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Hybrid perovskite solar cells redefine photovoltaics Value Chain

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Abstract

More than one billion people around the world have no access to electricity. Despite its increasing trend, the growth of energy access was almost entirely fuelled by non-renewable energy resources. Therefore, improving the use of alternative resources is of paramount importance. Among the different renewable resources, solar photovoltaics (PV) is growing at a fast pace, thereby raising much expectation, especially for its enormous potential in "out-of-the-grid" applications. Nowadays, solar cells are (almost) exclusively made out of silicon, which has high costs of production both regarding infrastructure and energy consumption. This paper aims to provide insights on perovskite solar cell technologies, which constitute one of the most promising advances in the PV field. The lower costs of producing perovskite solar cells as well as the impact of a more accessible and manageable manufacturing process, compared to silicon solar cells, are the two most revolutionary aspects of this technology.

Keywords: perovskite, solar, photovoltaics, value chain, renewable energy

1. Introduction

The synchronous growth of global energy demand together with the urgency to lower carbon emissions constitute one of the hardest challenges of our times. As a recent MIT study highlights, by 2050 we will need 25 TW of low CO_2 content energy (Schmalensee, 2015). Among different possibilities, current trends report how PV could supply a considerable fraction of this demand, thereby largely contributing to overcome this unique challenge and providing a strategic asset to national and international policy-makers.

After five years of intense research, perovskite-based solar cells (PSC) reached outstanding performances, exceeding 23% efficiencies for single junction cells. This makes PSC the fastest improving PV technology: silicon PV took almost 30 years to achieve the same result (Li, 2018). Hybrid Lead Halide Perovskites (HLP) combine two key properties for harvesting the solar power: they are extremely efficient in both absorbing light and in separating/transporting charges. Nonetheless, HLP are gathering even more attention because of two additional but fundamental aspects: lower costs and a wider range of applications, compared to existing PV technologies (Chang, 2018). On the one hand, lower costs are determined by cheaper and abundant precursors used in low temperatures deposition processes, thereby eliminating the ultra-high temperatures and thus high energy consumption needed for the silicon PV. On the other hand, given the enhanced light absorbing properties, PSC are made of perovskite lightweight films that, being thin and possibly semi-transparent, disclose many possible applications beyond the traditional rooftop ones. In fact, the HLP light films "*can be attached to flexible materials which opens up a wide range of new applications going beyond rooftop and solar farm panels* (Dervojeda, 2017)". Despite being a relatively young technology, many of the challenges faced on the way of the commercial outbreak are being addressed through a collective effort of the scientific and industrial community. Indeed, when transferring PV technologies from laboratory scale to industrial and commercial applications lowering costs, retaining large area efficiencies, realizing high-throughput fabrication, while achieving long lifetimes and low toxicity are key challenges to be addressed (Li, 2018). So far, a handful of companies are focusing on PSC technologies and are addressing these challenges: GreatCell Solar, Toshiba, Saule Technologies, Microquanta Semiconductor, Oxford PV, and Solar-Tectic, Solaronix, Panasonic, Frontier Energy Solution.

The development of industry-compatible processes hitting levelised cost of energy (LCOE) and life cycle assessment (LCA) standard parameters is the toughest hurdle to overcome to fulfill requests by policy-makers and investors, such as those set in US DOE Sunshot 2020 (Ibn-Mohammed, 2017). Being the production process of silicon highly refined throughout decades of research, the production cost of silicon wafers has fallen, thereby making harder the competition for PSC. Even though recent papers estimated an energy cost for PSC outpacing that of silicon PV, we believe that the enormous potential of PSC resides in the possibility of fabricating competitive and easy-to-install solar cells with low-temperature processes and common deposition equipment. These aspects have considerable implications also in terms of the value chain (VC) analysis. We adopted a value chain perspective analysing the main differences with the silicon VC, especially concerning material sourcing and manufacturing production. PSC have peculiar characteristics that are likely to disrupt the existing VC.

The paper is organised as follows: section 2 defines the methodology used in this paper, section 3 is the core of the study with the analysis of the main findings both in terms of PSC characteristics and its impacts on the PV value chain; section 4 considers the major implication from a socio-economic perspective and section 5 addresses conclusion and policy implications.

2. Methodology

This paper presents a descriptive methodology integrated by a case study of one of the most important actors in the process of PSC scaling up. We conducted informal interviews with a representative from Saule Technologies, the first start-up that intends to commercialise flexible, low-cost PSC. A detailed description of the PSC structure and of different manufacturing processes involved in its production permits to bridge a material science perspective with a supply chain-production perspective. This approach stems from a ‘transition perspective' (Grätzel, 2014) where the analysis is built at the intersection of evolutionary studies, economics, science, and technology. Being PSC a relatively young technology, the comparison with well-established Si PV that is presented in this paper helps in understanding the main challenges. Moreover, the paper adopts a Global VC approach, which focuses on the value chain concept introduced by Porter in the 1980s and revisited by Gereffi, among others, in the last two decades. Gereffi (1996) adopted the VC method from a global perspective, thus looking also at power relations that characterise different parts of GVCs. This approach looks at economic organisations as made of subsystems with specific inputs, processes, and outputs; every step of the value chain requires specific resources, labour, machines, and equipment. This perspective disentangles economic activities allowing an evaluation of geographical distribution and interdependencies of PSC activities.

3. Findings

3.1. From Silicon to Perovskite Age: why PSC are different

Solar Cells (SC) exploit the photovoltaic process to harness sunlight and transform it into disposable electric energy, thereby providing a potentially unlimited clean energy source. Since their inception, a wealth of different SC devices has been proposed and used, differing either by the active material, cell size or conversion efficiency. The common architecture is the following: a semiconductor material is sandwiched between two selective carrier contacts (i.e., an anode and a cathode), which allow to extract positively and negatively photo-generated charges, respectively, and generate a continuous electric current, which can be either used, converted or stored.

The classification of SC is based on the active materials, i.e., the semiconductor that can absorb light and generate charge carriers. Three generation of solar cells can be described, each one with peculiar advantages and issues, as summarized in Figure 1. Briefly, the first generation of SC is based on well-established crystalline semiconductors wafers (i.e., crystalline or multi-crystalline silicon) technology. Some intrinsic issues affect these solar cells: the low absorption coefficients, high production costs and the use of expensive balance of systems (BoS) components (Battaglia, 2016). Furthermore, the high purity needed implies high-temperature treatments. The collective effort of scientists, engineers and, policy-makers resulted in a reduction of production costs, and therefore, despite their problems, more than the 90% of produced SC is based on crystalline Silicon (c-Si) (Ibn-Mohammed, 2017). Second generation SC use different semiconductors with increased light absorption for thinner layers of materials, thereby opening to lightweight SC, as well as building integrated SC. Unfortunately, the resulting devices reported sensibly lower power conversion efficiencies (PCE<20%) with respect to c-Si standards (PCE ~ 25%), but fabrication costs remain high due to the employment of vacuum-based evaporation or sputtering deposition methods. On the other hand, cheaper CdTe solar cells suffer from the low abundance of tellurium supply (Ramanujam, 2017).

Solar Cell Type	Active Material	Advantages	Issues
First Generation	Crystalline Silicon Multi-Crystalline Silicon	Mature Technology Earth Abundant Materials High PCE (>20%)	High production costs Need for Infrastructures
Second Generation	Amorphous Silicon Cadmium Telluride CIGS	Lightweight Cells Building integrated PV Smaller Ecological Impact	Lower Efficiency Complex stoichiometry and reduced durability
Third Generation	Hybrid Lead Halide Perovskites Dye-Sensitized Organic	Flexible and Lighter Cells Lower LCOE Advantageous production	Heavy metal toxicity Production Scalabilty Long-term Stability

Figure 1. Summary of advantages and issues of the three SCs generations

Increasing the PCE and lowering production costs (i.e., reducing the LCOE) are the key challenges for future SC. Hybrid lead halide perovskite (LHP) solar cells (PSC) lay at the forefront of the third generation of SC, which are based on solution-processed materials, promising to shrink production costs. However, differently from solution-processed organic and dye-sensitized SC, which are affected by low PCEs, PSC have displayed unprecedented high PCE. Indeed, these SC have shown the steepest increase in their performances, passing from 3.8% to >22% in only five years (Ibn-Mohammed, 2017). Although PSC are not commercial yet, IREA estimated that PSC would occupy 9.3% of the growing PV market share by 2030 (Kadro, 2017). This testifies the large expectations on this material to shift the paradigm of the solar energy market, which is still relying mostly on silicon PV.

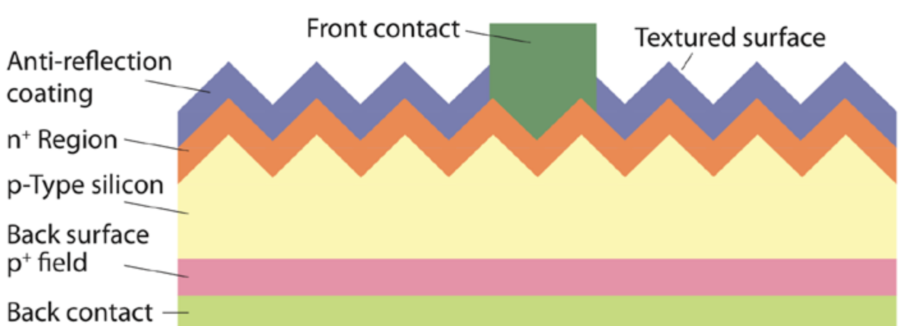

Figure 2. Typical silicon solar cell architecture (Source: Saga, 2010)

Even if Si SC make use of stable, non-toxic, and earth-abundant materials, major setbacks of this technology come from low absorption coefficients and its needs for high purity. These issues cause higher costs for additional BOS components (texturing, anti-reflection) and refined silicon ingot production. Furthermore, the possibility of flexible cells is ruled out by large thicknesses needed (>120 um). Briefly, Si SC production starts with silicon dioxide, which undergoes several chemical and physical purification processes, each of which is carried out at high temperature (T>1400°C). Resulting silicon ingots (obtained via the Czochralski method) can then be cut into wafers (Battaglia, 2016). These wafers are doped by the introduction of boron and phosphorus and heating. Afterwards, silicon texturing, contacting and encapsulation are carried on. The resulting cell architecture is shown in Figure 2. It is easy to understand how most of the cost for these SCs stems mainly from the production and processing of the silicon wafer itself (50%) and is further boosted from the additional BoS components (Saga, 2010).

Inasmuch as their structure is different from that of silicon SC, the fabrication of PSC requires different precursors and deposition techniques. In PSC, a layer of active material is sandwiched between two layers transporting positive and negative charges, upon which contacts are applied. As shown in Figure 3, the architecture of PSC can be either n-i-p or p-i-n (also referred to as inverted structure), depending on where negative and positive carriers are extracted. The active material is always composed of a 150-500 nm thick film of HLP, which is three orders of magnitude thinner than silicon. This is a man-made ionic crystal, whose structure is described as ABX_3 where A is generally a monovalent cation (either organic methylammonium (MA), formamidinium (FA) or inorganic Cesium (Cs)). B is a divalent cation, lead (Pb) or tin (Sn) and X is the halide anion (chloride (Cl), bromide (Br) or Iodide (I)). Although different formulations are possible and research is still going on, two main LHP stem as candidates for commercial PSC production: $MAPbI_{3-x}Cl_x$ and $Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$.

These are solution-processable semiconductors with optimal light absorption, which can work either with direct or diffuse sunlight, differently from silicon. To deposit perovskite thin films, precursors salts (i.e., the organic/inorganic and lead halides) are dissolved in organic solvents, and then a low-temperature crystallization is induced (Li, 2018). Therefore, these materials combine the ease of processing (typical of organic materials) with the high-quality electronic properties of inorganic materials. The electron and hole transporting layers (ETL, HTL) allow extracting selectively the carriers generated by sunlight absorption. The direct PSC structure uses different materials (ETL: TiO_2, ZnO, SnO HTL: organic molecules) from the inverted structure (ETL: ZnO,C_{60}, HTL: NiO, CuSCN or PEDOT:PSS), thereby increasing the range of possible combinations. Lastly, these cells are sandwiched between two contacts: a transparent conducting oxide (TCO) and a contact, fluorine-doped tin oxide (FTO) and gold/copper/carbon/aluminum, respectively.
The substrate of these PSC can be either glass or plastic. However, being cost reduction the most impactful advance of PSC, we focus on plastic substrates that are cheaper and can be coupled with R2R production.

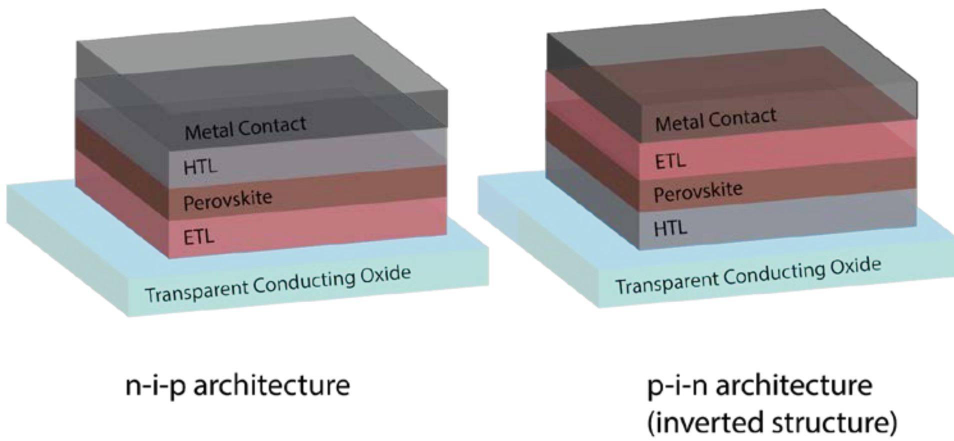

Figure 3. Direct (n-i-p) and inverted (p-i-n) architectures for PSC

Albeit lab-scale PSC are continuously breaking PCE records (now >23%), the industrial scale production is focused on overcoming some of the impellent challenges for module scale SC: (i) uniform large-scale deposition of HLP, (ii) transporting layer and (iii) improving stability.

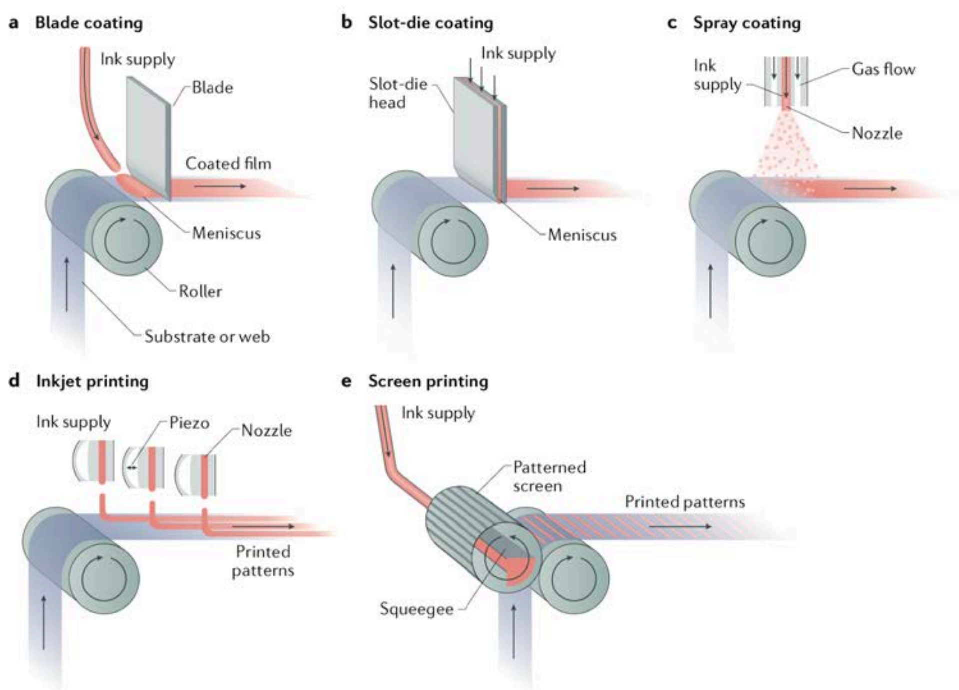

Figure 4. Common scalable techniques for PSC active layer deposition (Source: Li, 2018)

(i) Uniform large-scale deposition methods involve a controlled crystallization of HLP from its precursors' solution. Despite numerous challenges underlying the upscaling process, PSC showed an impressive improvement towards large-area cells. Indeed, although an efficiency loss is inevitable and variability due to composition and deposition methods, most recent works report PCE>16% for large-scale PSC (Li, 2018). As shown in Figure 4, there are many different large-scale deposition techniques, which can be adopted for PSC fabrication: slot-die coating, spray coating, and inkjet printing are most commonly used.
The basic principles underlying these techniques are the controlled deposition of a certain amount of precursor (ink) on a substrate, and its controlled evaporation to induce crystallisation of the HLP thin-film uniformly over a large area. Although recent papers reported >18% PCE for blade coating and spray coating, research is focused on the

improvement of these techniques, introducing either anti-solvents or chemical additives to achieve higher -quality films, without affecting production costs (Deng, 2018).

(ii) Upscaling of HTL and ETL is another crucial challenge for PSC. A wealth of different materials has been proven to extract carriers selectively from HLP, thereby providing a large set of alternatives at the industrial level. The development of low-temperature, solution-processed FTO, ZnO, NiO and, TiO_2 is paving the way to the realization of highly efficient PSC on plastic substrates in either p-i-n or n-i-p configuration (Qiu, 2018). Conversely, the back electrodes are generally deposited by thermal evaporation or sputtering of TCOs. These processes involve a large outlay of capital for deposition equipment and relatively lower throughputs.

(iii) Stability is the most compelling challenge posed by these materials, as HLP are prone to decompose into their precursors by moisture and heating-driven degradation. Over the past years, a huge scientific effort resulted in considerable improvement of PSC stability. Early papers on PSC reported minutes-to-hour stabilities, while most recent works report stability above thousands of hours under atmospheric conditions and heating. Improving stability and reliability of the modules involves the appropriate choice of cell components, as well as an accurate encapsulation of the cell. As mentioned above, different chemical formulation of HLP are possible and the mixed phase HLP $Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})_3$ resulted in increased thermal and chemical stability. Furthermore, current research is tackling stability issues by the introducing additional passivating layers in the structure (Qiu, 2018). Contacts play an even more important role in stability as their corrosion severely impairs cell and modules performances. Carbon-based contacts are the most promising candidates as their use in PSC resulted in exceptionally long stability (>10000h). Although engineering the choice of PSC material contributes to achieving better stabilities, encapsulation of these SC is prerequisite to obtain the above mentioned long-standing solar cells. Indeed, encapsulation further protects the SC from atmospheric agents, such as moisture and oxygen and UV light. Although UV-filtering glass has proved to be highly effective for sealing PSC, this would introduce large costs, which directly conflict with the achievement of low LCOEs. Considering R2R fabrication, fluoropolymer thin foil could be used as low-cost and reliable materials for encapsulation. Nevertheless, future industrial research direction will certainly encompass the quest for other efficient encapsulation procedures.

3.2. PSC value chain analysis

The European Commission (EC) inserted perovskite into the Key Enabling Technologies considering that PSC are the fastest advancing solar technology to date. The urgent need to lower carbon emissions as well as the complexity of reaching the technological frontier and maintaining competitiveness regarding renewable resources makes the world particularly interested in this new technology. This section will provide insights into the PSC value chain with a focus on two main aspects: costs reduction and an easier manufacturing process compared to Si PV. The analysis is conducted using a comparison with Si PV and qualitative materials coming from a semi-structured interview with one of the main actors in the scaling up market, the Polish company Saule Technologies.

Compared to the Si PV value chain, PSC value chain is much shorter, and it is likely to be more vertically integrated: the lower energy requirements, as well as an easier process compared to the Si PV, would enable in site production closer to the destination use (Saga, 2010; Dervojeda, 2017). The first part (a) of Figure 5 is also known as the value-added distribution activities section; differently from the well-known pattern of the smiling curve (Mudambi, 2008), where the value added lies at the two extremes of the curve (and of the sequence reported in the Figure 5 (a)), in the case of PSC the value distribution is different for two reasons: an important part of their value is based upon manufacturing, and it stems from a cluster of multiple highly interrelated and partially parallel activities (Dervojeda, 2017). In other words, the value added is more equally distributed and it is highly dependent on the functioning of different parts.

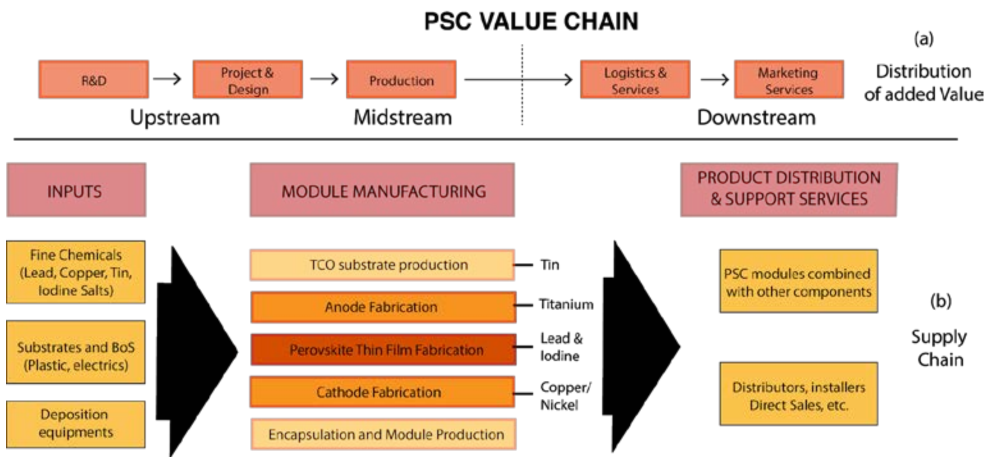

Figure 5. Perovskite Solar Cells Value Chain

Having considered this aspect, some elements of the value added in the PSC can be said with a specific reference to the Si PV that, accounting for more than 90% of PV, is the typical VC of the industry. Following Su (2013) analysis, we apply his framework to the PSC VC, where there are three main parts: upstream (perovskite materials production), midstream (deposition of solar cell layers and assembly) and downstream (solar PV systems and support services). Inasmuch as Si PV is an oligopolistic industry, and the high-purity Silicon needed is very complex to obtain, the first part (upstream) achieves the highest profit and the second part (midstream) the lowest. The situation is likely to be completely different for PSC: the part with the highest value added in PSC is the midstream, because of the complex techniques needed to deposit perovskite on SCs; the first part, upstream, is likely to be the lowest profitable, unless an oligopoly market will be established by companies that provide perovskite materials. The conversion from raw materials to fine chemicals needed for Si SCs is more complex and energy consuming than that needed for PSCs; thus, the complexity of Si SCs encouraged the development of a limited amount suppliers. The disruption of existing mechanisms of governance and supplying sub-systems are likely to stem from this change: the revolutionary aspect of perovskites is that they do not need costly wafers and their input materials are cheap and abundant. Finally, the downstream part of PSC VC is likely to be similar to the existing PV; at the moment, it does not exist yet (Dervojeda, 2017).

The upstream and midstream parts are the focus of this study: an analysis of the inputs required, the manufacturing process and how these aspects could challenge existing supplying and manufacturing dynamics is provided. The main inputs required for the production are raw materials, which are then used to create fine chemicals and the equipment machinery. First, following the analysis of Kadro and Hagfeldt (2017), the materials embedded in the PSC production are:

· *Glass*: it provides structural integrity and protection to the active material. It is important because it gives the cells structural integrity and it protects them from the environment. Because of the thin film property of PSC, glass is not an essential material: the first attempts concerning scaling up are using plastic instead of glass because it permits the fabrication of flexible cells and can be coupled with R2R production. This was possible even with organic cells but, differently from PSC, they suffer from low PCEs.

· *Lead*: it is the fundamental material for the creation of the active material perovskite. Because of the many issues related to its toxicity, different materials have been tested but with a decrease in the efficiency. Lead toxicity concerns triggered studies on future lead-free PSC, to comply with RoHS 2011 (Abate, 2017).

· *Iodine*: it constitutes the other essential material together with lead. It is one of the scarcest nonmetallic elements on earth, and almost its entire production is in China and Japan (91%).

· *Tin*: it is used in the FTO glass production, as well as in the transport layers. Alternative HLP formulations suggested the potential replacement of lead by tin. Tin production is highly concentrated in a few countries such as China, Indonesia, and Peru.

· *Gold/Copper*: it is the most expensive component, which is mainly used in lab prototype of PSC. In scaling up processes, gold is substituted by copper. An important aspect of PSC, which contributes to lower its cost, is the high substitutability of anode and cathode materials. In view of plastic PSC, carbon-based contacts will be a viable alternative.

Second, to understand the equipment, it may be useful to consider Figure 6. Although the diagram flow shows a quite long production line useful mainly for lab-type fabrication, it provides a useful description of the PSC's production. As mentioned above, PSC fabrication achieves lower energy requirements ruling out high-temperature treatments as for silicon PV. The fabrication process is almost completely automated in an assembly line that builds the SC from the substrate to the final piece. As described in Section 3.1, this process involves the sequential sputtering of the contacts, and the deposition of an anode, the HLP active material, and a cathode by one of a large-scale deposition method (e.g., inkjet printing, slot-die coating or spray coating).

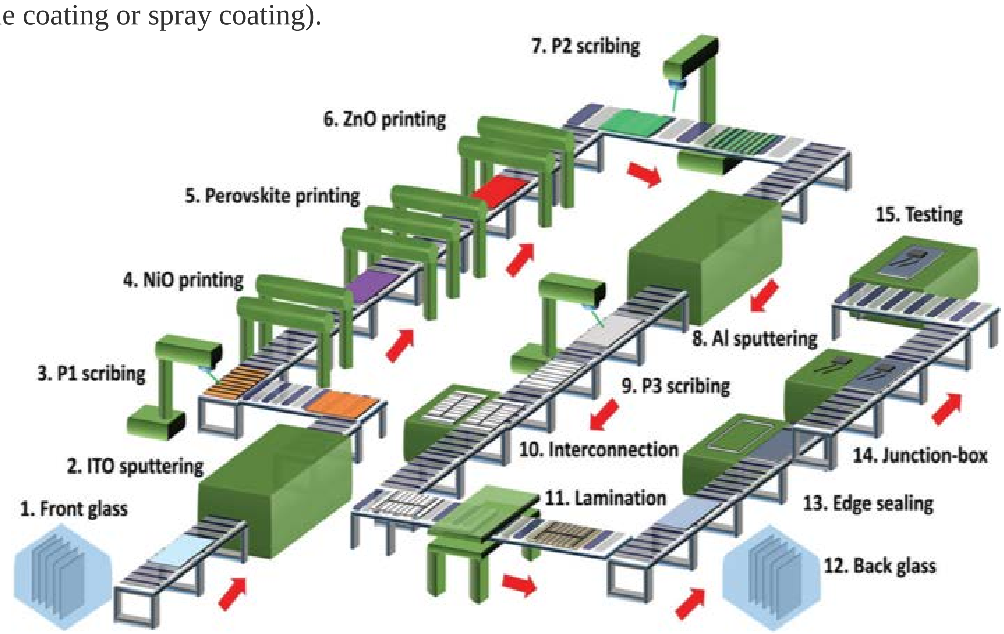

Figure 6. Flow diagram of the manufacturing process for perovskite solar modules (Source: Song, 2017)

New materials embedded in the production system, as well as new equipment, open up for a wide range of key actors in the PSC market: substrate suppliers (mainly glass and plastic), equipment manufacturers, module developers, and fine chemical suppliers are just some of the new figures in the PSC development. Both big firms with a wide portfolio and small companies are involved in the process; small firms may have an advantage because many of the activities such as cutting, coating and assembly can be done by small companies (Dervojeda, 2017).

This new market is gaining attention from different kind of suppliers; we had the opportunity to conduct an informal interview with a representative of Saule Technologies (ST), a Polish start-up that is among the first in the world in scaling up PSC production through a low-temperature method to manufacture flexible solar cells. The start-up is particularly interesting because of its goal to produce the cheapest PSC possible: they adopted solution-processing with inkjet printing technique. " We have developed the concept of our production line, and a prototype version will be launched next year. This will initiate the commercial production, which we intend to scale hundreds of thousands of square metres per annum in the upcoming years.", said Dávid Forgács from ST.

The interview with ST shed light on some aspects regarding the role of suppliers and the interrelation between different steps of the production described above. ST has a B2B approach, in the sense that their output is directed to other companies. The multiple properties of perovskites allow the interaction of a wide range of actors: for instance, because of the property to absorb even scattered and diffuse light, PSC may be used in skyscrapers buildings. "We have signed an agreement with SKANSKA company, which is one of the largest construction companies in Europe. Our joint development is aimed at developing BIPV (Building Integrated Photovoltaics) components, that can be readily integrated as structure elements, offsetting installation costs. This approach could enable the design and construction of zero-energy buildings", said Dávid Forgács from ST. The interactions between suppliers coming from different sectors have important implication in terms of knowledge spillovers. Suppliers both from the building production field and from the fine chemicals sector are realising that there is a strong potential in this market, "Until recently, we had to buy the perovskite precursor salts that were available on the market. Now, chemical industries are interested in developing materials with properties that are tailor-made to match the needs of PSC", concluded Dávid Forgács.

Costs' implication for PSC production

As aforementioned one of the most relevant characteristic of PSC is the decrease in costs of production, which is related to the following main elements: lower processing costs deriving from the use of lower costs materials, lower energy needs and less capital-intensive processes (Song, 2017). Song et al. (2017) contribution estimates a cost pie chart like the one in Figure 7 where manufacturing costs are materials, utilities, engineer and production line labour, equipment maintenance and depreciation of the equipment and building. The major cost is *material cost*, with 76%: nonetheless, it is important to consider that out of this number just 6.5% is related to the perovskite cell, the remaining costs stem from the BOS category.

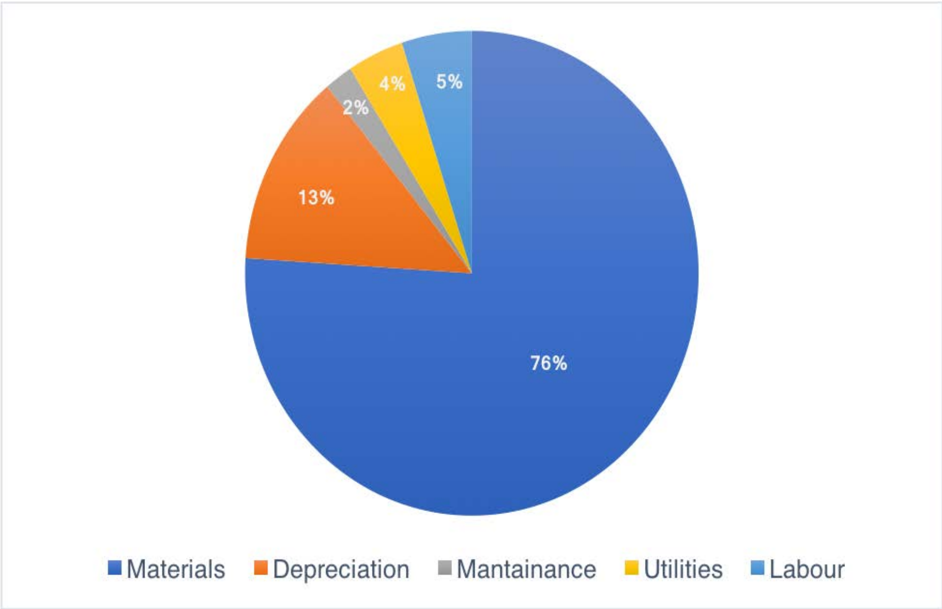

Figure 7. PSC costs estimation (Song, 2017)

BOS costs are likely to be decreased as well: as an example, glass fabrication, considered in the study, is already substituted in some scaling up processes with plastic material, "we are using transparent foils with plastic instead of FTO glass, and this requires to use lower temperatures fabrication", said Dávid Forgács. "Considering the importance that Saule Technologies is giving to the production of cheap energy we have an LCOE estimation of 5 cents/kWh for the first product with the aim to reach 1.5 cents/kWh", he said. Moreover, two possible accessory costs are encapsulation and assembly. If on the one hand, encapsulation could theoretically be cut off from the process, "no firm should ever allow themselves to sell solar cells that cease to function in the presence of environmental agents. As such, the development of a robust and fail-proof encapsulation is a requirement for commercial production", said Dávid Forgács. On the other hand, assembly costs are not an essential part as they are for Si PV because, being PSC flexible and with many possible applications, assembly costs will depend on the specific end-use.

4. Socio-economic implications

Several implications are stemming from the aforementioned considerations, deriving directly from the reconfiguration of this new PV value chain. First of all, concerning economic implications, the main shift from some raw materials to others will have an impact on countries that are well endowed with materials such as lead and tin. This has important implications in terms of export and of dynamic triggers to develop new domestic sectors. The insertion of new actors in the VC is likely to have impact both in terms of VC reconfiguration and value distribution: it is well acknowledged that the mere fact of being part of a VC does not guarantee economic growth, therefore the opportunity for new companies and new countries of being part of PSC will have to consider value-added and power dynamics. Manufacturing equipment used for perovskite deposition is likely to have important linkages to existing PV industry: as mentioned during the interview with Saule Technologies, "at the moment engineers are designing the system they need and then they look for companies to build the machinery, but the market is growing, and we expect to have taylor-made equipment soon".

Moreover, the rise of a new sector is likely to create expectations regarding employment. Due to the high level of automation in the PV sector, the employment multiplier is believed to stem more from the fact of providing a stable and reliable energy supply rather than because of the creation of more formal jobs (Dubey, 2013). The lack of reliable energy sources is one of the major issues in developing countries, and especially in Africa, where continuous breakdowns are one of the main challenges for industrial production (Vanheukelom, 2016). In fact, from a social perspective, we believe that the main impact of PSC large-scale production will come both from the many "off-the-grid-applications" and from the possibility to have a stable energy supply.

The final aspect to be mentioned is related to policy. According to Dervojeda et al. (2017), the EU is investing many resources to gain competitiveness in this new field. As observed for Si PV, is important to consider the role that policy-makers have on the development of this new technology: subsidies both at the European and global level have been already put in place. It is important to consider that PV is a sector with high knowledge and technology applications and a considerable amount of time and investments are needed to reach competitiveness. For instance, countries that were leaders in electronics facilitated the rapid development of the PV industry, like Taiwan and China (Su, 2013). Policy measures are needed to stimulate demand: PSC benefited from a strong technological push, from the supply side, but the market pull still needs to be initiated.

5. Research Limitation and Conclusion

This study analysed the main aspects related to the opportunities provided by PSC, holding promises to enhance cheap PV energy supply. Albeit some inherent limitations of this study come from the novelty of this field, we provided a broad view on both advantages and disadvantages based on most recent literature and knowledge accumulated on HLP materials.

Uncertainty on the production side mainly stems from the fact that PSC have not been commercialised yet. Notwithstanding, our interview with one of the key players in PSC fabrication provided deep insight into the future fabrication of PSC. Other limitations are inherently linked to the nature of HLP as active materials. As previously described, stability, toxicity and, upscaling issues are the toughest hurdles to overcome for HLP, but these challenges will be readily undertaken by current research. Finally, concerns about our VC analysis and its incompleteness: being perovskite a new technology the overall production, application and use are not fully in place. In conclusion, our study underlines the disruptive potential of PSC on PV industry with specific reference to the socio-economic impacts: low production costs and more accessible fabrication together with numerous off-the-grid applications will cause a paradigm shift in the renewable energy sector.

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