The European Commission Policy towards the Key Enabling Technology in Photovoltaics - the Perovskite Solar Cell and its Urban Applications Potential for Buildings

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Abstract

The paper covers European Commission policy on the emerging solar cell technology based on perovskites. As perovskite photovoltaics was identified as one of just 12 Key Enabling Technologies (KETs) for the European Union to be able to achieve and sustain global technological supremacy, it is considered a strategic area for the European development. Perovskite solar cells demonstrated spectacular growth of efficiencies from 2.6% back in 2006 up to 25% (in pure perovskites) and ca. 30% (in tandem) in 2020. The competition is fierce internationally (with Asian companies investing strongly in pilot production lines) but Europe has secured a forward position with early undertaken R&D and has a chance to successfully secure a leading position in this technological international race in PV and more generally in renewables, repositioning itself in global value chains after over a decade of surrendering the field in PV modules production. Perovskite solar cells are becoming very attractive for commercialization (especially for smart buildings) not only due to cheap costs of fabrication (full printing in roll-to-roll configurations) but also due to material properties (semi-transparent and elastic thin-films).

Key words: European Union, European Commission, policy, PV, perovskite, solar cells, buildings

1. Introduction

At the end of 2017 the European Commission concluded a study on the Key Enabling Technologies (KETs) for the EU to achieve technological global supremacy (Dervojeda et al. 2017). A total of only 12 promising KETs were identified across many industry sectors as technologies that hold potential to assure through further development that the EU will stay ahead of the international competition. One of just 12 identified KETs was a perovskite solar cell, a very cheap and universal thin-film emerging class of SCs, strongly developed in the EU in the recent years.

The promising KETs based technologies were identified as growing in such an intensity to guarantee a strong potential for the EU to lead globally, scaling impacts in terms of economy and jobs - may be thus considered as strategic for the further EU development. This is where the EC policy, particularly enabling high quality R&D is strongly pronounced. The European Commission granted PV R&D funding amounted to over 500M Euro vastly increasing from below of 100M Euro back in 2015 (Jaeger-Waldau, 2019). The PV prices drop enabling economic forces to drive energy transition are directly due to exponential nature of efficiencies growth observed throughout the last half of a century. 47 years of data prove that each time the installed PV power capacity doubled, the price fell by 28% (Wang, 2018). This progress was mostly driven by development of the traditional p-type wafer Si cells representing until 2017 over 90% of the market. Yet this domination is nearing to an end with emerging new PV technologies, especially very cheap and universal thin-film solar cells based on perovskite. Perovskite SCs undergo strong R&D that has resulted in lifting their efficiencies from only 2% back in 2006 to over 25% for single-junction perovskite cells in 2020. Four-years old market forecasts for perovskite SC devices estimated reaching $214 million value in 2025, but this figure is already considered underestimated, with expected surpassing Euro 1B when the technology is mass-produced.

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2. Perovskite Solar Cell

Perovskite solar cells which can be relatively easily chemically synthesized are currently considered as one of the most promising and economically viable base materials for mass-scale commercial PV. In contrast to traditional p-n junction semiconductor solar cells (like Si cells), perovskite cells (considered third generation solar cells, or qualified as one of the most important emerging PV technology) are soluble in many different types of solvents and remain semi-transparent after crystallization in very thin layers. As such, perovskite SCs may be easily ink-jet or screen printed in simple roll-to-roll processes or even sprayed onto large surfaces similarly like ordinary paints that when activated with chemically induced crystallization process create untra-thin-film layers (below 1 μm) also relatively easily further integrated in elastic perovskite SC device. Those properties make the perovskite cells significantly cheaper in fabrication and very well suited to mass-output market uptake and vast applications (such as so called energy smart buildings elevations coverings of variety of geometries, semitransparent windows, roofs coverings, outdoor furniture, vehicles or even clothing external surfaces that may produce enough power from the sunlight to e.g. charge a personal mobile device). The same properties make these cells specially interesting for advanced space applications in replacing of the sturdy and heavy panels with in-orbit printed (from the liquid solvents containers) flexible and large-surface sheets of thin-film solar modules or coverings for objects in space, even facilitating the planned future self-sustained missions to the Moon or Mars. Perovskites may be a game changer not only due to its excellent efficiency/cost ratio (nearing 0,014 Euro/kWh) but also due to key properties of semi-transparency and elasticity allowing bending and forming in different shapes and surfaces coverings. As buildings are estimated to account for over 40% of the energy demand, building-integrated solar cells are primary application for PV. Perovskite in contrast to sturdy Si panels offer simple whole-surface coverings techniques including aspects such as architectural freedom and so called smart windows with tunable semitransparency. Thus the potential for perovskite thin-film modules to cover roofs, facades and glass is already beginning to be commercially addressed by construction companies (like e.g. Skanska partnering with Saule Technologies commercializing perovskites cells in a mass production lines launched in March 2020). Futher technological developments (especially in plasmonic efficiencies enhancements by inclusion of metallic nano-structures) yet even more increases the potential of this emerging photovoltaic technology.

Following chapters study the progress of this KET and the EU policy support towards it.

3. Perovskite Solar Cell Technological Challenges and Perspectives

A perovskite solar cell utilizes a perovskite structured compound (i.e. material with the same crystal structure as the $CaTiO_3$ – calcium titanium oxide, originally discovered in 1839 and named after Russian mineralogist Lev Perovski), most commonly a hybrid organic-inorganic lead or inorganic tin halide-based material. It represents an emerging class of thin-film photovoltaic cells. Perovskites are efficient at absorbing light and transporting charges which are the key material properties for producing electricity from the sunlight. The main problem of the perovskite solar cells are lower efficiencies in applications-required chemically stable solar cell device configurations that might be greatly improved with optimized metalization in form of nano-particles inclusions and plasmonic energy mediation effects (Schaadt et al. 2005, Lim et al. 2007, Jeng et al. 2015, Matheu et al. 2008, Losurdo et al. 2009, Luo et al. 2014, Pillai et al. 2007, Stuart and Hall 1998, Pillai et al. 2006, Jacak et al. 2016, 2018, 2020). This concept was proven specifically in perovskites in the initial experimental trials (Zhang et al. 2013, Yao et al. 2019, Wu et al. 2016) with a surprisingly strong magnitude of the plasmonic efficiency enhancement observed for perovskite (well beyond magnitudes in traditional p-n junction solar cells) but is not yet understood in terms of physical mechanisms involved and not described in physical models, nor developed commercially. Current R&D initiatives focus on mastering and employing a very strong plasmon photovoltaic enhancement in metalized perovskite solar cells in order to commercialize it on a wide scale. This among others requires development of a microscopic quantum mechanical model of the new channel of plasmon mediated enhancement of the PV effect in perovskites (Laska et al. 2020) which was confirmed in the recent experiments (Zhang et al. 2013, Yao et al. 2019, Wu et al. 2016), taking into account that perovskite SCs hold a strategic potential for the EU, which managed to secure in the recent years a very strong position in terms of global competition in this area. The lacking quantum description of the nano-plasmonic perovskite photovoltaic effect enhancement is deemed to enable its technological optimization and further development towards devices designs, industrial production processes and market-ready metalized perovskite solar cells of highly increased efficiencies. A strong increase of the perovskite SCs efficiencies (the experimental record is 40% relative increase due to metalization as achieved experimentally by Wu et al. 2016) is most probably due to the reduction of the exciton binding energy, but not of plasmon induced strengthening of photon absorption known from the p-n junction solar cells (like the metalized Si cells). On the technological side, nanoparticles are embedded in the perovskite compounds close to the interface with the electron or hole absorber in the architecture of a hybrid chemical perovskite cell. Such cells operate in a different manner than conventional p-n junction cells, resulting in a different type of the plasmonic PV effect, which, however, is surprisingly strong.

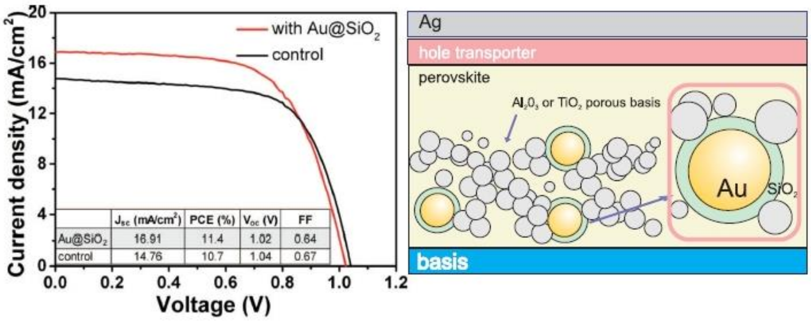

Fig.1. The I-V characteristics of the perovskite cell with porous Al_2O_3 basis filled with $Au@SiO_2$ core-shell nanoparticles after experiment (Zhang et al. 2013); a strong increase of the photo-current is noticeable with simultaneous lowering of the voltage; (right panel) the scheme of location of dielectric coated core-shell gold nanoparticles.

The R&D plans are to scientifically explain this effect enabling its further technological development by applying various quantum techniques, including the Fermi golden rule to the coupling of the dipole near-field-zone (lower distance than the wavelength) radiation of surface plasmons in nanoparticles to the band electrons in a nearby semiconductor. The research plans involves simultaneously both components of this effect, i.e. optical (the one in p-n junction cells and resolving itself mainly to a photon absorption growth) and electrical (the newly discovered in perovskite cells apparently beyond absorption) ones in a common general microscopic model, allowing for the parameter optimization in a technological fine-tuning towards the innovative products development. The objective of the research in this domain is thus to commercialize the new technology of plasmon enhanced metalized perovskite solar cells, allowing for commercialization of the initially proven feasibility of relative increasing of the perovskite SCs efficiencies in a magnitude of 40%, depending on the particularities of the solar cell design towards harnessing the investigated technology and prepare the perovskite metalized solar cells in terms of prototype devices to be introduced to the market. This research objective holds a potential to support novel breakthrough in a general PV uptake due to an improved cost/efficiency ratios and practical advantages of the thin-film and elastic perovskite solar cells devices with efficiencies significantly exceeding current state of the art (with cost nearing towards 0,009 Euro per kWh from the current value of ca. 0,015 Euro per kWh achieved in 2020).

The objective of technologically mastering particularities of the new plasmon effect in the perovskite SCs is of a major significance as the efficiency of these cells without any metallic components has been lifted from 2% (2006) and 3.8% (2009) to 25.3% (2019) and circa 30% (in tandem) and its further increase (up to 40% relative increase as proven in trial experiments) due to metalization is highly impressive and carries with itself very significant market potential for a mainstream proliferation of PV (very realistic at the mentioned above target energy production unitary costs).

Cheap and relatively simple low-temperature chemical technology of perovskite cell production, the possibility to produce ultra-thin plastic panels in a roll-to-roll processing including ink-jet or screen printing and covering arbitrary substrates (windows, walls, tiles) with thin elastic cells, indicate that perovskite cells might become a default choice for many application sectors as the future mass industry PV solution. Recent advances in durability enhancement of perovskite SCs are also encouraging and motivating interest in metalization of these cells. As mentioned in 2019 NASA announced the beginning of trials using ultra-thin perovskite panels ink-jet printed in space and transported on e.g. to the Moon or Mars in liquid form instead of the conventional large and heavy PV panels. This is considered additionally feasible as the main destructive factors temporarily degrading perovskite cells, such as humidity and oxygen, are not present in space or on the Moon.

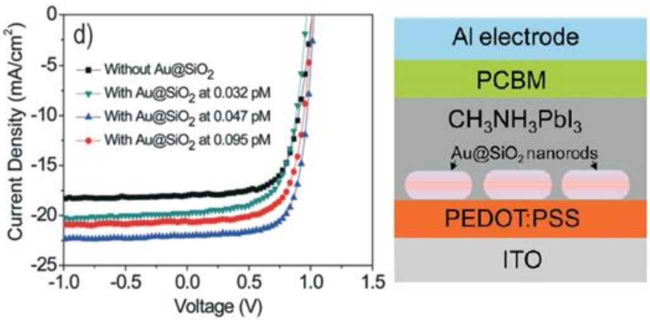

Fig.2. The I-V characteristics of the perovskite solar cell metalized with gold code-shell nanorods (right panel) embedded at the interface between the PEDOT:PSS later and the perovskite later, after the experiment (Wu et al. 2016).

Therefore, the lasting metalization of perovskite cells would provide an important contribution to optimize their efficiencies and also to accommodate the spectral characteristic of final cells to a different solar radiation spectrum in various circumstances beyond Earth's atmosphere. Identification and technological fine-tuning of the microscopic mechanism of both the branches of the plasmon PV effect in perovskites is of major significance for development of the plasmonic enhanced photovoltaics.

4. European Commission Policy in Support of the Perovskite PV R&D

The Horizon 2020 Work Programme 2018-2020 in its Section 10. defines major research directions towards achieving a goal of building a low-carbon, climate resilient future for Europe with secure, clean and efficient energy. Upon these directions Research and Innovation actions calls have been planned focusing on novel technologies on renewable energy. The scope of these efforts resolve to achieving climate neutrality in the energy sector with securing economically justified energy sources with minimized environmental signatures.

The perovskite solar cells R&D directly adheres to the main measures as defined in scope of the revised H2020 Work Programme. The perovskite SC R&D aims at progress in cheaper and more performant renewable energy generation technologies in domain of PV, as well as in supporting increase of the renewable energy innovations market-uptake for solidifying an already pronounced capacity of the European Union in this area. The relevant H2020 calls focus on the efforts in research activities aimed at identifying and harnessing solar energy breakthroughs that will feed the innovation cycle and become the basis of the next generation of the EU photovoltaic technologies. The Work Programme requires that the R&D contributes to implementing priorities for strengthening of the EU leadership in renewables articulated in the Communication for Accelerating Clean Energy Innovation – European Commission COM(2016) 763. This communication points that further accelerating the transition to low-carbon competitive economy is both an urgent necessity and at the same time a tremendous opportunity for Europe being also a central challenge of our time, while taking into account pollution impacts and the global warming. As the EU is well placed to lead in the clean energy transition it also holds a strong technological position in this domain. In recent decades Europe was leading global efforts to fight climate change and was a driving force in developing renewables. As further pronounced in the Clean Energy for All Europeans – European Commission COM(2016) 860, innovation in renewable energy is one of the key areas where action can be strengthened by current technological position of the EU on a global scene with synergies achieved in successful proposals implementation results, assumed to support jobs, growth and industrial investment in Europe. The impact of the perovskite SC R&D as one of the EU KETs thus addresses global competitiveness of the EU in regard to photovoltaics.

The Energy Union policy set out on the basis of the above mentioned European Commission communicated standpoints in particular address the two following goals: 1) putting energy efficiency first and 2) achieving global leadership in renewable energies. The EC has estimated that in order to reach the EU's 2030 climate and energy targets, about €379 billion investments are needed annually over the 2020-2030 period (with €27 billion devoted to public and private research annually) with significant shares targeted at the further development of PV.

It should be however stressed that photovoltaic industry in the EU experienced significant problems with employment reductions in the recent decade due to industrial PV production downfalls in Europe resulting from overseas market competition, mainly from Asia (and in particular China). The Chinese competitors are reported (cf. European Commission funded study by Dervojeda et al. 2017) to be actively supported by the local government using multiple means, such as special tax exemptions, access to low interest investment, direct subsidies to sell the products on the EU and US markets below their production costs, IP looting, etc. targeted at reaching a global economic domination on the market of PV devices and enjoying the benefits coming from such position, enabling also increasing the technological edge. Furthermore, Chinese PV advancing production processes and technologies are usually associated with a considerable environmental pollution levels, much beyond the norms accepted in Europe. As stipulated by European Commission, in the current situation the main direction to re-establish a fair play competition with Asian players in a domain of emerging PV technologies is by providing stimulatory and widely-scaled R&D funding in Europe, developing many possible directions simultaneously to possibly create a strong synergy between European technologies. The technology planned for R&D in perovskite PV holds such a potential with its universal character, enabling to enhance almost all types of perovskite SC fabrication techniques with initially proven as impressive relative efficiencies increases (in relative improvement of up to even 40% as demonstrated Wu et al. 2016).

Also the market-enabled impact is pronounced in the revised Work Programme of the H2020 priorities in regard to photovoltaics. Emerging and new PV technologies including perovskite cells are specially promoted on the level of Research and Innovation actions in H2020 Work Programme, with the priorities involving maximising industry engagement in development and commercialization activities of the researched renewable energy technologies. The European Commission has e.g. recognized a goal – cf. European Commission Decision C(2020)4029, 2020 – in the H2020 program to overcome the short-term orientation of industry and engage it in activities with a longer-term focus (at least 3-5 years ahead), which is also well aligned with the investigated R&D in metalized perovskite SCs nano-plasmonic efficiencies enhancements.

In general we all realize that the depletion of fossil fuels and global warming resulting from the use of these traditional energy sources reveals the need to focus on renewable and clean energy sources. This is especially underlined by the so called European Green Deal policy in the new appointment of the European Commission that continues the same direction with however a new impetus and yet even stronger focus of the renewable energy strategic significance for the problems related to climate changes and the fossil fuels caused pollution and its social and economic impacts. As renewable and clean energy, photovoltaics have secured its position as one of the most promising and dynamically developing sustainable and clean energy source. Since the production of first modern solar modules in 1954 in Bell Labs, many types of solar cells have been developed and successfully commercialized. Solar cell technologies advances are usually connected to new achievements in theoretical and experimental studies in the domain of light absorbing materials. In the recent decades, a huge effort has been focused on enabling new PV materials to produce high quality SCs with increasing efficiencies in converting sunlight to electric energy at decreasing costs.

The perovskite PV research has therefore a strongly applicative and prospective character of commercial significance which directly responds to the expectations outlined in the relevant section of the H2020 Work Programme. The main expected contribution of this research domain is targeted at the reduction of the solar power costs with PV efficiencies enhancements and the objectives straightforwardly support the Strategic Targets of the H2020 Work Programme in its corresponding scope. Additionally the H2020 WP sets emphasis on including international cooperation opportunities whenever relevant to the proposal and the domain, in particular in the context of the Mission Innovation Challenges. This is widely addressed in the present cooperation in the EU scale within this PV R&D domain with a lasting partnership between the partners, who already cooperated in numerous research endeavours, including recent years lasting cooperation in the H2020 EU COST program MultiScale Solar (http://multiscalesolar.eu). The corresponding RIA H2020 calls expect bottom-up proposals addressing any renewable technology currently in the early phases of research which is the topic that our proposal focuses on. The current research of the metalized perovskite PV technology is between TRL 1/2 to TRL 4/5. As with the programmed H2020 Work Programme requirements, the expected impact of research must be based on the concept already proven, which ist he case, and further developed to contribute to accelerating and reducing the cost of the next generation of sustainable renewable energy generation. It should also directly advance the knowledge and scientific proofs of the technological feasibility of the plasmonically enhanced perovskite SCs, including environmental, social and economic benefits from this technology. This research area also demonstrates the required contribution for establishing a European innovation base and supporting a sustainable renewable energy system. Yet even more importantly the impact of the researched metalized perovskite SCs hold a potential to provide a real breakthrough in applied photovoltaics in general, facilitating its major market uptake, as a combination of cheaply produced (yet low energy-efficient in stable chemical configurations) perovskite cells with advanced quantumly enabled plasmonic efficiency improvements by metallic nano-modification (that as validated are able to enhance the efficiency by even 40% relative growth). This holds a strong potential for overall PV proliferation as a mainstream electricity source in multitude of everyday applications.

Currently, the most commonly developed inorganic (synthesizable with chemical crystallization techniques convenient for mass production and ink-jet/screen printing) perovskite solar cells are $CsPbI_3$, $CsPbI_2Br$ $CsPbIBr_2$ and $CsPbBr_3$. The $CsPbI_3$ with a narrow band (of 1.73eV) is one of best candidates for harvesting solar energy. The CsBp perovskite solar cells show the best performance among inorganic cells (Ho-Baillie et al. 2019), yet its black phase (α-$CsPbI_3$) suffers from notorious instability at room temperature, causing rapid degradation to the so called yellow phase (δ-$CsPbI_3$) of poor-efficiency (Sutton et al. 2016, Hu et al. 2017, Eperon et al. 2015, Luo et al. 2016, Akkerman et al. 2015, Stoumpos et al. 2013). There are thus many challenges in the fabrication of stable cells devices. Incorporation of bromide ions into Cs perovskites in place of iodide ions to form $CsPbBr_3$ is currently considered the most promising alternative for improving phase stability, but its large band gap (2.25 eV) limits light collection thus reducing the cell efficiency (Li et al. 2018, Liu et al. 2019). Recently much effort has been put into the development of completely inorganic cells to improve phase stability, which is its main limitation and the results are promising. Within those efforts over the few past years, multiple companies and researchers have reported new efficiency records in area of perovskite SCs.

The current record for perovskite SC efficiency is 29.1% from Helmholtz-Zentrum Berlin achieved in January 2020 which is a result directly competing with much more complicated and expensive to produce GaAs thin-film SCs. However this result was achieved for the tandem perovskite/Si configuration. Before this in June 2018 Oxford PV announced that it had developed 27.3% perovskite-silicon tandem device (in December 2018 the same company announced a 28% world performance record for tandem Si perovskite cells), so there is a steady growth of circa 1% annually.

For multi-junction tandem configurations the Shockley-Queisser limit can be overcome and advanced (yet much more complex to fabricate and expensive as well as less practical in terms of flexibility) SCs of these type will be characterized with further-on increasing efficiencies. On the other hand for single junction perovskite cells the upper limit is the Shockley-Queisser limit, theoretically accepted for perovskite SCs at the level of circa 31% (Sha et al. 2015), which is close to the theoretical SQ limit of 32% for single junction Si-based solar cells and 33% achievable by GaAs cells. The current record for laboratory achieved single-junction perovskite cell efficiency is circa 25% first approached in September 2019 by Korea Research Institute of Chemical Technology (KRICT) and MIT cooperation and later on surpassed with 25,2% by University of Korea (however in unstable regime precluding a practical device as of yet). For market applicable perovskite cells (or whole modules) the achievable efficiencies are however much lower. In Japan, in July 2018, Toshiba and NEDO cooperation announced similar 703 cm^2 perovskite module with a stable performance at 11.7%. In Europe, in April 2018, the EU Solliance Project announced its most effective perovskite module of 144 cm^2 and stable efficiency of 13.8%. In July 2018 Chinese Microquanta announced a new record for the mini perovskite commercial module at 17.3% (the module module contained 7 cells and had an area of only 17 cm^2). In October 2019, the company achieved a record conversion rate of 14.24% for a large perovskite solar module of 800 cm). Each cell in the module has an efficiency of 14.5%. More recently, in September 2019, Solliance and the American company MiaSolé announced another achievement: 23% energy conversion efficiency in a flexible tandem solar cell: an upper flexible translucent perovskite solar cell with an indium and gallium selenium lower flexible cell (CIGS).

In April 2020 Saule Technologies in Poland secured funding to launch mass production of stable ink-jet printed perovskite modules (following few years long large scale investment for R&D) with efficiency slightly surpassing 10%, but with relatively large surfaces of $1m^2$. The technology of metalized perovskite improvement by nano-plasmonic effects mediating energy transfer in a newly discovered exciton channel beyond the currently known mechanisms in standard p-n junction solar cells has highly universal character in terms of applications to improve the practically achieved efficiencies in stable perovskite chemical configurations to support reaching the objectives set out in H2020 WP. This technology is easily scaled from a PV cell level to a complete SC module. The main property of this technology, enables metallic nanoparticles inclusions into the liquid screen printing of the solar cell upon a process of perovskite chemically induced crystallization after screen-printing takes place. This allows to fabricate metalized perovskite cells in a roll-to-roll approach conditioned by the scale of the printing device. The efforts are thus focusing on research and prototypes development and testing on the level of cells and modules with a goal to obtain a universal efficiency increase, stability and large-scale manufacturability for thin film PV that will be competitive with existing commercial perovskite PV technologies at a very low cost of modification of the production processes addressing the novel PV technology requirements as defined in the H2020 Work Programme. The results of the research are aimed at supporting European Union in improving its position in global competition for the efficient thin-film solar cells research and economically viable convenient mass production techniques supporting goals of the WP and the European Strategic Energy Technology Plan (SET Plan - https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan).

In terms of Key Performance Indicators (in connection to the SET-Plan) the research objectives aim at overcoming the economic barrier in PV cost/efficiency ratio that currently withhold solar energy transition. The R&D efforts hence address the issue on how to optimize metalization of perovskite cells and how to design and produce such devices, including also a challenging question on space-applications (i.e. addressing different spectra of solar radiation). This research domain also enhances knowledge diffusion in the EU increasing innovation capacity in the low-carbon economy sector and integrating advanced research capabilities upon a prospective PV technology. Growing share of Renewable Energy Sources represents a strong contribution to the COP21 objectives and United Nations Sustainable Development Goals (IEA 2018, IRENA 2018). In 2018, the renewable energy share in the EU represented 17.5% of total energy consumption with increasing share of PV (amounting 4% share – Eurostat 2019). The PV energy is positioned to soon dominate RES and slowly starts to challenge fossil fuels in the recent years in many sectors due to increasing ratios of efficiency per cost, continuously brought up by the new solar cells technologies (IRENA 2018). In 2020 PV may have already finally become the cheapest source of the electrical energy in general (cf. Qatar General Electricity & Water Corporation, 2020).

The PV energy, as an already top effective renewable energy source, is deemed to become in the near future a mainstream economically viable option for ensuring carbon-free and ubiquitous electricity source to our civilization. One of main problems of modern solar cells is the robust design of PV panels which are limited in scope of their possible applications. The much more universal SC technology of flexible perovskites that can be integrated on any surfaces (including window tiles, surface coverings of any objects or devices, including electronics, cars, clothing, etc.) is on the other hand hampered by lower efficiencies. The research objectives thus focus on understanding and improving perovskite SCs efficiencies by plasmonic enhancement due to metalization, thus not only ensuring high efficiencies but also pushing economically viable thin-film elastic SC devices towards the market. This addresses applicable research with goals in commercialization of the new technology, including such critical issues as devices designs, production costs, operational reliability and durability. The significance of the researched metalized perovskite PV technology in domain of renewables can be well compared to other competing technologies, such as CSP (Concentrated Solar Power, with lensing designed to collect solar radiation in heat) as targeted in further development by the European Strategic Energy Technology Plan.

The SET Plan has established strategic targets for CSP development, of which the first target is *"More than 40% reduction of energy costs by 2020, reaching a price <0.10 €/kWh".* The target CSP unitary price of SET-

Plan is thus greater by 1 order of magnitude in comparison to the unitary price of PV energy generation that current research plans in the scope of plasmonically enabled perovskite solar cell pursue: i.e. values of 0.01 Euro/kWh and below. This research adheres to the H2020 Work Programme in contributing to the development of the next generation of highly efficient and flexible-structure solar cells based on plasmonically activated metalized perovskites, thus focusing on potential cost-effective solutions enabling further proliferation of PV energy, as well as renewables in general to support decarbonization and sustained development. It pursues optimizing of the the perovskite SC technology by researching innovation of plasmonic enhancement due to metallic nano-modifications with contributions of quantum effects on the verge of frontier of basic science. This R&D domain involves fundamental study to provide clear scientific description of not yet fully understood core physical mechanisms involved in the proven effect to be able to optimize and later bring this technology from a prototype stage towards the commercial product, scaling its market potential and competitiveness upon ongoing fine-tuning of the product designs and its reliability.

5. Summary and Conclusions Regarding Future Prospects of Perovskite PV

At the summary the author would like to stress the role of the the Perovskite Solar Cell as the EU Key Enabling Technology. As stipulated in the introductory chapter at the end of 2017 the European Union in its study on Key Enabling Technologies for achieving technological global supremacy for the EU has identified only a total of 12 promising KETs among all technologies as the ones holding potential for the EU to assure through further development that the EU industry in those KETs respective areas will stay ahead of international competition. In energy context the Perovskite Solar Cell was defined as the KET for the EU, mainly due to the EU's secured leading position in this technology as well as due to high efficiency/cost ratio (ca. 0,014 Euro/kWh) and other key properties such as semi-transparency or elasticity supporting wide applications of this PV technology.

As buildings are estimated to account for over 40% of the energy demand in the EU, building-integrated solar cells are the primary application for PV. Perovskite in contrast to sturdy Si panels offer simple whole-surface coverings techniques including aspects such as architectural freedom. The advantages of the Perovskite Solar Cells are primarily due to the elastic thin-film PV technology being easily and cheaply ink-jet or screen printed in simple roll-to-roll processes or even sprayed onto large surfaces similarly like paints that when activated with chemically induced crystallization process make thin-film layers (thickness below 1 μm).

These devices are thus well suited to mass-output market uptake and vast applications (such as energy smart buildings elevations coverings of variety of diff. geometries, semitransparent or smart windows, roofs coverings, outdoor furniture, vehicles or even clothing external surfaces that produce enough power to charge a phone).

Skanska partnering with Saule now commercialize Perovskite SCs in newly developed buildings as large area elevations and windows coverings. Perovskite eff. rose rapidly from just 2% in 2006 to 25.3% in 2020 and up to 30% in tandem, however have stability / durability problems at higher efficiencies (are currently stable at ca. 15% eff.) Therefore the R&D initiatives are needed in this emerging PV technology domain.

In May 2019 the Cost of Ownership of just 0.20 EUR/Watt-peak was proven achievable for single-junction pure perovskites modules prototypes by CHEOPS project (cheops-project.eu). Other research initiatives (including e.g. the 2020 PLASMPERCELL H2020 proposal, involving scientific partnership of European Solar Network - Belgium, National Centre for Scientific Research - France, Technical University of Clausthal, Friedrich Schiller University Jena, International Solar Energy Research Center Konstanz - Germany, University of Rome Tor Vergata - Italy, Aristotle University of Thessaloniki and Organic Electronics Technologies - Greece, PlasmaSolaris - Poland, Endüstriyel Elektrik - Turkey and the University of Belgrade - Serbia and with the present paper's author holding the role of the coordinator of the consortium on behalf of the European Solar Network) targeted R&D in the perovskite SCs efficiency increases with up to 40% relative increase proven achievable due to the nano-plasmonic enhancements (inclusion of metallic nano-particles).

A relative growth of about 40% as already demonstrated means that if one has a cheap and stable perovskite SC production technology at just circa 15% efficiency one can releatively easily grow this efficiency to circa 21% with similar chemical morphology and stability of the original cell employing quantum processes of plasmonic energy transfer mediation (noble metals or TMN nanoparticles). This with a very marginal additional cost of few % (in materials, cell fabrication, module assembly, installation, etc.) diminishes the Cost of Ownership towards values of 0.15 - 0.14 EUR/Wp.

This is an example of the perovskite PV R&D direction that is well aligned with the EU's PV research support priorities and policies (involving the KET, following priorities set out in the SET Plan, including maximizing the efficiency/cost ratios), pronouncing perovskite SCs KET role for the EU.

6. References

Akkerman, Q.A. et al., 2015. Tuning the optical properties of cesium lead halide perovskite nanocrystals by anion exchange reactions, J. Am. Chem. Soc., 137, pp. 10276-10281, 10.1021/jacs.5b05602

Dervojeda, K., Lengton, M., Koonstra, A., 2017. Perovskite Solar Cells, Report on promising KETs, KETs Observatory Phase II, EASME/COSME, European Commission

Eperon, G.E., Paternò, G.M., Sutton, R.J., Zampetti, A., Haghighirad, A.A., Cacialli, F., Snaith, H.J., 2015. Inorganic caesium lead iodide perovskite solar cells, J. Mater. Chem. A, 3, pp. 19688-19695, 10.1039/C5TA06398A

European Commission, 2020. Strategic Energy Technology Plan, 2014-2020, https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan

European Commission COM(2016) 763

European Commission COM(2016) 860

European Commission Decision C(2020)4029, 2020. Horizon 2020, Work Programme 2018 - 2020

Eurostat, 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics

Ho-Baillie, A., Zhang, M., Lau, C.F.J., Ma, F.-J., Huang, S., 2019. Untapped potentials of inorganic metal halide perovskite solar cells, Joule, 3, pp. 938-955, 10.1016/j.joule.2019.02.002

Hu, Y., Bai, F., Liu, X., Ji, Q., Miao, X., Qiu, T., Zhang, S., 2017. Bismuth incorporation stabilized α-$CsPbI_3$ for fully inorganic perovskite solar cells, ACS Energy Lett., 2, pp. 2219-2227, 10.1021/acsenergylett.7b00508

International Energy Agency, 2018. Market Report Series: Renewables 2018 - English ES

IRENA, 2018. Global Energy Transformation. A roadmap to 2050, Microscopy Research and Technique

Jacak, W., 2020. Quantum nano-plasmonics, first edition, Cambridge University Press

Jacak, J., Jacak, W., 2018. "Plasmon-induced enhancement of efficiency of solar cells modified by metallic nano-particles: Material dependence", J. Appl. Phys. 124, https://doi.org/10.1063/1.5040014, p. 073107

Jacak, W., Popko, E., Henrykowski, A., Zielony, E., Luka, G., Pietruszka, R., Witkowski, B., Wachnicki, L., Godlewski, M., Chang, L.-B., Jeng, M.-J., 2016. "On the size dependence and the spatial range for the plasmon effect in photovoltaic efficiency enhancement", Sol. Energy Mater. Sol. Cells 147, p. 1

Jaeger-Waldau, A., 2019. PV Status Report, Joint Research Centre, Publications Office of the European Union, Luxembourg

Jeng, M.-J., Zih-Y, C., Xiao, Y.-L., Chang, L.-B., Ao, J., Sun, Y., Popko, E., Jacak, W., Chow, L., 2015. "The efficiency enhancement of silicon and CIGS solar cells by the incorporation of metal nanoparticles", Materials 8, p. 6761

Laska, M., Krzemińska, Z., Kluczyk-Korch, K., Schaadt, D., Popko, E., Jacak, W.A., Jacak, J.E., 2020. Metallization of solar cells, exciton channel of plasmon photovoltaic effect in perovskite cells, Nano Energy

Li, H. et al., 2018. Interface engineering using a perovskite derivative phase for efficient and stable $CsPbBr_3$ solar cells, J. Mater. Chem. A, 6, pp. 14255-14261, 10.1039/c8ta03811b

Lim, S. et al., 2007. "Photocurrent spectroscopy of optical absorption enhancement in silicon photodiodes via scattering from surface plasmon polaritons in gold nanoparticles", Journal of Applied Physics 101(10), p. 104309

Liu, X. et al., 2019. Boosting the efficiency of carbon-based planar $CsPbBr_3$ perovskite solar cells by a modified multistep spin-coating technique and interface engineering, Nano Energy, 56, pp. 184-195, 10.1016/j.nanoen.2018.11.053

Losurdo, M. et al., 2009. “Enhanced absorption in Au nanoparticles/a-Si:H/c-Si heterojunction solar cells exploiting au surface plasmon resonance”, Sol. Energy Mater. Sol. Cells 93, p. 1749

Luo, P., Xia, W., Zhou, S., Sun, L., Cheng, J., Xu, C., Lu, Y., 2016. Solvent engineering for ambient-air-processed, phase-stable CsPbI3 in perovskite solar cells, J. Phys. Chem. Lett., 7, pp. 3603-3608, 10.1021/acs.jpclett.6b01576

Luo, L., Xie, C., Wang, X., Yu, Y., Wu, C., Hu, H., Zhou, K., Zhang, X., Jie, J., 2014. “Surface plasmon resonance enhanced highly efficient planar silicon solar cell”, Nano Energy 9, pp. 112–120

Matheu, P., Lim, S., Derkacs, D., McPheeters, C., Yu, E., 2008. “Metal and dielectric nanoparticle scattering for improved optical absorption in photovoltaic devices”, Applied Physics Letters 93(11), p. 113108

Pillai, S., Catchpole, K., Trupke, T., Green, M., 2007. “Surface plasmon enhanced silicon solar cells”, Journal of Applied Physics 101(9), p. 093105

Pillai, S., Catchpole, K., Trupke, T., Zhang, G., Zhao, J., Green, M. A., 2006. “Enhanced emission from Si-based light-emitting diodes using surface plasmons”, Appl. Phys. Lett. 88, p. 161102

Sha, W.E.I., Ren, X., Chen, L., Choy, W.C.H., 2015. The Efficiency Limit of CH3NH3PbI3 Perovskite Solar Cells, Appl. Phys. Lett. 106, 221104

Schaadt, D. M., Feng, B., Yu, E. T., 2005. “Enhanced semiconductor optical absorption via surface plasmon excitation in metal nanoparticles”, Appl. Phys. Lett. 86, p. 063106

Stoumpos, C.C. et al., 2013. Semiconducting tin and lead iodide perovskites with organic cations: phase transitions, high mobilities, and near-infrared photoluminescent properties, Inorg. Chem., 52, pp. 9019-9038, 10.1021/ic401215x

Stuart, H. R., Hall, D. G., 1998. “Island size effect in nanoparticles photodetectors”, Appl. Phys. Lett. 73, p. 3815

Sutton, R.J., Eperon, G.E., Miranda, L., Parrott, E.S., Kamino, B.A., Patel, J.B., Hörantner, M.T., Johnston, M.B., Haghighirad, A.A., Moore, D.T., Snaith, H.J., 2016. Bandgap-tunable cesium lead halide perovskites with high thermal stability for efficient solar cells, Adv. Energy Mater., 6, p. 1502458, 10.1002/aenm.201502458

Qatar General Electricity & Water Corporation, 2020. Kahramaa and Siraj Energy Sign Agreements for Al-Kharsaah Solar PV Power Plant

Wang, 2018. Solar modules to get even cheaper and more efficient, Bloomberg New Energy Finance

Wu, R., Yang, B., Zhang, C., Huang, Y., Cui, Y., Liu, P., Zhou, C., Hao, Y., Gao, Y., Yang, J., 2016. “Prominent efficiency enhancement in perovskite solar cells employing silica-coated gold nanorods”, J. of Phys. Chem. C 120, p. 6996

Yao, K. et al., 2019. “Plasmonic metal nanoparticles with core-bishell structure for high-performance organic and perovskite solar cells”, ACS Nano 13, p. 5397

Zhang, W., Saliba, M., Stranks, S., Sun, Y., Shi, X., Wiesner, U., Snaith, H., 2013. “Enhancement of perovskite-based solar cells employing core-shell metal nanoparticles”, Nano Lett. 13(9), p. 4505