# The 'glass route' for improving the sustainability of photovoltaic technology

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At the end of 2023, the total installed photovoltaic (PV) power capacity globally reached almost 1.6 $TW_p$, and in 2050, the installed capacity is expected to be more than 8 TW (IRENA, 2019). This trend of increasing the number of solar power capacity installations requires the adaptation of generators to different environments and shapes. Photovoltaic technology will be a main contributor, and together with the big utility plants, they also must be adapted for application in already industrialised and/or urbanised areas such as industrial estates, farmland, residential areas and even the interior of buildings.

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## Energy sovereignty and transition in Europe

After the last two major crises, the COVID-19 pandemic and the war in Ukraine, the need to maintain energy and industrial sovereignty in Europe has been pointed out as almost an emergency after the increasing risk of losing power capacity for the industry (especially German industry), a fact that was a real possibility during the winter of 2022. Europe realised that it needed to reinstall power capacity, and the best way to do so sustainably is to reduce fossil fuel consumption and install more renewable capacity.

The energy system is responsible for 75% of the EU's greenhouse gas emissions. Therefore, one of the priorities is the transition towards an energy system based on renewable sources. A massive deployment of photovoltaic energy, such as that proposed by the REPowerEU Plan, will reduce 4.9 gigatonnes of carbon dioxide (Gt $CO_2$) emissions by 2050, which represents 21% of the total mitigation potential of the emissions in the energy sector (European Commission, 2022).

Furthermore, greater direct electrification of end-use sectors is necessary, given that the electricity sector will have the largest share of renewables. This implies bringing the use of renewable technologies closer to society: in buildings, in transportation, in small appliances or IoT sensors, in agrivoltaic systems, etc.

## Sustainability and technological innovations in photovoltaic modules

In all these new environments, the standard PV modules (increasingly of larger size) can be adapted for roof-top or small façade size systems, but if the market possibilities are to be extended for new applications, technological alternatives must be explored, not only regarding the active layer of the photovoltaic cell, but also all other components of the module, and with special attention to the glass cover.

Solar PV energy, thanks to its characteristics of distributed generation capacity, abundance, cost and efficiency, is the technology with the best growth prospects to meet the objectives of renewable energy penetration in the whole range of applications. Additionally, for solar PV manufacturing technology, it is now considered necessary to install in Europe part of the production capacity that is now predominantly carried out in Asia, as shown in Figure 1, where the strong dependency on Asian production is evident, with China dominating the market with more than 77% of the share (International Energy Agency, 2023).

The sustainability of the future European energy system will strongly depend on two factors: the electricity mix (in a future of increasing electrification of energy consumption) and the environmental and human health impacts of the newly installed capacity (impacts in different categories per kWh produced and consumed in Europe). Renewable energies have been assumed to have lower impacts than fossil fuels, and the detailed quantification of those impacts by life cycle assessment studies in the past decades has confirmed this expectation.

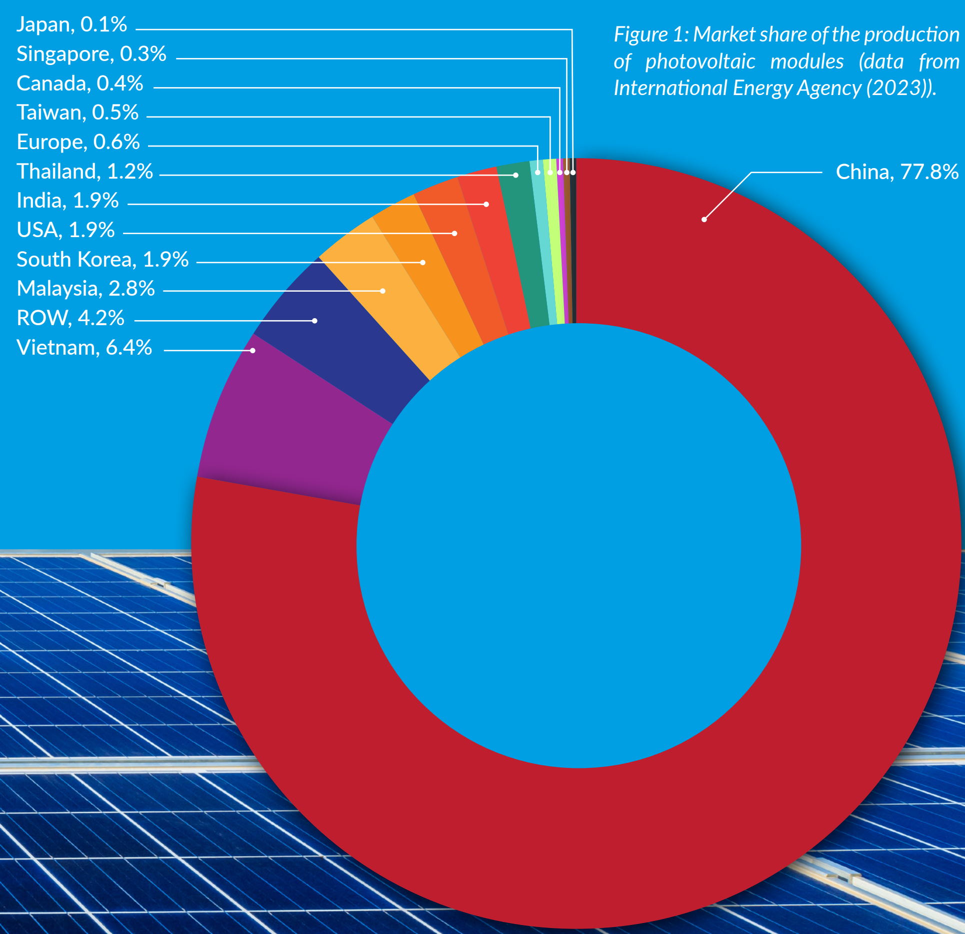


*Figure 1: Market share of the production of photovoltaic modules (data from International Energy Agency (2023)).*

Figure 2 shows an example of impact reduction by comparing the $CO_{2eq}$ (g/kWh) emissions of various energy sources. These sources include several photovoltaic technologies, other renewable energies, fossil fuels (carbon or natural gas, with and without carbon capture and storage) and nuclear energy. Despite the big uncertainties surrounding new nuclear capacity, its greenhouse gas emissions are low and comparable to the lowest renewable energies; the problem of nuclear residues and potential risks have not been included in this calculation (Urbina, 2023).

## Advances in glass technology for PV modules

Photovoltaic technology, especially crystalline silicon (c-Si) technology, is at a highly mature stage. The manufacturing process is optimised, delivering solar modules with a high power conversion efficiency. However, there is still some room for improvement from the actual 27.6% to the single-junction Shockley-Queisser limit of 33.7%, although this increment will come with an increasing technological difficulty. The reduction of embedded emissions in module fabrication and the simultaneous increment in electricity produced during its lifetime by extending the module's operational time will provide a virtuous cycle in which the sustainability of photovoltaic electricity will grow in the coming years.

In our ION4PV project, we are exploring a route in which the embedded emissions of the PV module can be reduced without relying on the very difficult task of increasing power conversion efficiency. The objective is achieved by improving the properties of glass produced for PV modules, a complex and crucial aspect of our research.

Once a solar cell has been manufactured, the assembly of a photovoltaic module requires a significant amount of materials, with the cover glass contributing considerably to the environmental impacts and the overall economic cost. The prevailing cover material for PV modules is 3-mm-thick soda-lime-silica (SLS) glass, representing 10% to 25% of the total cost (Allsopp *et al.*, 2020).

Research is being carried out with the aim of reducing the thickness of the glass, taking a direct approach to lower embedded emissions, reducing its weight and providing limited flexibility to the glass pane. However, reducing the thickness of flat glass has proven a difficult task; it is essential to enhance the mechanical properties of the glass to achieve a thickness reduction below 3 mm without increasing the risk of breaking.

Glass accounts for approximately 75% of the weight of a framed crystalline silicon module and exceeds 95% in a frameless thin film module (Wambach, Heath and Libby, 2017). The strength and toughness of flat glass are primarily influenced by surface properties rather than the bulk characteristics of the glass. The most used strategies to increase glass strength are thermal or relaxational toughening and chemical (ion-exchange) toughening. The addition of ions provides additional benefits with regards to its optical properties for PV applications. Using iron oxides incorporated into the glass for UV filtering functions unavoidably results in absorption in the visible ($Fe^{3+}$) and near-infrared bands ($Fe^{2+}$).

In contrast, initial outcomes with bismuth ($Bi_2O_3$) show good promise, demonstrating effective UV filtering capabilities while maintaining the glass free from absorption in both UV and IR bands. Despite this promising path, the production cost is two to six times higher than conventional thermally toughened glass, thus making it very challenging to get an alternative that can compete in the market.


*Figure 2: Life cycle greenhouse gas emissions (in grams $CO_{2eq}$ per kWh) of different electricity supply technologies, modelled for 1 kWh produced in Europe, comparing photovoltaic, other renewables, fossil fuel and nuclear technologies ($CO_2$ capture and storage [CCS], integrated gasification combined cycle [IGCC] and gravity-based [GB] foundation).*



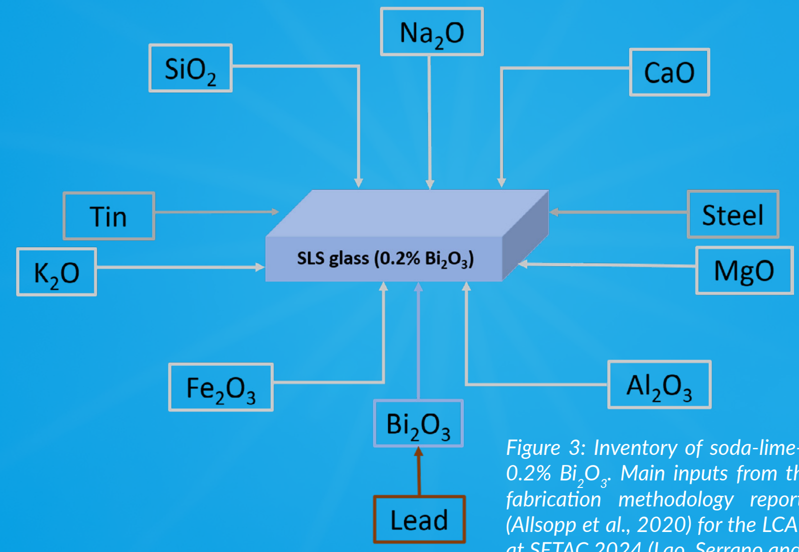


*Figure 3: Inventory of soda-lime-silica glass with 0.2% $Bi_2O_3$. Main inputs from the structure and fabrication methodology reported by Allsopp (Allsopp et al., 2020) for the LCA study presented at SETAC 2024 (Lao, Serrano and Urbina, 2024).*

In the project ION4PV, we have explored a double route for improving SLS glass for PV modules with enhanced optical functionality and extended lifetime:

i. inclusion of superficial $K^+$ ions by chemical doping, where the larger $K^+$ ions block the motion of $Na^+$ and avoid them escaping from the glass and contaminating the solar cell by potential ion degradation (PID) mechanism
ii. inclusion of $Bi_2O_3$ for a more efficient UV filtering and durability of the solar cell and plastic encapsulants.

A detailed life cycle assessment (LCA) study has been carried out according to standards ISO14040 and ISO14044 and includes a detailed life cycle inventory (see Figure 3 for the main substances entering the manufacturing process of the new proposed glass composition). The LCA provides a global environmental evaluation of the improvements that can be achieved with the proposed approaches for "glass for PV" production methods.

Despite bismuth becoming an auspicious material not only for this specific application but for many others, such as battery electrodes or optoelectronic devices, it is still considered a secondary product since it is a co-product of lead mining and its purification process; this fact makes the inventories more complex and does not facilitate a clear roadmap for bismuth industrial production.

Globally, although the improvement of glass for PV applications is more expensive than currently used flat SLS 3 mm thick glass, it could be beneficial in the long run as the glass becomes more resistant, potentially lasting longer and extending PV module lifetime by reducing potential induced degradation and exhibiting improved efficiencies by enhancing its optical properties with $Bi_2O_3$. It is a clear path to increase the sustainability of future PV module production in Europe.

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### PROJECT NAME

Controlling ion dynamics in glass and plastic to reduce degradation and environmental impacts of photovoltaic modules (ION4PV).

### PROJECT SUMMARY

Building upon previous life cycle assessments of photovoltaic technologies, the sustainability of photovoltaic modules will be increased by improving the mechanical and optical properties of the glass and plastics (PET and EVA) used to manufacture the modules. The reduction of ion migration towards the active solar cell will extend the lifetime of the modules and facilitate its recyclability at the end of life. Bismuth oxide has been tested as a material to improve the properties of the glass cover.

### PROJECT PARTNERS

The project is being carried out at two Spanish universities that work in coordination: Universidad Pública de Navarra (UPNA, researchers: A. Urbina (PI), V. Sánchez-Alarcos, V. Recarte, J. I. Pérez-Landazábal and A. López-Ortega) and Universidad Rey Juan Carlos (URJC, researchers: L. Serrano (PI), B. Romero and B. Arredondo.

### PROJECT LEAD PROFILE

After working on the study of electronic transport in low-dimensional systems, A. Urbina has devoted the past few years to fundamental and applied research on photovoltaic systems. He was a postdoctoral researcher at the University of Wisconsin (Madison, USA), the University of Cambridge and Imperial College London. He is Professor of Physics at Universidad Pública de Navarra and has recently published the monographic book *Sustainable Solar Electricity* (2022, 317 pages) in Springer International Publishing (ISBN: 978-3-030-91770-8).

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### FUNDING

This research was funded by the Spanish Ministry of Science and Innovation : projects TED2021-132368A-C21 and TED2021-132368A-C22.