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First Workshop on Identification of Future Emerging Technologies for Low Carbon Energy Supply

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Foreword

As part of the European Commission's internal Low Carbon Energy Observatory project, the Joint Research Centre is developing an inventory of future emerging technologies relevant to energy supply. A key part of this initiative is consultation with external experts.

This workshop is the first step in this process. It targets two main energy research areas: electricity from electromagnetic irradiation (principally photovoltaics, but also thermo-electric concepts) and fuels (comprising fuel cells, hydrogen and biofuels). Issues of general interest are also considered. The goal is to identify innovative technologies and processes for energy supply, possibly not sufficiently considered in current research funding programs.

Further workshops on other research areas for low carbon energy supply will be organised.

Acknowledgements

We would like to express our gratitude to all the participants and contributors of the first Workshop on Identification of Future Emerging Technologies for Low Carbon Energy Supply. Especially to all the external experts without whose contribution this report would not be possible. Together with the participants, listed in Table 1, we would like to thank the contributors who could not attend to the workshop Table 2.

Also, we want to thank the two rapporteurs: Professor Andrea Li Bassi and Professor Andrea Casalegno from Politecnico di Milano and Marco Massa, a JRC colleague who helped in the organisation.

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Jolina Hubenova	University of Plovdiv, Bulgaria
Arnulf Jaeger-Waldau	JRC, Ispra, European Commission
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Table 2. Other workshop contributors

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Figure 1. The panel of invited experts and the European Commission organizers of the workshop in the ESTI Laboratory of the JRC Ispra site (01/12/2016)

Executive Summary

The Joint Research Centre is developing an inventory of future emerging technologies relevant to energy supply, as part of the Commission's internal Low Carbon Energy Observatory project, a key element is consultation with external experts, addressing both those with in-depth experience in specific fields and those with a broad perspective on relevant science and engineering aspects.

The LCEO Workshop held 1 December 2016 was the first step in this process, bringing together a group of 20 experts from European and international universities and research organisations, as well as several JRC experts. The programme targeted photovoltaics, thermo-electric concepts, fuel cells and biofuels. The participants, organized in two working groups: "Fuels" and "Photovoltaics"; identified a set of FETs and discussed about different aspects of these technologies: potential, challenges, applications and assessed their technology readiness level (TRL). This document summarises the outcome of the discussions in order to facilitate its use by the European Commission policy makers and the scientific community in general.

The first working group had a broad scope, considering several technologies not directly related to each other but falling under the general denomination "fuels".

Metal fuel technology addresses the potential of many metallic materials to either be burned in powder form in a combustion engine, or used in the production of electrochemical or fuel cells batteries.

Microbial fuel cell technology can be used for electricity generation and wastewater treatment. Time was also devoted to sub-technologies such as the microbial electrolysis cell, used in the production of hydrogen, and sediment microbial fuel cells, an early stage technology whose cost-effectiveness and the stability of its devices were highlighted by the experts. Direct carbon fuel cells, a technology allowing the quick conversion of raw biomass with direct production of electrical energy, were also assessed.

The experts also discussed the advances in algal biofuels, taking in the latest progress all along the production chain, from the cultivation to the production of the biofuel, as well as some new cross-cutting applications, such as the coupling of the harvesting devices with photovoltaic modules.

Plasma activation of stable molecules or plasma assisted catalysis, a technology based in the capacity of plasma to transfer or store electric energy into gaseous molecules, was also considered.

The second working group, on photovoltaics, focussed its attention in a larger set of technologies producing electricity from (solar) radiation, and some auxiliary or subsidiary technologies representing advancements in the production methods of photovoltaic devices. Hence, even if the number of technologies discussed in this working group was larger, these technologies were more similar among them so it was possible to group them in categories.

In the photovoltaic working group, the concepts discussed can be divided in three broad categories. The first is characterised by a clear potential to impact the market, recent progress and the capacity to reach high efficiency levels. It includes innovative thin film multi-junction solar cells, innovative III-V compound based solar cells, kesterite and perovskite solar cells. All could especially benefit from the development of novel contacts improving the efficiency of the PV devices. All also still have many challenges, for example materials research needed on certain aspects and on processability of devices.

The second PV category covers technologies that still need significant development to demonstrate that their theoretical potential could be realised in practice. Examples include intermediate band solar cells and ferroelectrics, multiple exciton generation solar cells, hot carrier solar cells or the application of plasmonics to photovoltaics; the panel recognize the scientific interest in these technologies but expressed doubts about their future development and about their possibilities to reach a commercial level.

A third PV group covers the multidisciplinary technologies, not strictly photovoltaics, such as photoelectrocatalytic or thermophotovoltaic devices (both at an early stage of development and with a moderate impact and chances of success). In this group we can also find technologies which are considered as new methodological approaches or as general manufacturing methods. For example the production of solar cells from semiconductor foils, the development of new photovoltaic materials via combinatorial and computational design and the development of low cost manufacturing techniques. For instance for the later, roll-to-roll manufacturing with flexible substrates is considered more for an industrial research needing adaptation and scale-up of processes than a fundamental process to be studied at a scientific level.

Outside of these two working groups, *new thermoelectric materials* where presented. These technologies are being investigated for building low-cost heat-recovery devices, which could be used to provide electrical energy in various situations.

Finally, as a general comment, the panels considered it very important to devote more efforts on basic research, since for several technologies a TRL advancement is possible only if a deeper comprehension of the basic physical mechanisms is achieved. Indeed the group highlighted the importance of material science and device oriented research to the development of the new FET technologies.

Introduction

As part of the Commission's internal Low Carbon Energy Observatory (LCEO) project, the Joint Research Centre (JRC) is developing an inventory of Future Emerging Technologies (FET) relevant to energy supply. In year 2016 the JRC identified a first set of potential FETs reporting them in the "First annual report of future emerging technologies for low carbon energy supply" (First FET report").

A key part of the LCEO initiative is the consultation of external experts, addressing both those with in-depth experience in specific fields and those with a broad perspective on relevant science and engineering aspects. In this context, the LCEO organised this First Workshop on Identification of Future Emerging Technologies for Low Carbon Energy Supply that took place at the Joint Research Centre Ispra site on December 1, 2016.

This first workshop was mainly focused on the low carbon energy technologies described in the First FET report (photovoltaics, fuels cells and advanced biobuels). Other research areas will be explored in next LCEO workshops.

The aim of this document is to gather and organize all the knowledge and information issued from this first workshop in order to facilitate its leverage by the European Commission policy makers and the scientific community in general. This report summarises the outputs provided by the invited panel of external experts attending the workshop, and noted down by two independent rapporteurs from Politecnico di Milano. Hence, this document should not be considered as the voice of the JRC experts, who have only contributed to the process of gathering the information and to its final editing, but not to its content.

The workshop was organized on the idea of a colloquium between international experts to discuss about future emerging technologies considering different aspects as their technology readiness level (TRL), or the potential advantages and challenges that characterise their development. Many of the technologies discussed were directly proposed by the invited experts on the condition that they respected the following criteria:

- To be a technology for energy supply/conversion.
- To be a radically new technology/concept, not achievable by incremental research on mainstream technologies (this should match the concept of the Future Emerging Technology in the Horizon 2020 work program http://ec.europa.eu/programmes/horizon2020/en/h2020-section/future-and-emerging-technologies).
- To be in an early stage of development: their Technology Readiness Level should not be more than 3 (See Annex 2).
- Should be not included in the list of the technologies already identified by the JRC experts in the "First FET report" (Table 3).

Table 3. Future emerging technologies identified by the JRC experts in the "First FET report"

Photovoltaics	Hydrogen and fuel cells	Advanced Biofuels
• Kesterite thin film solar cells • Perovskite thin film solar cells • Organic and dye-sensitized solar cells • Intermediate band solar cells • Solar cells with nanostructures: e.g. quantum dots, nanowires • Plasmonic solar cells • Roll-to-roll manufacturing	• Photo-catalysis • Dark Fermentation • Photo-biological water splitting • Photo-fermentation • Electrochemical Compression • Advanced hydrogen storage materials • Reversible fuel cells • Microbial fuel cells	• Biochemical/chemical production from lignocellulosic material or other wastes • Thermochemical production from lignocellulosic material or other wastes • Algal biofuel

The new FETs were proposed by external experts by using a FET concept sheet template that they filled in and sent back to the organisers before de date of the workshop (See Annex 3).

The workshop followed the structure and methodology detailed here below (See also Annex 1):

1. Introductory session to explain the scope and proposed working method.
2. Sector-specific sessions: two groups, one on photovoltaics and one on fuel cells, hydrogen and biofuels, called "Fuels". The experts could attend one or the other according to their background and preferences.
   For each FET concept sheet, the expert that had proposed this technology presented it very briefly (5 minutes), sketching why this could be considered promising and relevant.
   Then, the other experts could debate and brainstorm about it, also by adding new inputs, ideas and suggestions connected to that technology (the total time devoted to each FET concept was about 10-20 minutes). The moderators (experts from the JRC) coordinated the discussions, assisted also by the independent rapporteurs. Among the final statements, enriching the FET concept sheet initially proposed, the idea was to try to assess a TRL and to comment some pro and cons of the technology.
3. Plenary session: the results of the morning sessions were briefly presented by the rapporteurs and discussed by the whole group. Some further FET concept sheets of general interest (on thermoelectric materials and energy storage) were debated. The discussion was also open to new concepts at this stage.

The information gathered from both the concept sheets and the contributions of the experts during the workshop have been presented in this report in the same way for each technology: the technology is introduced with a few keywords and a technical description and in a second point, called "Degree of development, challenges and potential" it is resumed what can be considered a more personal contribution from the experts.

It is important to mention that the way in which the information was gathered and debated was not the same for the different working groups. This is due to the number of technologies discussed in each session, and consequently the time devoted to each one; the background of the experts or even their attitude during the workshop.

In the working group on fuels (section § 1) fewer technologies were discussed, this allowed the experts to present each technology with a higher level of detail and longer expositions. In addition to this, the profile of the participant in this working group was more specific. In general, each contributor had a deeper expertise in their own field but a more general knowledge one in the others. This combination of factors lead to longer technical descriptions of the technologies with less room for debate between experts as it is reflected in the first part of this report.

On the contrary, in the "PV" working group (section § 2) a higher number of technologies were discussed with less time for each one; this lead to shorter technical presentations, sometimes only a very brief introduction was necessary since everybody was already familiarised with the technology, and proportionally more time was left for the debate. In addition, many of the technologies discussed presented some similarities among them, and also the experts exhibited a more cross curricular knowledge, showing their expertise in different sub technologies. This set of circumstances lead to more animated debates with opposing positions on some subjects. Consequently, in the part of this report devoted to photovoltaics, we can find more technologies with shorter technical descriptions and more comments gathering opposing opinions on certain matters.

A third approach was adopted during the plenary session, when the technologies described were more cross-cutting. After a broad introduction the participants had the opportunity to brainstorm and to propose to the debate specific technologies or applications not presented in any FET concept sheet.

To conclude this introduction, we would like to comment one last point. One of the outputs obtained from this consultation with international experts is the estimation of the TRL for each technology. It must be said that this indicator, which is a relatively new concept in the field of energy technologies, can sometimes be not univocally defined, especially when referring to a technology in an early stage of development. Thus, different experts on one field can have a different appreciation of the readiness level of a certain technology. Consequently, the TRL indicators appearing in this report, even if they come from the agreement of the invited experts, have an intrinsic component of subjectivity and they are open to discussion.

Considering this, while comparing TRL of different technologies it is more appropriate to do it in relative terms, by comparing only TRL values assessed inside the same panel of experts. In order to compare TRLs from different working groups it would be necessary to perform a "calibration" on the scale used.

1 WORKING GROUP ON FUELS

In this section is reported the information gathered during the workshop on the Future Emerging Technologies related to the following energy sectors: metal fuels, advanced fuel cells, innovative processes for algae biofuels and catalysis.

The relevance of research on these sectors is highlighted in several technology foresight exercises aiming at identifying the most important energy trends for the future of the energy industry.

For example, the study "Les Technologies Clés 2020" performed in 2016 by the French government, highlights as relevant: "Processes related to green chemistry", "New generation electrochemical batteries", "Hydrogen technologies", "New generation biofuels" and "Biofuels from algae".

The 2013 study "Long-term Science and Technology policy – Russian priorities for 2030" identified as strategic, in the Energy sector, to perform research on: "Bioenergy", "Fuel cells" and "Electrochemical batteries".

The Brookhaven National Laboratory of the U.S.A., in the document "Energy Innovation", shows how its main research interests on the low carbon energy sources are devoted to develop: "New catalysts for fuel cells and hydrogen generation", "Solar to fuel conversion" (artificial photosynthesis), "improving biofuel production" (algae).

The 2013 study "Metascan3" performed by "Policy Horizons" with the support of the Canadian Government, points out that the strategic energy sectors to develop are: "Second and third generation biofuels" involving "Bioreactors using algae", "Lithium air batteries", "Hydrogen" and "Fuel cells".

In the specific session dedicated to fuels the panel of experts discussed, on the base of the FET concept sheets previously filled in, about the potential future development of the technologies, by considering advantages, impact, feasibility, challenges and relevant parameters characterizing these technologies. An important parameter considered was the Technology Readiness Level, which was assessed, for each technology, at the present level of development, together as the time necessary to reach the next step of the TRL scale.

The order of the appearance of the Fuel technologies in this section is the random order followed during the session: there is no correlation between this order and the potential interest or impact of each technology.

1.1 Metal fuels

Keywords: *Alternative fuels, electrochemical batteries, fuel cells, external combustion engines, internal combustion engines, thermoelectric generators*

Technical description

Metal fuels seem to have great potential as energy storage materials which can be competitive with coal, gasoline or even hydrogen. They can be an attractive alternative to typical fuels in terms of energy density per volume or mass. Many Earth-abundant metals like: Al, Mg, Zn, Si, Fe etc. have very high volumetric energy densities from 12 to 24 kWh/dm3 and gravimetric energy densities from 5 to 9 kWh/kg. In comparison, for typical fuels (gasoline, diesel oil) corresponding values are about 8-10 kWh/dm3 and 12 kWh/kg. Above mentioned metals usually do not exist on the Earth in the metallic form and can be produced from minerals via typical metallurgical processes (reduction by coal, or coal containing gases) and electrochemical methods (electrolysis), is foreseen for this new application the possibility to improve existing processes or developing new approaches integrating extraction and production (TRL<4). The electrochemical technology opens the path for using these metals as carriers of chemical energy produced from renewable sources (wind, solar, geothermal etc.). The chemical energy stored in metals can be further converted into electricity (e.g. in typical electrochemical batteries – Li, Zn, Mg – or metal-air fuel cells), in mechanical power (combustion engines, jet engines) or in various forms of energy in cogeneration systems (e.g. Stirling engines, thermoelectric generators, etc.). Metals can also be used for production of other fuels (e.g. hydrogen) by chemical route e.g.: $Mg + 2H_2O \Rightarrow H_2 + Mg(OH)_2$.

Degree of development, challenges and potential

Metal fuels can be applied in several energy related technologies. The technological readiness level of each technology is different depending on many factors: size and power of devices (watts, megawatts, etc.), potential application (automotive industry, large storage energy systems, etc.), technology of reproduction of the metal as a fuel (recyclability). Another problem is the potential of the selected technology for its adaptation to the whole concept in the chain: (micro) producer of metal fuel – reformer of the fuel – distribution system – end user.

1) Electrochemical (metal-air) batteries

The concept of using metals for the direct production of electricity seems to be most attractive because of its simplicity. Moreover, electrical energy can be easily converted into other forms: mechanical energy or heat. Indeed, electrochemical batteries (e.g. Li, Zn, Ni, Ag_2O based) are the most developed technologies (TRL 9). However, typical batteries have an energy density much lower than fossil fuels, because they contain both metallic fuel and oxidizer. Therefore their application in transportation (e.g. in small passenger cars) can be limited. In the concepts of metal-air batteries the oxidizer is oxygen from the air. For example the aluminium–air batteries (TRL > 7) have one of the highest energy densities of all batteries; an electric vehicle running on aluminium batteries has a potential range up to eight times higher than those with a lithium-ion batteries. They are not widely used because of problems related to the high costs of the anode and the electrolytes. Moreover, aluminium–air batteries are non-rechargeable. However, it is possible to exchange aluminium anode with new one made from recycling of the hydrated aluminium oxide. The electrolyte should also be replaced. This technology is at an early stage of development (TRL~3). Other currently developed similar technologies use Li, Mg and Fe as fuels (anodes). (TRL~3).

2) Fuel cells and flow battery

The alternative to the typical batteries are fuel cells or flow batteries. The metal as a fuel can be provided continuously as a fluid. One of the propositions concerns the application of liquid Sn to the typical solid-oxide fuel cell. The products of the operation are tin oxides, which can be later removed or reduced by using hydrogen or other reducing agents. The concept is at an early laboratory stage (TRL~3).

3) Internal-combustion engines

The combustion of metal fuels within internal-combustion engines has been proposed by several authors. Unfortunately, the properties of metal powders are not well-suited for fuelling typical engines. The solid and abrasive metal-oxide combustion products formed during metal combustion seem incompatible with the design of combustion engines. (TRL~3).

4) External-combustion engines and systems

Since the combustion of metal-powder fuels is not realistic in internal-combustion engines (ICEs), external-combustion engines (ECEs) are seriously considered. ECEs based on the Rankine cycle have been used ubiquitously for stationary power generation at a wide range of power levels. The key requirement for zero-emission metal combustion and efficient recycling of the metal fuel is the complete capture of all metal oxides from the combustion exhaust, this possible by the solid nature of the metal-oxide combustion products. However, the separation of particles from the filter materials is energy intensive and such filters are technically difficult to implement within high flow rate. (TRL~3).

Other original concepts concern the application of direct combustion of metal fuels with air in turbulent combustors to achieve higher power densities. The high-grade heat produced through metal-fuel combustion could be used directly for clean heating, or to drive Stirling ECEs, as well as thermoelectric generators. The concepts are at an early stage (TRL~3).

Considering the physical storage conditions, metal fuels seem to have significant advantages in comparison to hydrogen. They are safe and do not require special containers for transportation nor complicated storage technologies (e.g. high pressure pumps and decompression (gasification) systems). They can be easily applied in various types of electrochemical batteries for direct production of electrical energy. Despite that gravimetric energy density of hydrogen is 2-4 times higher than most reactive metals, the mass and size of energy storage systems is comparable due to high pressures required for sufficient compression of this gas.

On the other hand, it must be considered that metal nanopowders can be harmful for humans. Another risk is related to flammability, pyrophoric properties or even explosiveness if mixed with air, as observed for many metal nanopowders.

Generally, technologies of production of pure metals using electrochemical methods are well developed (TRL 9). It seems that the main challenge is in adapting the existing devices (e.g. engines, turbines, heaters) for using metals as fuels. However, some important issues are also connected with the special preparation of metals (down to TRL 3) in the required form of electrodes (e.g. electrochemical batteries), nanopowders (e.g. for direct burning in combustion systems) or to keep their microstructural properties (e.g. porous electrodes in electrochemical rechargeable batteries) for long period of time.

Metal fuels seem to have great potential as energy storage and the experts consider that they could become an attractive alternative to typical fuels in term of energy density per volume or mass.

For the technologies with low TRL (3-4) the panel foresees an increase to TRL+1 in 5-7 years, while a TRL equal to 6 in 15 years.

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1.2 Microbial fuel cell

This technology can be used simultaneously for electricity generation, biosynthesis and/or bioremediation, including wastewater purification.

1.2.1 Microbial fuel cell

Keywords: *electrode materials, power generation, renewable energy, MFC, electricity generation, biosynthesis, bioremediation.*

Technical description

Microbial fuel cell (MFC) is an interesting and novel technology that belongs to the much wider group of the BioElectrochemical Systems (BES). In a MFC, an electroactive biofilm formed on the anode oxidizes organics generating electricity. The MFCs act on the same principles as the chemical fuel cells with the difference that living cells are utilized as biocatalysts. The red-ox reaction is then closed at the cathode in which the reduction reaction takes place. Usually, oxygen is used as oxidant due to its high availability and high red-ox potential. The obtained electrons/protons flow in the intracellular catabolic processes (substrate oxidation) is associated to a useable electrical current (Figure 2). At the same time, the presence of an alternative electron acceptor leads to an enhanced metabolic activity. MFC can degrade several organic wastes generating electricity. This technology can be used to substitute energy consuming wastewater treatment for treating organics. Moreover, this technology can be used for practical applications like sensors, robots, etc.

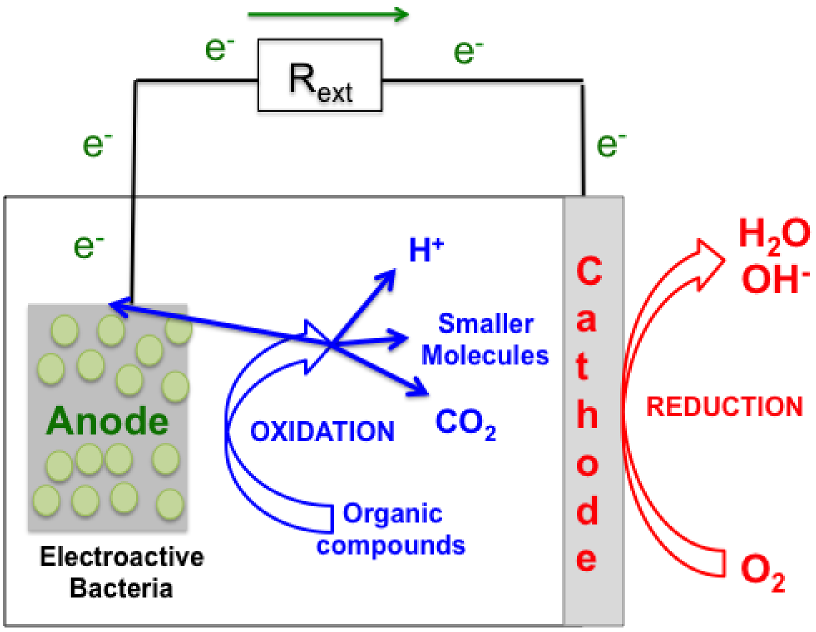

Figure 2. Working principle of a Microbial Fuel Cell (Courtesy of C. Santoro)

As all the fuel cells, MFCs are based on an anode and a cathode electrode an electrolyte, in this case liquid, between the two electrodes. The anode is mainly based on low-cost high surface area carbonaceous materials allowing increase of the interface between bacteria and electrode surface. Electroactive bacteria work as catalyst for the oxidation reaction. At the cathode, the oxygen reduction reaction (ORR) takes place. The ORR is severely limited by the low concentration of reactant (H+ and OH-) available at neutral pH. In order to overcome those losses, the cathode electrode is usually decorated with inorganic catalysts. Those catalysts are mainly based on: i) platinum materials; ii) carbonaceous materials and iii) earth abundant transitional metals (e.g. Mn, Fe, Co and Ni). Electrolyte used varied among several wastewaters (e.g. civil or industrial), human urine, fresh water (e.g. lake or river) and salty water.

Degree of development, challenges and potential

The experts presented the critical points and challenges that this technology must overcome in its development:

The panel commented that the cost of the anode materials have to be reduced drastically in order to have low cost materials for large scale applications. Interaction between bacteria and electrode surface has to be fully understood and then optimized. The challenges include establishment of the pathways contributing for extracellular electron transfer and increased electrical outputs for practical applications behind the lab scale. (TRL 3).

Regarding the cost of the cathode, it also has to be reduced significantly in order to have low cost materials for large scale applications. The experts mentioned the need of innovative low-cost materials, i.e. novel platinum group metals free catalysts, which have to be incorporated into the cathode. (TRL 2/3).

The panel also mentioned a lack in long terms operations experiments running in real conditions (e.g. real wastewater and room temperature) that are needed to establish the feasibility of MFC for depurating wastewater and generating electricity as well as for testing the previously commented materials for anodes and cathodes (TRL 4).

The group also commented some lacks in terms of design: Several designs have been showed in literature but still there are several issues identified. Further developments of MFC design have to be studied and proposed for efficient organics removal and electricity generation for the specific applications of MFCs technology, i.e. supplying power in remote areas, purification of biotechnological waste, monitoring of the ecological state of the environment (TRL 4).

Some other applications for MFCs were suggested. For example, it can be applied for treating, degrading and/or transforming any organics into electricity while cleaning the water simultaneously. This co-generative aspect of cleaning water and generate electricity makes the system suitable for wastewater treatment (for specific niche) and generation of a small amount of electricity.

The panel of experts estimated that this technology has reached a general TRL of 3-4. The introduction of some innovative materials, like the conversion of more complex substrates or improving the growth of some specific bacteria, are recent activities with a TRL of 2. Considering the increasing resources dedicated to this technology, the panel foresees an increase to TRL+1 in 5 years, while a TRL equal to 6 in 10-15 years.

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1.2.2 Microbial Electrolysis Cell or Bio-hydrogen production by M.E.

Keywords: *electrode materials, power generation, renewable energy, MFC, electricity generation, biosynthesis, bioremediation*

Technical description

A microbial electrolysis cell (MEC) is strictly related to Microbial Fuel Cells (MFCs). In MFCs the electricity is directly produced from the degradation of organics. In a MEC, the current is applied to generate hydrogen from organics.

Microbial electrolysis cells are similar to conventional electrolyser based on an anode and a cathode electrode with a liquid electrolyte in between (Figure 3). However, MECs require relatively low potential difference, to start hydrogen production, compared to typical water electrolysis, thanks to the neutral operating conditions, even though the achieved current density is different order of magnitude lower. The anode is mainly based on low-cost high surface area carbonaceous materials that allow to increase the interface between bacteria and electrode surface. Electroactive bacteria work as catalyst for the oxidation reaction. At the cathode, the hydrogen evolution reaction (HER) takes place. The HER is severely limited by the low concentration of reactant (H+ and OH-) available at neutral pH. In order to overcome those losses, the cathode electrode is usually decorated with inorganic catalysts. Those catalysts are mainly based on: platinum group metals or earth abundant transitional metals (e.g. Mn, Fe, Co and Ni). Electrolyte used varied among several wastewaters (e.g. civil or industrial), human urine, fresh water (e.g. lake or river) and salty water.

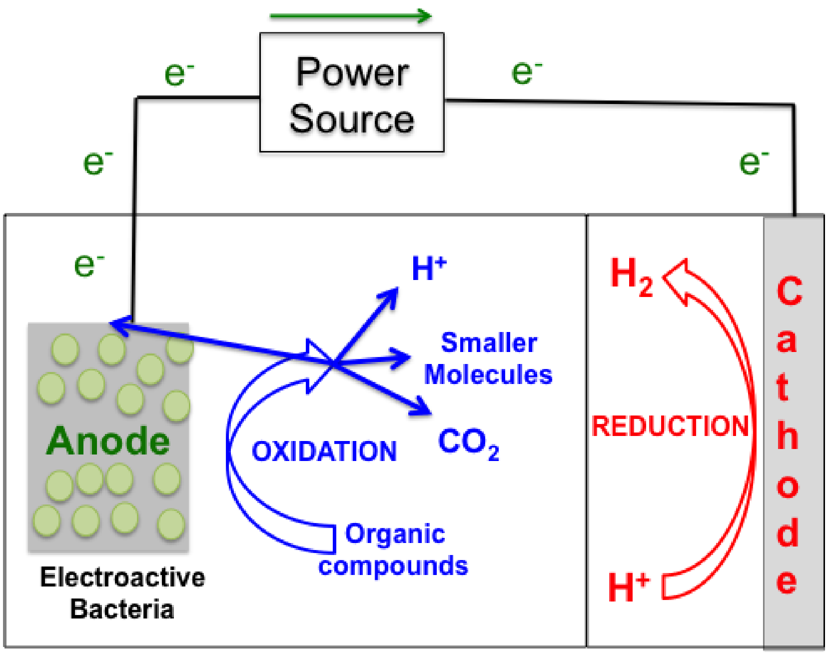

Figure 3. Working principle of a Microbial Electrolysis Cell (Courtesy of C. Santoro)

Degree of development, challenges and potential

It was commented that the microbial electrolysis cells are a cutting edge technology with great potential to become an alternative to the conventional wastewater treatments (anaerobic digestion, activated sludge, etc.). As a new concept, the MEC-technology is still at an early stage of R&D. Most of the studies are carried out on a laboratory scale and currently only one pilot-project worldwide is in progress.

One of the main features of MECs commented is that they allow organic matter present in wastewater to be converted into hydrogen thus helping to offset the energy consumed during the treatment. Hence, the major advantage that may be critical to the commercial viability of MECs is a possibility for simultaneous wastewater treatment and hydrogen production.

They commented that enhancing the hydrogen production rate and lowering the energy input are the main challenges of MEC technology. MEC reactor design is one of the crucial factors which directly influence the hydrogen and current production rate in MECs. The reactor design is also a key factor to up-scaling. Traditional MEC designs incorporated membranes, but it was recently demonstrated that membrane-free designs can lead to both high hydrogen recoveries and production rates. The obtained up-to-now highest hydrogen production rates with MEC range from 3.1 m3/day/m3 (with single-chamber MECs) to 6.3 m3/day/m3 (with MEC operated in a continuous- flow mode). In the expert's opinion even if these values are far behind the productivity of the available commercial water electrolysers, the electrohydrogenesis using MECs may be considered as a promising approach for combining both hydrogen generation and wastewater purification.

As far the MECs use the same bioanodes as microbial fuel cells (MFCs), a crucial challenge for their practical application as a hydrogen producing technology is to find cost effective cathodes for near-neutral pH and ambient temperature (TRL 3). The choice of a proper cathode catalyst and support material strongly affects the hydrogen production rate. Substitution of Pt and decrease of catalyst amount are among the main strategies for cost reduction (TRL 2/3).

In addition, they said, fundamental understandings on the unique electron transfer mechanisms between bacterial cells and electrodes as well as among different microbial species are crucial for further system development (TRL 2).

By using similar strategies in MECs, other inorganic chemicals (alkaline bases, hydrogen peroxide, etc.) can be also produced in the cathode chamber (TRL 2).

It was commented that there have been very limited evaluations of different systems regarding to their life cycles in terms of function selections or comparisons with established technologies (TRL 3). It has been assumed that the most important environmental benefits from MECs come from the displacement of fossil fuel dependent resources through co-product production from renewable sources. There is a lack in long terms operations experiments regarding the MECs running in real conditions (e.g. real wastewater and room temperature). Long terms operations are needed to establish the feasibility of MEC for depurating wastewater and generating hydrogen.

Finally, they indicated that several designs have been showed in literature but still several issues have been identified. Further developments of MEC design have to be studied and proposed for efficient organics removal and electricity generation (low power density values are achieved). They highlighted that one of the problems is due to the bacterial consumption of hydrogen and consequently new way of capturing hydrogen have to be studied (TRL 3).

The experts commented that an increase to TRL+1 is foreseen in 5 years, while a TRL equal to 6 in 15-20 years.

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1.2.3 Sediment microbial fuel cell

Keywords: *Biological fuel cells, sediment fuel cell, submerged fuel cell.*

Technical description

A sediment microbial fuel cell (sMFC), is a specific type of MFC where the anode is submerged in soil and the cathode faces the air as shown in Figure 4. The system design is very simple as there is no need for a membrane and autochthonous microorganisms are involved in the redox reactions.

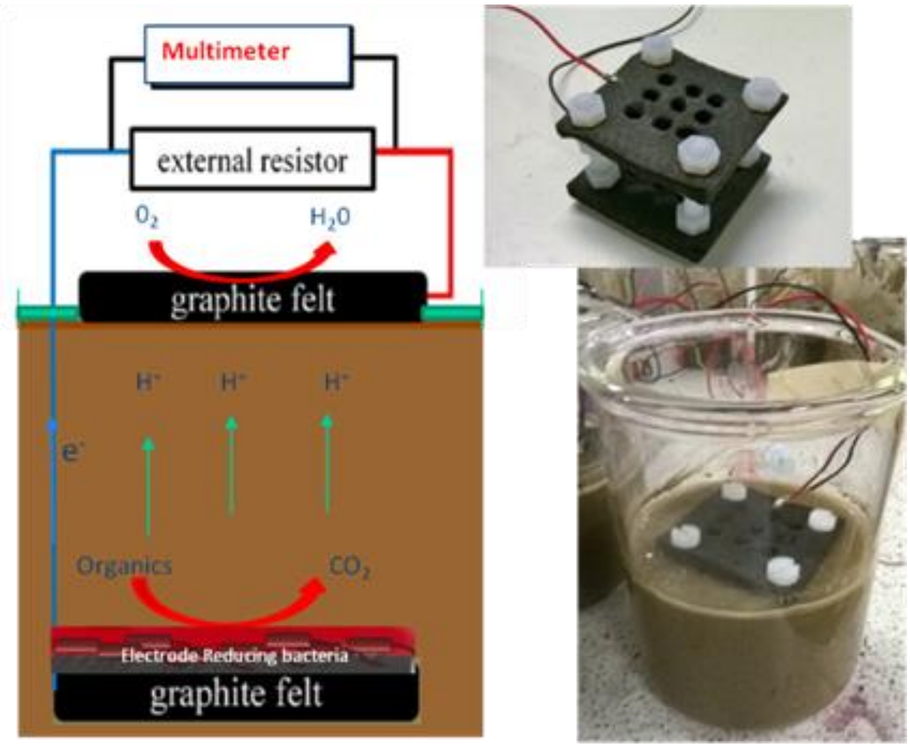

Figure 4. Scheme and photograph of a sediment MFC (Courtesy of M. Di Lorenzo)

Degree of development, challenges and potential

The experts highlighted the cost-effectiveness of this technology, especially if materials, such as biomass-derived carbon electrodes and oxidation reduction reaction catalysts are used, and the high stability of the devices as its main advantages.

Regarding the challenges to overcome, it was indicated that there are only a few studies on sediment-MFC, since the technology is still at an early stage of the development. The key challenge is related to the poor power output generation. In their opinion, the research should be focused on innovative materials and design, as well as functional arrangement in stacks of multiple units to scale-up the power.

Some applications were mentioned as the wastewater treatment and power generation (for example for the power supply of remote marine sensors), or for *in situ* desalination process and denitrification systems. Another application considered was the development of self-powered sensors for soil quality monitoring or for activated sludge monitoring in wastewater treatment plants.

The panel considered that the present TRL is 2, and they foresaw an increase to TRL+1 is in 5 years, while a TRL equal to 6 in 15/20 years.

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1.3 Photo-microbial fuel cell

Keywords: *Biological fuel cells, algae, photo fuel cell*

Technical description

Within the field of biological fuel cells, a less explored technology, complementary to microbial fuel cell (MFC), is photo-microbial fuel cell (photo-MFC). In photo-MFCs algae and cyanobacteria at the anode catalyse the conversion of organic matter into useful electricity. Initially, algae have been tested as a source of oxygen at the cathode of MFCs. Preliminary studies have shown, however, that algae can be used effectively at the anode as well, although the working principle is still not fully understood. The best performing photo-MFC contains cyanobacteria that are capable of using the electrode surface as the terminal electron acceptor in their photosynthetic processes. The current generated follows the day/night cycle. In particular, the highest power densities are obtained when the micro-organisms are photosynthesising under illumination.

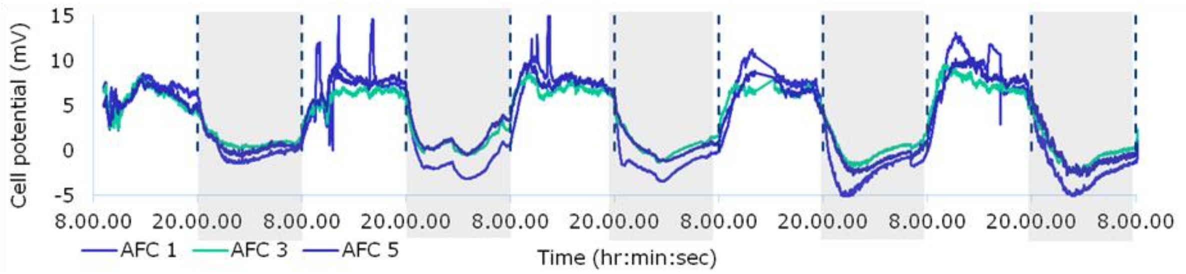

Figure 5. Voltage generated by three photo-MFCs over time (Courtesy of M. Di Lorenzo)

In Figure 5 it is shown the Voltage generated by three miniature photo-MFCs over time (manuscript by M. Di Lorenzo in preparation). The shaded areas indicate the night time. The photo-MFCs have an air-cathode configuration. The total volume of the anodic chamber is 1 µL. The anode and cathode are connected through an external load of 500 Ω.

Degree of development, challenges and potential

As for the sMFC, the experts highlighted the following characteristics as the main advantages of this technology: the cost-effectiveness, especially if materials, such as biomass-derived carbon electrodes/oxidation reduction reaction catalysts are used, and the high stability of the devices.

On the other hand, some challenges were mentioned: There are only few studies on photo-MFC since the technology is still at an early phase of development. The key challenge is related to the poor output power generated. A study by Pisciotta et al. (2011) proposed that the electrogenic activity of photosynthetic organisms is an overflow mechanism which protects the plastoquinone pools from over-reduction at high light intensities. This finding suggests that for photo-MFC the highest power outputs would be expected for light intensities greater than those required for normal photosynthetic metabolism. If this theory is correct it has important implications for reactor and anode design. Useful light intensities for photo-MFC power generation would have to be sufficiently high to cause a state of considerable light stress in the cells without killing them. Other authors have suggested that flickering illumination would give the highest power densities, that is short bursts of intense light that can be used efficiently by the cells, followed by short dark 'recover periods'. While the 'flickering light' approach has been used in algal bioreactors it has never been applied to photo-MFCs. Research should also focus on innovative materials and design, as well as functional arrangement in stacks of multiple units to scale-up the power. Finally they said that the presence and influence of interaction of algae with anaerobic and aerobic bacteria have to be investigated.

An interesting application of photo-MFCs mentioned, is that it could be used in combination with algal pond for the treatment of wastewaters and energy harvesting, thus reducing the high energy demands of wastewater treatments. Photo-MFCs can also be used as self-powered sensors for water quality monitoring.

The present TRL is 2 with a limited activity in laboratories, an increase to TRL+1 is foreseen in 5 years, while a TRL equal to 6 in 20 years.

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1.4 Algal Biofuels

Keywords: *Microalgae, Photosynthesis, Biofuels*

Technical description

Photosynthetic microorganisms have the ability to fix and convert carbon dioxide (CO2) into biomass by using light as energy source. Algae have the potential to produce considerably greater amounts of biomass and lipids per hectare than terrestrial biomass, and can be cultivated on marginal lands, so do not compete with food or other crops. Algae can be cultivated photosynthetically using sunlight for energy and CO2 as a carbon source. Some of them can be also grown heterotrophically on organic substrates in darkness.

Microalgae can be classified into three main groups: triacylglycerol, carbohydrate and hydrocarbon producing algae. Most efforts to produce biofuels from algae have focused on fatty acid producing algae species, the lipid fractions of which can be converted to conventional biodiesel, i.e. triacylglycerol methyl esters (FAME). Hydrothermal liquefaction (HTL) of the entire biomass has also been investigated.

Algae may be used to produce biofuels in several ways:

- Extraction of starch/carbohydrates and conversion to bioethanol
- Extraction of oils and conversion to biodiesel
- Production of oils from organic feedstock via dark fermentation
- Conversion of whole algae to biocrude via pyrolysis
- "Green crude"
- Algal biorefinery - biofuels and other products

Figure 6. Photobioreactor for algae cultivation (Courtesy of M. Tredici)

Degree of development, challenges and potential

Direct photosynthetic production of energy carriers provides a sustainable carbon-neutral alternative. However, so far the application of photosynthetic microorganisms for biofuels/energy carriers has been limited due to the high production cost.

In the expert's opinion engineering towards more efficient photosynthetic microbial platforms and production systems is one of the grand promises and challenges in the coming years. The field needs cheaper, more efficient and stable production systems and robust strains which can cope with the changing outdoor conditions. They consider that a significant investment in research is required before high levels of productivity can be guaranteed on a commercial scale. Algae to biofuels plants may be developed on land adjacent to industrial plants producing CO2, for converting the carbon dioxide from exhausts into fuel.

The TRL for microalgae biofuels is high since demonstration project have been developed (TRL 6-7). However in order to improve the technology and make it suitable for biofuels, there is a need to go back to fundamental questions (TRL 3).

In order to increase the algae yield were considered interesting the following processes:

- Design highly efficient green algal cell factories with the target of creating efficient direct biocatalytic production pathways by metabolic engineering for the synthesis and secretion of products and to design specific composition of e.g. lipids and terpenoids.
- Construction and discovery of new algal strains and metabolic engineering (by both GMO and non-GMO approaches) by mean of high throughput screening techniques for bioprospecting phenotypes in unique environments, breeding of algae, genetic modification and implementation of CRISPR/CAS9 technology

- Integration of algae photo-bioreactor (PBR) with photovoltaics (TRL 2-3). In example, by using a solar tracking system with one polar axis for PV, integrated with a photo-bioreactor. The goal is to optimize irradiance so as to avoid photo-inhibition, maximize growth and reduce heating. The integrated system uses mainly diffuse and reflected light for algae growth, and most of the direct radiation for PV generation of electric energy (Tredici et al. 2015, 2016).

An interesting innovative process was also the integration of cultivation and *in situ* product removal, where photosynthetic cells are used as a photo catalyst; energy is used for product formation and excretion of the product allowing continuous product removal. In this way there is product selectivity and the downstream process is facilitated.

For what concerns the downstream/extraction processes, innovative and mild technologies need to be developed to disrupt the cells and fractionate the biomass components. Some ideas were:

- De-emulsification and mild separation techniques such as ultrasound. Ultrasound technology can be used to destabilize emulsifications and therefore separate lipids from carbohydrates.
- Used of electrical field for sorting and fractionation of biomass, by using a charge difference.
- Use of ionic liquids for phase separation

For the listed innovative aspects with a low TRL, around 3, an increase to TRL+1 is foreseen in 5 years, while a TRL equal to 6 in 15 years, taking advantage of the wide presence in European and International research plans.

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1.5 Plasma activation of stable molecules – towards plasma assisted catalysis

Keywords: *greenhouse gases, plasma, catalysis, sustainable energy*

Technical description

Plasma is an excellent medium to transfer/store electric energy to gaseous molecules. By the nature of the plasma energy transfer, it leads initially to internal excitation of the molecules, especially of vibrational modes. It has been shown (Friedman 2008) that, in particular for CO2, N2, and CH4, this lowers activation (dissociation) barriers and offers opportunities to save energy in translation kinetic energy, in lost work. Plasma can be implemented in gas phase reactions for increasing the reactivity of the involved molecules via their vibrational excitation. Another interesting approach is the interaction of vibrational excited molecules with a surface in the frame of heterogeneous catalysis or electrocatalysis. This approach may relax demands on the interaction strength between catalyst and reactant, and thus will open windows on new classes of materials. Implementation in electrocatalysis is aiming at improving the energy efficiency by spatial separation of reactants. This can be realized via an oxygen-ion or proton conducting membrane, making possible reactions of activated molecules with ionic species diffused via the solid state electrolytes.

Degree of development, challenges and potential

It was said about this technology that, together with characteristics such as low investment costs, easily switchable, no scarce materials, it is a perfect match to intermittent electrical energy production such as from renewable energy sources. Thus can be considered as an important element towards the so-called "Power-to-X" research (section § 3).

The panel also commented that process concepts underlying plasma activation/catalysis have been formulated, however, a proof that the approach can increase selectivity and efficiency for relevant applications is presently lacking. Moreover, the integration of plasma with solid state electrolytes is under exploration

A TRL of 2 was assigned to this technology and the panel considered that a TRL+1 is foreseen in 5/7 years, while a TRL equal to 6 in more than 20 years.

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1.6 Direct Carbon Fuel Cells

This technology was identified in a FET concept sheet by an expert who could not attend the workshop. Due to time constraints, this FET was not presented and debated during the workshop as the others. However, we present here the technical description provided by this expert as well as his comments on this technology.

Keywords: *fuel cell, biomass, solid oxides, molten carbonates*

Technical description

A hybrid solid oxide/molten carbonate fuel cell is applied for the direct conversion of solid biomass (sugar char, rice starch, wood chips), which are directly fed at the anodic compartment. The direct carbon fuel cell (DCFC) is based on the following concept: a traditional solid electrolyte, such as YSZ (Yttria stabilized Zirconia), which is able to transfer oxygen ions, is coupled on the anodic side with a molten carbonate liquid anode. The biomass is dispersed in the molten carbonate matrix, where it is converted with production of CO_2 and electricity; conventional materials are applied at the cathodic side of the solid electrolyte. The oxygen ion is formed at the cathodic side and transferred to the anodic side by the solid electrolyte: since a direct conversion of the solid biomass by oxygen ions is unlikely, it is dispersed into the molten carbonate matrix, which is able to transfer the oxygen ion much more efficiently, via the CO_3^{2-} ion. The liquid nature of the anode allows to feed continuously the biomass and to sweep away the unreacted fraction, also allowing for a recirculation mode. The cell would be operated between 600 and 800°C depending on the nature of the molten carbonate.

DCFC have a high theoretical thermal efficiency (up to 100%) and they are ready devices for transport and storage of solid carbon fuel. Batch reactors can be designed, with reduced volumes, which are suitable for middle-scale applications. Important and unresolved issues are the contamination of the anode compartment by impurities from the biomass (ashes, phosphates, char); molten carbonates are very corrosive, they prompt the dissolution of the current-collecting metals and are in general difficult to handle; under the corrosive environment, the electrolytes also tend to be unstable. The research challenges are thus the identification of materials (composition of the carbonates, formulation of the electrolyte) able to stand continuous operations.

Degree of development, challenges and potential

This technology can be considered promising since it allows the quick conversion of raw biomass with direct production of electrical energy. Other than biomass, several different carbon energy sources can be used, spanning from waste to coal. In this latter case, DCFCs would constitute an alternative mean for converting coal in a much less environmentally-critical way than traditional combustion methods. Although both the technologies of molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) are well known since many years ago, and pretty well established, their coupling was considered as a highly innovative idea since it allows results which are unprecedented for both MCFCs and SOFCs.

The Technology Readiness Level of DCFCs can be estimated to be around 4, since the technology has been demonstrated in a few laboratories, although at a level that is still basic and with a very short operative time on stream (around a few hours, 5 – 10 h). Potential large-scale applications can include the realization of hundreds of kW power units working on raw biomasses.

An increase to TRL+1 can be foreseen in 5-7 years: in this respect, tests have been performed (by HCV LLC company, and Tokyo Institute of Technology) with small-scale tubular DCFC units based on liquid molten carbonates mixed with other additives (vanadium carbides, aluminum clays) in order to improve the ionic transfer at the anode.

A TRL equal to 6 can be expected in 15-20 years.

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2 WORKING GROUP ON PHOTOVOLTAICS

Photovoltaic technology exploits our most abundant renewable energy resource and is fast becoming one of the most important means for implementing the COP-21 commitments and for realising the goals of the Energy Union. Amongst the various renewable energy technologies, PV has the most scope for improving energy conversion efficiency. In fact PV already boasts a broad range of technologies. These can be broadly classified as: "commercial", i.e. being used in mass production, "emerging" i.e., small production volumes and "novel", i.e. concept or early laboratory stage. No single technology can satisfy all the different applications and requirements, which range from mobile and consumer products with a few watts, up to the multi-MW utility-scale power plants.

A common factor is however needed to further reduce the cost of PV electricity, while also addressing a range of other factors including operation, integration and sustainability

In the workshop session dedicated to photovoltaics the panel of experts discussed the potential future development of various technology options, on the basis of the FET concept sheets previously filled in. They considered advantages, impact, feasibility, challenges and relevant parameters characterizing these technologies. An important parameter considered was the Technology Readiness Level, which was assessed for each technology at the present level of development, together as the time and investments necessary to reach the next step of the TRL scale.

After the general discussion about potential impact and challenges of the 17 FETs described below, an anonymous survey was conducted in order to know the experts' opinion about the most promising FETs in PV.

A few general comments from the participants, common to the analyzed technologies, can be here summarized:

- It is not obvious to assign a unique TRL to PV technologies, because many aspects of each technologies may be characterized by a different degree of advancement (comprehension of physical/chemical mechanisms and properties and their optimization, device production, stability, etc.) and because experts often have a different (sometimes contrasting) opinion on the current level of the technology, and also on the foreseen TRL advancement or roadmap.

- The perceived technology TRL is often not correlated to the technology potential impact or interest (i.e. technologies with high TRL may be potentially less relevant than others with low TRL, if promises of technological advancement are fulfilled; economic considerations are not taken into account at this stage).

The order of the appearance of the PV technologies in this section has been randomly determined, consequently there is no correlation between it and the potential interest or impact of each technology.

2.1 Intermediate Band Solar Cells

Keywords: *IBSC, intermediate energy band, Quantum Dots, GaAs*

Technical description

"*The intermediate-band solar cell (IBSC) is designed to provide a large photogenerated current while maintaining a high output voltage. To make this possible, these cells incorporate an energy band that is partially filled with electrons within the forbidden bandgap of a semiconductor. Photons with insufficient energy to pump electrons from the valence band to the conduction band can use this intermediate band as a stepping stone to generate an electron–hole pair. Nanostructured materials and certain alloys have been employed in the practical implementation of intermediate-band solar cells, although challenges still remain for realizing practical devices." (Luque at al., 2012)*

Degree of development, challenges and potential

The participants agreed in highlighting the potential impact of the Intermediate Band Solar Cells (IBSC) technology, but they also said that, until now, only the physical principle of this technology has been demonstrated, and that there are not any known cases of high-efficiency devices (with enhanced current and voltage) using the IBSC apart from GaAs cells.

In order to develop this technology, the panel considered that a better knowledge of its basic principles is needed. In particular, they highlighted the necessity of better understanding the physics related to the light absorption by quantum dots and the light management in order to increase the efficiency, as well as the necessity of performing further research in the field of the novel materials for implementing the IBSC concept. The necessity of a clear benchmark on IBSC devices in order to prove its contribution to the efficiency increase was also mentioned by the experts.

The fact that quantum dots do not exhaust all the possibilities for implementing IBSCs has also presented by one of the contributors. Other possibilities are, for example: new alloys that intrinsically exhibit the intermediate band as one of their properties, materials that exploit the band-anticrossing mechanism, insertion of impurities and exploitation of the triplet-triple annihilation mechanism in some selected molecules. Also the implementation of this technology in the thin-film solar cells was commented by one contributor.

According to this, a TRL of 2 has been determined for the present level of development of this technology. The panel also indicated that between three and ten years would be needed to reach the TRL 3 with an estimated budget of several millions euros allocated to R&D projects focussed on different materials.

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2.2 Plasmonics applied to solar cells

Keywords: *Plasmonic, light trapping, optical enhancement*

Technical description

Metal nanoparticles (<200 nm) can strongly interact with visible light due to the localized surface plasmon resonance, i.e. collective excitation of surface electrons. This phenomenon has been observed e.g. for Au, Ag, Cu, Al. It has been recently proposed to use plasmonics to enhance photovoltaic or photocatalytic performances, e.g. for the development of more efficient solar cells or for solar fuel production and photocatalysis. Embedding of plasmonic metal nanoparticles in an oxide semiconductor (TiO2, ZnO) with morphology controlled at the nanoscale (e.g. with a hierarchical structure) has been reported to lead to an increase of light harvesting beyond the UV region and to enhanced light scattering, thus improving photoconversion efficiencies.

Degree of development, challenges and potential

The idea of using plasmonics for enhancing the efficiency of solar cells has been on the table for the last ten years. However, according to the experts' opinion, this technology has never contributed to the development of high-efficiency solar devices, but only to make low-efficiency solar cells slightly better. In the panel's opinion, the interest of this technology would be rather in the field of the basic science than in the applied research on photovoltaic enhancement.

Some participants suggested, without a general agreement, other uses for this technology beyond the field of the photovoltaics, like enhancing light harvesting and efficiency in other solar driven applications, e.g. solar water splitting or photocatalysis. Hence, even if the application of plasmonics in other fields has resulted in some interesting technologies (with an estimated TRL of 3 or 4), there was a common agreement in not identifying this technology as a promising photovoltaic technology and reaching the next TRL was not even considered by the experts.

2.3 Innovative multi-junction solar cells

Keywords: *Silicon solar cells, multi-junction solar cells, thin film, high efficiency, perovskite tandem solar cells, heterojunction hybrid organic, novel highly efficient perovskite absorbers, Chalcogenides (CIGS, CZTS)*

Technical description

The inherent advantages of silicon and thin films are well known, and also the approach of the enhanced utilization of solar spectrum for efficiency increase through stacked multi-junction solar cells of different bandgaps is a very promising option. So, combining these two attractive features and adding the ambitions for lightweight and flexibility (in terms of shape, size and power output) opens a wide range of possibilities in photovoltaics.

Perovskite and chalcogenide thin-film multi-junction solar cells

A break through solar cell technology would be based on cheap all thin film tandem or multijunction structures with efficiencies approaching those of traditional single absorber thin film cells (e. g. CdTe or CIGS). The combination of organic halogenide perovskite cells with CIGS thin films cells is considered as a suitable option. However, the development of novel wide band gap absorbers with a bandgap of around 2.0 eV would be required for the development of this technology. Preferentially, more stable absorber materials with optoelectronic properties compared to halogenide perovskites as chalcogenide based perovskites or spinels (for example CuSnS3, SnZrS3) and other compounds may be considered. It can be expected that such materials would combine the preferential optoelectronic properties with high performance stability and less hazardous composition. With advance device structures conversion efficiencies beyond 30% may be expected for such all thin film multi-junction structures with strongly reduced costs and lowered material's criticality.

Silicon-based tandem cells

Current Si-based solar cells in the market are single-junction devices, meaning that only one absorber material is used. This results in inevitable transmission and thermalisation losses due to the characteristic bandgap of the material. Further optimisation potential for single-junction cells exists. However, theoretical calculations lead to an upper efficiency limit of 29.4% for c-Si cells although the practical limit might be closer to 27%.

Greater efficiency can be achieved through tandem structures, in which two solar cells with different band gaps are stacked. Each solar cell is optimised for a different part of the solar spectrum, thus reducing transmission and thermalisation losses. A promising concept is to use a Si-based bottom cell with a high band gap solar cell on top. For the top cells, Perovskites, III-V materials, Cu2O or Si quantum dots are interesting options.

Using advances in polymer science to enable low cost cells by using conducting or semiconducting polymers as top material in a heterojunction cell with silicon as the bottom material has shown some recent progress.

Degree of development, challenges and potential

The experts commented that the multi-junction technology has already been proved on III-V cells for many years, and that it has reached at this moment a high TRL, for example, it has been used successfully in space-related applications. However, at this moment, they mentioned, the great interest and potential of this technology lies in the development of "all thin film" tandem cells. Considering this, they said that the main issues to solve in order to develop the thin-film tandem PV are related to the development of the top cells, being the technology of the bottom layers much more consolidated nowadays (TRL 5-6), even if it can still be optimised, especially for matching to the top cell and low absorption loss transparent electrical contacts. It is also important that these top cells could be manufactured in a homogeneous way and with a large-scale development potential without losing in efficiency or transparency.

The stability of the devices and the transition from small cells to mini or large area modules without losing efficiency were also some of the concerns of the panel regarding this technology.

Apart from this, another interesting field of study related with this technology would be the optimisation of the combination of the different materials. Finding the ideal combination and the right balance between the top and bottom materials properties is also a key aspect in the development of this technology.

Supporting a more sceptical opinion on this subject, some of the experts mentioned the fact that even though the potential is there, no thin film tandem solar cell with efficiencies beyond 25 % has been developed yet, besides the 4-terminal concept with low absorption losses in transparent contacts or interconnects, the monolithic approach (see III-V tandem cells) could exploit the full efficiency potential.

Finally, the panel determined a TRL of 2 or 3 depending on each sub-technology, and suggested that a three to five years period and big research projects (7-10 M€) on each specific sub-technology would be necessary in order to push the TRL of this technology one step further.

Experts made also specifics comments about of the above-mentioned technologies:

Perovskite multi-junction:

The panel commented that multijunction cells combining MAPbI3 with Si or CIGS are recently investigated in many research labs around the world. The development of this kind of multijunction cells needs a thorough material science approach, by combining a number of expects in different fields. So far few research actions seems to be performed in this field.

Silicon-based tandem cells:

Some experts commented that the standard PV products on the market are Si-based flat plate modules. Silicon-based tandem solar cells can be used in similar modules, but with significantly higher efficiencies. Their potential is hence very high and they need to be seen as one of the major FET in the field of PV.

Such structures have been realized recently with a high efficiency using wafer-bonding and a top cell made of III-V materials. This approach can be considered TRL 3. Other options, e.g. using different top cell materials, are at even lower TRL levels. Significant research needs to be carried out. One aspect is the method on how to combine the silicon bottom cell and the top cell. This can either be done by wafer bonding or by direct growth or deposition. In addition, material research needs to be carried out to improve the top cell and to adapt the bottom cell accordingly. Another aspect is whether a two-terminal device (monolithic) is preferable to a 4-terminal device, considering also how this could be realised in practice.

Organic-silicon solar cells:

The development of polymers happens at a very fast pace, an expert commented, and many of these advanced polymers are at a low TRL level. Therefore the concept is at a low TRL level as the progress depends mainly on the polymer research progress.

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2.4 Thermo-photovoltaics

Keywords: *Thermo-photovoltaics, heat recovery, photon-enhanced thermionic emission*

Technical description

The main idea of thermophotovoltaics (TPV) is the conversion of thermal radiation into electrical energy through the photovoltaic effect. A typical TPV system is composed by an emitter and a PV cell, which absorbs the emitted light and produces electricity. There are two main fields of application. The first one is to use an emitter which absorbs sunlight and then emits infrared light onto a tuned solar cell. Several studies show that this approach could allow high system efficiencies. A second application is to use TPV cells for the absorption of light emitted from fire, e.g. in a gas turbine combustion chamber. By using this wasted energy the overall system efficiency can be increased

Degree of development, challenges and potential

This was considered by the experts to be a cross-cutting subject and not only a PV technology, because the real interest of this technology relies on the implementation of the TPV devices in more complex energy systems, increasing their overall efficiency, and not in TPV devices operating independently. According to the experts, the light-to-electricity efficiency of the TPV device itself (not being part of a more complex energy system) is currently around 5%, which could be considered as a very low value.

Even if the idea was considered to be interesting, for example for waste heat recovery applications, the panel expressed its doubts about the relevance or potential impact of this technology since it is not foreseen to replace other PV technologies in the PV market. Moreover, according to the panel's opinion, the most important challenges to overcome in the development of this technology are neither in the field of the solar cells nor in the development of the emitter material, but in the optical management of the whole system.

The panel estimated that the current TRL is 1-2 and that next level could be reached in a three to five years period.

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2.5 Innovative III-V compounds based solar cells

Keywords: *IBSC, III–V semiconductors, high efficiency, quantum-dots, multi-junctions (five to six-junctions), diluted nitrides, GaInNAs*

Technical description

Two different sub-technologies are studied under this designation: the "III-V and IBSC" and the "five-to-six-junctions solar cells".

III-V and IBSC

The PV devices made with this combination of materials are expected to reach high efficiency levels. Theoretically, the targeted efficiency levels for the III-V lab-scale cells should be >28% and >30% for the IBSC. However, further research in the field of the material science is needed in order to be able to produce this kind of devices. For example, several solutions can be envisaged to produce IBSC such as using Quantum Dots or highly mismatched alloys or using materials with naturally filled IBs. In addition, in the opinion of some of the experts, developing new materials to ensure perfect contact on Si absorber should be considered such as III-V or directly passivating contacts. The development of material and deposition processes should be compatible with the underlying Si active wafer and they could rely on novel device concepts such as polarization induced junctions.

Five-to-six-junction solar cells

Multi-junction solar cells made of III–V semiconductors have reached the highest efficiencies of any photovoltaic technology so far. The materials used in such solar cells are composed of compounds of elements in groups III and V of the periodic table. A record efficiency of 46.0% under concentrated sunlight has already been realized with a four-junction solar cell of Fraunhofer ISE (see Annex 4). The theoretical efficiency limit of a multi-junction solar cell under reference conditions increases with the number of junctions. However, going to five or six junction solar cells requires new materials with suitable bandgaps. Promising options are diluted nitrides, e.g. the quaternary alloy GaInNAs. In addition, these materials need to have very good quality to be applicable in solar cells. This is particularly challenging for diluted nitrides as impurities are easily included during growth in the std. approach metal organic vapour phase epitaxy (MOVPE). For example, good quality has been realized in molecular beam epitaxy (MBE) growth, which is however too expensive. Consequently, in the expert's opinion, further research in the field of the material science is required for the production of diluted nitrides and other III-V semiconductors.

Degree of development, challenges and potential

Being accepted by all the experts that this kind of PV are expected to reach very high efficiencies in the future, the panel agreed in considering the development of new materials and the improvement in terms of processability of the materials as the biggest challenges to overcome in order to develop the III-V compounds based PV cells.

They also highlighted a tendency, in the monolithic multi-junction cells research, towards the five-to-six-junction solar cells, with higher efficiencies and a parallel reduction of the production costs. Indeed developments should focus on new production processes that would allow these products to be available for terrestrial applications.

After these considerations, the experts determined that the TRL for the III-V and IBSC technology is 1-2, and that in the case of the five-to-six-junctions it is TRL 3-4. The panel also estimated that the next TRL could be reached in a three to five years period.

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2.6 Photoelectrocatalytic devices

Keywords: *CO2 conversion, Photoelectrocatalysis, PEC, fuels, TiO2 doping, TiO2 hydrogenation, photoelectrochemical or solar water splitting; hydrogen production*

Technical description

The aim of photoelectrocatalytic devices (PECs) is to reduce CO2 to high added economic value liquid/gas fuels (hydrogen or carbon based fuels). In this field, the so-called black titania (i.e. reduced or sub-stoichiometric TiO2) have recently emerged as one of the most promising approaches for the realization of a TiO2 material with reduced bandgap and increased photocatalytic activity in the visible range. This has been first shown for anatase nanocrystals treated in a pure hydrogen atmosphere; afterwards, several works have been devoted to this topic, with various experimental methods and results depending on the procedure employed. Moreover, an accurate comprehension of the physical mechanisms underneath has not been achieved yet, together with an optimization of the material properties in view of the targeted application. A relevant application could be hydrogen production for solar water splitting

Degree of development, challenges and potential

Ideal photocatalytic semiconducting materials share many common features with materials for photovoltaics; however, development of novel photocatalytic materials for CO_2 conversion or solar fuel production (e.g. hydrogen production via photoelectrochemical water splitting) are considered a bit out of topic regarding the analysed PV technologies. The panel of experts considered this as a multidisciplinary technology. In the group there were divergent opinions about this technology: while some of the contributors maintained that this is a not very promising technology, others supported it assigning a certain potential and linking it to PV technologies since it involves the coupling of a solar cell (also novel solar cells such as organic PV) with a reactor in order to drive catalytic reactions.

The main challenges to overcome in the development of this technology are the improvement of the overall efficiency of the process, the improvement of the materials processability for large area scaling focusing on solution processes and the development of good catalytic materials and electrodes.

The panel considered that the current TRL for this technology is 2, and they estimated the time to reach TRL+1 in five to ten years.

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2.7 Ferroelectric PV

Keywords: *ferroelectric, centrosymmetry, high voltage, ferroelctric absorber, PCE exceeding the Shockley-Queisser*

Technical description

It has been known since the 1970's that some non-centrosymmetric materials show unexpected behaviour when exposed to light: they can promote carrier separation and provide large voltages much above their bang-gap, as well as significant current densities. Also, the current direction changes depending on the polarisation of the light. Considering this, ferroelectric absorbers are attractive candidates for developing solar cells. Although the performance of lab-devices is still very low, theoretical calculations suggest that ferroelectric absorbers efficiencies could exceed the Shockley-Queisser limit.

Degree of development, challenges and potential

The panel highlighted that even if this idea has been known for decades, the research on this technology have not result so far in the realisation of any working-efficiency device. It is not clear for the experts whether the causes of this lack of success lie in the fact that this technology actually does not work or in an insufficient research in this field. Nevertheless, they also commented that the interest in this field has been renewed by recent papers on scientific journals. They maintained that in principle this technology could be very interesting because it has the potential to overcome the Shockley-Queisser limit and to reach very high efficiencies due to the possibility of obtaining a $V_{oc} > E_{gap}$. The panel experts also agreed in considering this topic at the borderline between basic science research and applied research.

Considering this, the panel estimated a TRL of 1-2 for this PV technology. An investment of several millions euros focused on few projects (e.g. 2-3 projects) will be the best approach to support this technology efficiently. A research effort of no less than three to five years was considered to be necessary in order to push this technology to the next TRL.

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2.8 Multiple exciton generation solar cells

Keywords: *multiple exciton generation solar cells, quantum dots*

Technical description

The Multiple exciton generation solar cells (MEG) technology aims to extract energy from photons by creating more than one electron-hole pair per photon. Technically, these electron-hole pairs are more properly addressed as "excitons" because the system in which this phenomenon is envisaged to take place are quantum dots.

The proof of concept has taken place in the USA (Semonin et al. 2011) by experimentally demonstrating a solar cell with external quantum efficiency higher than one. In spite of this, efficiency of the cell is still low and no commercial cell is available. Conceptually, this technology has the potential for achieving high efficiencies.

Degree of development, challenges and potential

The panel commented that even though some researches taken in the U.S.A. some years ago demonstrated that peak external photocurrent quantum efficiency could exceed 100% via MEG in a quantum dot solar cells, no further progress has been reported and no devices with improved efficiency based on this concept has been realised so far. Also, some basic issues remain open to investigation (e.g. MEG leads to improved photocurrent, but it is not clear the impact on the photovoltage). Experts do not seem to trust too much this approach for future developments and there is scepticism about assigning a high priority to this topic, however they recognised its interest from a scientific point of view or basic research.

The panel indicated a TRL=2 for this technology, and mentioned that, in their opinion, a 3-5 M€/year project would be necessary in order to take this technology to the next TRL. However, there are doubts on the worthiness of this investment.

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2.9 Hot carrier solar cells

Keywords: *hot carrier, solar cells*

Technical description

This technology assumes ideally, on one side, a light absorber in which electrons only interact among themselves and, on the other side, the so-called energy selective through where the electrons are extracted from the absorber and their energy is converted into electricity. By preventing electrons interaction with phonons, electrons do not loose energy in the form of heat. Alternatively electrons can be allowed to interact with optical phonons as long as optical phonons are not allowed to decay into acoustic phonons (the way acoustic phonons vibrate is what allows heat to be dissipated)

Theoretically, hot carrier solar cells have the potential to achieve conversion efficiencies above 50 %. However there are only partial experimental demonstrations of some of their working principles.

Degree of development, challenges and potential

The panel of experts said that, even if the generation of long living hot carriers and reduction of relaxation events have been demonstrated, together with the possibility of realizing energy selective contacts, these elements have not been put together and no working hot carrier solar device has ever been made to their knowledge.

They also considered that further research is needed in this field, especially on the materials field (e.g. on Quantum Dot-based materials, or others). Research on this topic is active, e.g. in Australia (UNSW), while in Europe mostly theoretical research has been performed.

They concluded that the potential impact of this approach would be very high if successful, even disruptive in perspective (generation of hot carriers not interacting with phonons would be of capital importance for the new physics that it would lead to, and for many other application fields, e.g. electronics/optoelectronics); however, the current situation does not promise to lead to significant advances in short times and there is some scepticism about the development of this technology.

The panel considered that the current TRL of this technology is between 1 and 2, and they indicated that an investment of around 3-4 M€ and at least three years of research at basic science level would be necessary to push the level one step further.

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2.10 Novel contacts for PV technologies

Keywords: *novel contacts, novel transparent conducting oxides (TCO), flexible TCM, non-oxide TCM, hierarchical nanostructures, light trapping, defect chemistry, hybrid organic-inorganic devices, carrier-selective contacts*

Technical description

The experts said that the development of new contacts may represent a great leap for novel PV technologies. In this field of research, they highlighted two different technologies:

Transparent conducting materials

Research on Transparent Conducting Materials (TCM) is a cross-cutting field, not only aimed at energy production but also to the development of transparent electrodes for a wide variety of applications, ranging from photovoltaics, photocatalysis, photoelectrochemistry, transparent electronics, optoelectronics and light emitting diodes, to smart windows, flat panel displays and touch screens. Traditionally, TCM are transparent conducting oxides (TCO) and some of them are commercially available and widely employed. However, a number of challenges are currently addressed in this field:

- The development of new TCM is necessary in order to reduce the production cost and ensure the stability of the materials in aggressive environments (non-oxide TCM, p-type TCM).

- The achievement of additional functional properties beyond electrical conduction and transparency is often desirable: e.g. compatibility with plastic substrates or flexibility; light scattering/trapping; large surface area/interface for the realization of heterojunctions e.g. in organic/hybrid solar or photocatalysis devices.

- Better understanding of the TCM physics, e.g. in terms of comprehension of the relationship between the defect chemistry and the electronic/optical functional properties.

Carrier-selective contacts

Carrier-selective contacts (i.e., minority carrier mirrors) are one of the last remaining obstacles for approaching the theoretical efficiency limit of silicon solar cells and other solar cell technologies. Such contacts need to be carrier-selective with low minority carrier recombination and efficient majority carrier transport.

One example of a solar cell with carrier-selective contacts is heterojunction solar cells with intrinsic thin-film (HIT), where record efficiencies of 26.3% (Kaneka, 2016) have already been achieved. However, this surface passivation scheme can withstand only low process temperatures (~250 °C) and therefore requires a dedicated back-end processing (low-temperature TCO deposition and metallization). Various other concepts have been followed, e.g. polysilicon emitter (PE) or the related semi-insulating polycrystalline silicon (SIPOS) technologies. However, both have not shown sufficient performance. Research is still ongoing to identify suitable materials and processes. One option is for example the use of a transparent conductive oxide.

Degree of development, challenges and potential

In the expert's opinion, this is a very interesting cross-cutting topic that may have an impact on many different PV technologies. The development of novel contacts is especially interesting for what concerns their combination with organic/hybrid cells or perovskite cells.

The panel highlighted different research lines as the investigation of novel/efficient electron and hole selective layers, hole transporting materials or transparent contacts, e.g. for perovskite cells. They also maintained that there is a whole field of investigation to be addressed and further research to be done in this field. The development of non-oxide transparent contacts (e.g. GaP, GaN in addition to others) was considered an important topic, especially if endowed with novel multi-functional properties in addition to transparency and conduction, such as low processing temperature, flexibility, light scattering, proper work function tuning for improving charge transport at interfaces etc.

Regarding the challenges to overcome in this field, the panel agreed in considering the improvement of the stability, the solution processing of the materials, the better selectivity and the exploration of organic/inorganic materials as the points of improvement to be achieved.

Finally, they estimated a current TRL of 2, and they indicated that at least another five years of research and four or five dedicated projects, with an important economic support, would be necessary in order to achieve the next TRL in this technology.

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2.11 Kesterite thin film solar cells

Technical description

Keywords: *Chalcogenides, Cu2ZnSn(S,Se)4, CZTS, CZTSe, CZTSS, earth-abundant materials*

Thin film solar cells based on polycrystalline CuInGaSe2 and CdTe absorber materials have reached record efficiencies of 22.6% CIGS and 22.1% CdTe for laboratory scale devices (Annex 4) and have already reached the commercial production stage with a respectable market niche. However, these thin film photovoltaic technologies suffer from serious issues of manufacturing complexity, highly fluctuating material costs and limited commercial availability of raw materials, which limit the production, mass deployment, and economic attractiveness of these solar cells. In order to avoid the use of expensive and scarce In and Ga of the CIGS thin film solar cells, the research on indium-free materials with similar properties to those of the very efficient chalcopyrite compounds has led to the kesterites or earth-abundant materials solar cells.

Degree of development, challenges and potential

The opinions expressed by the panel of experts regarding the development and impact of kesterite thin film technology and its capacity for substituting CIGS solar cells were divergent: from the more optimistic ones, which presented the fact that the cells efficiencies have increased from 5% to around 12% (Annex 4) in the last years and the advantages of using earth-abundant materials; to those more sceptical which highlighted the low efficiencies and the critical issues related to the synthesis and preparation of the kesterite cells, and the presence of defects and secondary phases.

On the other hand, there was a general consensus about the fact that the achievement of efficiencies of at least 15% in the next five years is mandatory in order to maintain the interest on this technology.

Considering all these factors, the panel agreed in assigning a "quite high" TRL of 3-4 to this technology.

2.12 Perovskite thin film solar cells

Keywords: *CaTiO3, Perovskite, CH3NH3PbI3, Meso-superstructured, TiO2, organic-inorganic hybrid solar cells*

Technical description

A perovskite-based solar cell is a type of photovoltaic device which includes a perovskite compound as absorber or active layer, most commonly a hybrid organic-inorganic lead or tin halide-based material, as the light-harvesting active layer. The name "perovskite solar cell" is derived from the ABX3 crystal structure of the absorber materials, which is referred to as "perovskite structure" (derived from the mineral CaTiO3).

Regarding the efficiencies of the perovskite-based devices (at laboratory scale and in small areas), they have experienced an impressive evolution increasing from 3.9% in 2009 up to a certified efficiency of 22.1% in 2016 (Annex 4). However, some aspects related to the long-term stability of the components of the devices remain unclear (causing decreasing on the efficiencies) and normally the devices degrade fast, are in small areas and they are classified as "not stabilized". Another major challenge for perovskite solar cells is that the most efficient perovskite solar cells contain lead (Pb), which is highly toxic and water soluble, representing a potential environmental danger. In this way, the research on Pb-free perovskite materials is becoming necessary in view of up-scaling and mass production.

Degree of development, challenges and potential

During the workshop the panel of experts highlighted the interest and potential of this technology and predicted an important development in the forthcoming years due to the attention that the scientific community and the industry are currently paying to this technology after its rapid development in terms of efficiency during the last years; some of them even suggested the possibility of reaching the commercial level in no more than five years.

Considering all these aspects, the panel agreed in assigning a TRL of 4-5 to Perovskite technology.

However, in order to assure the viability of this technology, some important issues like the stability of the devices must be solved. The environmental problem of the lead-based materials used in the perovskite cells was also discussed and presented as a major obstacle on the path to the commercial development of this technology. At the same time, a lower TRL of 2-3 was estimated for the lead-free perovskite devices.

2.13 Organic photovoltaic cells

Keywords: *polymer solar cell, OPV, plastic photovoltaics, plastic solar cells, PH3T, PCBM, organic polymers, organic solar cells, thin film photovoltaics, low cost process*

Technical description

An organic solar cell or plastic solar cell is a type of photovoltaic device that uses thin films (in the nanoscale) of conductive organic polymers or small organic molecules as active material. An example of an organic photovoltaic (OPV) device is the polymer solar cell. Organic solar cells aim to provide an Earth-abundant and low-energy-production photovoltaic solution. This technology also has the theoretical potential to provide electricity at a lower cost than first- and second-generation solar technologies due to its low cost production process. Because various absorbers can be used to create coloured or transparent OPV devices, this technology is particularly appealing to the building-integrated PV market. Organic photovoltaics have achieved efficiencies around 11%, but efficiency limitations as well as long-term reliability remain significant barriers.

Current research focuses on increasing device efficiency and lifetime. Substantial efficiency gains have been achieved already by improving the absorber material, and research is being done to further optimize the absorbers and develop organic multijunction architectures. Improved encapsulation and alternative contact materials are being investigated to reduce cell degradation and push cell lifetimes to industry-relevant values.

Degree of development, challenges and potential

The panel considered that regarding the TRL of this technology (5-6), this is high enough to put the OPV out of the FET scope. They also commented the loss of interest of this technology after the arrival of the perovskite solar cells, even if the OPV has shown a slow but steady progress in terms of efficiency and stability. Several of the experts agreed that the research and development on this technology is now more in the scope of industrial research.

2.14 Dye-Sensitized Solar Cells

Keywords: *dye-sensitized solar cells, DSSC, DSC, nanostructures titanium dioxide, photo-electrochemical cell, electrolyte, thin film photovoltaics, low cost, conducting polymers*

Technical description

The Dye-Sensitized Solar Cells (DSSC) provide an alternative concept to p–n junction photovoltaic devices and are part of a third generation of thin film solar cells. They are based on nanocrystalline and conducting polymer films. In contrast to the conventional systems where the semiconductor assume both the task of light absorption and charge carrier transport the two functions are separated here. Light is absorbed by a sensitizer, which is anchored to the surface of a wide band semiconductor. A donor and an acceptor type of organic/inorganic materials form a heterojunction favouring the separation of the exciton into two carriers. Whereas, the charge generation in DSSC is conducted at the semiconductor–dye interface and the charge transport is done by the semiconductor and the electrolyte. The carriers transport properties can be improved by optimizing the semiconductor and the electrolyte composition and the spectral properties optimization can be done by modifying the dye alone. Nearly quantitative conversion of incident photon into electric current is achieved over a large spectral range extending from the UV to the near IR region. Overall solar (standard AM 1.5) to current conversion efficiencies (IPCE) over 10% have been reached. DSSCs offer the prospective of very low cost fabrication process and present attractive features that facilitate market entry.

Degree of development, challenges and potential

The panel considered that regarding the TRL of this technology (5-6), DSSC are already out of the FET scope. They also commented that even if during the last decade this technology has attracted the attention from the scientific community and the institutions, the arrival of the perovskites has pushed it into the background, leaving it more in the scope of industrial research.

2.15 Solar cells from semiconductor foils

Keywords: *semiconductor foils, epitaxially grown layers, reduced cost, more efficient, reduced energy payback*

Technical description

This matter can be considered as the description of a new industrial methodological approach rather than a new photovoltaic technology itself.

Wafer-based Silicon PV is dominating the PV market. The basis of such solar cells is a solar cell wafer, which is cut from a block resulting in substantial material losses and hence leading to higher costs. A method to work around this is to use semiconductor foils, which are for example epitaxially grown (epitaxial silicon layers, kerfless wafers). These then serve as base layer for solar cell production. This approach is not limited to Silicon, but can also be applied to other semiconductor materials. The main advantage for PV would be a substantial decrease in cost of the wafer (factor of 50%), a much better use of silicon resources (no kerf loss) and much less use of energy for wafer fabrication leading to strongly reduced energy payback time.

The challenge of this approach is first to produce semiconductor foils with sufficient material quality in a process that later allows for competitive costs. Process and material research is needed. In addition, solar cell manufacturing processes need to be adjusted to produce solar cells from foils and not from wafers. The proof-of-concept has been realised. Hence the approach is considered to be at TRL 3.

Degree of development, challenges and potential

The panel considered this technology to be an interesting approach also for Si solar cells, but not only. In their opinion, the main challenge related to this technology is to solve the processing problems and to better understand the materials properties and their impact on the cell performance; of course, the challenge is not only manufacturing "good" foils but also to make efficient cells. The panel didn't consider this approach particularly relevant.

Considering these aspects, the experts assigned a TRL of 3 to this technology and they indicated that it would be necessary a long time before a new TRL could be reached: a great effort is needed since it involves the whole cell production and test processes.

Short Bibliography

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2.16 New photovoltaic materials via combinatorial and computational design

Keywords: *Combinatorial and computational materials design*

Technical description

This technology can be considered as a new methodological approach implemented on the photovoltaic field research or as an enabling technology that may influence the investigation on this field, but this is not a new photovoltaic technology itself.

Conventional PV materials are well studied and the investigations in this field is mainly based on intensive experimental studies and supported by model-based calculations of material properties to describe experimental findings. This includes describing the atomistic structure, calculating electronic material properties on the nanoscale and deducing macroscopic properties. The combination of computational modelling and experimental findings has led to excellent research and development of photovoltaic devices. Based on the past experience, codes and computing power employed by these computational methods have been developed to a very high level. They can predict well matching material combinations and can potentially guide laboratory work on the base of these calculations. This approach has been demonstrated in other research fields and could be used for PV materials as well.

These methods are already available. However, they have not been established in European PV research to a large extent.

Degree of development, challenges and potential

Even if the panel decided not to consider this approach as a new PV technology itself, they agreed in the fact that this can be a very promising methodology for the development of better materials not only in the field of photovoltaics but also in other fields, especially if it's coupled with proper computational design and theoretical investigation. In any case, it was considered as an important topic.

2.17 Low-cost manufacturing processes, roll-to-roll and flexible substrates

Keywords: *low-cost manufacturing, roll-to-roll, R2R, flexible substrates*

Technical description

In the field of electronic devices roll-to-roll processing, also known as web processing, reel-to-reel processing or R2R, is the process of creating electronic devices on a roll of flexible plastic or metal foil. Roll-to-roll processing is a technology that is still in development. If flexible and lightweight PV devices can be manufactured in this way on large substrates, many applications on system levels could be made in a cheaper way. This would be particularly disruptive for application of solar cells in markets where traditional bulk (mono- or polycrystalline) silicon modules have limitations due to weightand rigidity constrains. The production of CIGS, OPV and perovskite PV devices via R2R techniques has been already demonstrated and pilot production lines already exists in the labs and on the market. The efficiency and stability of PV devices fabricated by R2R processes is still low and need to be improved.

Degree of development, challenges and potential

The panel commented that the development of solar cell roll-to-roll fabrication processes on low cost flexible substrates is considered to be interesting only if this approach does not lead to a significant efficiency loss. Also there is a need for technology-specifc in-line measurement systems to ensure quality. It is not believed to be a topic for research in academic labs but it is considered to be more suitable topic for industrial research.

2.18 Survey on photovoltaic future emerging technologies

After the general discussion about potential impact and challenges of the 17 FETs described above, an anonymous survey was conducted among the nine external experts of the photovoltaic working group in order to know their opinion about the most promising FETs in PV. The aim of this survey was to try to quantify the impact, the chances of success and the required level of investment of the most interesting future emerging technologies.

The technologies described by the JRC in its First annual Report on FET (Kesterite and Perovskite), those more advanced like DSSC and OPV, those unanimously identified as "not promising" such as Plasmonics, as well as those more interesting for industrial purposes than for the H2020 FET program were excluded from the scope of this survey.

The questions of this survey were formulated in the following way:

Please rate the following aspects of each technology identified and discussed within this workshop (0=low, 5=high)

1) ***IMPACT***

Eventual role of this technology in the renewable energy sector (considering al the aspects: efficiency, environment, cost, availability)

Low score: niche product, limited application and market share

High score: potential mainstream, product with significant market share

2) ***CHANCE OF SUCCESS***

Assuming the same initial investment for all the technologies, please rate the chance to get to real application

Low score: extremely challenging, many barriers to overcome: e.g. production processes, market, segment, infrastructure critical materials

High score: technically challenging but not major barriers, synergies with existing products, markets, sustainability

3) ***INVERMENT AND SCALE OF EFFORT***

Please rate the amount of investment necessary to make this technology successful (or real application)

Low score: low level of investment, effort at the scale of a single organisation

High score: high level of investment needed, multinational efforts

The results of this survey can be found here below in the Figure 7

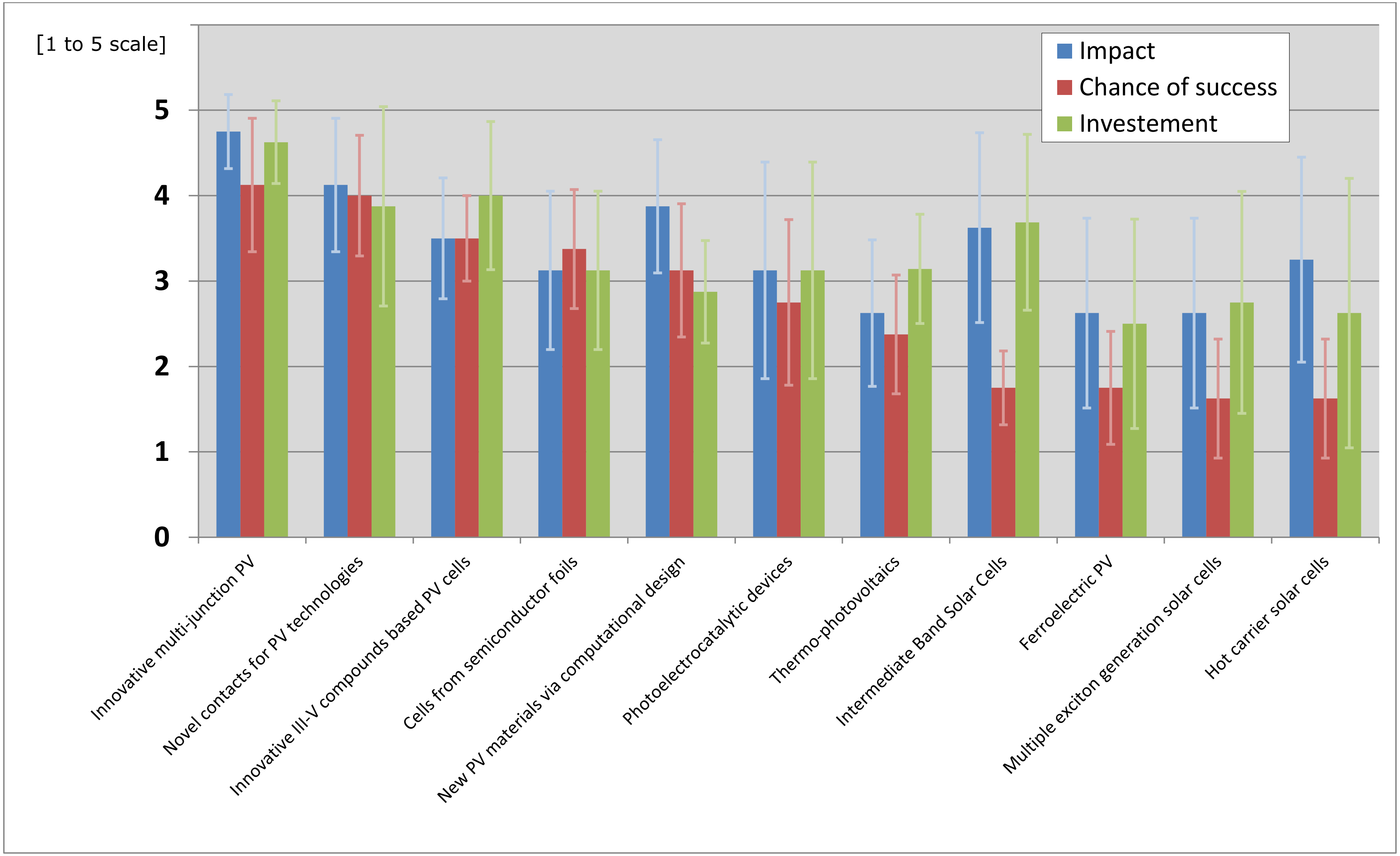

Figure 7. Results of the survey on chance of success, potential impact and investment needed for the most interesting FETs in the PV sector

2.19 Conclusions of the photovoltaic working group

The different technologies discussed by the PV expert group can be broadly grouped as follows.

In a first category we can include all the PV technologies that have been considered as promising by the expert panel. They highlighted their potential impact in the future PV market, their recent progress and their capacity to reach high efficiency levels. This group includes *innovative thin film multi-junction solar cells, innovative III-V compound based solar cells* and *perovskite solar cells* (probably the most discussed new PV technology of the last few years due to the fast improvement of its efficiency). This group could also include *kesterite solar cells*, but opinions were divergent about its capacity to reach the market level. All these technologies could especially benefit from the development of *novel contacts i.e. selective and transparent contacts,* a transversal item considered very important by the group of experts. It is stressed that all these technologies have many challenges to overcome in their path to the commercial level, for example in terms of materials research and processability.

Secondly, we have the technologies that are less promising in the expert's opinion or which still need significant development to show their potential for energy supply. In this group we identify different levels: firstly we can find some early-stage technologies like the *Intermediate Band Solar Cells,* which is considered very interesting but still waiting to be practically demonstrated with the production of a high-efficiency device; or the *ferroelectric PV* technology, theoretically demonstrated but needing further basic research in order to understand its feasibility. In this group, but at a lower level in terms of chances of success, we can also find technologies, including *multiple exciton generation solar cells, hot carrier solar cells* or the *application of plasmonic to photovoltaics*; the panel recognize the scientific interest in these technologies but expressed doubts about their future development and about their possibilities to reach a commercial level.

In a third group we put together the cross-cutting technologies that are considered as not purely photovoltaics, because they are either multidisciplinary FETs like *photoelectrocatalytic* or *thermophotovoltaic devices* (both at an early stage of development and with a moderate impact and chances of success), or because they are considered as new methodological approaches or as general manufacturing methods. For example the production of *solar cells from semiconductor foils,* the development of *new photovoltaic materials via combinatorial and computational design* and the development of *low cost manufacturing techniques.* For instance for the later, *roll-to-roll manufacturing with flexible substrates* is considered more for an industrial research needing adaptation and scale-up of processes than a fundamental process to be studied at a scientific level.

To conclude with this categorization, two technologies were placed by general agreement outside the FET limits: *dye-sensitized solar cells and organic photovoltaic*, both with a TRL between 5 and 6.

Finally, as a general comment, the panel considers it very important to devote more efforts on basic research, since for several technologies a TRL advancement is possible only if a deeper comprehension of the basic physical mechanisms is achieved. Indeed the group highlighted the importance of material science and device oriented research to the development of the new PV technologies.

3 OTHER TECHNOLOGIES OF GENERAL INTEREST

This third part of the report is devoted to the last session of the workshop. All the experts from both working groups: "Fuels" and "Photovoltaics" attended this session.

At a first moment, the two rapporteurs briefly presented the technologies discussed in each working group and the main conclusions to the other group, leaving some time for questions and comments.

Secondly, other technologies of general interest proposed by the experts, that could not be placed in any of the two working groups (*Thermoelectric materials*), were presented and discussed in this plenary session.

Finally, some technology field related to the energy storage sector were described and discussed in order to stimulate a general brainstorming allowing the experts to identify further future and emerging technologies or synergies among them. The technology fields debated were: *Thermal and chemical energy storage*, the so-called *Power-to-X* applications, distributed generation, hybrid systems embedding the production and storage of renewable energy. The debate didn't led to the identification of specific FETs, different from those already treated in this workshop, consequently this part of the debate is not presented in this report.

3.1 New thermoelectric materials

Keywords: *thermoelectric, waste-heat recovery*

Technical description

New low-cost thermoelectric materials are being investigated for building heat-recovery devices, which could be used to provide electrical energy in various situations: in industrial applications, mobility, emergency rescue situations, etc.

Among the new thermoelectric materials they can be highlighted: the printed inorganic thermoelectric films, the organic thermoelectric thin films and also, exploiting the thermoelectric effect in liquids, the ionic liquids and ferrofluids.

Degree of development, challenges and potential

It was commented that there has been a significant reduction in the number of projects devoted to thermoelectrics in the last years, and that this trend should be reversed as thermoelectricity could play a major role in the energy mix of the future. I was also said that promoting 2nd generation (thin film, ideally printed) and 3rd generation (new concepts, low cost new materials), could be a great interest for both the scientific community and the European energy industry.

In the case of the 2nd and 3rd generation thermoelectric devices, it was commented that the printed inorganic thermoelectrics start to appear as a new emerging technology, and that organic thermoelectrics start to show interesting performances.

The problem of low electric conductivity of some of these materials has been highlighted. Since the thermoelectric efficiency depends on the figure of merit ZT, (indicator of the thermoelectric performance), proportional to the electrical conductivity, to obtain high performances, higher electrical conductivity is needed.

Some expert expressed their doubts about these materials reaching the condition of ZT>1, which could make the thermoelectric materials interesting.

Possible applications are foreseen for waste-heat recovery applications (e.g. from heat pumps), also for low temperature gradients.

It was estimated that the TRL of these thermoelectric materials can be around 2, and that the next TRL step could be reached in about four years. The TRL 6 could be reach in about fifteen years.

Short Bibliography

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Gunawan, A., et al. *Liquid thermoelectrics: review of recent and limited new data of thermogalvanic cell experiments*. Nanoscale and Microscale Thermophysical Engineering 17(4), 2013: 304-323.

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List of abbreviations

BES	BioElectrochemical Systems
CIGS	CuInGaSe2
CZTS	Cu2ZnSn(S,Se)4
DCFC	Direct Carbon Fuel Cell
DSSC	Dye Sensitized Solar Cell
ECE	External-Combustion Engine
Egap	Energy gap
ERC	European Research Council
FAME	Fatty Acid Methyl Esters
FET	Future and Emerging Technologies
GMO	Genetically Modified Organism
HER	Hydrogen Evolution Reaction
HTL	Hydrothermal Liquefaction
IBSC	Intermediate Band Solar Cell
JRC	Joint Research Centre
LCEO	Low Carbon Energy Observatory
MCFC	Molten Carbonate Fuel Cell
MEC	Microbial Electrolysis Cell
MEG	Multi-Exciton Generation
MFC	Microbial Fuel Cell
OPV	Organic Photovoltaics
ORR	Oxygen Reduction Reaction
PBR	Photobioreactor
PCE	Power Conversion Efficiency
PV	Photovoltaics
SMFC	Sediment Microbial Fuel Cell
SOFC	Soild Oxide Fuel Cell
SQ	Shockley-Queisser [limit]
TCM	Transparent Conducting Material
TCO	Transparent Conducting Oxide
TPV	Thermophotovoltaics
TRL	Technology Readiness Level
Voc	Open Circuit Voltage

Annexes

Annex 1. Agenda of the Workshop

*8:30 – 9:30 [Room 101/1003] **Introductory session** and general issues: introduction on the LCEO project and the WP on Future Emerging Technologies (FET); the FET concept; description of the approach to be used in the workshop (JRC, All)*

9:30 – 9:45 Coffee break

*9:45 – 13:00 [Room 101/2302] **Working group on Fuels** (Hydrogen and fuel cells, metal fuels, biofuels): brief presentation of related FET templates and brainstorming.*

*9:45 – 13:00 [Room 100/1102 "Terra"] **Working group on Photovoltaics**: brief presentation of related FET templates and brainstorming.*

13:00 - 14:00 LUNCH BREAK

14:00 – 14:45 Visit to the JRC laboratories

*14:45 – 17:45 [Room 101/1003]. **Plenary session:** summary of the two morning sessions; (coffee break); joint working group on FETs of General interest; "free" brainstorming on other FETs.*

17:45 END of the activities

Annex 2. Technology Readiness Level Definition

TRL 1	**Basic principles observed and reported:** Scientific problem or phenomenon is identified. Essential characteristics and behaviours of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.
TRL 2	**Technology concept and/or application formulated—applied research activity**: Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3	**Analytical and experimental critical function and/or characteristic proof of concept:** Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.
TRL 4	**Component and/or process validation in laboratory environment—alpha prototype (component):** Standalone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.
TRL 5	**Component and/or process validation in relevant environment—beta prototype (component):** Thorough prototype testing of the component/process in a relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.
TRL 6	**System/process model or prototype demonstration in a relevant environment— beta prototype (system):** Prototyping implementations are partially integrated with existing systems. Engineering feasibility is fully demonstrated in actual-or high-fidelity system applications in an environment relevant to the end user.
TRL 7	**System/process prototype demonstration in an operational environment—integrated pilot (system):** System prototype demonstrated in an operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near production quality prototype.
TRL 8	**Actual system/process completed and qualified through test and demonstration—pre-commercial demonstration:** End of system development with full-scale system fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.
TRL 9	**Actual system proven in operational environment:** Actual application of technology is in its final form - Technology ready to manufacturing

Annex 3. FET Concept Sheet Template

Name of the technology
Introduced by Professors:
Keywords:
Brief technical description:
Degree of development and potential *Why this technology should be considered FET/innovative and why not enough developed (estimation of TRL, potential relevance/applications…)*
Short bibliography:
Research projects/stakeholders (not mandatory): *(e.g. developed by University X under the project Y in Country Z)*

Annex 4. NREL Best Research-PV Cell Efficiencies

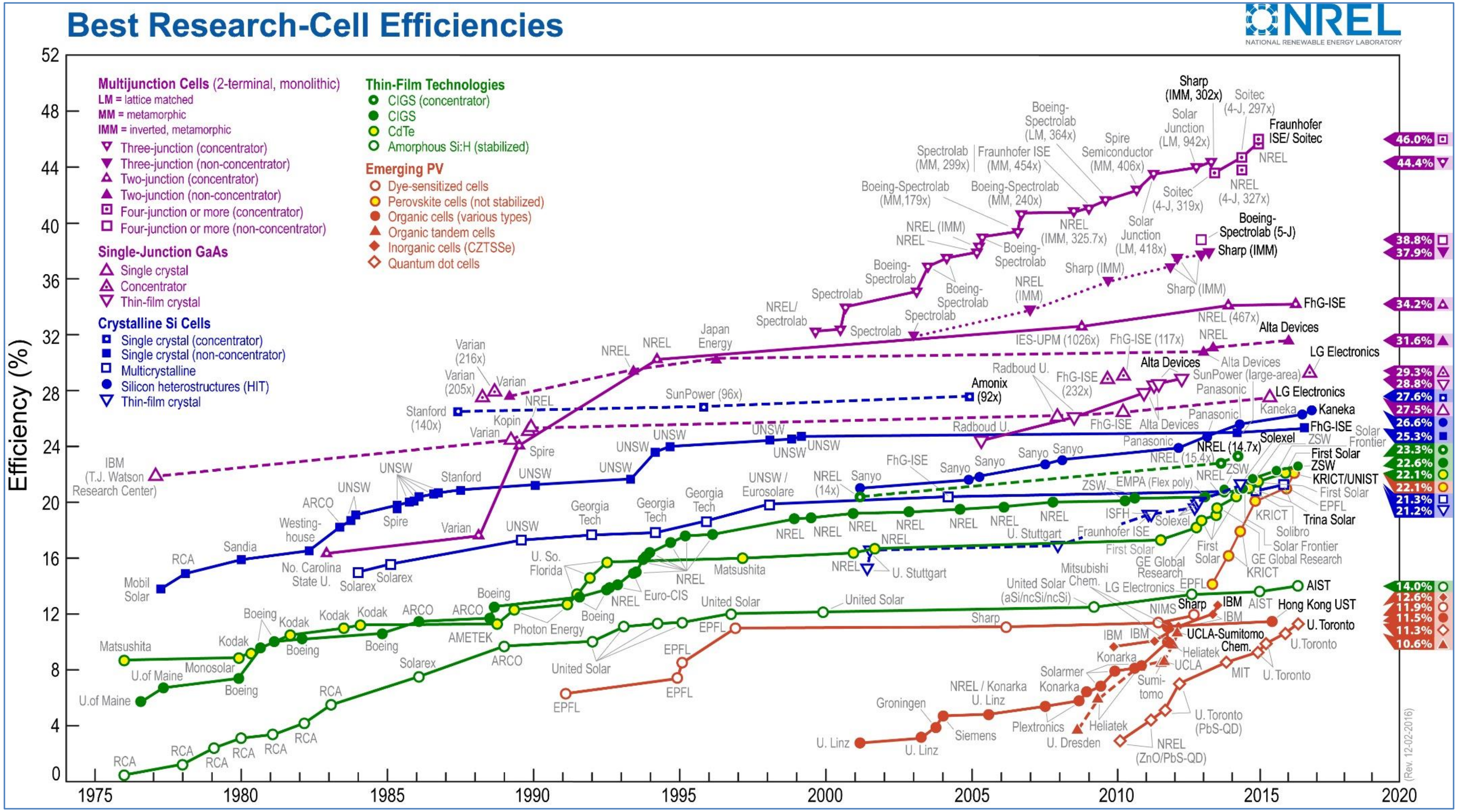

Figure 8: Best research PV cell efficiencies. Source: http://www.nrel.gov/pv/

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