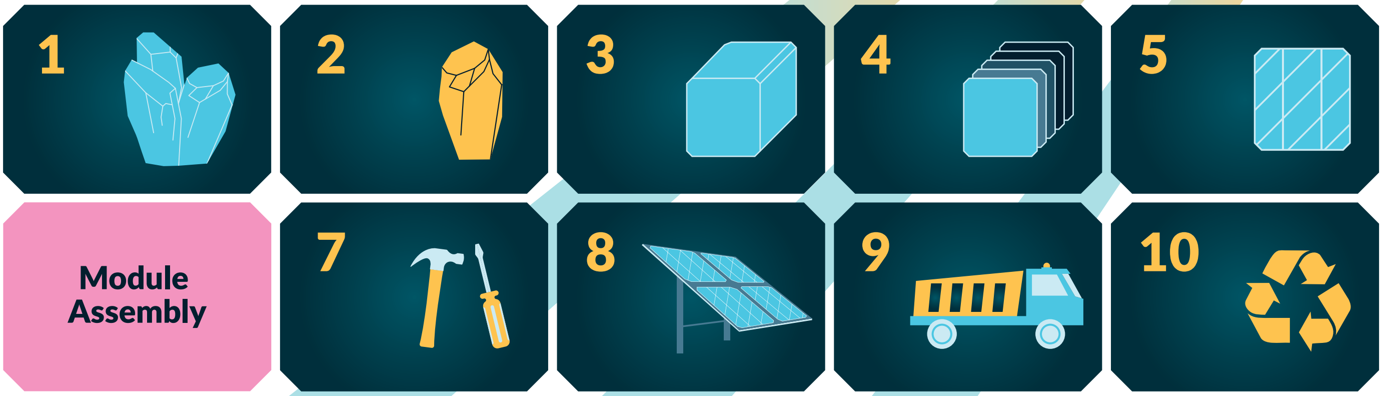

STEP 6 - MODULE ASSEMBLY

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 m^2)

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 m^2 of modules**

- 0.005 — Water (in m^3)
- 14 — Electricity (in kWh)
- 17.62 — Solar glass (in kg)
- 2.13 — Aluminum (in kg)

OUTPUTS

- 226 — Emissions of CO_2 equivalent per watt (in g)

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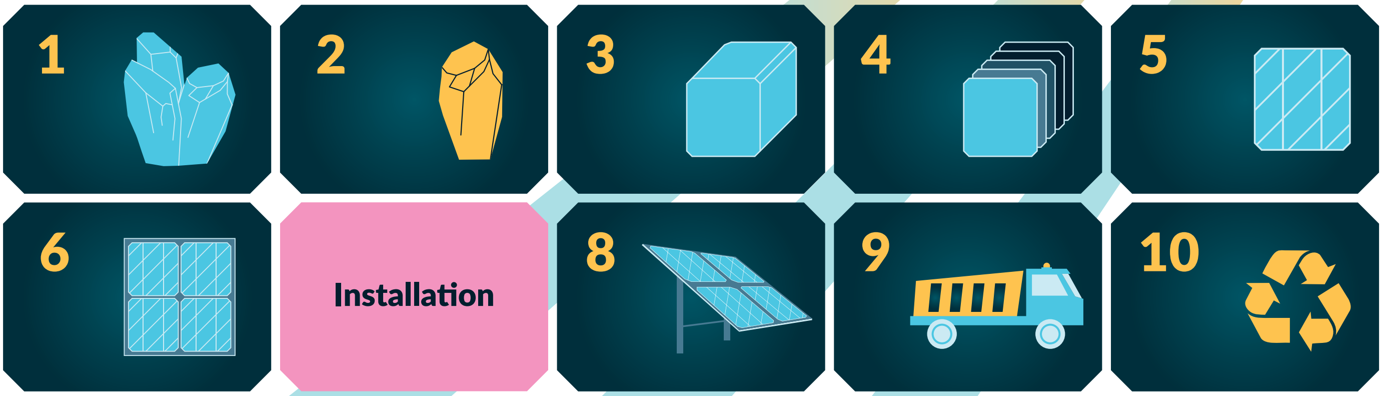

STEP 7 - INSTALLATION

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 CO_2 equivalent per watt (in g)

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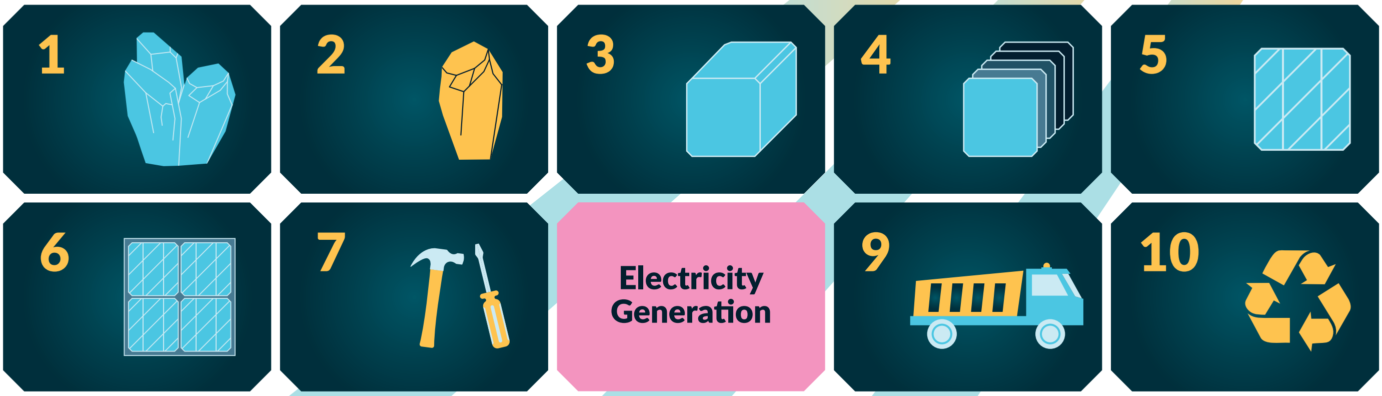

STEP 8 - ELECTRICITY GENERATION

OBJECTIVES

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

PROCESSES

- **Suitable electric connections**
- **Maintenance of facilities**

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**

INPUTS

- **Consumes very little energy** (except for maintenance)

OUTPUTS

- **No CO_2 emissions**

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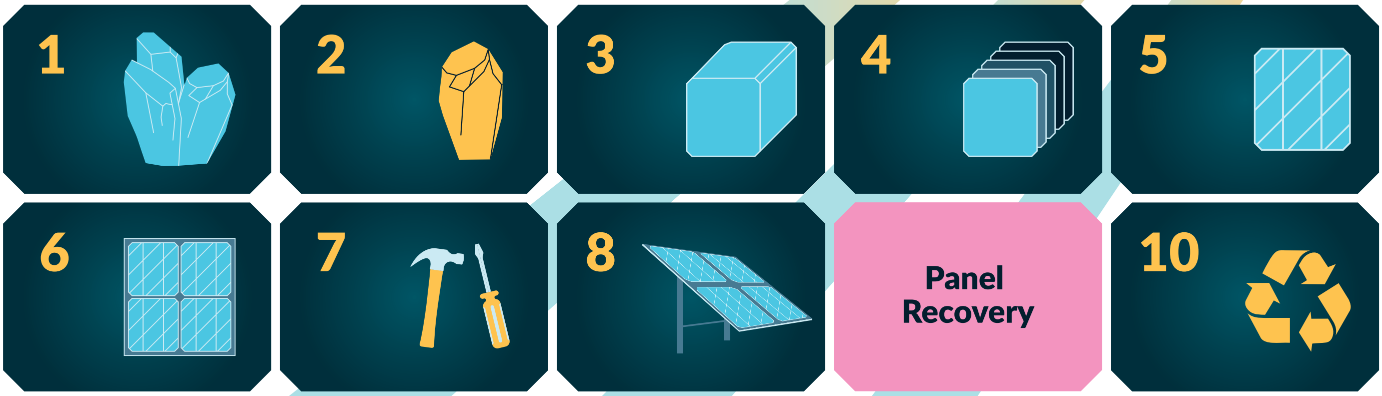

STEP 9 - PANEL RECOVERY

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 CO_2 equivalent per watt for the last two **steps 9 and 10:**

- **Collection and recycling of used panels**

382

Emissions of CO_2 equivalent per watt (in g)

- **Recovery of 94% of the materials** means that emissions estimated at **-124 g CO_2eq/W can be deducted from the final energy balance**

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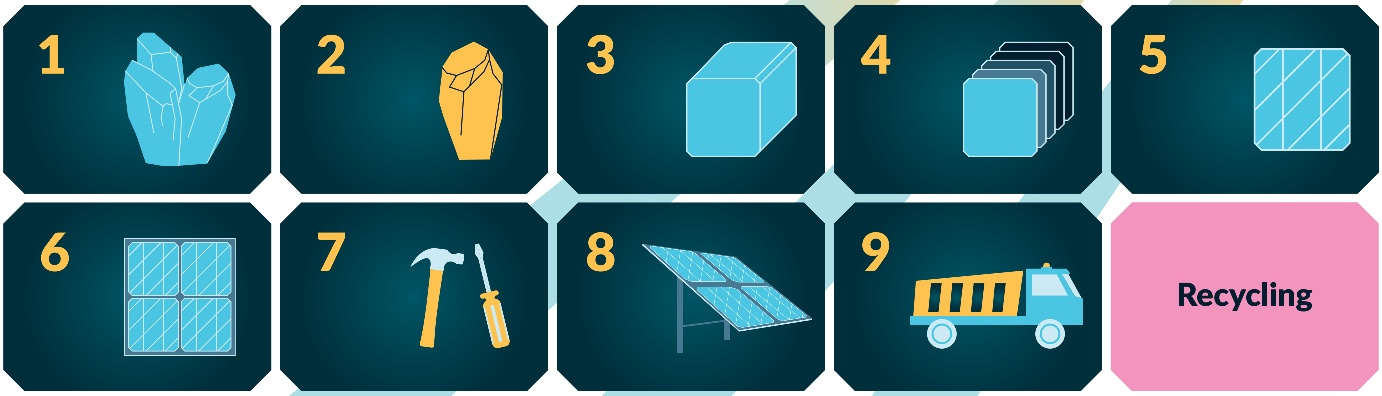

STEP 10 - RECYCLING

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

Electricity (in kWh)

Various chemicals (in kg)

- 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 CO_2 equivalent per watt for the last two **steps 9 and 10:**

- **Collection and recycling of used panels**

382

Emissions of CO_2 equivalent per watt (in g)

- **Recovery of 94% of the materials** means that emissions estimated at **-124 g CO_2eq/W can be deducted from the final energy balance**

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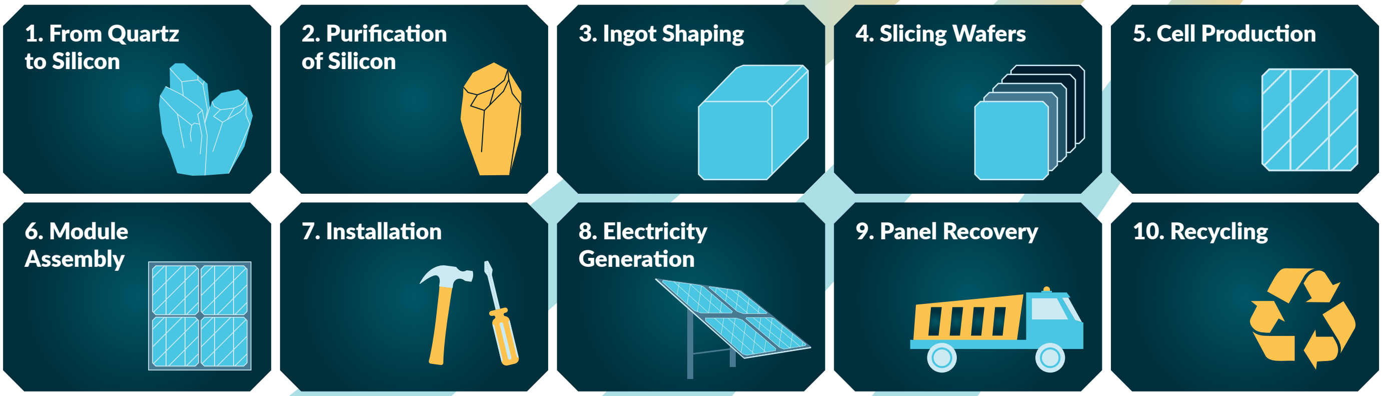

THE ENERGY BALANCE

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.

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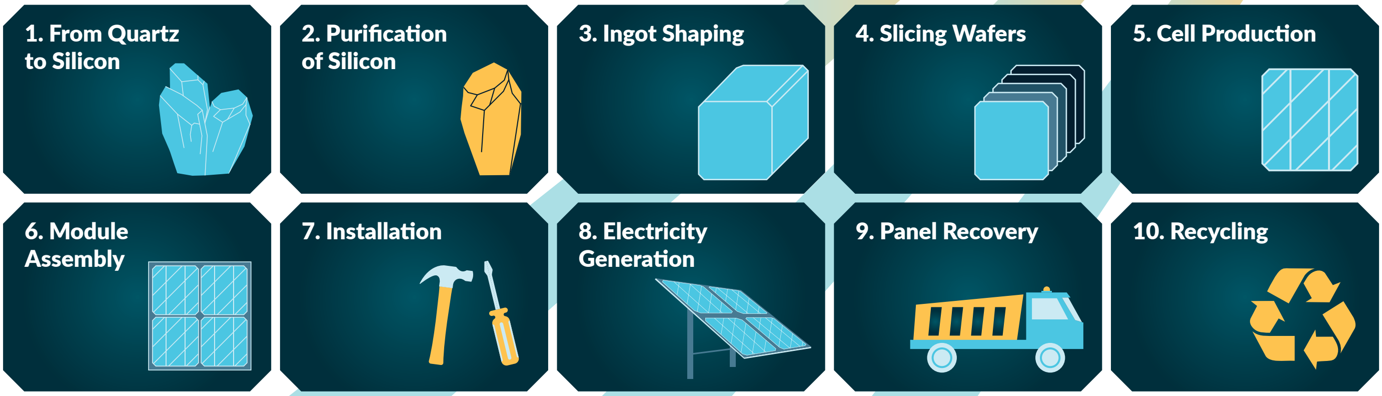

THE CARBON FOOTPRINT

1. **The carbon footprint corresponds to the amount of greenhouse gases emitted** during the lifecycle of a product and expressed as CO_2 equivalent (gCO_2eq).

2. **In France, for systems fitted with Chinese photovoltaic panels, the standard value is 43.9 gCO_2eq/kWh produced.** By way of comparison, a gas power station emits almost 500gCO_2eq/kWh. The figure drops to 32.3 gCO_2eq/kWh for European panels, and to 25.2 gCO_2eq/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.