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"Promoting a Sustainable Future through a Large-scale Utilisation of Renewable Fuels"

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Background Document

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Promoting a Sustainable Future through a Large-scale Utilisation of Renewable Fuels

CNR Foresight project
Topic: Energy Storage
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1. Introduction

It is widely known that energy storage will play a strategic and mediating role in future emerging energy technologies [1]. Energy storage is one of the three pillars of the energy infrastructure system mediating between variable sources and variable loads [2].

A smart energy storage is the "missing link" between the variable renewable power production and the grid demand at different times and scales. Concurrently, there is an urgent need to address immediately the global warming effects caused by carbon dioxide accumulation in Earth's atmosphere [3-5]. These two aspects, i.e. a novel approach for storing renewable energy and mitigation of environmental issues, are strongly interrelated.

Prompted by the growing environmental impact of the processes underlying modern society [6], new energy policies indicate as long-term (2050) goals the production of electricity mainly from renewable energy sources, and a significant reduction of greenhouse gas (GHG) emissions linked to energy production [7]. In this regard, distributed energy generation using renewable power sources and advanced energy storage technologies are of paramount importance for the future energy system [8]. Because of the intermittent nature of renewable power generation, an advanced energy storage is needed to provide an efficient use of renewable sources, favoring an approach based on renewable fuels [9-11]. In this regard, it is necessary to identify priorities and specific research directions, make a down-selection and suggest a road map for future activities.

In spite of the fact that the long-term goal of the decarbonisation of energy production is very well defined [1,7, 12,13], climate change and global warming concerns have clearly evidenced the need of reducing atmospheric green-house gases concentration on the shortest time scale possible [14,15]. Therefore, in transitioning the global energy economy away from fossil fuels to renewables, it will be necessary to address the management and recycling of CO_2 to mitigate the dramatic effects of climate changes [1,7]. Chemical energy storage into organic fuels is seen as one of the most important methodologies being developed because it is both scalable and geographically independent [16, 17].

On the other hand, hydrogen, as fuel alternative to the organic carriers, is characterized by proper energy density and clean combustion [18-22]. Its wide use will assume in the future increased environmental and societal relevance in addressing energy issues, pollution, global warming and related effects of climate changes [18]. Concerning the hydrogen economy [23], well defined, targeted, long-term breakthrough research, to address both social and technological problems, is still needed. For instance, for the two billion 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.

The Foresight workshop "Next Generation Energy Storage Technologies: Challenges and Opportunities (Taormina, Italy, 2-3 December 2015)" [24] and the scoping workshop on STEM materials (Rome, 23-24 March 2017) have pointed out the need of exploring scientific gaps and perspectives in two specific research directions: "Carbon Dioxide Management and Valorisation" and "Green Hydrogen Generation and Use on a Wide-scale". These research directions concern two relevant energy cycles:

i) A carbon-neutral cycle involving conversion of CO_2 from various sources/emissions into a renewable fuel, using the excess of renewable energy. In this framework, CO_2 is the substrate and methanol, dimethyl ether, syngas, ethanol etc. are the renewable fuels.

ii) The hydrogen cycle involving production of "green" hydrogen from water, using the surplus of renewable energy. Here water is the substrate and H_2 is the energy carrier.

Both cycles are sustainable and can cover the full energy chain (electric power, heat, and cold using heat pumps). The "Carbon Dioxide Management and Valorisation" approach is mandatory in a medium time scale, to reduce the amount of greenhouse gas in the atmosphere before a complete decarbonisation of the energy system will be possible. In order to achieve a complete decarbonisation, renouncing the use of fossil fuels, it is necessary to solve the storage problem of the surplus of renewable energy. In this regard, the "Green Hydrogen Generation and Use on a Wide-scale" approach can give an important contribution.

In the following, we outline for both cycles the specific research needs and the challenges which will be object of future discussion within the Foresight Project workshops.

2. The carbon-neutral cycle

The key aspect of this cycle regards the future development of an efficient CO_2-based storage technology characterised by high energy density [16, 17]. CO_2 utilization (recycling) is at the crossover of this evolving energy scenario [25, 26]. Carbon dioxide is progressively seen not as a problem, which may be eventually solved by capture and sequestration approaches only, but rather as a resource, i.e. an important and critical substrate useful to move towards a sustainable future. In general, CO_2 management represents both an urgent requirement and a long-term target [27, 28]. This topic is characterised by an interdisciplinary nature since it involves environmental, energy, agriculture etc. aspects [28-32].

There is a general consensus on the fact that a carbon-neutral cycle will require to address efforts, among others, on processes such as power-to-fuel, e.g. carbon dioxide recycling by using advanced CO_2-H_2O co-electrolysis systems [33, 34], and microalgae-mediated CO_2 capture and biorefinery [35].

On a long-term basis, good perspectives 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 [35]. This may regard the use of micro-algae and CO_2 valorization in bio-refineries/-factories, including possibilities for their synergetic cooperation and symbiosis, as well as integration within the agro-energy value chain [35,36].

However, there are several challenges in this field that require breakthrough solutions. Relevant issues are associated to the slow microalgal growth caused by the sensitivity to flue gas components, local climatic conditions, large energy requirements for mixing during growth, low volumetric productivity, the need to handle large quantities of water, poor harvesting and conversion [36].

Alternatively, it may be important to pioneering new knowledge and technology for the chemical synthesis of renewable alternative fuels e.g. methanol, dimethyl ether, syngas, methane etc. by converting CO_2 and water from various resources, e.g. from industrial waste flue gas [28, 33, 37]. Co-electrolysis of CO_2 and water sustained by renewable energy, photo-electrolysis and photocatalytic conversion processes appear as key technologies for an efficient recycling of CO_2 and to promote carbon-neutral processes [28]. The overall process should aim at a carbon neutral cycle, where the energy input is provided by renewable power sources. The main challenges concern the chemical inertness of CO_2, especially at low temperatures, as well as the need to develop CO_2 recycling processes on a wide and distributed scale [28]. The new processes must be economically competitive, using non-critical raw materials, e.g. for the catalysts, and achieve substantial results in terms of both efficiency and longevity.

An efficient CO_2 conversion into a renewable fuel appears to require a two-step conversion at high and intermediate temperatures and high pressure, being CO_2 relatively inert at ambient conditions [38]. The advantage of this process is linked to the possibility of producing liquid fuels that can be handled, transported and distributed using the current infrastructure. On the other hand, pioneering an effective solution for converting CO_2 to high energy density organic fuels by developing one-step co-electrolysis of CO_2 and water may provide a new approach characterized by high efficiency and system simplicity [39].

The energy carriers generated from CO_2 are characterized by excellent gravimetric energy density and can operate on a wide time-scale, covering both the requirements of grid stabilization due to the intermittency on a short-time scale (peak shaving), while addressing the need for daily and seasonal energy storage [38,39]. As an important source for balancing the energy system, together with other options, the utilization of renewable fuels will become essential for a sustainable development and to contribute to the decarbonisation of the energy system.

3. The hydrogen cycle

The main challenges to overcome for an effective wide-scale utilization of hydrogen as energy carrier regard both the overcome of technical bottlenecks and an 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 [18, 19, and 23].

Technical problems are primarily dealing with storage of hydrogen with high volumetric energy density, using low-energy consumption and cost-effective technologies characterized by intrinsic safety. The game-changer can be represented by the development of new chemical compounds as efficient hydrogen carriers. Other relevant aspects that require step-change approaches are the stability and reliability of fuel cells and electrolysers, economic concerns on the cost of system integration and required infrastructure, and supply chain for large scale hydrogen production and transportation, as well standards and regulations [21].

Since fuel cells are characterized by very high energy density and low environmental impact, they can have a strong impact on the next generation energy systems. However, they will need to address relevant aspects like a significant increase of energy efficiency, durability and a large reduction of capital costs. Regarding cost reduction, transition to non-noble metal electro-catalysts (Pt is currently used in the electrodes) and novel ion conducting membranes, covering a wide range of operating temperatures, are research directions of relevant interest [40-42]. 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, can play a relevant role. 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.

Other specific breakthroughs in the field of fuel cells and electrolysers involve novel oxide-based proton conductors operating preferably at intermediate temperature. 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 [43, 44].

Water electrolysis is a very promising technology for sustainable hydrogen generation using renewable electrical energy. The excellent performance and the dynamic behaviour for storing electrical energy in hydrogen allow these systems to cover the gap between the intermittent renewable power production and the grid demand [45]. The “green” hydrogen obtained from electrolysis systems connected to renewable power sources is widely considered a promising energy vector that can act as a mediator between renewable energy and sustainable mobility [20]. However, being molecular hydrogen in the gaseous state at ambient temperature, it needs to be compressed at 700-900 bars to reach appropriate volumetric energy density [21]. The challenge here is to store hydrogen in chemical systems with fast adsorption-desorption kinetics and high efficiency, to achieve proper energy density for the storage medium, as well as easy handling [40].

Part of the required cost reduction for the hydrogen system should be achieved by the economy of scale in the future [18]. However, supply chain and supporting infrastructure are also relevant problems to realize hydrogen economy. Distribution costs also represent a relevant issue since nickel pipelines are required to avoid hydrogen embrittlement of conventional steel systems. Finally, the efficiency of power-to-power systems is today below 55% and, despite the much higher energy density of hydrogen, this bottleneck does not allow this technology to actually compete with batteries for short-time scale storage [18].

All these aspects clearly indicate that radically new approaches are required to promote hydrogen economy.

The CNR Foresight project approach

The objectives of the CNR Foresight project in this field are to organize two workshops and support specific studies to address the challenges of the "Carbon dioxide management and Valorization" and "Green hydrogen production and utilization on a wide scale" with medium (2030) and long-term (2050) goals. The goals are to identify research breakthroughs in these fields to rapidly address the need of reducing polluting emissions and global warming, as well as mitigate the climate change. The activities should put the basis for a knowledge assessment with the identification of new and advanced approaches and related socio-economic impacts, pointing out obstacles, gaps in knowledge, funding needs, and social acceptability.

According to a consolidated approach, the list of participants to the workshops include scientists, policy makers and industry representatives. Stakeholders from other topics such as agriculture, environment/climate, health, food etc. are invited to participate to the debate. A limited number of participants will be asked to introduce the brainstorming among all participants, presenting:

- The possible research pathways with radically new approaches;
- The socio-economic impacts of the proposed approaches, indicating possible funding mechanisms and identifying potential obstacles;
- The challenging aspects, market needs, and how novel solutions can be combined with the market aspects indicating the main obstacles to overcome.

All participants to the workshops are selected to stimulate the debate, achieve a consensus on the new research directions, and prepare a report of the most relevant conclusions of the workshop. This survey is agreed with all speakers and provides the basis for preparing a report.

Priority areas of research in this field are identified, documented and discussed in the report. These usually contain an assessment and identification of relevant research pathways and their medium-long term potential applications including socio-economic impacts, funding needs, market potential and social acceptability aspects.

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