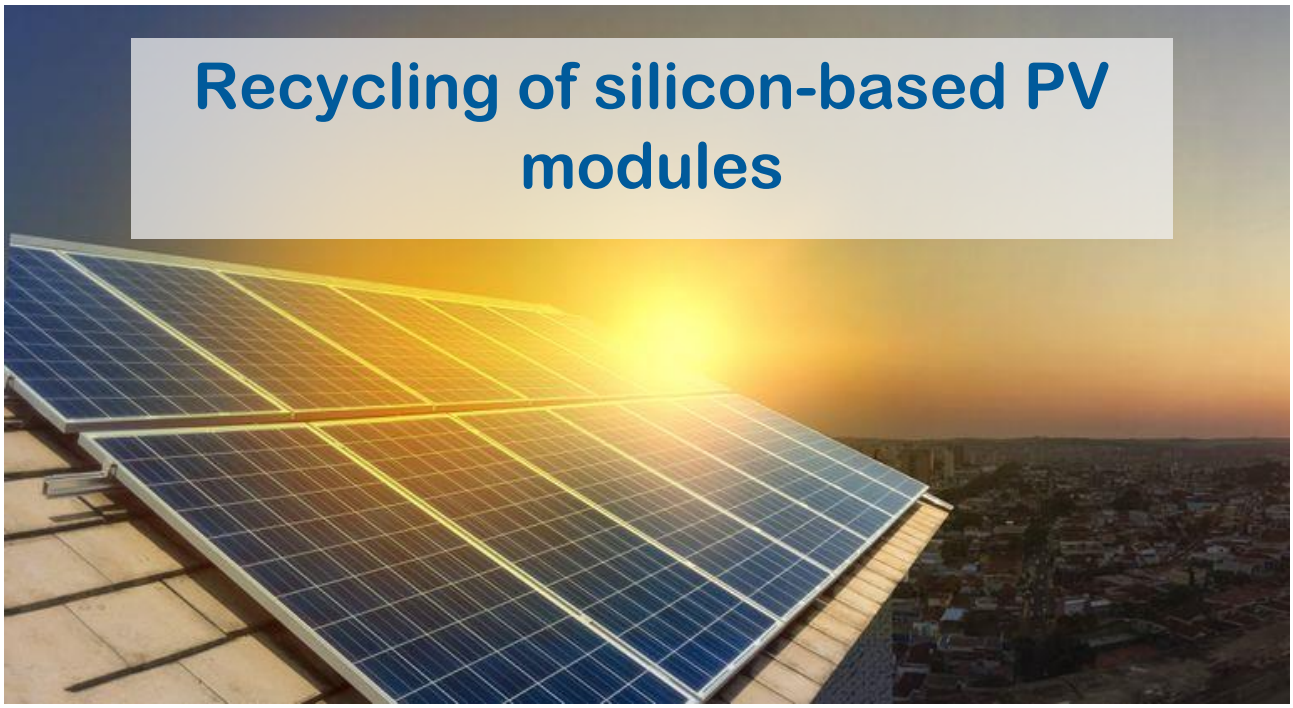
Teachers' Card

Recycling of silicon-based PV modules



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General Introduction

Renewable energy, or also called clean energy, is defined as the type of energy coming from natural sources that are constantly replenished. The renewable sources are sunlight, wind, geothermal activity, water, biomass, tides and waves.

The solar energy comprises the photovoltaic energy, namely the exploitation of sunlight to produce electricity, thanks to the photovoltaic panels usually installed on the roofs of buildings. Photovoltaic panels have a lifetime of more than 30 years, after which they can be disassembled and recycled.

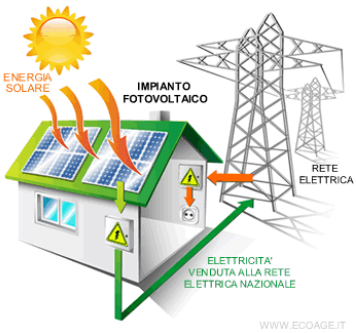
The proposed laboratory activity is designed for pupils aged 14 years old and over. During this activity, pupils are first introduced to the topic of solar photovoltaic (PV) understanding the basic principles about the composition of panels and the importance of the recycling processes. The experience is composed of one module, where students will assemble and disassemble a photovoltaic mini-panel with the use of high temperature, simulating the thermal recycling process of silicon PV panels.

Key words:

Photovoltaic, Sustainability, Recycling, Recovery, Critical Raw Materials

Extended background information

In the year 2020, photovoltaic (PV) was the first most installed renewable energy source[1]. Several are the reasons of the success of the photovoltaic technology: its safeness, the spread availability of sunlight around the globe, its reliability, non-polluting, the possibility to be placed where electricity is required.



What does the word "photovoltaic" mean?

The term *photovoltaic* comes from the joining of two words: the Greek word "phos" meaning "light", and the last name of the physicist Alessandro "Volta" who invented the battery, in reference to electricity.[3] In fact, a photovoltaic panel is a device that can convert sunlight into electric current. In particular, light excites the electrons inside the material, that move out of the device and produce usable electric current.

How many types of photovoltaic panels exist?

Solar panels can be divided into two main types: silicon panels and thin-film panels. The silicon panels are made of crystalline silicon c-Si ("crystalline" means that all the atoms are placed in an ordered matrix - imagine a diamond made of silicon atoms instead of carbon), while thin-film panels are made of

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compounds such as CdTe, $Cu(Ga,In)Se_2$ (CIGS) or based on amorphous silicon. The main difference between the two types is related to how they absorb sunlight: silicon absorbs less light than thin-film compounds for the same thickness of material, requiring the use of a thicker material in silicon panels than in thin-film panels. However, both are good options for the production of electricity. In 2019, the market was dominated by the silicon-based c-Si panels, which accounted for a more that 95% share, while the remaining part consisted in thin-films panels.[5]

Why are the most installed panels made of Silicon?

The success of silicon panels is due to the unique properties of silicon, that hardly can be rivalled in future. First, silicon is one of the most abundant elements compared to other elements on Earth: there is not any risk of shortage. Also, it is not toxic and so can be treated and worked without any danger. Another good point in its favour is the very well-established production method. For decades, industries and universities have been researched silicon for microelectronic applications with the purpose of improving our knowledge on such material. For this reason, the Si solar panels have high efficiency and have a long lifetime of 30 years.[6]

Why recycling Si solar panels?

We said that silicon is one of the most abundant elements on Earth, so why recycling Si solar panels?

Many are the reasons of its recycling. As it will be learned with this lab experience, Si panels are not just made of Silicon. They contain other raw materials as aluminium and silver. In particular, silver (its chemical nomenclature is Ag) is an extremely necessary and expensive material because it is economically and strategically important for the quality of life in Europe and, because of that, there could be high supply-risk in future. As shown in *Figure 1*, Ag is used in other electrical applications, such as fuel cells, robotics, drones and Information and Communications Technology (ICT). Furthermore, it has been estimated that the 56% of the Ag usage is addressed to PV technology. Therefore, recycling PV panels is beneficial for the Europe economy that can supply part of the total Ag needed for the devices.

Another reason is related to the possibility to exploit such end-of-life devices to produce new panels, using silicon as secondary raw materials and therefore lowering the price of production of Si PV panels. The energy payback time (EPBT) is the required period for an energy production system to generate the same quantity of energy used to make it. Among several parameters, the calculation of the EPBT considers the location of the installed PV panels because of the amount of light reaching the panels throughout the year. Generally, in northern Europe a PV systems needs around 1.5 years to balance the input energy, while PV systems in the South equal their energy input after 1 year and less. It was estimated that EPBT for different types of technologies is around one year: 1.5 years for c-Si, 1.0 years for CIGS panels and 1.0 years for CdTe [7]. Using recycled materials, the EPBT lowers, lowering the price of the PV panels.

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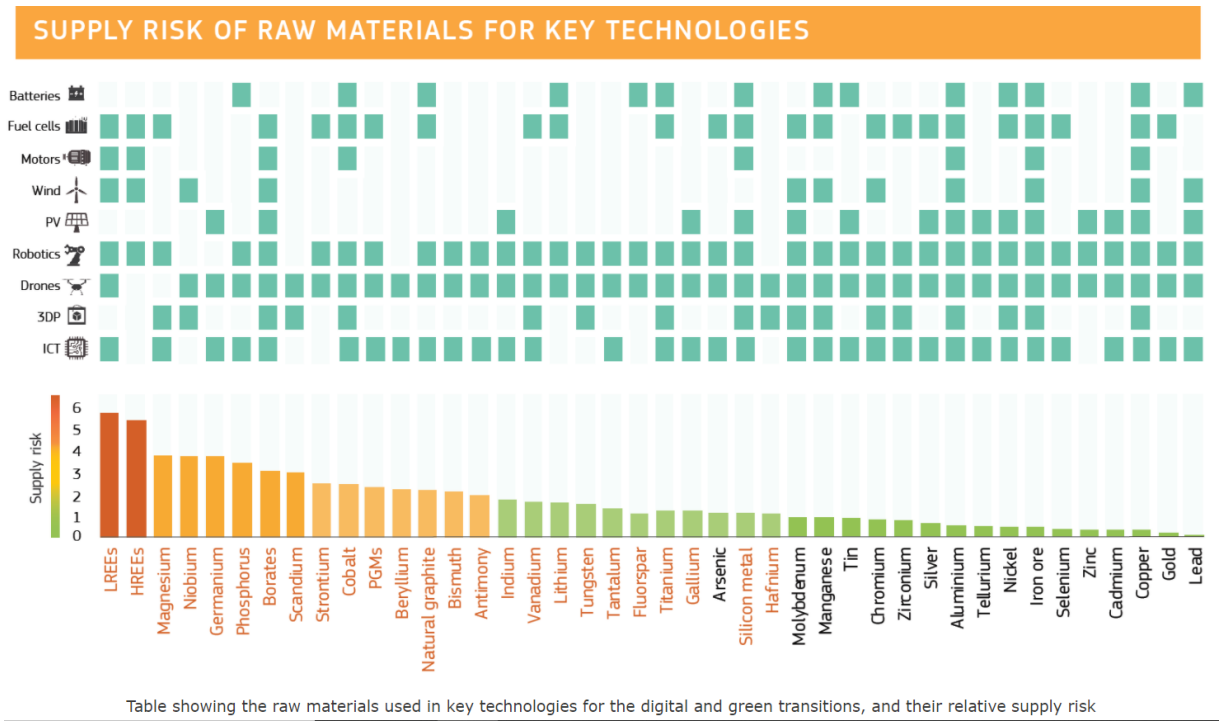

Figure 1: Below, the supply risk of important elements for modern technologies in a colour scale from green (no supply risk) to red (high supply risk). In the upper part of the figure, the applications of such elements in the modern technologies.

Glossary

PV = abbreviation of the word photovoltaic

Si = chemical nomenclature related to Silicon

CdTe = cadmium telluride (molecule made of Cadmium and Tellurium)

$Cu(In,Ga)Se_2$ = molecule made of four atoms: Cu = Copper, In = Indium, Ga = Gallium, Se = Selenium.

Learning Outcomes

A learning outcome is the specification of what a student should learn as a result of a lesson or course, and for this purpose

- Learning about the photovoltaic energy
- To be introduced to the concept of silicon PV panels
- To be introduced to the importance of the recovery of materials
- To be aware of the importance of recycling end-of-life PV modules

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Key Competence European Framework

Literacy competence
S4. Ability to interact in an appropriate and creative way in any situation.
Multilingual competence
S7. Ability to use technical language accordingly to the field of work.
Mathematical competence and competence in science, technology and engineering
S8. Ability to design experimental and observational studies and analyse data resulting from them.
Citizen competence
S3. Ability to work effectively and collaborate with other team members

United Nations' Sustainable Development Goals

The Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice.

	1 NO POVERTY, 2 ZERO HUNGER — Enable access to basic services		10 REDUCED INEQUALITIES — Equal access to global expertise
	3 GOOD HEALTH AND WELL-BEING — Safe medical devices	✓	11 SUSTAINABLE CITIES AND COMMUNITIES — Sustainable urbanization
	4 QUALITY EDUCATION — Access to education	✓	12 RESPONSIBLE CONSUMPTION AND PRODUCTION — Responsible consumption and production
	5 GENDER EQUALITY — Less hardship, more opportunities	✓	13 CLIMATE ACTION — Strengthen resilience, reduce disaster impact
	6 CLEAN WATER AND SANITATION — Safe and affordable water		14 LIFE BELOW WATER — Reduce marine pollution
✓	7 AFFORDABLE AND CLEAN ENERGY — Energy – the golden thread	✓	15 LIFE ON LAND — Sustainable use of terrestrial ecosystems

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	8 DECENT WORK AND ECONOMIC GROWTH — Safety of workers and economic growth		16 PEACE, JUSTICE AND STRONG INSTITUTIONS — Promote peaceful and inclusive societies
✓	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE — Resilient infrastructure and sustainable industrialization		17 PARTNERSHIPS FOR THE GOALS — Better access to technology and innovation

Contents – Theoretical principles

In the last decades, the fast increase of the global energy demand and the progressive run-up in the world oil price, along with the growing global pollution and climate changes, pointed out the strong need of a cheap and sustainable clean energy supply. In the last fifteen years, all renewable energies grew strongly and, by the end of 2018, electricity generated from new wind and solar photovoltaic (PV) plants had become more economical than power from fossil fuel in many places. Moreover, in 2018 roughly 2.8% of the worldwide electricity came from solar PV, which was the main source of newly installed capacity in many countries, mainly in China, India, United States, Japan and Australia. One of the reasons behind such a development is the much lower CO_2 emission related to PV installations (23-81 gCO_2-eq/kWh) with respect to electricity generation from fossil fuel (400–1000 gCO_2-eq/kWh). Together with the increase in installations, however, the number of solar panels reaching their end-of-life (EoL) stage will increase steadily, with an estimated peak of cumulative PV waste around 900'000 tons/year by 2042. According to a recent EU Commission decision, PV panels are included into the new Waste of Electrical and Electronic Equipment (WEEE) directive, the legislation that regulates the recycling of electronic wastes. Basing on this principle, PV panel manufacturers and distributors have to ensure the right collection and recovery of EoL products within the European borders. This is a very important achievement for several reasons, first of all because presently PV waste recycling is legally regulated only in Europe. Moreover, large scale recycling can ensure both a long term sustainability of the supply chain and a shortening of both the energy and the greenhouse-gas payback times related to the PV manufacture. Last but not least, the use of recycled materials in PV production may improve economics by providing a less expensive feedstock supply. From a general point of view, providing a sustainable supply of raw materials is vital, since the EU is highly dependent on imports of many raw materials.

The minimum recovery for any EU WEEE is 80% by weight, which for solar panels (see Figure 1 for a sketch) is obtained by the only recycling of glass and aluminium (see Table 1). However, the residual panel components (e.g. silicon, silver, copper), despite the light weight, cover more than 75% of the recycling panel potential value (see Table 1). In 2045, the cumulative value of the recycled Si market would be of the order of 2.5 billion € (<10 $/kg), while the recycling of other elements (e.g. silver) could be estimated around 500 million €/year. At present, aluminium, glasses and silicon are mainly recycled through thermal, mechanical and chemical methods. In particular, after pre-disassembly for removal of the metal frames and terminal boxes from the modules, processes for PV module recycling can be roughly divided into eliminating encapsulant from laminated structure and recovering metals from the Si cell. Eliminating the encapsulant from the laminated structure (i.e. delaminating) is the most difficult process and the most important target of recycling technology R&D. As a process for eliminating the encapsulant from the

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laminated structures, thermal, mechanical, and chemical approaches can be used. The thermal approach is a combustion process; the expected materials recovered are glass, Si cells, and electrode ribbons. Under certain conditions, glass and Si cells can be recovered without breakage, which represents the benefits of this approach, as is the expected higher value of the recovered materials for recycling. If the cells have flaws such as edge chipping and/or micro-cracks they typically cannot be recycled into an intact wafer and would be allocated as Si raw materials. All mechanical technologies (i.e. cutting, crushing and grinding) are basically combined with a post-treatment step, typically a chemical treatment, to separate Si cells and other metals from the remaining mixture. It should be remarked that a mechanical process will consume less energy compared to a thermal process at temperatures up to 450°C. Finally, despite metals are presently recovered by chemical methods, new technologies are being developed to get greater sustainability.

Panel component	Weight (kg)	Weight (%)	€ per kg	Value (€)	Value (%)
Glass	14.7	72.6%	0.05	0.74	5,8%
Aluminium	2.5	12.3%	1	2.5	20%
Silicon	0.61	3.0%	10	6.1	48%
Silver	0.0066	0.03%	500	3.3	26,2%
Other	2.44	12.2%	-	-	-
Total	20.3	100%		12.6	100%

Table 1. Weight and cost of the different PV panel components.

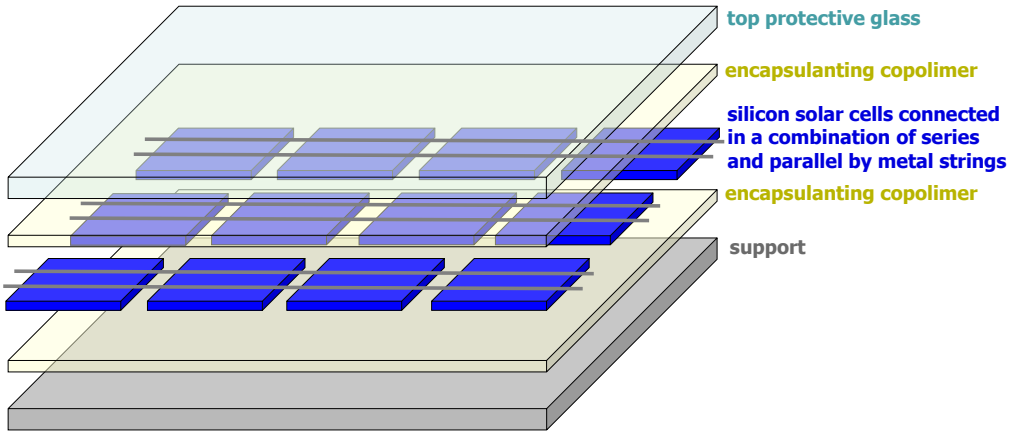

Figure 1. Sketch of a PV panel.

All this considering, the industrial processes involved in both the assembling and disassembling of a PV panel cannot take place in an ordinary classroom or school lab, first of all due to the large size and weight of a PV module. Furthermore, several high temperature steps are involved both in the assembling and disassembling of PV panels: for instance, curing and fast curing of the encapsulating copolymer Ethylene Vinyl Acetate (EVA) usually take place between 140 and 150°C (assembling), while, as mentioned above, the thermal removal of EVA requires annealing at temperature higher than 450°C (disassembling). Conversely, the preparation of a simple mini-module like that reported in Figure 2 is compatible with an ordinary classroom or school lab. As well, the simplified procedure reported during this lab experience enables students to disassemble the mini-module after preparation, partially mimicking a recycling process.

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Nevertheless, it should be noted that the simplified procedure leads just to an EVA softening which allows to roughly detach EVA from glass and silicon.

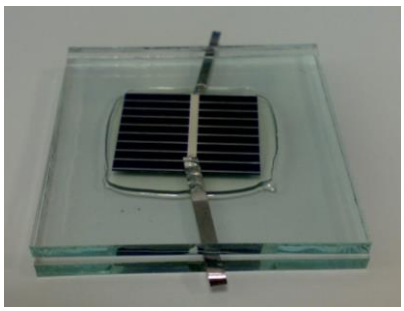

Figure 2. Picture of a silicon mini-module for education purposes (including 2 glass slices 5x5 cm^2, 2 EVA sheets 3x3 cm^2, 1 silicon PV cell 2.5x2 cm^2).

Lab Procedure/Activity

The laboratory activity is composed of one module, where pupils will assemble and then disassemble a photovoltaic mini-panel with the use of high temperature. For this reason, heat-resistant gloves are necessary to handle hot instruments.

Module 1 - Extraction of Recycling of silicon-based PV modules

Learning Pathway

Step 1- Time & Activity: - 60 min – Teachers give a short introduction with a prepared PowerPoint presentation about PV energy and silicon PV modules. To understand the level of knowledge about this topic, the Kahoot! quiz can be used at link: https://create.kahoot.it/details/0f466b52-990a-41a0-9487-67da56b7ebcb

Step 2 – Time& Activity: 30 minutes- Students are divided into groups (preferably the number of students in one group is 3-4) and start the lab activity, disassembling and assembling a silicon PV module.

Step 3 – Time & Activity: 40 min - follow-up: Teachers give a presentation about the state of the art about the silicon PV panels, their end-of-life and recycling processes using the sources (the given powerpoints)

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Evaluation

1. **How can a photovoltaic panel produce electric current?**
   A photovoltaic panel produces electricity thanks to the photovoltaic effect, where the photons (in the light) hit the device and excites electrons of the materials that move out of the panels (the electric current is given by the electronic motion along the same direction).
2. **CO_2 emissions related to PV installations are higher or lower with respect to electricity generation from fossil fuel? How much?**
   One of the reasons behind the strong development of solar PV is the much lower CO_2 emission related to PV installations (23-81 gCO_2-eq/kWh) with respect to electricity generation from fossil fuel (400–1000 gCO_2-eq/kWh).
3. **Are PV panels WEEE? Are PV panels WEEE? What does it mean?**
   EU Commission recently included PV panels into the new Waste of Electrical and Electronic Equipment (WEEE) directive, the legislation that regulates the recycling of electronic wastes. This is a very important achievement for several reasons, first of all because presently PV waste recycling is legally regulated only in Europe. Basing on the WEEE directive, PV panel manufacturers and distributors have to ensure the right collection and recovery of end-of-life products within the European borders.
4. **What are the advantages of a proper recycling of PV wastes?**
   A proper recycling of PV wastes not only can ensure a long-term sustainability of the supply chain but also a shortening of both the energy and the greenhouse-gas payback times related to the PV manufacture. Last but not least, the use of recycled materials in the PV production may improve economics by providing a less expensive feedstock supply.
5. **Are high temperature steps involved in the industrial processes for assembling and disassembling of PV panels?**
   Yes, they are. Curing and fast curing of the encapsulating copolymer Ethylene Vinyl Acetate (EVA) usually take place between 140 and 150°C (assembling), while the thermal removal of EVA requires annealing at temperature higher than 450°C (disassembling).
6. **Is the economic potential value of the recycling panel high or low? What are the most precious elements in the recycling panel?**
   The economic potential value of the recycling panel is high. Silicon, silver and copper, despite the light weight, cover more than 75% of the recycling panel potential value. Aluminium is a further element with moderately high economic value.

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Description of Student's Cards

Students' Cards is materials that can be printed and directly distributed to students before the activity.

Student's Card 1 – Recycling silicon-based PV modules

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