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Report

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

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WG ENERGY

National Research Council of Italy

F2F Workshop on

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

Rome (Italy), 8th-10th July 2019

FULL REPORT

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1. Preface

In July 2019, a face-to-face workshop on *Promoting a Sustainable Future through a Large-scale Utilisation of Renewable Fuels* was organized in Rome.

The workshop focused on Energy Storage according to the Foresight CNR project. The aim of the CNR Foresight project is to address relevant social needs. As it is well known, the development of a clean, secure and efficient energy system is considered one of today's most important challenges and is strictly connected to finding a solution to the ever-growing climate concern.

These topics were widely discussed at the workshop by focusing on sustainable fuels, in particular hydrogen and organic fuels produced from CO_2 reduction using renewable energy.

In the workshop background document, the urgent need to address Climate Change and its related issues by individuating both short - and especially long-term solutions was considered. Experts agreed that the main approach should radically lower green-house gases (GHG) emissions. This should be achieved in the shortest time to avoid major effects on climate such as extreme temperatures, with consequent relevant issues in terms of desertification and migration of population, rising of sea levels, change of the oceans pH, biodiversity losses etc.

In this regard, it was largely agreed that the objective to accelerate the development and deployment of new or advanced low carbon technologies should be a priority for all countries. As it is well known, during the 2015 United Nations Climate Change Conference, COP 21, in Paris, members agreed to reduce their carbon output "as soon as possible" and to do their best to keep global warming "to well below 2°C". Despite the evident difficulties to implement this agreement emerged during the recent Conference of the Parties (COP-25 Madrid), this remains the most important goal identified to date to allow a sustainable future.

Decarbonisation of the energy sector was recognised at the workshop as a major challenge in the energy roadmap to 2050. In this regard, alternative and renewable fuels are considered necessary in order to reduce GHG emissions and to achieve the challenging 2050 objectives in energy, transport, climate and economic and social policies.

At the workshop, the need to develop large-scale hydrogen technologies was largely recognized as the crucial point to achieve the required energy transition. Hydrogen is widely considered as an appropriate energy vector for sustainable development and, most of all, it would allow a deep decarbonisation of transport, buildings (heating and cooling), and industry. However, it is also recognised that several issues related to its storage, transportation and distribution have hindered the wide utilisation of this energy carrier. According to such introduction, it was thus considered at the workshop that a step-change would be necessary in the field of hydrogen technologies in order to widely deploy them in the transport, industry, residential and stationary sectors by 2050, when a large penetration of renewable energy is expected to cover almost 100 % of energy production.

On the other hand, participants at the workshop largely agreed that collection and sequestration of CO_2 emitted from transportation as well as from industrial activities do not seem to be now a practical, safe, cost-effective and long-lasting solution. In particular, no reliable approach has emerged for its disposal. Workshop participants instead focused on the fact that CO_2 could be efficiently converted into value added compounds such as liquid organic fuels, biochar etc. These processes aim at achieving carbon neutral cycles where the energy input is provided by renewable energy and in specific cases by the surplus power of intermittent renewable sources. The aim is to deploy large-scale sustainable CO_2 recycling processes in the next decades and to assist the transition towards an almost decarbonised energy system.

Accordingly, the activities of the workshop were essentially focused on "*Carbon Dioxide Management and Valorisation*" and "*Green Hydrogen Generation and Use on a Wide-scale*".

After a brainstorming session, the activities of the F2F workshop aimed at identifying specific research directions as foresight priorities, to carry out a down-selection and to suggest a road map for their implementation.

This report is aimed at providing specific recommendations for prioritising research programs in this field while describing the approach used and how conclusions were achieved.

2. Methodology

According to the aims of the Foresight project, the main approach of the workshop was to consider the society needs by 2050 in terms of the environmental and economic impacts of the energy processes, both at local and global level, as well as the necessity of energy security and energy independence for all countries.

The basis to elaborate the workshop contents was provided by an analysis of the current literature reports that allowed to identify the challenging aspects in the field of renewable energy use and storage on a wide scale in order to address the society needs in the long term. In particular, the main discussion focused on how to completely switch from a fossil-fuel based society to a sustainable future.

Acknowledged scientists, young researchers, and industry representatives were invited to participate in the workshop in order to involve them in specific discussions on these themes. Industry representatives came from companies which are currently developing advanced solutions for energy processes that are expected to find widespread application by 2050. The approach was to identify at least one industry representative involved in hydrogen and CO_2 valorisation and one representative expert in managing electricity grids and energy storage through batteries. The aim was to favour an in-depth discussion about pros and cons of the two different approaches for energy storage.

For each sub-topic, scientists have been selected according to an analysis of their recent literature reports and the impact of their scientific publications in terms of their number of citations in Scopus® and presentations at important international conferences.

It is worth to mention that the holistic approach was the base of all discussions, to avoid focusing on one single aspect of the energy issue while leaving others behind. The energy and environmental issues were thus considered as an interlinked and mutually reinforcing set of challenges.

In this regard, the Foresight project representatives covered various disciplines including physics, chemistry, energy, health, food, and information and communication technology. They were fully involved in the discussion in order to express their concerns on the possible impact of the suggested solutions in the different fields. Accordingly, most of the topics having direct or indirect relationship with the energy theme were represented by the Foresight participants with the aim of keeping the above-mentioned holistic approach as a starting point for all the discussions.

Invited speakers were required to focus on long-term objectives. They were asked to introduce, in a short speech, their points of view regarding future challenges in the energy sector. From the very beginning, the related discussion was aimed at identifying the possible scenarios, a preliminary individuation of priorities and an analysis of interdisciplinary aspects.

The final goal of the workshop was the identification and setting of priorities for the topics of future research programmes, focusing in particular on the definition of appropriate research directions for hydrogen technologies and renewable fuels.

3. Activities

The list of participants to the workshop included 10 international experts and 10 representatives from the Foresight project. The experts were well-known scientists in the field of chemistry, physical chemistry, biology, environment, economy, and included industrial representatives from the fields of energy, batteries, CO_2 and hydrogen.

The agenda of the first two and a half days was structured to include an Introduction about the S&T Foresight Project from the scientific director and a preliminary discussion about the Workshop context and objectives from the workshop convener. This session was followed by three introductory speeches focusing on green hydrogen generation and use, CO_2 recycling on a wide scale and related socio-economic aspects.

3.1 Background session: Focus on Green Hydrogen generation and use, CO_2 Recycling on a wide scale and related Socio-economic aspects

The objectives of the workshop, namely the identification of a sustainable fuels pathway and its relationships with the energy storage context in the framework of the S&T Foresight project were introduced.

The emphasis was put on the main effects of the increasing atmospheric CO_2 concentration and the associated rise in global temperature. These effects and their mutual dependence have become evident in the last decades. Accordingly, the specific points discussed in these introductory speeches were:

- ✓ Global Temperature Rise
- ✓ Desertification
- ✓ Warming Oceans
- ✓ Shrinking Ice Sheets & Glacial Retreat
- ✓ Sea Level Rise
- ✓ Extreme Events
- ✓ Ocean Acidification

According to most of the literature reports in this field, there is a clear evidence that the main causes of global warming are associated to the release in the atmosphere of greenhouse gases such as CO_2, water vapour, CH_4, NOx. The increase of atmospheric CO_2 concentration has been convincingly related to anthropogenic activities including continuous fossil fuels burning to supply energy, deforestation, land use changes etc.

This observation provided the background for the initial discussion about the specific sustainable energy challenges, which are summarised as follows:

- ✓ Decarbonise the energy system
- ✓ Use clean energy in industrial, mobility and domestic applications
- ✓ Make sustainable development compatible with the expected growth of population
- ✓ Address increasing energy demand
- ✓ Promote distributed generation
- ✓ Increase security of energy supply and availability
- ✓ Etc.

As follow-up of the convener's discussion, the three introductory speeches from the experts also pointed out the aspects of the growing environmental impact of the energy processes and the increasing need of energy supply for the development of a modern society.

Climate change is recognized as the most relevant current risk and, consequently, the most significant challenge we are facing; this makes it urgent to activate all possible strategies for mitigation and adaptation.

All of the experts have substantially agreed on the need to achieve a climate-neutral energy system as a long-term (2050) goal. This would mean a complete decarbonisation of the most relevant segments that contribute to the energy consumption or, alternatively, a promotion of efficient approaches for CO_2 sequestration and recycling when decarbonisation is not achievable.

It was agreed that this transition should be fully accomplished by a wide utilisation of renewable energy being it abundant and well distributed. However, because of the intermittent nature of renewable power generation, the development of advanced approaches for energy storage was indicated as necessary to provide effective solutions for an efficient use of renewable sources. Implementation of a smart energy storage has been also considered as the key-aspect to promote local, micro-distributed energy generation and use; moreover, this can provide an effective support for smart grids. As a realistic and long-term approach, this transition can very likely occur through a large-scale utilisation of renewable fuels.

In this regard, "*green*" hydrogen was identified as a nearly perfect energy carrier for the future energy system (Fig. 1).

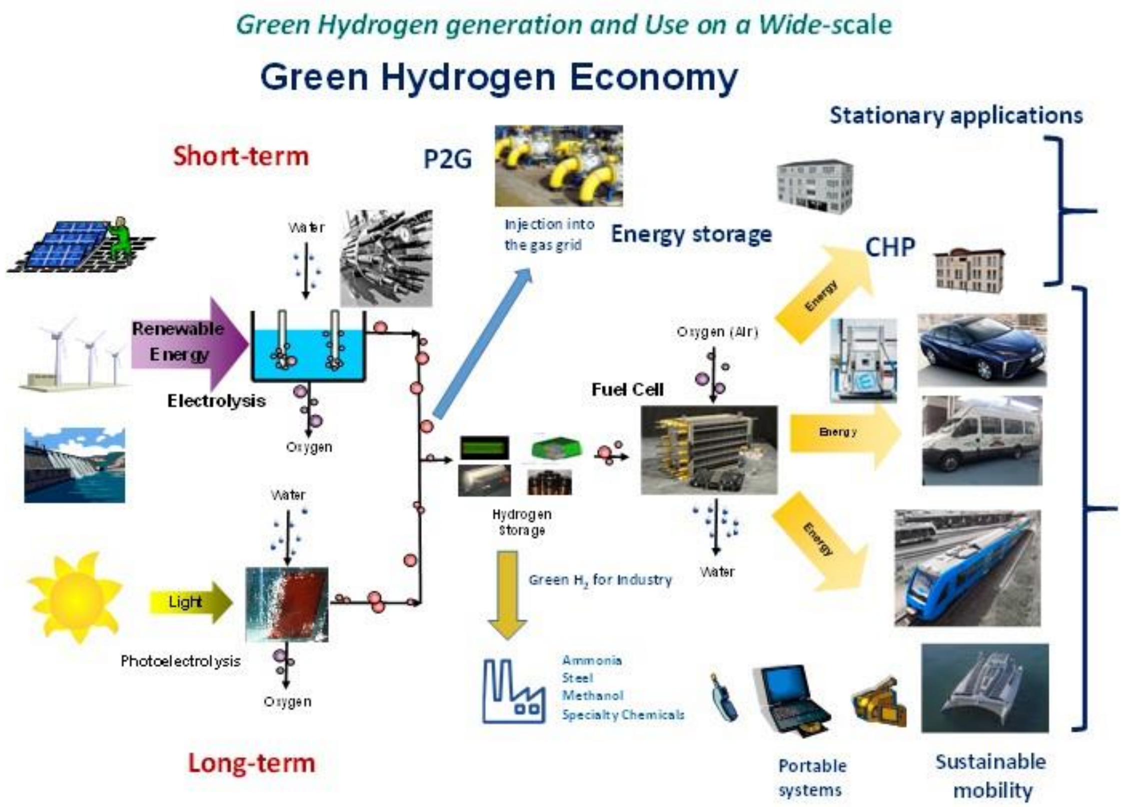

Figure 1. Green hydrogen generation and use in different segments

Hydrogen, on the one hand, can be easily and efficiently converted into electricity in fuel cells and, on the other hand, just as easily and efficiently generated in electrolysers. Because of the highly reversible nature and cleanness of these two electrochemical processes, the importance of hydrogen as an energy carrier is expected to increase significantly between now and 2050, the chosen target date of the Foresight Workshop discussions. Unlike most fuels, hydrogen offers a major advantage of being highly flexible in terms of its source, which ranges from fossil fuels (natural gas in particular), through nuclear and thermal, to the renewables (wind, solar, biomass). Hydrogen is also highly flexible in terms of use, finding applications as diverse as automotive, grid-related, residential, and industrial. This general flexibility of hydrogen makes it equally suitable for its integration in small- and large-scale energy systems.

Green hydrogen can be conveniently produced from water using the surplus of renewable energy. It can be directly utilised or converted into a more convenient hydrogen carrier compound. In fact, while hydrogen is characterised by high gravimetric energy density, its volumetric energy density is lower than other conventional liquid fuels especially if it is stored at relatively low pressures. Thus, compressed hydrogen (700 bar) is a practical solution for the moment, whereas cryogenic liquid hydrogen or hydrogen stored in inorganic or organic carriers can be the long-term solution. Cryogenic production of liquid hydrogen requires significant energy consumption; thus, the most convenient option would be to store hydrogen into useful chemical compounds acting as hydrogen carriers.

The debate about the possible alternative hydrogen carriers has made it possible to identify some interesting points of discussion. Among a variety of covalent bonds broadly considered for chemical energy storage and efficient conversion of chemical energy into electricity by electrochemical means, four types of bonds are particularly interesting. They include carbon-hydrogen (C-H) bond (*e.g.*, in simple hydrocarbons such as methanol and ethanol), carbon-carbon (C-C) bond (*e.g.*, in ethanol), nitrogen-hydrogen (N-H) bond (*e.g.*, in ammonia or hydrazine), and hydrogen-hydrogen (H-H) bond in the hydrogen molecule. In theory, all of these bonds can be formed by reducing various precursor molecules, including carbon dioxide (CO_2), nitrogen (N_2), and water (H_2O). The formation of the first three types of bonds in electrochemical processes faces numerous challenges including multiplicity of reaction products with low Faradaic efficiency, poor reaction kinetics, absence of efficient electrocatalysts, low concentration of the substrate in case of CO_2 *etc.* Performing the reverse process of harvesting chemical bond energy in the form of electricity is similarly challenging. This is particularly evident in the case of molecules containing C-C bond (or bonds), which cannot be efficiently broken using known electro-catalysts. That serious limitation applies to molecules as simple as ethanol (otherwise, a very attractive liquid fuel and one of the most effective hydrogen carriers thanks to its very high energy density). Both the formation and electrochemical conversion to electrons of the first three bond types show continued challenge to electrocatalysis, which calls for even more advanced research.

The main conclusion of this discussion is that significant progress in materials science, electrocatalysis and process development is needed to make such processes efficient, practical and reliable for wide scale application in the next decades. It is thus necessary to focus research on such directions in order to allow these advanced carbon neutral technologies to replace most of the current energy processes by 2050.

Regarding the hydrogen utilisation, both the creation of the H-H bond *via* water electrolysis and its electrochemical conversion to electricity (and water) in a fuel cell are highly efficient and have by now proven to be practical. Thanks to favourable thermodynamics, the reaction is also associated with the highest open cell voltage in a fuel cell (1.19 V at 80 °C) of the four type of covalent bonds considered above.

Thus, water electrolysis to produce hydrogen from the excess of renewable energy and hydrogen utilisation in fuel cells to produce electrical energy and heat (in a carbon-free cycle) appear the most practical solutions in the short term especially for mobility, industry and residential applications. However, a step-change is required for these technologies in order to replace precious metal catalysts with cheaper alternative materials, enhance efficiency and reliability, improve dynamic behaviour and decrease capital costs etc. In parallel to the step-change in technology development, a strong decrease of renewable electricity costs is required to economically produce hydrogen through electrolysis.

The scenarios by 2050 indicates a prevailing share of renewable energy that will very likely cause a reduction of its cost and possible negative prices of electricity in some periods (otherwise this should be curtailed by grid operators or wind mills should be stopped in specific periods).

Besides the required developments in fuels cells and electrolysis technology, a game changer in this field would be constituted by a new, efficient, practical and safe means to store hydrogen in appropriate carrier molecules with high volumetric and gravimetric energy density and its easier conversion back into hydrogen for re-electrification, heating purposes, industry utilisation etc.

Alternative processes of relevance to clean energy conversion, closely related to hydrogen, have been therefore considered and discussed. These include a small-scale distributed generation of hydrogen peroxide in a two-electron oxygen reduction reaction (ORR) and, the formation and conversion to electricity of C-H bonds in a cycle involving CO_2 reduction to dimethyl ether (DME) and DME oxidation in a direct dimethyl ether fuel cell. The latter process while involving CO_2 also holds the potential of being carbon-neutral.

Among the new technologies for CO_2 recycling, solid oxide electrolysis cells (SOECs) appear very promising as an energy conversion technology to store the surplus electrical energy from renewable energy sources with the possibility to produce green H_2 but also for a re-use of captured CO_2. Figure illustrates how SOECs can be integrated in an energy system involving a large share of renewable energy and CO_2 re-cycling processes.

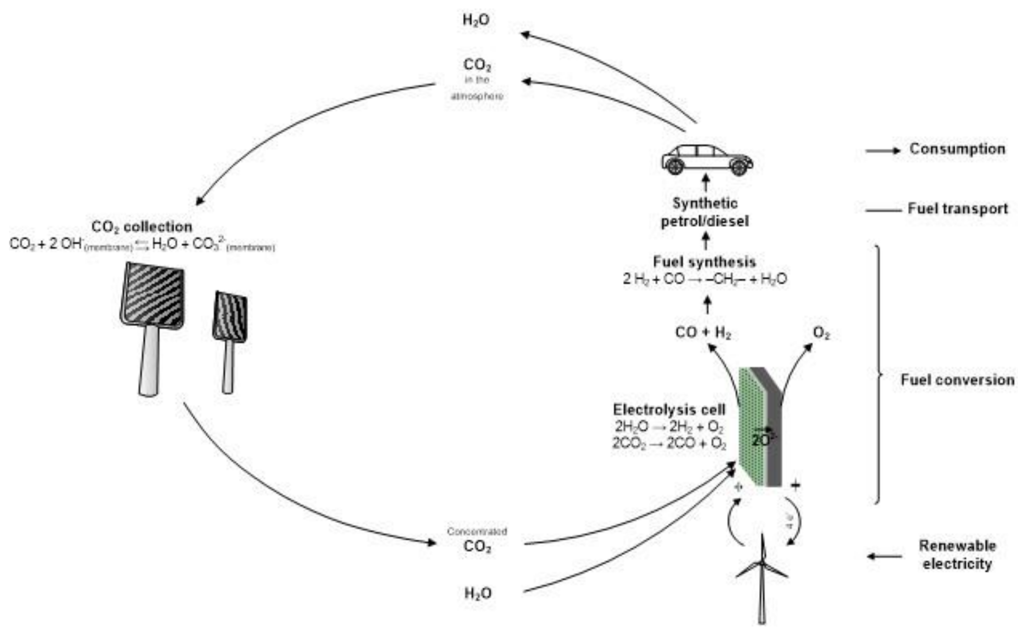

Figure 2: Sketch of electrolysis cells as part of renewable energy system integrated with CO_2-recycling [Chem. Rev. 114 (2014) 10697–10734].

This technology provides the possibility to do both steam electrolysis for H_2 production, CO_2 electrolysis for CO production and, co-electrolysis of steam and CO_2 for synthesis gas ("syngas", a mixture of CO and H_2) production. The SOEC technology can also be viewed in the perspective of CO_2 recycling and the possibility of transforming CO_2 to valuable products such as synthetic fuels. The SOEC can produce methane (synthetic natural gas) directly; however, this requires low temperature and a high-pressure operation. A system in which the SOEC produces synthesis gas ($CO+H_2$) that is subsequently transformed via well-known catalytic processes into synthetic fuels such as methane, DME, methanol or longer CH-chains seems a more viable path for the technology.

The critical aspects lay in the minimisation of nickel and rare earths elements, the enhancement of dynamic behaviour (rapid start-up, shut-down, thermal, load and redox cycles) for interfacing with intermittent renewable power sources and implementation of poly-generation systems where electricity, and renewable fuels, from CO_2 recycling, can be alternatively produced.

Another relevant aspect is the technology scaling-up. For micro-distributed generation in residential buildings, solid oxide fuel cells (SOFC)-based combined heat and power systems (CHP) can provide a convenient solution on a wide scale. However, for centralised processes, much larger SOEC/SOFC systems (MW scale) are required to assist the transport sector in turning from fossil fuels to synthetic fuels based on renewable electrical energy and re-use of CO_2.

Socio-economic aspects related to these new technologies are discussed in the following part.

The decarbonisation of the current economies or the wide scale use of low-carbon processes in general are clearly expected to primarily involve the energy sector. Both energy consumption activities and the way how energy is produced and made available are part of this upcoming "revolution". We are progressively moving from a centralized to a local energy supply chain, to self-consumption, to self-production, to the creation of ever more complex but manageable systems through new technologies, products and solutions available today and planned for the next future. Thus, it is important to look carefully at the significant constraints and barriers related to the development of such new technologies.

In addition to the need of an economic viability for these sustainable processes, it has also been pointed out how the lack of education towards the new technologies and social awareness as well as the negative public perception linked to a long-standing mistrust on how to replace coal and oil industries have limited the elaboration of deployment policies.

Socio-economic analyses are thus strongly required to address some key-aspects related to the new technology developments:

- ✓ The economic costs to implement the new solutions appear still very high, compared to the expected returns. Thus, it is necessary to think about how they could be reduced over time, thanks to the learning curve that manifests itself with the growth of applications. On the other hand, the significant benefits, in terms of environment, health, reduction of global and local pollution, enhancement of life-quality, should be taken into account in every socio-economic analysis and a precise estimation needs to be carried out to show, in a holistic context, the effective impact of the new technologies.

- ✓ In relation to this, incentives and public support policies appear appropriate especially in relation to a long-term strategic vision needed to address the huge resources deployed. However, also in the economy and financing context, it appears clear that a different approach is needed; in particular, innovative financing instruments for these technologies would be appropriate.

- ✓ Finance should increasingly focus on technological solutions in the context of the climate change challenge. Specific tools appear necessary for the various financial actors that are involved in the development of entrepreneurial initiatives related to CO_2 recycling technologies and hydrogen, especially in the early years, to share a business risk portfolio and to deal cumulatively with uncertainties.

- ✓ In this context, it is necessary to develop the ability to *do system* with participation in networks, clusters and technological platforms, not only on a national, but also on a European and Worldwide scale, in order to develop technological solutions that take into account the socio-economic issues in an integrated way.

- ✓ The theme of cultural awareness and social acceptability regarding potentially implementable solutions also appears as a crucial element. It is thus important to develop tools to increase awareness transforming potential constraints into opportunities.

- ✓ The technological innovations that need to be widely implemented in the economic and energy system in order to face the challenge of climate change must make users increasingly aware of the choices they will have to make, adapting their lifestyles to dynamic consumption patterns that will allow to qualify increasingly what is today called the *demand response*. It is important to develop economic models for distributed energy prosumers capable of storing and generating energy along with consuming it. A proper prosumer model can have a strong impact on environmental awareness and on how energy is valued with regard to an optimal management of a distributed energy system.

3.2 Focus on innovative routes for Hydrogen and Carbon Dioxide Management and Valorisation

The introductory session has made it possible to start defining the context of green hydrogen generation and use, CO_2 recycling and related socio-economic aspects. Appropriate pathways related to the achievement of long-term solutions were anticipated. These themes were largely debated by the successive speeches with the aim of proposing alternative or innovative solutions to tackle specific issues.

The main themes under discussion concerned innovative routes for hydrogen and carbon dioxide management and valorisation with an analysis of relevant scenarios for the energy system by 2050.

The point of view of the industry involved in the development of advanced energy technologies is to start considering the scale of the problem (climate change and global and local pollution extent).
Accordingly, the current rate of 30 Gt of CO_2 emissions per annum implies that the global temperature will increase of more than 3-4 °C by the end of the century. Evidence that dirty air is killing about a million of people in Europe every year requires the urgent phasing out of fossil fuel burning. The scale of the problem is so large that technologies have to be financially viable (competitive) to make a difference.
Achieving the transition towards a new and clean energy system will require hydrogen deployment on a large scale. Focusing only on the implementation of energy grids is not practical in terms of infrastructure upgrade and it would miss the complete decarbonisation objective. Running the gas grid and liquid fuel market in parallel to the electricity grid in the future is still needed.

Considering that 10^7 tons of hydrogen are produced per year in US (1/6 of annual production) for industrial applications, if that hydrogen was "green hydrogen" produced by electrolysis, 10^5 GW of electrolysis plants would be required. If hydrogen, beside industry, is used for mobility applications and residential uses, the expected impact would be much larger. Recent estimates of the European Commission indicate that there is a potential for generating approximately 2,250 terawatt hours (TWh) of hydrogen in Europe by 2050, representing roughly a quarter of EU's total energy demand. Thus, low cost solutions are of primary importance.

If the focus is on mobility, where hydrogen should be widely employed in relation to fuel cells vehicles, it appears that there is a separation between refuelling and renewable generation of hydrogen. For refuelling, the large tanks need to be full whereas for renewable generation, the tanks need to be empty. In addition, a large amount of energy is needed to maintain the systems when they are not generating hydrogen. Most of refuelling stations are connected to electrolysers that use electricity from a grid sharing now only a moderate fraction of renewable energy. The conclusion is that, at present, 32 kg of CO_2 are emitted per 100 km operation of a hydrogen FC vehicle, whereas we completely need green hydrogen to have a favourable impact on the environment. The small number of actual FC vehicles means the systems are not working most of the time and therefore these refuelling stations are currently uneconomic. The envisaged solution is to develop centralized green hydrogen generation delivering hydrogen as needed for refuelling stations in order to maximize the utilization of assets and enhance economic viability. This vision shows that the approach of distributed energy generation could not be the only solution for the future energy system and centralized processes will still represent an important option to proceed more rapidly towards the energy transition.

In this regard, the research directions that can be prioritized are mainly to simplify the balance of plants (BOPs) for centralized processes, to match energy generation to hydrogen generation, to implement heat storage, understanding weather patterns so as to be able to know when to turn them on or off, and, where solar hydrogen is feasible, to use heat to compress hydrogen as an alternative to electrical compression. Beside these aspects, industries still consider a strong decrease of renewable energy costs as the main drive to reduce hydrogen cost. It is also important to operate in a different way e.g. using smart systems to follow load, curtailment funding for renewables, and most of all reducing the need for energy storage by developing a smart energy system. The need to widely use the hydrogen produced as a waste product of chlor-alkali electrochemical plants plays a dominant role. In this context, the technology challenge is the development of poison-resistant catalysts for electrochemical hydrogen compression. This would make the hydrogen from chlor-alkali plants a saleable product. In general, economically viable hydrogen would lower CO_2 emissions and stimulate the hydrogen economy.

Changing our perception together with some short- term innovations can make hydrogen commercially viable and a short-term solution. If economics stands up, then “research money” will not be put into demonstrations, leaving more for fundamental research. That is vital to develop game changer solutions to avoid precious metal catalysts, produce cheap membranes, and use efficient ways for hydrogen compression or develop effective high energy density hydrogen carriers.

Combining renewable energy (e.g. solar and wind), water and CO_2 to produce liquid or gaseous fuels with a very low carbon intensity is also expected to produce a step-change since this will allow to achieve up to 83% reduction in GHG emissions. The approach of renewable fuels appears to provide better or complementary potentialities compared to other renewable energy storing tools such as pumped hydro, compressed air, fly wheels and batteries. In particular, pumped hydro-storage is characterized by low expansion potential. Compressed air storage appears limited in terms of availability of storage sites e.g. salt caverns, storage sites far from energy sources and relatively large volume of storage as well as difficulties in the implementation of this concept on a larger scale. An expensive scale-up characterises flywheels. As it is well known, batteries for storage of renewable energy are characterised by low energy density, degradation issues and high costs in terms of €/MWh.

The general approach for renewable organic fuels is to consider CO_2 as a resource and not as waste. Carbon dioxide can be obtained from several sources but primarily, it would be important to recycle the flue gas from the industries (e.g., cement, iron & steel, refineries, thermoelectrical plants).

CO_2 can be obtained from biogas in the bio-methane upgrading. In particular, biogas from anaerobic digestion contains ≈30-35 % of CO_2 that can be removed through physical and chemical adsorption, pressure swing adsorption, membrane or cryogenic separation.

In principle, CO_2 can be also extracted from air, but being relatively diluted in the atmosphere, related capture processes are very expensive and do not represent a mature technology yet. In particular, CO_2 recovery in these processes is an energy intensive process.

CO_2 hydrogenation pathways (Fig. 3) are wide and complex, requiring different approaches, various steps and a range of catalyst formulations. Some of these processes are far from being sufficiently developed and their potentialities are still not completely known. Low productivity is a challenge: proposed systems so far only produce μmoles/min of CO, while commercial processes convert thousands of mol/min per cell. Currently, only CO, formic acid (HCOOH) and ethylene have been obtained with a relevant productivity to be scaled up. Instead, higher energy density products (ethanol, methanol, propanol, etc) have not reached high selectivity and conversion efficiencies. Therefore, there are still significant challenges for liquid fuels production. It is still very difficult to reach a high selectivity for a single product (e.g. CH_3OH, ethanol, propanol, etc.) due to the multiple-steps of CO_2 reduction reaction. Advanced and low-cost catalyst designs are strongly required in this field. In particular, it would be appropriate to develop a multidisciplinary approach for catalyst engineering, electrocatalytic reactor and process conditions.

Despite the above-mentioned issues, the high potential of the CO_2 hydrogenation process suggests that significant research efforts (and the corresponding resources) should be addressed to this direction. In particular, cost estimates indicate that assuming as an optimistic scenario a pure CO_2 price of $30/tonne, faradaic efficiency (FE) of 90%, current density of 500 mA/cm^2, electrolyser cost of $ 300/kW, plant lifetime of 30 years, renewable electricity cost equal to 4 cents/kWh, energy conversion efficiency larger than 70%, electrocatalytic CO_2 conversion could be cost-competitive with fossil fuels derived sources, making sustainable fuels production profitable. Application of carbon tax to industries can accelerate the development of technologies based on renewables for CO_2 utilisation. Thus, the aim should be to simultaneously achieve these targets in a process plant and, of course, this can be more appropriate in a context of centralised production.

The recycling of carbon dioxide in the cement industry to produce added-value additives ($CaCO_3$) or to synthesise polymers are examples of parallel processes for CO_2 recycling in particular for CO_2 sequestration (carbon negative process), representing a step towards a CO_2 circular economy

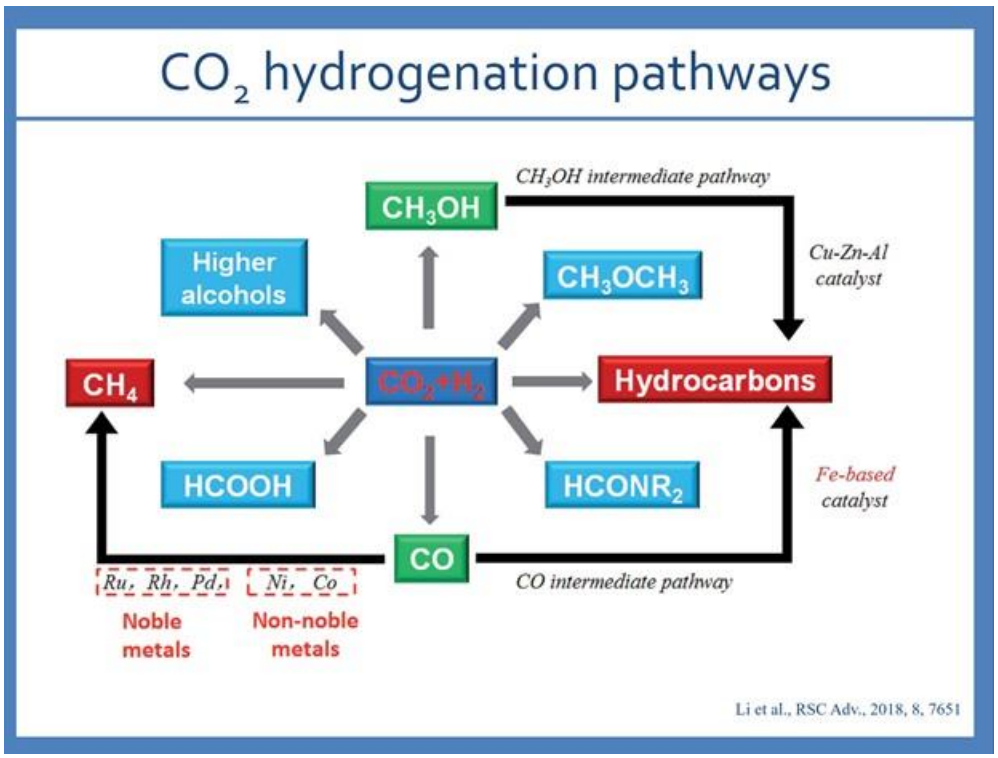

Figure 3. CO_2 hydrogenation pathways

Several experts participating in this workshop, pointed out that high temperature (800 °C) solid oxide electrolysis (also treated in the previous chapter) is one of the most advanced and promising approaches, much more reliable and practical than the above-mentioned low and intermediate hydrogenation pathways. SOEC needs to be combined to a methanation process to produce synthetic renewable methane. Dynamic behaviour or intermittent operation of the power to gas system is agreed to represent one of the key challenges and it would require specific research efforts to be properly addressed. Using this approach, the levelized product cost for the synthetic renewable natural gas by 2050 could be highly competitive with high volumetric and gravimetric energy density in line with several other C-based energy vectors. Although alternative catalytic routes for CO_2 conversion to methanol, DME, olefins and aromatics are today characterised by low conversion efficiency and modest selectivity, thereby requiring high pressure and internal recycles, they can represent the key transformations to introduce renewable energy in the transportation and chemical sector. This could pave the way for a massive decarbonisation of these sectors, an unavoidable step to meet CO_2 emissions' mitigation, although breakthroughs in terms of materials and process development are definitely required in these fields to achieve this target.

Considering that global solar irradiation provides about $174\cdot 10^3$ TWy of energy and about 70% of this (~$121\cdot10^3$ TWy) is absorbed by the Earth (30% is reflected back to space), this is by far the largest energy resource. It is largely prevailing if compared, as annual potential, to the retrievable energy from finite reserves (fossil fuels and nuclear energy) and other sources (most of them still deriving, more or less directly, from solar energy) such as wind energy 25-70 TWy, biomasses (2-6TWy), hydro (3-4 TWy), geothermal (0.2-0.3 TWy), wave (0.2-2 TWy).

The primary energy use by human consumption is 18 TWy and it will approach 23 TWy at 2040. Thus, proper exploitation of the large potential of solar energy is mandatory for the future energy system. However, this energy is intermittent; thus, the strong limitations related to the upgrade of the electricity grid infrastructure will require the energy storage at scale. The combination of photovoltaic plants (and windmills) with electrolysers offers a solution for the long term as well; however, this approach is still characterised by high costs, system complexity etc. Whereas, using a process capable of transforming solar energy into hydrogen in a single step by using photo-electrolysis cells would represent a cheap and reliable approach especially for distributed generation. However, technological development in this field is still ongoing and moreover, also in this case, costs and system complexity increase almost exponentially with the increase of solar-to-hydrogen efficiency. This approach is still considered valid in the long term because economic viability could be achieved through a game-changer approach in materials science (semiconductors, electro-catalysts, polymers, use of CRM-free materials) , which is still possible given that technological maturity has not yet been reached. Costs analysis have shown a strong potential for this technology in reducing hydrogen cost to less than 1 Euro/kg (current cost for green hydrogen production is about 10 Euro/kg). Moreover, the photo-electrolysis technology is characterised by a very low environmental footprint.

Beside chemical processes, also biological routes can be quite effective for recycling CO_2 into valuable fuels. A well-known approach is based on microalgae processes for fuel production in a carbon neutral cycle. Photosynthesis can contribute in reducing the GHG emissions and thus the level of CO_2 in the atmosphere. In particular, photosynthesis produces an uptake of CO_2 by plants of about -120 PgC y^{-1} (petagrams carbon per year); however, respiration and decomposition produce emissions by +116.4 PgC y^{-1}. Accordingly, the amount of CO_2 sequestrated in biological processes should correspond approximately to 3.6 PgC y^{-1} (as absolute value). Unfortunately, this is largely compensated by anthropogenic activities. For example, C-emission from fossil fuels corresponds to +9 PgC y^{-1}, cement production contributes for +0.4 PgC y^{-1} and land use change by +1.3 PgC y^{-1}.

Pyrolysis and pyro-gasification of biomass can indeed allow a modification of the carbon cycle by including a carbon-negative step related to the production of biochar while providing a substrate (syngas or tar) for energy production in a carbon neutral cycle. The overall process is carbon negative because of the amount of CO_2 sequestrated as biochar (Fig. 4).

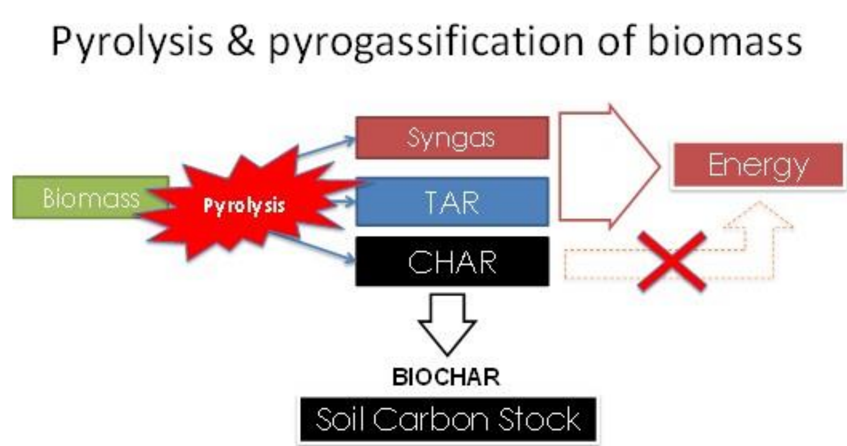

Figure 4 Biochar and energy production from biomass

Biochar is a solid by-product of biomass pyrolysis, specifically produced for applications into soil for agronomic or environmental purposes. In particular, biochar is used as a plant growth enhancing soil amendment. It is a natural soil ingredient, which is found in soils in most parts of the world improving the microbial habitat. Moisture and nutrient retention improvements are evident as a result of biochar's ability to absorb both moisture and nutrients and to retain them longer. Biochar can be also obtained from various feedstocks such as biomass energy crops, agriculture and animal wastes, compost, kitchen waste plastic, food, sewage sludge etc. Pyrolysis or gasification processes are used to transform these feedstocks into biochar and proper substrates (syngas, hydrocarbons) for energy production. Depending on the feedstock and the final application of the energy conversion system (production of heat or electricity; internal combustion or solid oxide fuel cells), pyrolysis processes are modulated into fast or slow pyrolysis, anhydrous or steam assisted processes, fed with oxygen-free or oxygen-containing streams.

The positive effect of biochar on soil amendment is due to a series of features, such as neutral / slightly alkaline pH, porosity generation to retain water, water filtration and adsorption of contaminants (gas, liquid or solid) and cation exchange. All these effects produce robust benefits to plant growth. Biochar has a high content of stable carbon, typically 50–85%, which resists decaying and it remains in soils for a long time producing durable benefits. In general, a process based on biochar production can avoid up to 25 % of CO_2 emissions (more properly it allows 25% of CO_2 sequestration, the remaining carbon content can contribute to a carbon-neutral energy cycle). According to some recent estimates reported by the experts, about 1.8 Pg CO_2 per year reduction corresponding to 12% of anthropogenic emissions can be achieved without endangering food security, habitat or soil conservation. The relevant benefits associated to the use of biochar are essentially its high porosity and the charged surface producing an increased soil water content, and a decrease of nutrients leaching resulting in a relevant increase in yield and productivity as a consequence of the enhanced soil fertility. However, different feedstock and processes mean different biochar characteristics, varying in terms of carbon content, pH, ashes etc., and not always, the produced biochar is suitable for soil applications. In the future, this will require biochar certification, traceability of biomass, appropriate land use etc. Other possible negative aspects are related to the change of the reflectivity of the soil and the fine powder released during biochar deposition over the soil. Thus, the use of biochar should be governed by a proper legislation and guidelines. A risk of contamination of biochar exists (polyaromatic hydrocarbons, heavy metals, dioxins) when contaminated feedstocks are used and/or the process conditions used to make the biochar are such that temperatures are higher than 500 °C. Moreover, soil loss by erosion can be an issue during top dressing biochar to soils. This occurs by wind and/or water transport of small, light biochar particles. Proper incorporation into a soil blend is necessary.

However, despite some drawbacks, biochar-based processes can result in a quantifiable, sustainable and efficient strategy for climate change mitigation, able to address the Water-Energy-Food Nexus in a scalable manner. Efficacy and sustainability are ensured when biomass traceability and characterization are applied and its use is in line with proper micro-climatic conditions and agronomic practices. More research is needed to fully map biochar life cycle and its effects on soil organic matter. Biochar effects on the nitrogen cycle depend on many factors which have not been fully explored yet and the ability to sequester carbon in soils amended with biochar is still largely unquantified. Distribution and availability of contaminants that are adsorbed by biochar require further research to assess the rate of bioavailability and toxicity of the contaminant depending on the biochar type, application rates, feedstock, production conditions, soil types, and environmental conditions. Other specific research topics regard a better understanding of the rate of decomposition of biochar as a function of agricultural management, its effects on larger soil organisms etc. Significant research efforts are needed to better understand biochar behaviour and the holistic approach appears very appropriate in this context.

3.3 Analysis of relevant contexts for the energy system by 2050: challenges, approaches and policy aspects

The focus of this session was on global energy storage policy and implementation of economic energy policy objectives implementation. In parallel, the role of one of the currently most pursued approaches for renewable energy storage was discussed, i.e. electrochemical energy storage through batteries and supercapacitors.

Batteries and supercapacitors are not necessarily considered as competitors of sustainable fuels. These systems are characterised by different levels of energy density, system complexity, response time and dynamic behaviour. Such characteristics make, in some cases, batteries or supercapacitors the preferred choice for relevant applications, e.g. management of electric energy spikes in grid service, energy source for the electrical power train of city cars etc. On the other hand, renewable fuels appear more appropriate for seasonal storage and as a solution for heavy-duty vehicles such as buses and trucks, for trains, ships and long-driving range cars. The implementation of hydrogen technologies will complement the use of batteries in the energy storage system. In particular, it will avoid a large upgrade of the electricity grid that appears not feasible from both economic and practical point of views. Moreover, it will avoid the congestion of the electricity grid when the expected large diffusion of electric cars will require simultaneous recharging of many cars. Hydrogen refuelling takes 3-5 minutes and it is not particularly different from the present refuelling of an internal combustion engine-based vehicle, whereas a battery of an electric vehicle requires a recharging time of about one order of magnitude longer. Hydrogen can also allow replacing diesel trains (a relevant number of railways is not electrified) with fuel cells-based electric trains. This will not have any impact on the catenary infrastructure and will avoid modification of the landscape while in the case of ships it can avoid the local pollution in tourist-ports etc.

For new technologies, the development of an appropriate infrastructure for energy generation and distribution will be crucial. For example, it is envisaged that high-voltage direct current (HVDC) transmission technology, as opposed to the alternating current power lines, would allow to more properly integrate renewable energy into the energy system. Expanding HVDC lines, however, will not only require new investments, but also supportive policies to favour their construction. According to some recent IEA report (2018), relevant changes in energy technologies, markets, and policies will affect the energy system vulnerabilities. In this regard, it has been discussed that a resilient energy supply is increasingly important as telecommunications, transportation, and other critical systems are more interconnected than ever. Accordingly, specific actions should be taken to enhance energy security, reliability, and resilience with regard to the new energy technologies. This progress should occur through improved data collection, modelling, and analysis to support resilience planning, private and public–private partnerships and both development and deployment of new, innovative energy technologies to adapt energy assets to extreme weather hazards. Although barriers exist, opportunities remain to accelerate the pace, scale, and scope of investments in energy systems resilience. The path to zero carbon context by 2050 (or before) should thus include all the energy mix and specifically a portfolio of renewable energy solutions including storage/batteries, sustainable fuels, and demand vs. generation modelling. Thus, renewable electricity and green hydrogen-fed (generated from photovoltaic plants and wind mills) fuel cells should be complemented by biofuels, geothermal, hydro, wave, municipal solid waste recycling etc. Priority is to focus on new technology/innovations that will bring a strong reduction in GHG emissions for household and transportation uses. Social aspects, economies of scale, life cycle analysis must all play leading roles in our way of thinking. These analyses need to “monetize” social factors such as health, climate change mitigation etc., include alternative routes based on biological pathways such as microalgae and biochar processes for feed, food, and fuel.

In general, the sustainable development goals include, among other aspects, the need to provide universal access to affordable, reliable and modern energy services, enhance international cooperation to facilitate access and promote investment in clean energy technology and infrastructure. Moreover, support for sustainable energy services for developing countries and, in particular, least developed countries should be provided. With regard to the infrastructure, the goals are to develop a reliable, sustainable and resilient energy framework, including regional and trans-border infrastructures to support economic development and human well-being, with a focus on affordable and equitable access for all.

For the climate, improving education, awareness-raising, human and institutional capacity on climate change mitigation, especially in relation to the energy processes, appears of primary importance. Moreover, it is also important to promote mechanisms to raise capacity for effective climate change-related planning and management in all communities.

The roadmap for the deployment of hydrogen technologies has already started in Europe and other developed countries by the formation of important dedicated platforms such as the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), Mission Innovation: Challenge 8, IPHE, EERA FCH etc. However, it has been recognised that to turn the vision of hydrogen economy into reality, more research, large-scale demonstrations and deployment projects are needed. Although good progress has been achieved in the last decade, the situation is still not substantially changed. While concerted efforts for regulations and standards, that are appropriate for the future development of the hydrogen economy, have been slowly implemented. It is clearly evident that the required step-change has not yet been achieved and incremental research has just allowed for a very slow progress, making the competition hard with the well-established and relatively cheap fossil fuel economy. In particular, the technologies for hydrogen production and conversion to power are just emerging technologies, i.e. they have to compete with technologies that have been on the market for half or even more than one century. That is why hydrogen technologies will still need logistic and financial support for some decades, combined with local efforts while progressing in terms of technological, legislative and educational aspects. The expertise and public awareness should cover all countries. Efforts should concern technological development in the context of the application environment of a populated eco-system – town, region etc. with all the economic specifics of the territory (industrial, touristic, cultural etc.).

Accelerating the development of the technology base towards market deployment of FCH technologies and search for innovative, disruptive or breakthrough solutions addressing the specific gaps that these technologies still have, should run in parallel and be supported by proper resources. Aligning the R&D activities of individual research organization to the global priorities is also very important to create a “critical mass” effect. Establishing a worldwide effective joint programming framework to support the coordination of national research programs, also in the case of developing countries, would also be very appropriate.

4. Main outcomes

An interdisciplinary brainstorming was organised to debate about the different visions for the future of the energy system both in general terms and in relation to the specific topics of the workshops. The participants were asked to speculate on the major technological breakthroughs necessary to achieve the ideal scenarios.

The interdisciplinary brainstorming treated, in particular, specific challenges, approaches and policy aspects. This was structured in two parallel sessions through an open and guided discussion in order to address all the treated themes in a systematic approach.

The main points of discussion were properly organised to address the following questions:

- ✓ How to address challenges and priorities in the field of energy storage?
- ✓ Which technologies and processes can better support energy transition?
- ✓ Which are the most urgent aspects to be addressed?
- ✓ Which topics should be considered as a priority? Or which are the technologies worth supporting in the future?
- ✓ What could the impact of the proposed technologies in addressing sustainable development and future energy needs be, and how can these benefit the environment?

Relevant discussions involved both general and specific aspects such as the:

- ✓ Scenarios for both the transition period and the complete decarbonisation by 2050.
- ✓ Common denominators for hydrogen technologies and CO_2 management and valorisation
- ✓ Socio-economic challenges of a future economy based on "Renewable Fuels".

The rapporteurs collected and aggregated the main points of discussion in relation to the workshop objectives. These were successively reported to all participants in order to individuate commonalities and diversities for the different point of views.

The main outcomes of the interdisciplinary brainstorming are discussed in the following.

4.1 General aspects

Climate change mitigation requires big changes in the energy, industry, residential and transportation systems. Regarding the energy system, large storage capacity is fundamental. Energy storage is a key aspect to drive growth to renewable energy generation. Moreover, all processes should be accompanied by significant progress in terms of energy efficiency in order to contribute to decrease atmospheric CO_2 concentration.

The holistic approach is at the base of the Foresight methodology. This should be applied in all contexts when considering new energy technologies. Such approach is absolutely necessary to understand how to radically transform the present energy system into a coherent low-carbon, resource-efficient and sustainable economy. In this regard, energy should be connected to other important issues such as access to food and water. The energy system should be flexible with respect to the demand and supply. Improvement of infrastructures must go together with energy storage devices development and should be inexpensive and based on easy-to-maintain storage systems.

There are several technologies available for the next-generation energy system. At the present, no leading technology is envisaged. More properly, it appears that a portfolio of solutions will have to be developed, including considerations about economics, impacts and the situation of each single territory.

It is widely accepted that strong efforts must be addressed to unlock the potential of energy storage and conversion of electricity to alternative energy carriers. In particular, renewable fuels such as green hydrogen, organic fuels obtained from the recycling of CO_2 using the excess of renewable energy, syngas obtained from bio-mass pyrolysis with partial CO_2 sequestration as biochar represent important and valuable options to assist the energy transition. In the new energy system, CO_2 should be progressively considered as a resource and not as a waste enabling to move towards a sustainable future.

4.2 Technology considerations

Consensus was achieved on focusing efforts on power-to-fuel processes with particular preference given to hydrogen generation by advanced low temperature water electrolysers and high temperature CO_2 co-electrolysis in solid oxide systems, coupled with a down-stream methanation step to produce synthetic methane. Considering electrolysis as one of the most important storage technologies of choice, there are two pathways to consider: the short-term one, where we produce advances in the available technologies, and a more advanced solution, where we aim at developing new technologies with a long-term perspective. To some extent, these routes could be developed at the same time. In the long term, direct electrochemical conversion of CO_2 to more complex organic chemicals is considered as a challenging but feasible approach.

Economics related to renewable fuel production from the excess of electricity should be considered in the context of a long-term vision. This relates to a wide-scale penetration (approaching 100%) by 2050 of distributed renewable energy production from variable sources, such as wind and sun. The consequent variations of supply can make the cost of renewable electrical energy very cheap, or even negative, in some periods of time, thus favouring excess energy storage as renewable fuels. The possibility to have a market for CO_2 is thus related just to the problem of finding a good use for it. Proper incentives and a clear regulatory framework for the new technologies can support this, in particular for the production of liquid fuels from renewable energy.

New energy carriers should be designed to address the need for daily and seasonal energy storage in contrast to batteries and supercapacitors, characterised by intrinsically lower energy density and usually employed to manage issues related with intermittency on a shorter time scale (peak shaving).

In this regard, renewable fuels should be not viewed as competitors for batteries or other electrochemical energy storage devices, but rather as a complementary option to further support sustainable mobility and avoid congestion of the electricity grid. The complementary fields of application for renewable fuels in sustainable mobility are thus dealing with the wide scale-deployment of heavy-duty vehicles such as long-driving range cars, buses, trucks, trains, ships. Renewable fuels also offer a sustainable option for residential building by fuelling CHP units and providing high-grade heat for industrial purposes. These are the fields where batteries are not expected to find relevant applications.

Moreover, renewable fuels should represent an important source for balancing the energy system, together with other options, by feeding the produced hydrogen or synthetic methane into the natural gas grid in order to progressive decarbonise the gas network.

Water splitting using sunlight was also agreed to be one of the most promising technologies on the long term, but substantial scientific and technological developments will be required to make it an economically viable option. Bio-char was indicated as one of the most effective solutions to sequester CO_2 (carbon-negative cycle) on a global scale while acting as a plant growth enhancing soil remediation. Other relevant biological routes were identified as useful options to contribute to the sustainability goals; in particular, 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.

4.3 Specific challenges

It was widely agreed among the participants that specific sectors such as hydrogen and fuel cells, CO_2 electroreduction and conversion into valuable fuels such as synthetic methane and liquid organic fuels need a well-defined, targeted long-term breakthrough research strategy. One of the general challenges is to produce step-changes and breakthrough innovations for the overall sustainable energy cycle, from the renewable power source to the final use and specifically on green hydrogen or renewable organic fuel generation, on storage, transport, conversion and consumption.

With regard to hydrogen and fuel cell technologies, being these devices characterised by high energy density and low environmental issues, their relevant impact on the next generation energy system is largely expected. However, this can only occur through costs reduction, a transition to non-noble metal electro-catalysts (Pt and Ir are currently used in the electrodes) and novel ion conducting membranes, covering a wide range of operating temperatures. As discussed in the specific sessions, the scale of the problem is so big that technologies have to be financially viable (competitive) to make a difference.
Technology breakthroughs in the field of fuel cells, electrolysers and CO_2 conversion are still identified as a key-aspect to more rapidly proceed towards the future energy system and to urgently address climate change and global warming. On the other hand, for the biochar route, the relevant challenges that require proper research efforts are the traceability of biomass, appropriate land use, addressing fine powder release into the environment, risk of contamination and soil loss by erosion, and, in general, a better understanding of the biochar behaviour.

Beside the required improvements in terms of cycle, processes and balance of plant optimisation, another crosscutting theme is to promote the research on functional materials, preferably critical raw materials-free systems, in particular nanostructured and smart materials obtained in proper amounts by cost-effective processes. Advances in terms of processes and materials are the key enablers to drive the energy transition.

Information and communication technologies (ICT) can strongly assist the energy transition. In this regard, decision-making should be based on solid data. Thus, having a correct picture of the energy sector is very important. This will be possible only by collecting very precise data coming from the system, which is already possible but only to a certain extent (e.g. using “smart” power meters). This activity should be implemented on a wider scale and the data should be elaborated and made available to the public. Such approach will help people understand the current situation and receive better information about their choices. For example, it is helpful to inform people where the energy they are using comes from, so that they could make decisions based on that. Experience has shown that public participation to challenges can be very successful.

Introducing something radically new (leap frogging) could also be a suitable action for developing countries, where a perfectly reliable energy system does not exist. In general, strong involvement of renewables is very appropriate in developing countries provided that a solution is found that is consistent with each country specific situation in the context of a “circular economy” approach. This will allow producing cleaner energy while providing enough access to energy for their development. Every country should be given the chance to be part of the global energy change.

4.4 Cross-cutting aspects

In general, there are several opportunities, and we need a portfolio of options to address future challenges. Priority should be assigned based on proper guidelines such as economic viability, equality and environmental compatibility. It is necessary to find a way to satisfy these fundamental needs with a range of technologies, whose combination can be different from country to country. Tools such as life-cycle analysis (LCA) can be very effective to help making decisions. It is thus important to employ metrics and frameworks regarding equality and quality of life, besides addressing the issues of climate changes.

Both academic and industry-driven research can result in significant advances in energy technologies. However, this may not be sufficient. These will need to be supported by proper business models and, government incentives appear necessary to boost innovation in the first phase. Active policies are especially needed to force people to give something up to facilitate change. First implementation of the new technologies in a limited context such as small islands (e.g. hydrogen valleys, hydrogen corridors etc.) can also provide useful indications for a wide scale deployment.

Promoting education and social awareness towards the new technologies is also fundamental to support the energy transition. Achieving a wide social acceptability of the new technologies is a required step while training end users in the field of energy is very appropriate to adapt their approaches to dynamic consumption patterns.

4.5 Specific technology innovations

With regard to some of the discussed technologies, a specific exercise was carried out to analyse the required innovations. In this regard, specific technology challenges were considered together with the identified long-term solutions and related impacts. This was done in relation to the proposed road-maps and the analysis of associated risks. This exercise is summarized in Table 1 below.

Table 1 Specific technology innovations

Specific Technology Challenge	**Proposed Long Term Solution**	**Roadmap**	**Associated Risks/Issues**	**Impacts**
Hydrogen handling and storage at high pressure on a wide scale for automotive and stationary applications	Centralised processes replacing compressed H_2 with liquid hydrogen carriers	*-Enhance efficiency for reversible hydrogen uptake and release*	-Cost; -Loss of overall energy efficiency; -Side reactions;	*High: the approach will allow to use present infrastructure for liquid fuels*

	including hydrogen refuelling stations (HRS)	*-Select high energy density hydrogen carriers (e.g. NH_3, DME, alcohols)*	-Environmental acceptability	*for large scale shipping*
Replacing precious metal catalysts used in some H_2 technologies (e.g. PEM electrolysers and automotive fuel cells)	Turn into non – PGM catalysts	*- Novel effective PGM-free and metal-free catalysts;* *-Catalyst nano-structuring* *- Alternative processes to bypass demanding reactions including 2e- ORR (peroxide production)*	Lower efficiency / performance	*High: large scale technology deployment*
Reduce energy intensive processes to produce hydrogen and sustainable fuels	-Co-generation of value-added chemicals and electricity in reversible fuel cells. - Co-electrolysis for chemical and/or hydrogen production in electrolysers - Develop selective catalysts	*-Distributed peroxide generation, e.g., for water purification in acidic and alkaline electrolysers* *-Combining electricity and fuel generation* *-Using depolarised processes to avoid energy intensive reactions like oxygen evolution e.g. oxidation of bio-fuels*	Lower stability	*Energy saving*

New catalysts for water electrolysis and CO_2 conversion in co-electrolysis and catalytic processes	Development of selective catalysts more resistant to poisoning	*-Non PGM catalysts* *-Novel materials and structures*	Economics: higher costs for catalysts and purification systems	*-Enhanced use of CO_2 conversion processes* *-Process simplification* *-Lower cost*
-Novel materials of construction for hydrogen technologies	-Novel materials for stacks; -Coatings of existing pipelines for hydrogen fed gas grid	*-Replacing Titanium with cost-effective steel protected by suitable and cheap coatings;* *-Modification of existing pipelines with Ni coatings to avoid hydrogen embrittlement of steel*	-Lower stability - Infrastructure investments	*- Decrease of capital costs* *-Increase of the hydrogen concentration in the gas grid*
-Economics for capturing CO_2 diluted in the atmosphere (450 ppm) *-Low cost and less energy intensive purification of CO_2 from centralised production*	Develop suitable and convenient absorption and purification processes	*-Absorption using base-type filters (ammines-type etc.)* *-Membrane processes*	-Reversibility -Finding economic solutions -Removal of contaminants e.g. sulphur compounds	*Strong benefits for the environment*
Financial viability:	Long-term investments	*- Business cases* *- Modelling*	Return of investment	*Promoting large scale deployment of*

		- Government incentives in the first phase		*the new technologies*
Centralised vs. distributed generation. *Flexibility of chemical plants vs. electrolysers*	Modelling	*-Simplify BoP* *-Match demand and production* *-Weather patterns* *-Smart systems* *-Combine bio-gas and renewables*	Investment costs	*Promoting large scale deployment of the new technologies*
-CO_2 sequestration (carbon negative cycle) *-Alternative use of CO_2*	CO_2 conversion into solid substances Photosynthesis	*-Nanoparticles of $CaCO_3$ for new cement production with enhanced properties;* *-Biochar;* *-Growth of new plants, microalgae*	-Investment costs -Light absorption -Particulates	*Strong impact on fixing diluted CO_2 from the atmosphere*
Photo-electrolytic water splitting and CO_2 conversion	Developing cheap and efficient materials and technologies	*-Combining cheap semiconductors and photo-catalysts* *-Nanostructured materials*	-Low efficiency -Insufficient understanding of CO_2 conversion mechanisms	*Strong reduction in hydrogen and renewable fuels production costs*

Develop enhanced ICT technologies for energy management	Wide use of ICT to assist the energy transition	*Shift from smart management of supply to smart management of demand (ICT technologies)*	-Investment costs	*-Energy saving;* *-Better efficiency* *-Reliability of supply*

5. Conclusions and recommendations

The requirements for the next energy system were discussed in relation to environmental issues and human needs on the long-term according to the aims of the Foresight project.

A general vision resulting from this workshop possibly sees the future energy system partially shifting 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, and cost effective, and characterised by an extremely low environmental impact. This scenario will involve all energy sectors i.e. conversion, storage and distribution. However, centralised processes will coexist with distributed generation especially in those contexts where economy of scale is relevant.

Long-term society needs include sustainable processes, energy security, independence and saving, low environmental impact, strong reduction of greenhouse gas emissions, widely available cost-effective technologies. New research directions should address these goals but will require an interdisciplinary approach including economic models for the possible future scenarios, health considerations, and an analysis of their impact on environment and society.

Electricity as an energy carrier will still be key in a carbon neutral energy system, as it enables an expanded use of renewables in a diversity of sectors of energy consumption, and improves overall efficiency of the energy system because of the intrinsic characteristics of many electric technologies and because it supports digitalization and related benefits.

The long-term vision of the energy system that has emerged from this workshop indicates the deployment of renewable gas and liquid fuel networks as complementary and strongly interconnected to the electricity grid and the electrochemical energy storage, while parallel innovative photosynthetic approaches for CO_2 sequestration can also contribute to a significant extent to address environmental issues.

Specific issues and necessary step-changes in relation to energy storage through renewable fuels were analysed in a broad sense by covering the most relevant subjects such as electrolysis, co-electrolysis, photo-electrolysis, hydrogen and fuel cells, power to gas and liquid fuels, CO_2 recycling, and distributed energy generation. Processes addressing sequestration of CO_2 (carbon-negative cycle) through biological pathways (such as biochar and microalgae) were analysed as possible parallel or alternative routes to renewable fuel production. Data treatment for energy storage using renewable fuels as well as socio-economic, financial and environmental aspects concerning newly emerging technologies were additional relevant topics discussed at the workshop.

Following an overview of all planned solutions and related challenges, the focus shifted towards a prioritization of future research directions based on long-term society needs. In this regard, the participants have underlined all possible positive outcomes and the possible issues of the proposed approaches.

The discussions clearly showed that a single technology solution to achieve all these goals does not exist, in fact a holistic approach is necessary. The transition to efficient and clean energy solutions necessarily needs to be supported by public financing. This is intended to provide subsidies 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. Microscale-operating energy technologies should be also supported by advanced data processing, supported by on-site data collection *via* sensors and real-time data sharing allowed by high-speed Internet connection.

The main outcomes are summarised as follows:

- The problem of energy storage should be considered by taking into account three main aspects: economy, equality and climate mitigation. Although climate change is perceived as the most important issue, it is connected to other aspects (food, water quality and security…) which should not be neglected.
- Currently, there is no individual technology that can be seen as the winner in the long term, also because breakthroughs cannot be predicted. However, hydrogen and renewable organic fuels, obtained from CO_2 and water using the surplus of renewable energy, and transformation of CO_2 in biochar through photosynthesis or in additives for cement production are recognised as important players for the future energy system.
- A common, "global", development path should be identified to give all countries the possibility to contribute to the energy system change, but each area will definitely require a different approach.
- In the shorter term, we will need to emphasize support for more mature technologies (such as power-to-gas solutions and electrolysers) while other solutions (power-to liquid fuels) will need more time to be developed. In parallel, we will also need to introduce fundamental changes in the infrastructures needed for energy supply.
- A possible approach would be to test more advanced, breakthrough solutions in some restricted systems, such as islands. That can provide useful data to be expanded to more general applications.
- For the development of CO_2 related technologies, it is very important to find an efficient way to capture CO_2 and release it in concentrated form in order to make its transformation feasible. It is also very important to develop catalysts able to tolerate poisoning. Regarding the use of the captured CO_2: solid oxide co-electrolysis to syngas following by methanation appears as one of the most promising routes in the short term, while liquid fuels could penetrate the market in the medium to long term.
- It is very important to develop a proper regulatory framework especially for the production of liquid fuels from renewable energy. Providing a suitable legal framework is as important as giving incentives. Furthermore, rules should be introduced to promote sustainable practices and penalize those leading to increased emissions.

- The role of ICT will be very important in two regards: first, to collect and process the huge amount of data on energy generation (e.g. through “smart” power meters) and use in order to allow politicians and consumers to make informed decisions. Second, to help demand and offer solutions in a more efficient way.
- Energy efficiency is a key factor. No technology for energy storage will be successful in reducing GHG emissions if a reduction in energy consumption is not implemented first.

A list of action items and recommendations is indicated below with the aim of suggesting the research areas that need to be prioritised:

- ***Target disruptive innovations in parallel with incremental research providing practical and rapid solutions:***
  - ✓ *Consider research as driven primarily by human needs*
  - ✓ *Consider the urgency to address global warming and climate change*
  - ✓ *Consider the urgency to address local and global pollution effects on health*
- ***Green Hydrogen as energy vector***
  - ✓ *H_2 should be produced from renewables using sustainable processes (e.g.* electrolysis*) not from fossil fuels*
  - ✓ *Green H_2 should contribute to wide-scale decarbonisation of the energy system (*sustainable mobility, domestic uses*) but also to decarbonisation of specific industry segments (metallurgy, cement production etc.). Green hydrogen should be also widely used as feed stock chemical*
  - ✓ *H_2O –H_2 cycle (from water to water) is sustainable and has a much lower impact on the environment and in terms of water availability for other relevant uses (e.g. agriculture).*
- ***CO_2 as a possible resource and not as a waste: renewable energy-assisted CO_2 reduction as means to produce renewable fuels***
  - ✓ *Production of sustainable chemical products (e.g. through* co-electrolysis*) especially high energy density chemicals such as DME or syngas, as base for synthesizing organic compounds and fuels (hydrocarbons etc.) in a carbon neutral cycle.*

- *Develop carbon negative solutions based on photosynthetic processes (e.g. biochar, microalgae) and chemical (e.g. catalytic) processes, and enhanced rock weathering.*
- *Carbon capture should be characterised by low costs and not based on energy intensive processes especially when CO_2 is diluted in the atmosphere (efforts should be addressed to adsorption and membrane processes).*
- *Carbon neutral processes are not enough to address global warming; these should be complemented by hydrogen technologies and CO_2 sequestration (carbon negative cycles)*

- ***Combination of different energy solutions and energy saving***
  - *A global approach is required for decarbonisation*
  - *It is necessary to identify each country and region's energy and environmental requirements and offer specific solutions to favour integration*
  - *Diversity in local approaches should be pursued*
  - *Shifting from supply smart management to demand smart management (ICT technologies)*
- ***Functional materials:***
  - *Developing more efficient, better-performing, smart, functional and new materials for energy conversion based on non-critical raw materials (e.g. platinum group metals-free electrocatalysts) and obtained through cost-effective processes.*
- ***Main drivers for the energy transition***
  - *Environment, Energy security, Accessibility and independence;*
  - *Social, Economics, and System approach*
  - *Energy saving: efficiency, life-style change (mobility, energy saving, prosumers), impact of ICT technologies, smart grids, internet of energy*
  - *Costs/benefits ratio is important. Alternative benefits will mitigate cost increase.*
  - *Energy Return on Investment (EROI): the amount of energy that has to be expended in order to produce a certain amount of energy should be > 1*
  - *Life-cycle analysis (LCA) and/or Life cycle cost analysis (LCCA) methodology should be widely used to assess novel processes including the "human factor"*

- ✓ *Raise social awareness and public acceptance*

Renewable fuels such as hydrogen, methanol, dimethyl ether, ammonia, obtained from water splitting, photocatalytic, electrochemical or catalytic processes, or from recycling of CO_2, using the surplus of renewable power, will complement the electrochemical storage. Those can also represent a proper solution for transportation by extending the driving range of electric vehicles and for domestic use to produce heat and power in micro-distributed generation through CHP systems. However, efforts in developing appropriate infrastructures for alternative fuels are also required.

Beside investing in transmission technologies to avoid congestion from increasing renewable energy facilities, alternative energy vectors will provide an efficient link between sustainable energy generation, distribution and use. CO_2 valorisation will provide an efficient tool to reduce greenhouse gas emissions. 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 also appear as key technologies for an efficient recycling of CO_2. These facilitate the wide occurrence of 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 innovative, efficient and sustainable electrochemical and catalytic processes to achieve high conversion efficiency, using non-critical raw materials and cost-effective technologies to favour large scale deployment.

The specific challenge for all these areas is to develop disruptive approaches, which can overcome the issues currently limiting the wide-scale sustainable technologies use. Breakthrough research should be supported in parallel with technology optimisation and upscaling while society and environment impact should be deeply analysed. The overall approach in developing or improving sustainable processes should be systemic and cover interdisciplinary aspects.

This executive summary has been circulated among and agreed with the experts participating to the workshop before being made available to the public through the Foresight web site.

Giuseppe Montesano has actively participated in the workshop, but he does necessarily agree with all the statements included in this report.

AGENDA

Face-to-Face (F2F) Workshop

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

8-10 July 2019

Venue: Crowne Plaza Rome St. Peter's

Via Aurelia Antica 415, Aurelio - 00165 Rome, Italy

8th July 2019 Afternoon – Workshop Context, Topics and Objectives

13:00 – 14:20 Get Together and Light Lunch

Session 1. Introduction about the S&T Foresight Project and the Workshop Context
Moderator G. Einaudi **-** Scientific Director of the CNR Science and Technology Foresight Project (IT)

14:20 -14:30 **Welcome and introduction of participants**

14:30 – 14:40 **Introduction to the CNR Science and Technology Foresight Project**
Giorgio Einaudi – Scientific Director of the CNR Science and Technology Foresight Project (IT)

14:40 – 14:50 **The energy storage context in the framework of the S&T Foresight project and the sustainable fuels pathway: Introduction and objectives for the F2F workshop**
Antonino Salvatore Aricò - Responsible of the Energy working group (IT)

14:50 – 15:05 **Questions and Answers (*Session 1*)**

15:05 -15:25 Coffee break

Session 2. Focus on Green Hydrogen generation and use, CO_2 Recycling on a wide

scale and related Socio-economic aspects:
Moderator A. S. Aricò

15:25 – 15:55 Introductory speeches (10 min each)

- ✓ Piotr Zelenay - FECS-FLANL, Professor of Chemistry Materials Physics and Applications, Los Alamos National Laboratory, Los Alamos (USA)
- ✓ Anne Hauch – Professor at the Denmark Technical University, Copenhagen (DK)
- ✓ Marco Frey – Professor at Scuola Superiore Sant'Anna, Pisa (IT)

15:55 – 16:15 **Questions and Answers**

16:15 - 18:00 **Discussion and possible interventions by the other participants (*Session 2*)**

20:00 – Dinner

9th July 2019 Morning – Workshop Context, Topics and Objectives

Cont'd

Session 3. Focus on innovative routes for Hydrogen and Carbon Dioxide Management and Valorisation
Moderator E. Einaudi

9:00 – 9:40 Arguing and completing the discussions from the previous session, addressing specific issues (10 min each)
Nicholas van Dijk - Chief Operating Officer, PV3 Technologies Ltd, London (UK)
Samir Bensaid – Professor at Politecnico di Torino (IT)
Franco Miglietta – Senior Researcher at CNR-IBIMET, Florence (IT)
Simelys Hernández - Assistant Professor, Politecnico di Torino, Turin (IIT)

9:40 – 10:10 **Questions and Answers**

10:10 - 11:00 **Discussion and possible interventions by other participants (*Session 3*)**

11:00 – 11:20 Coffee break

Session 4. Analysis of relevant scenarios for the energy system at 2050: challenges, approaches and policy aspects
Moderator C. Bartolucci

11:20 – 11:50 Focus on global policy and economics for the energy storage and implementation of energy policy objectives (10 min each)

Giuseppe Montesano - Deputy Director Enel Foundation (IT)

Megan Bettilyon - Director, Renewable Energy and Special Projects, Global Good (USA)

Daria Vladikova - Chair of the Bulgarian Hydrogen, Fuel Cell and Energy Storage Association, Bulgarian Academy of Sciences (BG)

11:50 – 12:10 **Questions and Answers**

12:10 - 13:00 **Discussion and possible interventions by other participants (SESSION 3)**

13:00 – 14:30 Light Lunch

9th July 2019 Afternoon – INTEDISCIPLINARY BRAINSTORMING

14:30 – 16:30 Parallel sessions: open and guided discussion.

Moderators E. Einaudi, A.S. Aricò, C. Bartolucci (Foresight)

Rapporteurs: Daria Vladikova (BAS); Lorenzo Zani (CNR)

- How to address challenges and priorities in the field of energy storage?
- Which technologies and processes can better support the energy transition?
- Which aspects are the most urgent to address?
- What could be the impact of the proposed technologies in addressing sustainable development and future energy needs, and how can these benefit the environment?
- Analysis of the proposed scenarios for both the transition period and an envisaged complete decarbonisation at 2050.
- Discuss common denominators for hydrogen technologies and CO_2 management and valorisation
- Discuss socio-economic challenges of an economy based on "Renewable Fuels".

16:30 – 17:00 Coffee break

17:00 – 18:00 Plenary: Report from parallel sessions and reflections

Moderators E. Einaudi, A.S. Aricò

- Points of view: commonalities and diversities
- Propose holistic solutions to address human needs at 2050
- Analyse the specific impacts

20:00 – Dinner

10th July 2019 Morning – CONSENSUS

09:00 – 10:30 **Select research priorities**
Moderators E. Einaudi, A.S. Aricò

10:30 – 11:00 Coffee break

11:00 – 11:30 **Analyse next steps**
Moderators E. Einaudi, A.S. Aricò

11:30 – 13:00 **Implement research priorities into concrete actions**
Moderators E. Einaudi, A.S. Aricò

- Discuss the role of academia, research organization, industry and foundations in promoting the selected research priorities
- Discuss how to implement the identified research priorities in the next topics of various calls in different organisations, countries etc.
- Discuss how policy makers should support the transition towards a sustainable energy system
- Drafting the general scheme and the contents of the workshop report to be finalized by the WG responsible and approved by the experts participating to the F2F.

13:00 – 14:00 Light Lunch

End of the meeting

F2F_Workshop "Promoting a Sustainable Future through a Large-scale Utilisation of Renewable Fuels"

LIST OF PARTICIPANTS

Participant	Affiliation	E-mail
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EXECUTIVE SUMMARY

Available at the Foresight web site:

http://www.foresight.cnr.it/

BACKGROUND DOCUMENT

(*document circulated before the meeting*)

Available at:
http://www.foresight.cnr.it/images/EVENTS/Sept_2018_energy/AArico_BCK_doc_on_Energy_settembre_2018.pdf