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REPORT

“Next Generation Energy Storage Technologies: Challenges and Opportunities”

2-3 December, 2015 - Taormina

WG ENERGY

National Research Council of Italy

Report on the Exploratory Workshop

"Next Generation Energy Storage Technologies: Challenges and Opportunities".

Taormina (Italy), 2nd-3rd December 2015

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1. Preface

In December 2015, an exploratory workshop on *Next Generation Energy Storage Technologies: Challenges and Opportunities* was held in Taormina.

As it is well known, energy-related aspects are extremely wide and complex, involving energy conversion, storage and distribution. The workshop activities were essentially focused on energy storage. This topic was selected because of its strategic and mediating role especially when it comes to the future emerging energy technologies.

The aim of this exploratory workshop was to identify specific research directions as foresight priorities, to make a down-selection and to suggest a road map for the following Face-2-Face workshops.

This report is aimed at providing specific recommendations for prioritising research programs in this field to describe the approach used and how conclusions were reached.

2. Methodology

In preparing this workshop, the main approach was to consider the society needs for the energy sector in 2050 including energy security, energy independence, environmental and economic impacts of the energy processes on both a local and a global level. Prompted by the growing environmental impact of the processes underlying modern society, new energy policies indicate most of the production of electricity from renewable energy sources (e.g., >65% in Europe) as long-term (2050) goals, and a significant reduction of green house gas (GHG) emissions linked to energy production (e.g., at least 50% in Europe). However, because of the intermittent nature of renewable power generation, an advanced energy storage is needed to provide a solution for an efficient use of renewable sources such as utility-scale solar and wind farm installations. Energy storage represents the "missing link" between the variable renewable power production and the grid demand at different times and grid scales. Energy storage is also one of the three pillars of energy infrastructure system acting in mediating between variable sources and variable loads. Energy storage devices supply energy to the grid during high demand periods and absorb excess electricity from generators during low demand periods for rescheduled sale during high demand or in case of high electricity cost. A smart energy storage is the key-aspect to promote local, microdistributed energy generation and use, and it can provide an effective support for smart grids.

According to the aims of the Foresight project, a long-term vision was considered while the issues related to energy storage were analysed in a broader sense, including electrochemical energy storage (batteries, supercapacitors), hydrogen and fuel cells, thermal energy storage, power to gas, CO_2 recycling, direct coupling of storage systems with renewable power sources and the distributed energy generation. Aspects related to data treatment for energy supply, storage, and demand as well as financial and environmental aspects concerning the new emerging technologies were among the workshop topics.

The basis for the workshop contents was provided by an analysis of the current literature reports in order to identify which were the challenging topics in the field of energy storage to address society needs in the long term. In this regard, well known scientists and young researchers, policy makers and industry representatives were identified to involve them in specific discussions on this theme. As for industry representatives, they were selected from companies currently developing advanced solutions for energy processes that can find a widespread application in 2050. In particular, industries involved in developing hydrogen technologies for the next generation zero emissions fuel cell cars or operating in power-to-gas processes to manage the issues associated with distributed energy generation or involved in data processing. Policy makers from the EU Commission were invited to participate. For each sub-topic, scientists were selected according to an analysis of the literature and the impact of their scientific publications in terms of number of citations in Scopus and invited presentations at important international conferences.

3. Activities

The invited speakers list for the workshop included well-known scientists (10), 3 industry representatives and 2 policy makers. The workshop also involved almost all Foresight project participants. They were all fully involved in the discussion.

Invited speakers were required to focus on long-term objectives. They were asked to introduce, in a short presentation, their point of view on future challenges in the energy sector. The related discussion was oriented, from the very beginning, to the identification of the possible scenarios, a preliminary individuation of priorities and an analysis of interdisciplinary aspects.

On day one, following a short introduction about the scopes of the workshop by the project coordinator, E. Andreta, the vice-coordinator, E. Einaudi and the topic responsible, A.S. Aricò, the invited speakers presented both the state-of-the-art and the future research directions to address the society needs on the long term. The state-of-the-art presentation was restricted to a few slides. The presentations covered their specific fields of expertise, underlining all possible positive outcomes and the critical issues as well. The purpose was to provide a general overview about the energy storage sectors, the challenging issues in relation to human needs and the suggested solutions. Each speaker indicated specific priorities he had identified in terms of new research directions and emerging technologies where efforts need to be addressed. For each set of presentations (about four) dealing with a similar topic there was a joint discussion.

On the second day, the workshop addressed the down-selection of ideas for future research programs. This session was chaired by S. Taylor who acted as a facilitator in order to achieve a consensus among the experts on the long-term objectives and to allow research priorities to emerge from the debate. Participants were asked to imagine potentially achievable ideal scenarios, only limited by the laws of thermodynamics, and the steps needed to reach such goals. Specific questions on several issues, arisen during the discussion, were asked to the experts starting from very general topics, *e.g.* whether, on a global scale, energy demand will increase, whether it is possible to imagine a future energy system 100%-based on renewable processes, and to define the degree of consensus among the participants on those issues. Furthermore, the experts were asked to speculate on the major technological breakthroughs necessary to achieve the ideal scenarios. After having pointed out and listed the main areas of interest, the discussion continued to identify the research priorities, *i.e.* which ones are more promising or more relevant or potentially more innovative.

4. Main outcomes

The main outcomes from the workshop are summarized as follows:

It was agreed among the scientists, industry representatives and policy makers that a holistic approach is necessary to radically transform the current energy system to become part of a future low-carbon, resource efficient and sustainable economy. Future efforts must be targeted at unlocking the potential of energy storage and conversion of electricity to other energy carriers e.g. chemicals such as hydrogen, methanol from CO_2 recycling, bio-fuels etc., and thermal energy carriers. This is essentially determined by the long-term vision of a wide-scale penetration of distributed electricity production from variable renewable sources such as wind and sun and the consequent variations of supply. There was an almost general agreement on the fact that the new energy carriers can address the need for daily and seasonal energy storage while batteries and supercapacitors can manage issues related with intermittency on a shorter time scale (peak shaving). As an important source for balancing the energy system, together with other options, the development of storage technologies will become essential for the decarbonisation of the energy system.

There was general consensus on the fact that this will require to address efforts on power-to-fuel processes and, among these, hydrogen generation by advanced electrolysis systems and CO_2 recycling. CO_2 utilization (recycling) is at the crossover of this evolving scenario and is progressively seen not as a problem, which may be eventually solved by capture and storage approaches only, but rather as a resource, i.e. an important and critical element useful to move towards a sustainable future. Good perspectives on a long-term basis are envisaged for the integration of solar energy and CO_2 use within bio-based production, to address the challenge of integrating bio- and solar-refineries. This includes the use of micro-algae and CO_2 valorisation in bio-refineries/-factories, including possibilities for their synergetic cooperation and symbiosis, as well as integration within the agro-energy value chain.

Chemical energy storage is seen as one of the most important methodologies being developed because it is both scalable and geographically independent. The main method of chemical energy storage still remains to convert the electrical energy to hydrogen via the electrolysis of water. Significant efforts need to be made to understand where future lies e.g. methanation and/or chemical conversion of the hydrogen to other fuels. The future of hydrogen economy includes these aspects and the concept of smart hydrogen grids. This is the link between hydrogen and distributed energy generation.

Water splitting using sunlight was agreed as one of the most promising technologies on the long term. Bio-fuels were also indicated in terms of global solution involving the growth of specific plants in some regions of the planet. However, aspects related to the impact on agriculture need to be properly considered.

Challenges such as electrochemical propulsion by electric vehicles (EV), and the need for large-scale storage of sustainable energy (i.e. load-levelling applications) motivate and stimulate the development of novel rechargeable batteries and super-capacitors. Instead, the present electronic revolution will continue in the future and rely on the extensive use of highly sophisticated portable power source devices with high-energy density, safe and cheap. It seems that lithium battery will continue to represent one of the electrochemical storage technologies widely used in the future. However, intercalation chemistry is not adequate yet for meeting the renewable power sources and electric vehicle energy storage requirements. In this respect, reduction in cost, as well as enhancement in safety, and particularly in energy density are required. This can only be achieved by totally renewing the battery chemistry, involving all three components, namely anode, cathode and electrolyte. The lithium-air battery, with a theoretical energy density orders of magnitude higher than the one of the present lithium-ion technology, appears an ideal candidate. However, some serious issues still hinder the practical development of this battery. A new solution can be brought about by the development of functional materials including graphene to progress in the lithium battery technology**.** Whereas the issues related to the availability of lithium in 2050 can be properly considered by promoting efficient recycling as well as stimulating the development of novel metal-air batteries based on other active metals which are much more abundant than lithium including Na-air and Mg-air systems. The approach to be pursued in the future is to implement the negative electrode and promote fast kinetics of Na ion intercalation in sodiated transition metal oxides to outperform their Li counterparts.

Supercapacitors are recognised as an emerging technology for sustainable energy processes and they will acquire more importance in the future to promote hybrid transportation. These systems can offer efficient storage solutions for the future electric cars. The novel approach towards high power and high energy density storage systems appears to be the use of asymmetric or hybrid capacitors. A hybrid capacitor combines a fast lithium insertion electrode with an activated carbon electrode. The use of hybrid electrodes appears very promising on both sides of the supercapacitor.

Currently, hydrogen and fuel cells need well defined targeted long term breakthrough research strategy, which address both social and technological problems. For instance for the two billions people who do not have access to reliable electricity supply and are far from a grid, stand-alone power systems based on hydrogen and coupled to a Renewable Energy Source (RES) are a definite option, which, however, still needs intelligent scientific and technical decisions. The general challenge that has to find its solution is the optimization of the energy cycle from RES to end use via hydrogen generation, storage, transport, conversion and consumption which covers the whole chain of hydrogen and fuel cell technologies. Since fuel cells are characterised by very high energy density and low environmental impact, they can strongly increase their impact on the next generation energy systems if these will address relevant aspects like cost reduction, transition to non-noble metal electro-catalysts (Pt is currently used in the electrodes) and novel ion conducting membranes, covering wide range of operating temperatures. In this context, the concept of converting a fuel cell system designed for one specific use, *e.g.*, transportation, into a "universal power supply" for a much broader range of potential applications was discussed. As an example, fuel cells in electrical cars can act as additional energy storage system/power source for powering residential buildings in the case of energy needs. Breakthroughs in the field of fuel cells and electrolysers involve novel oxide-based proton conductors operating at intermediate temperature, efficient and cost-effective water electrolysers, preferably a CO_2 co-electrolyser for generation of organic liquid fuels, and/or a fuel cell with internal splitting of biofuels into hydrogen. Such technologies are of essential simplicity and allow for kinetic enhancement so that the need for precious metal catalysts as in low temperature systems might be eliminated.

A cross-cutting theme involving electrochemical and thermal energy storage is the research on functional materials including nanostructured and smart materials obtained in proper amounts by cost-effective processes. These can represent the key enablers, driving this energy storage transformations. However, there was no unanimous consensus on the wide-spread use of nanomaterials in batteries. It was questioned that this can produce a dispersion of efforts or increase the "noise to signal ratio" causing significant deviation from the real objectives which are those identified according to human needs.

For thermal energy storage systems, the biggest challenges appear at the system and conceptual levels. Thus, research efforts in developing future systems should be looked at this regard.

It was agreed that specific efforts, at every level, are necessary to tackle the present challenges in terms of low energy density, poor reliability, low environmental impact of the new energy technologies. Whereas aspects related to the cost issues can be addressed through specific policies. Both academic and industry-driven research can contribute to enhance the potential of the new concepts and technologies for the next generation of storage device, carriers and the integration of these devices in the energy system. In parallel, it is considered that new business models are necessary to boost innovation whereas the governments must invest more in research. The transition to new energy technologies will include everything from public financing for clean energy solutions, to subsidies, to how distribution utilities and the private sector are paid for their services.

As to data collection and analysis, aspects dealing with “Big data” treatment in energy processes were discussed. In particular, the most appropriate methodologies to store, aggregate, and process data were discussed. A novel approach was proposed to embrace the inherent complexity by instrumenting storage devices in situ and characterizing them using data. In most applications, energy storage devices are already fitted with sensors and an internet connection. Enormous amounts of data already exist that describe real-world battery performance. In aggregating and analysing such data using contemporary data science, it is possible to accurately predict and optimize performance (physical, electrical, financial), providing the key link to future energy storage systems and related economy.

5. Conclusions and recommendations

A general vision stemming from this workshop was that the future energy system will shift from a centralised to a distributed energy generation. The latter will rely on a full set of renewable energy sources and related technologies which should be efficient, reliable, smart, cost effective and characterised by extremely low environmental impact. This scenario will involve all energy sectors i.e. conversion, storage and distribution.

Sustainable processes, energy security, energy independence, energy saving, low environmental impact, strong reduction of green-house gas emissions, cost-effective technologies, widely available, are the society needs for the long-term. New research directions should address these goals using an interdisciplinary approach including economic models for possible future scenarios, health considerations, impact on environment and society.

It appeared clear from the discussions that there is no unique technology solution to achieve all these goals whereas a holistic approach is necessary. The transition to efficient and clean energy solutions necessarily needs to be supported by public financing to provide subsides and incentives in order to speed up the transformation of the energy technologies towards a sustainable and environmentally benign system at local and global level. Energy technologies operating at microscale should be supported by advanced data processing, fitted with sensors and connected to internet.

According to the main outcomes, the research areas that need to be prioritised are summarised as follows:

1. **Functional materials:** Advanced energy technologies based on smart functional materials which combine properties of energy conversion and storage on a micro scale as key enablers to drive the transformation of the energy system.

2. **Electrochemical energy storage**: In the future, an advanced electrochemical energy storage will be a key technology in several sectors. However, energy density needs to be significantly increased. In this regard, research efforts should be addressed to new lithium-air batteries, to the development of new functional materials, e.g. graphene, as well as on replacing lithium with more abundant elements for electrochemical energy storage on a large scale, e.g. Na-air and Mg-air batteries. These efforts should be complemented by research on novel hybrid supercapacitors combining high power with proper energy density.

3. **Renewable fuels and CO_2 valorisation:** Renewable fuels such as hydrogen, methanol, dimethyl ether, ammonia, obtained from water splitting, electrochemical or catalytic processes, or from recycling of CO_2, using the surplus of renewable power, will complement the electrochemical storage on a larger time scale (e.g. seasonal storage). These can also represent a proper solution for transportation by extending the driving range of electric vehicles. However, efforts in developing proper infrastructures for alternative fuels are required.

   Smart grids and alternative energy vectors will provide an efficient link between sustainable energy generation, distribution and use.

   A foresight objective is to achieve a complete decarbonisation of the energy system. However, the transition period towards this scenario may be relatively long (a century or more) whereas there is an urgent need to address immediately the global warming effects caused by carbon dioxide accumulation in Earth's atmosphere. In this regard, an efficient and distributed CO_2 recycling on a wide-scale in combination with neutral (or even negative) carbon footprint processes can play a relevant role. Thus, CO_2 *management* represents both an urgent requirement and a long-term target. This topic is characterised by an interdisciplinary nature since it involves environmental, energy, agriculture etc. aspects.

   CO_2 valorisation will provide an efficient means to reduce green-house gas emissions in comparison to sequestration processes. Research efforts should be addressed to novel, efficient and sustainable electrochemical and catalytic processes. Water electrolysis supplied by renewable energy appears as the foremost technology for producing "green" hydrogen for fuel cell vehicles in the next future. Co-electrolysis of CO_2 and water sustained by renewable energy, photo-electrolysis and photocatalytic conversion processes appear also as key technologies for an efficient recycling of CO_2 and to promote carbon-neutral processes. Such new carbon-neutral processes will provide a smooth transition towards a complete decarbonisation of the energy system.

   Research programs should be addressed to achieve high conversion efficiencies, use of non-noble metal based catalysts, new oxide conductors operating at an intermediate temperature to fill in the existing gap.

4. **Thermal energy storage**: Advancement in thermal energy storage is another area of strategic interest for the future energy system as well as complementary to the technologies discussed above. All irreversible processes produce heat that can be stored in principle and efficiently used in specific utilities. Efforts should be targeted on both component (e.g. new phase transition materials) and system levels as well as to the integration of energy conversion technologies on a wide scale. Trigeneration systems able of producing power, heat and cold represent the ultimate frontier for an efficient energy conversion and use.

The challenges regarding all these areas are to develop disruptive approaches which effectively address human needs on the long term. Breakthrough research should be thus preferred to incremental research while impact on the society and environment deeply analysed. The overall approach should be systemic and interdisciplinary covering all aspects that a new technology may involve.

The next Face-to-Face meeting should deal with interdisciplinary aspects involving the selected directions for the next generation energy storage.

The invited speakers will read and agree with this report before it is made available to the general public through the Foresight web site.

Annex I

Workshop AGENDA

2nd December 2015:

Introduction session:

1. **9:00-9:10 Ezio Andreta (CNR) - Foresight Project Coordinator: *Welcome***
2. **9:10-9:20 – Salvatore Freni - Director of CNR-ITAE: Local organizer welcome**
3. **9:20-9:30 Antonino S. Aricò (CNR) -** Foresight Project, Energy Storage Responsible **/ Giorgio Einaudi (CNR) -** Board member Science & Technology Foresight Project**: *Introduction to the workshop project activities***

Presentations and Discussion:

Session 1: Energy: Key technologies, Policy strategies, Industry requirements – *Chairman Stephen Taylor (AREA Science Park)*

9:30-9:40

1. **Christos Tokamanis** Head of Unit "Advanced Materials and Nano Technologies"; Directorate-General "Research & Innovation" , European Commission
   Advanced Materials and Nano Technologies for Energy Storage applications: the contribution of policy makers

9:40-9:50

2. **Kate Burson** Chief of Staff, Energy & Finance, Office of the Governor of New York (USA)
   Financial and policy making aspects for the energy sector

9:50 -10:00

3. **Isotta Cerri** Senior Manager, Advanced Technology Division Production Engineering Group Toyota Motor Europe NV/SA (Belgium)
   Energy storage systems for automotive applications

10:00 -10:10

4. **Eli S. Leland** Co-founder Voltaiq (USA)
   Key technologies in energy storage

10:10 -10:20

5. **Nicholas Van Dijk** Research Director, ITM Power plc (UK)

Hydrogen Technologies and Power to Gas

10:20 -11:10
Joint discussion on Session 1

11:10-11:30 ***Coffee Break***

Session 2: Electrochemical energy storage - *Chairman Giorgio Einaudi (CNR)*
11:30 -11:40

6. **Bruno Scrosati** Professor, Istituto Italiano di Tecnologia (Italy)
   Electrochemical Energy Storage: Next Generation Li Batteries

11:40 -11:50

7. **Kioyshi Kanamura** Professor, Tokyo Metropolitan University (Japan)
   Metal-air batteries: Magnesium-air batteries

11:50 -12:00

8. **Doron Aurbach** Professor, Bar-Ilan University (Israel)
   Rechargeable Sodium Batteries

12:00 -12:10

9. **Margret Wohlfahrt Mehrens** Senior Researcher, ZSW, Ulm (Germany)
   Next Generation Supercapacitors

12:10 -13:00
Joint discussion on Session 2

13:00 -15:00 Lunch

Session 3: Hydrogen and Fuel cells - *Chairman Antonino S. Aricò (CNR)*
15:00 -15:10

10. **Piotr Zelenay** Senior Researcher, Materials Physics and Applications, Los Alamos National Laboratory (USA)
    New research directions for fuel cell systems

15:10 -15:20

11. **Daria Vladikova,** Director of Institute of Electrochemistry and Energy Systems, Bulgarian Academy of Sciences (Bulgaria)
    Advances in Hydrogen Technologies and Fuel cells

15:20 -15:30

12. **Qingfeng Li,** Professor, Department of Energy Conversion and Storage - Technical University of Denmark
    Novel intermediate temperature ionic conductors for fuel cells and electrolysers

15:30 -16:00

Joint discussion on Session 3

Session 4: Thermal storage, CO_2 recycling, distributed generation - *Chairman Ezio Andreta (CNR)*

16:00 -16:10

13. **Peter Schossig** Head of Department thermally active materials and solar cooling Division Thermal Systems and Buildings Fraunhofer-Institut für Solare Energiesysteme ISE (Germany)
    New ideas for thermal energy storage

16:10 -16:20

14. **Gabriele Centi,** Professor, University of Messina (Italy)
    New approaches to recycle carbon dioxide and reduce emissions

16:20 -16:30

15. **Siglinda Perathoner,** Professor University of Messina (Italy)
    Sustainable energy conversion and storage

16:40 -17:20

Joint discussion on Session 4

17:20 -17:40 Conclusions of the first day E. Andreta - A.S. Aricò – G. Einaudi

20:00 Social Dinner

3rd December 2015:

9:30-13:00 Brainstorming activities

Moderator: **Stephen Taylor** *(AREA Science Park)*

9:00-10:00

1. *Discussion about the proposed research directions: the point of views of the policy makers, industry representatives and scientists*

10:00-11:00

2. *Assessment and identification of priority topic areas and their medium-long term potential applications including socio-economic impacts*

11:00-11:30 Coffee break

11:30-12:00

3. *Discussion of funding needs, market potential and social acceptability.*

12:00-12:30

4. *Paving the way for preparing a Report on energy storage*

12:30-13:00

5. *Conclusions: Planning the program of a successive* F2F workshop. – E. Andreta, A.S. Aricò, G. Einaudi