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MINI-REVIEW

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Critical materials and PV cells interconnection

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Abstract. Assessment of the critical nature of a material for an application is a relevant notion to anticipate supply issues for an application and a territory. To establish a list of the critical materials, we have developed an approach taking into account geological scarcity, deployment logistics and societal aspects. This article aims to apply this framework to photovoltaic (PV) module interconnection. We draw the conclusion that even if concerns of critical materials are focused on Silver (Ag) scarcity (on metallization part), interconnection materials such as Tin (Sn) and Bismuth (Bi) are even more critical, mainly due to their mostly dispersive uses. This leads us to a standard module conception analysis and emphasizes the interest of improving a more modularized PV module architecture in order to improve high value recycling. An example of such a conception is given with NICE concept. Another example offering a way to optimize metallization conception toward a less consuming pattern is also described.

Keywords: Critical material / photovoltaic module / architecture

1 Introduction and context

1.1 Energy transition means huge mineral demands

CO_2 equivalent emissions have reached 59 GT/year in 2019 while 2050 target for 1,5 °C global warming is 10 GT/year CO_2 equivalent [1]. The resulting climate change requires us to deeply modify our societies in order to maintain a viable [2] and sustainable [3,4] environment. One of the main pillars of this upheaval consists in decarbonizing our energy production mix and prevailing electricity as primary energy source. This massive electrification of our societies involves tremendous adaptations on industrial level with many products disappearing from our everyday life and other ones replacing them. This shift in demand will result in significant growth in certain sectors (e.g., electricity production and distribution for example) and new industrial sectors with a strong expansion (+25% electric vehicles in 2022 [5] and associated batteries, biofuels, +33% forecast between 2022 and 2027 in renewable heating [6]...). One of the main consequences of this revolution is the switch from fossil fuel demand to minerals, required by renewable energy sources. As they are also limited resources, their markets follow the same rules but with specificities due to their non-fuel nature (ability to recycle them, for instance).

1.2 PV sector is to boom

Photovoltaic (PV) sector is a well-established renewable energy source and is currently experiencing exponential growth (+26% in 2022 [7]). This trend on installed capacity is to go on until 2050 when it should encounter a logistical ceiling of around 70 TWp [8,9]. 2050 is the energy transition horizon but once achieved, this new industrial and social model has to be maintained. Module production capacity is expected to follow the same trend until 2050 and then could stagnate or follow periodic waves of module production [9]. Thus, the module production volume is projected to remain an order of magnitude higher than today.

However, a great challenge already arising at module production scale lies in the Ag scarcity and its volatile price [10,11], as shown in Figure 1. From another point of view, the impact of so many PV modules being manufactured is drawing more and more attention: for instance, [13] reports the greenhouse gas emissions scenarios related to the glass amount required for 60 TWp production.

All the previous elements do emphasize the need to assess the feasibility of such high production volumes and drastically improve their recyclability. This is necessary to mitigate their impacts on the environment and secure their supply of raw materials. The concept of critical materials is relevant to review innovations in PV modules in response to this rising challenge.

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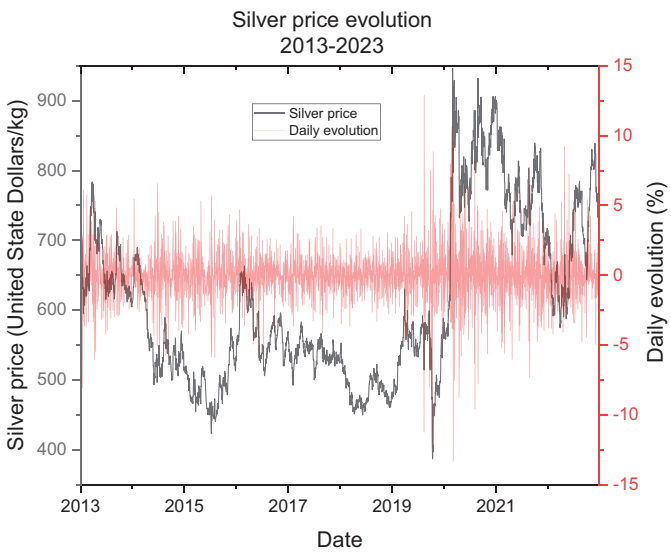

Fig. 1. Silver financial course from 2013 to 2023 and daily evolution on right axis, drawn from [12].

This article will first focus on critical material definition, then will present an application of this framework on PV module interconnection materials and finally review some interesting innovations from this point of view in the field of Silicium cell technology.

2 Critical material in PV interconnection

Many different raw material criticality definitions can be found from different sources, as it is open to question. That said, two points are common to almost every definition: economic and/or strategic importance and shortage hazards. Two definition examples are given below:

– From the European Commission [14] « materials that are the most important on economic level and present a high supply shortage hazard are called critical raw materials ».
– From the French Bureau of Geological and Mining Research (BRGM) [15] « Critical metal: remarkable properties metal that can trigger great industrial or economical negative impacts linked to difficult supply, prone to risks ».

Literature offers different sets of criteria and indicators to take into account [16] leading to different conclusions on the criticality of a material. No consensus seems to have yet arisen to define influencing factors on criticality. For this study, five supply hazard criteria are selected as a frame of reference in order to represent accurately each material supply situation: geological, logistical, industrial, geopolitical, and commercial. One has to keep in mind that triggering one of these criteria may initiate a domino effect on the others.

The scope of this study will encompass the most classical materials in PV interconnection and PV cells metallization at commercialization or R&D steps. Figure 2 presents these different materials in PV modules. Metallization is commonly made of Ag flakes in serigraphy paste but a possible alternative for Ag may be Copper (Cu) – due to being the second most conductive element –, with a Nickel (Ni) barrier layer if electroplated onto the cell surface. Aluminum (Al) could also be another candidate to replace Ag, given its high conductivity. Connectors are Cu ribbons or wires with Ag or solder alloy coating. Bonding between the metallization on the cell surface and the connector is made by means of soldering technology, which needs a soldering alloy. Low-temperature (<200 °C) alloys suitable for temperature sensitive cell technologies such as Silicon HeteroJunction (SHJ) or emerging Perovskite/Silicon tandem cells are usually made from Sn and Lead (Pb) or SnAgCu or Sn with Indium (In) alloys. The reader may refer to Table 1 for typical liquidus temperatures of such alloys. For toxicity reasons, Pb is to be substituted by Bi in these low-temperature soldering alloys to align with other electronic sectors already compliant with REACH regulations [19]. An alternative to soldering consists in using Electrically Conductive Adhesive (ECA), made from Ag or Cu.

This leads to narrow the scope of this study to the following materials: Ag, Al, Bi, Cu, In, Ni, and Sn.

2.1 Geological scarcity in the light of demand

For [10], Ag, In and Bi scarcity will limit drastically PV deployment whatever the cell technology mix is between Passivated Emitter and Rear Cell (PERC), Tunnel Oxide Passivated CONntact (TOPCon), and SHJ. Figure 3 presents estimations of the cumulative needs for various materials as well as the contribution of PV. Bi reserves volume is not estimated by USGS since 2017 as it is only produced as byproduct of Pb, Zinc or Tungsten [21]. According to these estimations, worldwide demands for these metals would deplete all reserves by 2050 (or even shorter term), to the exception of Al. This underlines the communicating vessels issue with betting only on substitution of a critical material by another less critical material, typically when trying to avoid Ag consumption by replacing it by Cu. The pressure on geological resources has to be decreased in order to remain viable. Goldschmidt et al suggest that it can be obtained by maintaining high learning rate on material intensity and cell efficiency through large deployment of tandem modules with efficiency as high as 30,7% in 2050 [23].

2.2 Logistics

There may be bottlenecks due to a fast or endlessly growing demand. Figure 4 shows the estimations of emergence of bottlenecks for different materials and technologies linked to the energy transition. One may see that Ag, In, Ni and Sn may experience logistical tensions between 2016 and 2050, while base metals such as Al and Cu would not. A market booming would induce a pull factor and then a huge increase in specific material demand. This new demand would be difficult to meet as a new mining site takes around 15 years from exploration to commissioning. This calls for a mid- to long-term planning concerning mineral resources uses.

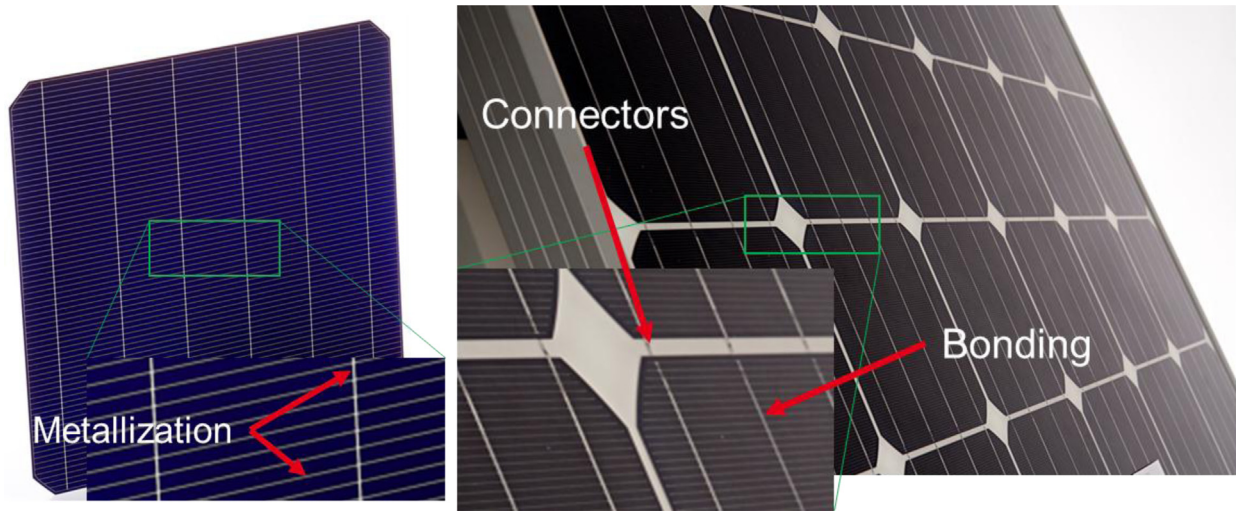

Fig. 2. Picture of a PV cell with metallization on the left and of a PV module with interconnection elements on the right.

Table 1. Liquidus temperatures for various soldering alloys.

Alloy	Composition (% wt)	Liquidus (°C)	References
SnPb	60/40	187	[17]
SnBi	43/57	139	[18]
SnBiPb	37/21/42	122	[18]
SnBiAg	41/57/2	142	[18]

2.3 Recycling opportunities

Recycling operations may provide an important supply source by replacing gradually the primary material sources from mining activities by secondary sources from scrap collecting and recycling for longer-term supply. Figure 5 presents the recycled contents of metals covered by this study, i.e., the part of recycled material in material production. All pictured materials present low recycle content in production (between 22% and 37%). The limit of this result [20,24] comes from dispersive uses, that come from applications that intrinsically prevent material recovery. Alloys are obvious instances of it and coatings definitely fall under this definition, as thin layers are difficult to recover and, in addition, are not viable to recover from an economic and/or energetic point of view [25].

2.4 Geopolitical context

Monopolistic situations (Fig. 6 presents the case of Cu with only 8 countries producing two third of global refined Cu) may favor major issues in material supply: in 1973, the decision of the Organization of Petroleum Exporting Countries decided to increase the oil price [26,27], thus creating a global financial and energy crisis. Critical material embargos may be used as leverage in geopolitical conflicts like China with In against Japan in 2010 [28] or in order to modify a country development project as is the case of Indonesia with Ni [29]. The consequences cover global crisis on specific applications and products. It can also take the form of local social and environmental conflicts around mining activities [30].

2.5 Applications competition

Competition between various applications considers difficulties to meet every material demand at the same moment. For instance, this may result from a booming in some market, like electric vehicles for Ni. Figure 7 pictures the different applications of Ag in 2021 and their respective shares in usage. Given that Ag supply is finite and is already close to its historical peak [20], any increase in PV and/or electric vehicles production means that other applications have to be decreased in volume. For a socially acceptable prioritization, Zhang et al. suggested a viable limit of Ag usage in PV of 2–5 mg/W per module [10], four times less than present 10 mg/W [32].

One may also notice that Bi or In are only produced as byproducts of other more common elements (Pb, Zinc, Sulfur...) [21]. As PV sector relies on these materials or perceives them as promising substitutes, such as Bi instead of Pb for low temperature soldering alloys, it makes it depending on the hosting ore material's market and trends.

2.6 Extraction and refining impacts

Out of critical material strict definition are the impacts of their supply and particularly their extraction from mining activities. However, it may have indirect incidence on their criticality as the pollution or energy or water consumption may result in local refusal of those activities.

Some mining coproducts are discharged in atmosphere or (sometimes unauthorized) landfills as they lack market opportunities. For most of them – Arsenic (As), Antimony

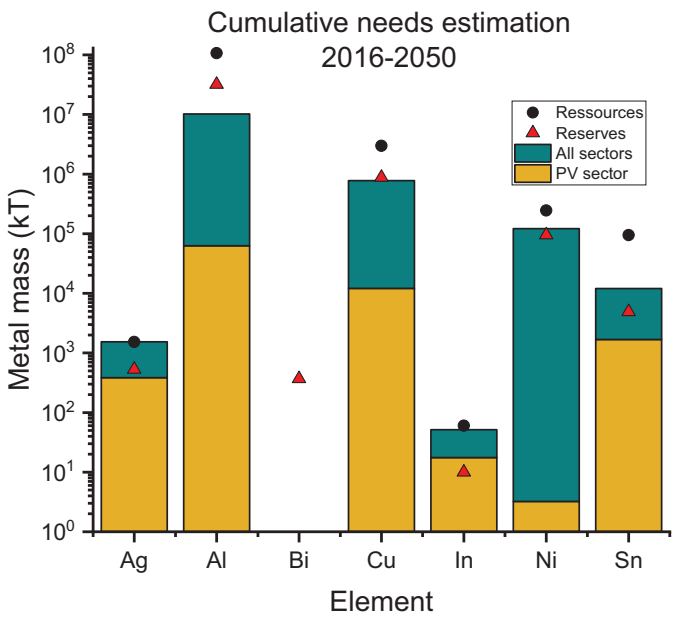

Fig. 3. Cumulative needs estimation until 2050 for different materials [20] reserves and resources numbers from[21], Bi reserves from [22] and Al PV-linked intensity for 70 TW from [13].

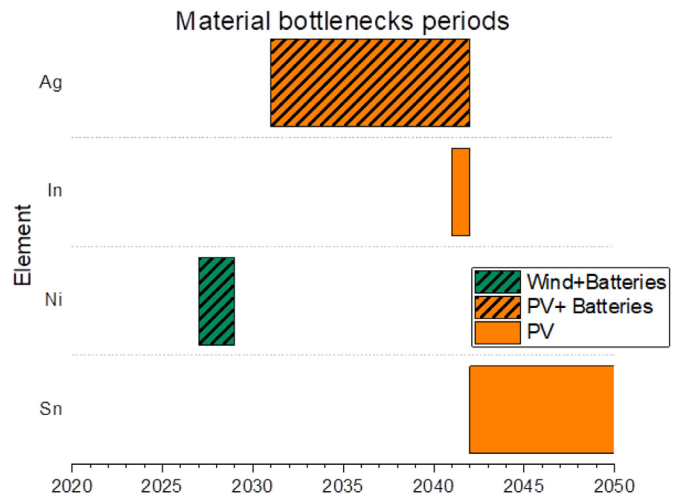

Fig. 4. Logistical bottlenecks for different materials involved in various energy transition technologies, redrawn from [20].

(Sb), Pb, Mercury (Hg), Cadmium (Cd), hexavalent Chrome (Cr^{6+})...[33] –, the main reason of this economical unattractiveness is their toxicity. Artisanal and industrial mines are the 1st and 2nd air and water Hg polluting sectors [34]. In addition to their deleterious effects, these heavy metals are not easily degraded in environmental conditions and their impacts last for centuries or even millennia [35]. Mining activities, especially grinding and comminuting, are highly energy consuming: mining sector concentrates 8% of global energy consumption [30]. After comminution step, metallurgical processing phases also consume chemicals like strong acids or bases or Sodium cyanide [36].

This situation is expected to worsen: ongoing ore grade decrease, as can be seen in Figure 8, which leads to an increase of process energy (cf. Fig. 9, more details in [37,39]). In addition, chemicals and water volumes used in purification and refining processes will follow the same sharp increase.

2.7 Interconnection and metallization involved materials

With the criteria described previously, materials (and their substitutes) used in the interconnections of PV modules are listed and, for each of them, criticality is assessed.

Although different dynamics may be observed depending on the concerned material, the main conclusion is that all listed elements supplies should face supply tensions by 2050, or even by 2030 for the most critical ones, with the exception of Al.

2.7.1 Rare metals: Ag, Bi and In

The key criticality issue in PV sector is Ag and In scarcity [8,40]. Ag is the dominant metal in metallization and ECA pastes, as well as coatings on Cu connectors (if bonding via ECA). Another raising concern deals with Bi availability [10,41] with approaching market share increase of SHJ and ToPCON cells. Even though Bi is rarely used in industrial soldering alloys, it is to substitute Pb in standard soldering alloys formulations like SnBiAg. Most of these soldering alloys are to reach industrial deployment step soon. The reason for this change is the end of the derogation PV sector enjoys from Reglementation of Hazardous Substances regulation [42]. Beyond their geological rarity, those materials are highly critical due to their dispersive applications: even though PV sector requires a limited amount of Bi and Sn, they are almost not recovered when used as metallization or soldering alloys. These applications must evolve otherwise the known reserves will end around 2040.

2.7.2 Semi rare metals: Sn and Ni

Sn is the main material for soldering alloys, lowering its melting point. Low soldering temperatures are crucial for passivated contact cells e.g., SHJ or Perovskite/Si tandem cells, whose market growth is projected in the next future [8]. Sn supply may suffer in the mid-term of its scarcity (Fig. 4) and from the great part of dispersive uses in its application (49% of soldering alloys in 2021 [43,44]). This reduces all the more the secondary (recyclable) reserves.

Ni could be used as an adhesion and barrier layer for Cu plating [45] but will endure a great pressure from electric vehicles batteries booming (demand in 2050 would be as high as 4 times 2020 global production [46]). In addition, Ni is mainly used in stainless steel, which recycling only produces stainless steel [47].

2.7.3 Base metals: Cu and Al

Base metals Cu and Al (high production and consumption volumes materials) are not often assessed as critical materials for PV sector. In fact, they should not restrict PV modules' production expansion in the short term but

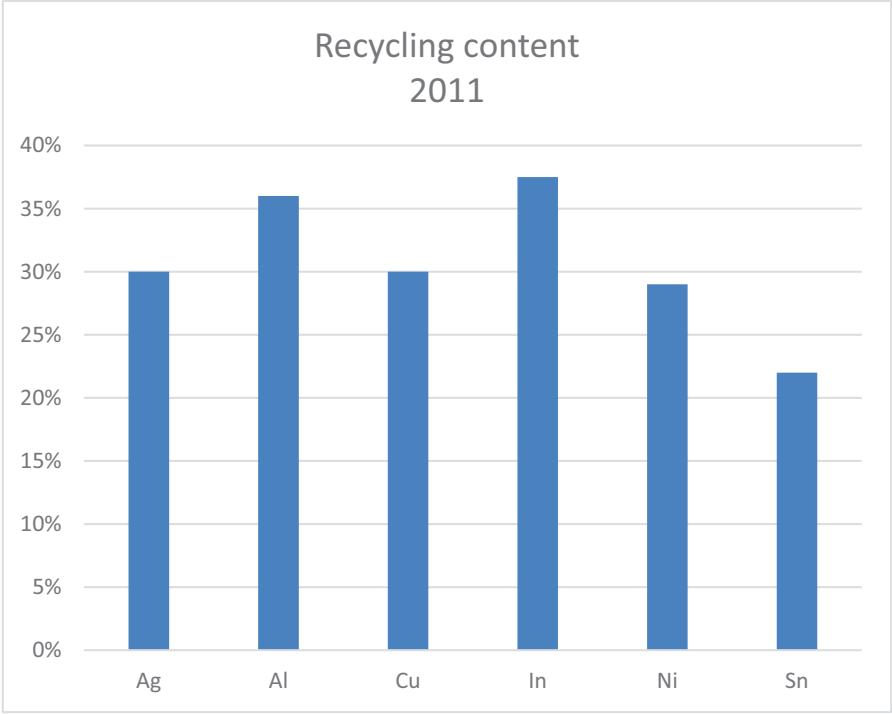

Fig. 5. Recycled contents of different metals from [20,24].

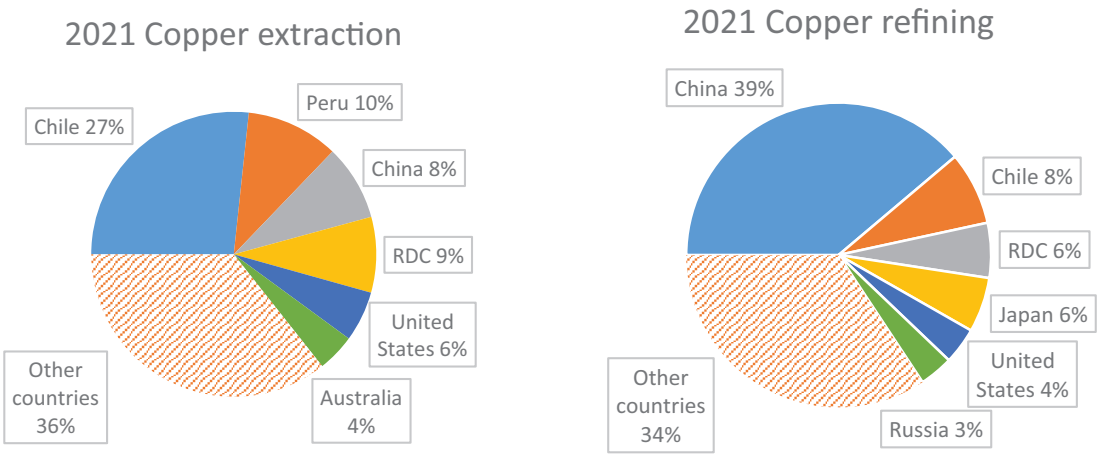

Fig. 6. Copper extraction (a) and refining (b) per country [21].

could adversely affect growth in the midterm. By 2050, Cu demand to electrify the whole society should indeed deplete global reserves so its supply is unreliable (cf. Fig. 3). It is then compulsory to deeply rethink energy networks, as well as implement a circular approach (reduce, repair, reuse, and finally recycle). Moreover, Al needed volume for PV on TW scale would induce huge CO_2 emissions [13]. It is important to note that the criticality of those base metals is not triggered by the PV sector demand but by infrastructures and transports [48].

3 Module architecture and recycling goals

Three strategies may be implemented separately or simultaneously to reduce critical material consumption: optimize process to reduce consumption, change material to reduce criticity and finally work on architecture to reduce material need or improve recyclability. Given the previous section conclusions, one may understand that mineral supply from primary mining will be limited by geological access. Secondary mining (i.e., materials from

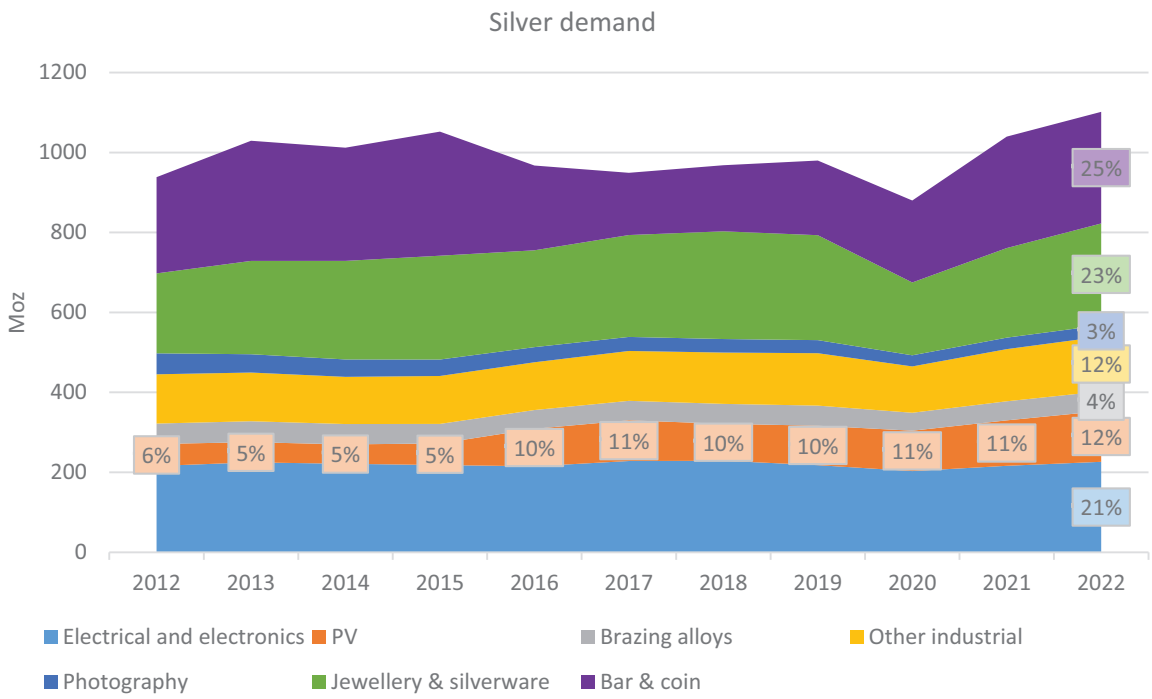

Fig. 7. Silver demand by sector from 2012 to 2022 with PV share of annual global production [31].

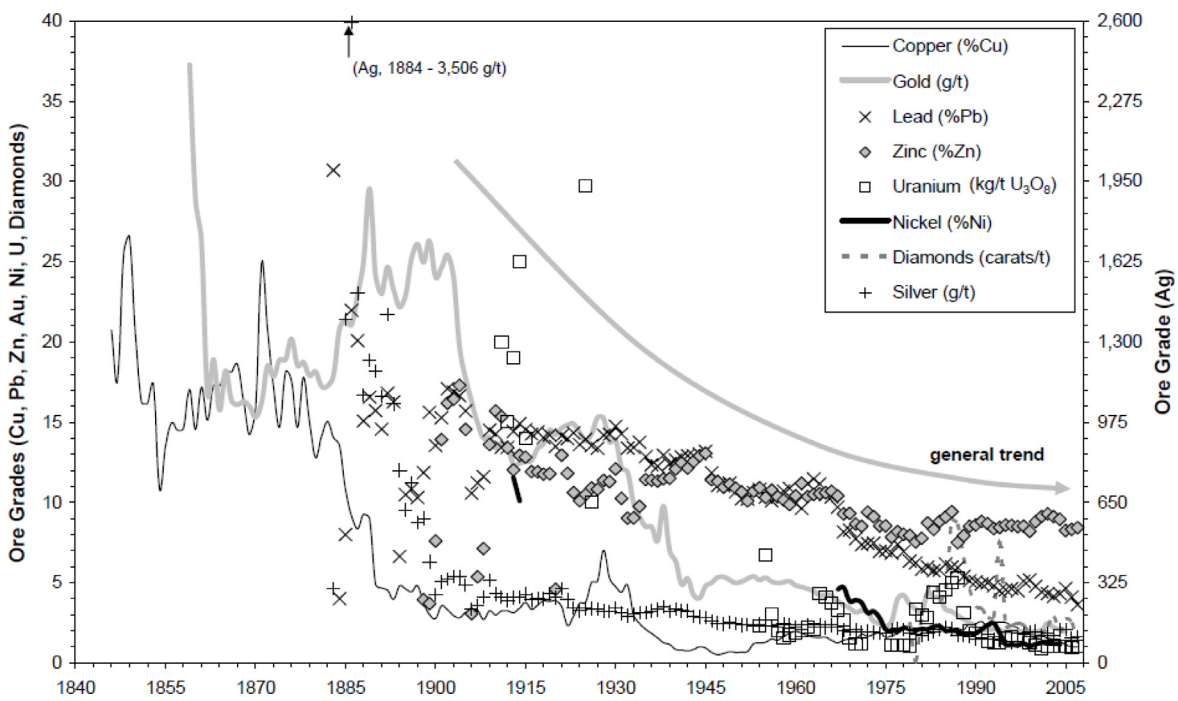

Fig. 8. Ore grades over times for different metals in Australia with a declining general trend (Reproduced with permission from [37]. This figure is subject to copyright protection and is not covered by a Creative Commons license).

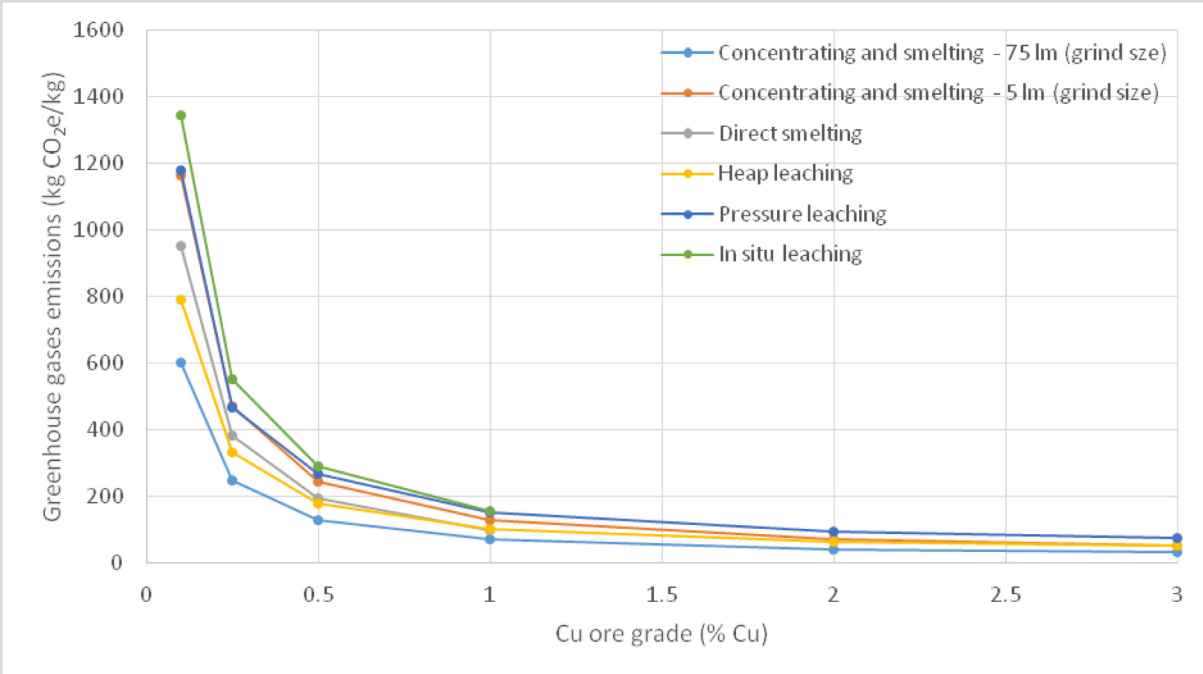

Fig. 9. Greenhouse gases emissions versus Copper ore grade extraction for different processes, redrawn from [38].

recycling) has the potential to offset this major shortage hazard. For this to be effective, high recycling opportunities must be integrated from specifications.

3.1 Separability of components interest

Circular economy is a material life cycle which ideally [49] may be modeled in a closed loop, meaning reusing the integrality of materials in order to overcome availability issues, especially for critical materials. On the road to this asymptote, several ways are possible and lead to different definitions:

- Up-cycling: use (often reuse) of materials from another application, with a gain of value. As critical materials usually add a great value to devices in regard of their small contents and then are used in tiny volumes mostly integrated with other materials, this recycling way mainly concerns base materials like wood or cement.
- Down-cycling: process from which one only recovers degraded materials, compared to the initial application. Usually, the new application is less material selective than the previous one. It implies that the number of recycling cycles for the same application is very limited.
- High value recycling: recovering of device and/or material while keeping most of the range of possible applications. This needs care from conception to be possible, meaning it is a supplementary constraint on conception.
- Low value recycling: process with important loss of future possibilities in the recycling step. Conception is free of constraint regarding the product's end-of-life.
- Side-cycling: process from which a recycled material is not relevant for its first application but for another one. It is the most common approach as it relaxes constraints compared to recycling material for the same purpose as its previous one.

Improved dissociation of different components would lead to a major leap forward in terms of recycling rates (even more in the case of material which main applications are dispersive), as it would allow to skip some separation steps and thus energy and chemicals consumption. This would either improve recycling attractiveness or turn some materials effectively recoverable through affordable processes [50].

3.2 Limitation of the standard module architecture

Generally, the more pure the recovered materials from recycling, the higher the value of recycling . Then, one has to separate the different elements involved in a device fabrication to complete high value recycling. The first step to achieve this goal is to separate the different components of the device. This will help treating the materials in each component without implying heavily energy- or chemicals-intensive processes.

In practice, a standard PV module comprises nowadays several components in which materials could theoretically be reused (ideal high value recycling). These elements could be reused with no or limited alteration of their critical properties, namely: glass plates and connectors.

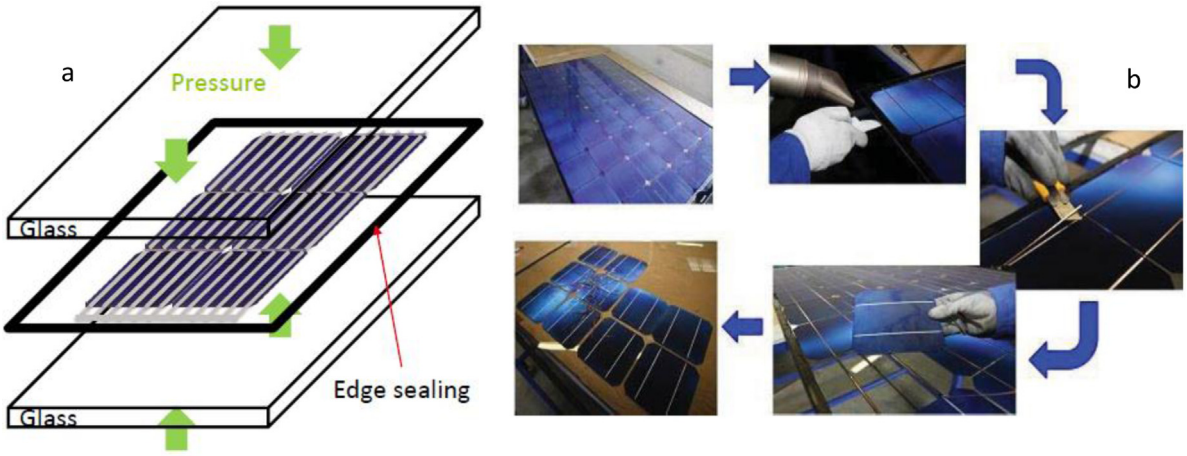

Fig. 10. NICE module structure (a) and NICE module disassembly process (b). (Fig. 10b © 2018, IEEE, reproduced with permission from [57]. This figure is subject to copyright protection and is not covered by a Creative Commons license).

In addition, processes exist to treat end-of-life solar cells and then use the recovered wafers to create new solar cells [51]. Moreover, solar cells are the most appealing components to recycle: they carry the most important embodied energy, as well as the most critical materials.

In standard solar modules, the melting of the polymeric layer aims at adhering glass to the cell surface: this adhesion guarantees that no air bubble remains between the two of them and would induce parasitic reflection. At the same time, strong adhesion between layers limits the ease of separation of the different components [52] and thus requiring recycling treatment, either chemical effluent treating or important amount of thermal energy. Moreover, connectors' bonding on solar cell make it hard to recover a wafer without breaking it into pieces, while the contact layer (soldering alloy or ECA) recycling is not economically viable given its thinness (a few tens of μm) and low material weight.

3.3 Review of module concepts for material resources management

From the criticality assessment and architecture analysis, the next two inventions are particularly relevant to tackle critical material consumption issue in PV interconnection by reducing their consumption and even increasing recycling opportunities. Industrial sector PV has been tackling this issue for several years now as one of the major innovation trends. As shown in Figure 2, critical material consumption is spread on metallization and interconnection. Cell metallization focused most of the efforts, as it carries a large majority of Ag consumption, with a sharp fall in Ag mass per cell in the last decade [8]. This is mainly due to optimization of the standard processes but alternatives, such as Cu plating [45,53] or screen printing of AgCu pastes [54,55] are widely investigated.

3.3.1 New industrial solar cell (NICE)

NICE [56–58] structure scheme is given on Figure 10a. It aims to improve the recycling value of PV modules by dispensing with first encapsulating layer and second, bonding of connectors to the surface of solar cells (by means of soldering or ECA bonding). It comes with drawback of parasitic reflections, which means optical losses, due to the optical indices' differences at the glass/air and air/cell interfaces. This is an interesting example of eco conception: the design of the whole device promotes easy recycling of the module at its end-of-life. The disassembly process presented in Figure 10b could be applied in two steps. First, one disassembles the module and removes (nearly) intact end of life solar cells to treat or recycle. Second, a new module can be re-assembled with re-used glass and connectors and new solar cells. A similar innovation is TPEdge concept developed inspired by the building sector [59].

3.3.2 Non uniform metallization

Research and industry have made a lot of progress in the last two decades solar cell metallization features, notably the finger width with classical screen printing. This has led to a reduction of shadowing and recombination losses and at the same lowered the Ag consumption. However, this improvement seems to face a limit [8]. Alternatively replacing the classical H-design with busbars and fingers by another design, where finger section is not uniform along the finger itself (example is given in [60]). This pattern could help to reduce material consumption with the same electrical losses. This design is indeed driven by electrical considerations more than production easiness.

4 Conclusions and perspectives

Assessment of the criticality of materials used in PV modules has been presented based on five criteria: geological availability, logistical bottlenecks, recycling opportunities, geopolitical tensions, and sectors competition. This frame of reference has more specifically been applied to interconnection materials of PV modules. The analysis underlined the economic danger on soldering alloys elements (namely Sn, Bi, In), as well as metallization and ECA metallic flakes with Ag and Cu. Ultimately, only Al is projected to meet the demand of TW scale PV manufacturing. Finding a way to avoid these shortage

hazards represents a major challenge for the PV sector as it is inherently depending on mineral supplies. Some of the assessed materials (like Ag, In or Sn) are considered critical because of the rising direct demand by the PV sector while some others (like Cu) are mainly consumed by other sectors (construction, transports for instance).

Three mitigation strategies are identified to overcome this issue: working on processes to reduce material consumption, substituting the most critical materials by less critical ones, and finally, proposing new concepts to reduce the material need and ensuring high value recycling. Changing or optimizing the deposition process is widely addressed in literature over the last 15 years: the potential reduction of Ag consumption seems to reach its limit. The use of alternative materials has been a rising research topic for the last 5 years and could reduce critical material consumption. In the meantime, critical materials consumption in interconnections could further decrease, thanks to disruptive innovation in module architecture.

Eco conception may also help to decrease the mineral pressure by favoring high value recycling of critical materials or even reuse of components of PV modules.

Conflicts of interest

The authors have nothing to disclose.

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Data availability statement

This article has no associated data generated.

Author contribution statement

Conceptualization, A. Perelman, V. Barth, F. Mandorlo and E. Voroshazi; Methodology, A. Perelman and V. Barth; Software, None; Validation, V. Barth, F. Mandorlo and E. Voroshazi; Formal Analysis, A. Perelman; Investigation, A. Perelman; Resources, A. Perelman and E. Voroshazi; Data Curation, A. Perelman; Writing – Original Draft Preparation, A. Perelman; Writing – Review & Editing, V. Barth, F. Mandorlo and E. Voroshazi; Visualization, A. Perelman; Supervision, V. Barth and F. Mandorlo; Project Administration, V. Barth, F. Mandorlo and E. Voroshazi; Funding Acquisition, V. Barth and F. Mandorlo.

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