IPHE

International Partnership for Hydrogen and Fuel Cells in the Economy

Final Report

IPHE Workshop "Hydrogen – A Competitive Energy Storage Medium for Large Scale Integration of Renewable Electricity"

Seville, 15-16 November 2012

Table of Contents

Final Report

IPHE Workshop "Hydrogen – A Competitive Energy Storage Medium for Large Scale Integration of Renewable Electricity"

Seville, 15-16 November 2012

Introduction

There is a growing need to increase the usage of renewable energy sources in the energy system and the power generation mix. Addressing the issues related to the intermittency and unpredictability of these renewable sources poses important technical and economical challenges particularly when integrated on a large scale. Approaches to overcoming these challenges include: improved prediction of renewable production, back-up capacity, expansion of electricity grids (e.g. transport), demand-side management (e.g. smart meters, smart grid), and energy storage. Energy storage technologies provide attractive and promising solutions for energy management, bridging power management, power quality and reliability. However, although regulators and policy makers acknowledge the need to address these challenges energy storage solutions are not yet seen as a high priority.

The progress of hydrogen and fuel cell technologies and the readiness of many of their applications suggest that they could play an important role in energy storage. However, they will have to compete with other well established energy storage technologies, such as batteries for modular applications and compressed air energy (CAES) and pumped hydro storage for large-scale applications. Although the relative round-trip inefficiency of a typical hydrogen energy system – including electrolysers, compressors, storage and fuel cells –

Glossary of Acronyms

CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Storage
CPUC	California Public Utilities Commission
EIB	European Investment Bank
EC	European Commission
EPRI	Electric Power Research Institute
FCEV	Fuel Cell Electric Vehicle
GHG	Green House Gas
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LCOE	Levelised Cost of Electricity
LTCAES	Low Temperature Compressed Air Energy Storage Economy
NOW	German National Organisation for Hydrogen and Fuel Cell Technology
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PV	Photovoltaic electricity generation
PEM	Proton Exchange Membrane
RES	Renewable Energy System
RTD	Research and technology Development
US DoE	United States Department of Energy
VRB	Vanadium Redox Flow Battery
ZEBRA	Zeolite Battery Research Africa Project

might be seen as a weakness in grid applications, there are important advantages over the above mentioned technologies. Hydrogen's advantages include its higher energy density and potentially lower storage cost, its flexibility for other off-grid end uses like fuel in fuel cell electric vehicles, and its utility as an industrial gas, and power-to-gas storage. Consequently, hydrogen could be an ideal electricity storage medium, particularly when intermittent generation exceeds demand and large amounts of energy need to be stored.

Workshop Purpose and Format

Purpose

The main objective of the workshop was to promote and facilitate a first exchange of views among the different stakeholders about the integration of Renewable Electricity through applications of energy storage technologies, with emphasis on the potential role of hydrogen as an energy storage medium. The workshop provided a forum for stakeholders to share technological, economical, financial, regulatory and policy knowledge, and experiences. The workshop also provided an opportunity to explore potential collaborations and for networking in the wider context. In particular, the goals of the workshop were to:

- Assess and compare the benefits and drawbacks of the current electric energy storage technologies and other conventional solutions (e.g. new generation and transmission capacity)
- Review the technical readiness of hydrogen and fuel cell technologies, and applications
- Assess the economics of hydrogen energy storage systems and compare with that of currently available technologies
- Discuss the current policy and regulatory frameworks of major member countries of the IPHE and explore potential synergies between IPHE member countries
- Present the available public and private financial mechanisms (and actors) for funding energy storage projects, showing illustrative business models, and exploring potential investment opportunities in global markets, particularly for hydrogen energy storage systems

Workshop Format

The two-day workshop began with three keynote speeches aimed at setting the scene for the workshop. This was followed by five sessions addressing different aspects of energy storage. Three of those sessions consisted of papers presented by eminent speakers, each concluding with a question and answer session. The final two sessions included short presentations followed by round table discussions led by representatives of industry, finance and government policy.

The first session addressed the wider energy storage options in order to put hydrogen storage into context. Session two then went on to focus on hydrogen and, in particular, progress in moving from Research and Technology Development (RTD) to implementation. Having discussed progress in the development of the technology, session three was dedicated to looking at the economics of hydrogen energy storage. The policy and regulatory issues were discussed in round table session four while session five was dedicated to a discussion on the financing of such systems.

Presentation Summaries

Keynote Speeches

The keynotes set the scene for the discussion of energy storage and the role of hydrogen and fuel cell systems.

Keynote 1 illustrated the characteristics of the renewable energy systems (RES) and the mismatches that occur between renewable electricity generation and demand, using real examples of the Spanish grid. The low capacity factors and the variability of RES together with the impact of daily weather patterns also result in an increased need for transmission line capacity compared to conventional power generation technologies. Since the interconnect capacity with neighbouring countries is very small it makes Spain almost an electrical island, so mismatches between demand and supply cannot be readily alleviated by national imports or exports. All of these factors combine to produce grid balance problems that will increase as the anticipated installed capacity of renewable energy is enlarged. Various measures are available to raise the limit for non-manageable renewable energy but these require time to implement. The main conclusions are:

i. Due to their variability and low power factor, associated with their dependency on wind or sun, the balancing of the electricity grid presents an increasing challenge as the installed renewable energy capacity is increased.

ii. New measures that go beyond increasing transmission capacity and flexible generation will have to be introduced to manage the grid as the level of RES is increased. Energy storage technologies, including hydrogen/electrolyser/fuel cell combinations will be a key factor in this.

Keynote 2 built upon the work of the previous talk by discussing the wide range of storage options that are available. Each of these has its own attributes, which makes it suitable for a specific range of applications, principally characterised by storage period and discharge power. It is important to understand those characteristics and to relate those to the type of storage required. At present, grid electrical storage at large scale is dominated by pumped hydro, accounting for 99%. Compressed air energy storage (CAES) is also a well-established technology for large-scale applications but not yet widely used whereas batteries of different types are advanced technologies for modular, lower scale applications. Hydrogen has characteristics that would allow the storage period to be extended beyond the current capability. Hydrogen is the most powerful fuel with regard to its mass and holds the possibility of long term, loss free storage, thereby opening up the prospect of seasonal energy load balancing. Unlike many of the other technologies, it also provides the option for off-grid applications such as fuel for heating and for road transport, thus providing additional flexibility. The main conclusions are:

i. In order to identify the optimal energy storage technology a number of factors have to be taken into account, in particular the efficiency over the complete storage cycle (from charging to utilization) and the economical boundary conditions for the application.

ii. The diversity of possible energy storage solutions enables increased stability for future energy systems,

Keynote 3 noted that renewable energy is growing at a faster rate than high voltage transmission line can be built; in the US for example, wind energy production increased by 100 TWh between 2006 and 2001. While the greatest US wind potential is in the mid-western states, the highest demand is in the Atlantic and Pacific coastal states but there is insufficient high voltage transmission line infrastructure to connect this supply and demand. Transmission lines typically take 10 to 20 years to build and cost around $2 million per mile. Hydrogen provides a flexible energy storage and carrier option which could defer new lines and would alleviate these transmission difficulties; it has diverse production paths and many established markets. When used as a feedstock for fuel cells it produces electricity at high efficiency and with no local emissions; a well-to-wheel analyses, conducted by Argonne National Laboratory, showed that this combination can provide road vehicles with the lowest range of greenhouse gas emissions of all the options addressed. Current research efforts, underway globally, are resulting in significant cost reduction for fuel cell systems with mass production costs for transport applications dropping from $275/kW in 2002 to $47/kW in 2012, as projected by the US DoE. In terms of electricity storage, hydrogen can provide competitive alternatives to pumped hydro and compressed air energy storage (CAES) at sites where these technologies are not feasible. Conclusions from this presentation are:

i. Hydrogen is a very flexible energy carrier/storage option

ii. Fuel cells provide high efficiency conversion with multiple end use opportunities

iii. More work is needed to reduce cost and address performance and durability

Session1: Electric Energy Storage Options for Variable Renewable Energy Sources – Today's Situation

Presentation 1 looked at pumped hydro storage systems, which make up the majority of current grid electricity storage capacity worldwide. These can have a cycle efficiency of around 80% and cost in the region of 500€ to 2000€ per kW. The current portfolio of pumped hydro schemes includes outputs up to 400 MW and water heads from 3 to 1200 metres. Storage capacity is around 8 hours at full load with a reaction time of approximately 15 seconds from 50% to 100% load. Recent advances in the technology have resulted in efficiency improvements, reduction in reaction time, a head range increase, variable speed pump turbines and a power range increase. The industry expects further improvements in flexibility, reliability and performance of the units and to find more challenging sites, although this might pose environmental issues.

Presentation 2 focused on compressed air energy storage (CAES). The importance of choosing a solution that fits the desired energy storage time was again stressed, with CAES offering higher cycle efficiency than hydrogen storage but a lower potential storage capacity. Two CAES plants are operational today; the Huntorf site in the Germany, a 290MW/2 hour plant commissioned in 1978 for black start duty and the McIntosh plant in Alabama, a 110MW/26 hour plant commissioned in 1991 and used for a range of power system duties. Both are diabatic, meaning the heat of compression is not stored; however the McIntosh plant uses a recuperated gas turbine to achieve a somewhat higher round trip efficiency. For the future, adiabatic systems are under development as well as more complex systems that use the hot air from the turbine to augment a separate gas turbine (CAESplus) and low temperature systems (LTCAES). A number of pressure vessel options are available depending on the storage time required; for large capacities underground caverns are used but these need to be sited in conditions where salt deposits occur which can be a limiting factor. The main conclusion from this is that CAES has the potential to be a competitive storage option, particularly at large scale where it is the only mature technology of comparable cost to pumped hydro.

Presentation 3 took an in-depth look at battery technology and its potential for large-scale energy storage. Batteries have applications where rapid intervention is required and where decentralised storage is needed; the technology is at different states of development but further progress is necessary in terms of safety, operating costs, rapid charge time and number of charge/discharge cycles. They can be used to support activities including frequency regulation, spinning reserve, distribution upgrade deferral, demand management and power quality, with storage support times of 1 minute up to 4 hours. A ranking process based upon different attributes showed that sodium sulphur batteries scored the highest and achieved a slightly higher score than pumped hydro. Conclusions drawn from this presentation are that:

i. Battery Energy Storage Technologies are expected to gain significant global market penetration for energy storage to 2030 (50% of the whole power foreseen)

ii. The most promising batteries are Lithium-ion, Vanadium Redox Flow (VRB), Sodium Nickel Chloride (“ZEBRA”), Zinc-bromide and, particularly, Sodium Sulphur.

Presentation 4 addressed system cost benchmarking of “near-term” energy storage solutions; this is part of a long term EPRI programme which will see the creation of a database encompassing a wide range of near term technology options together with their supporting infrastructure. The factual data is based upon information provided by companies active in their respective fields and is used to provide outputs on total installed capital cost, net present value (NPV) and levelised costs of electricity and capacity. This presentation concluded that factual-based cost benchmarking and related value analysis are essential to support potential business cases for specific applications. However, the estimated life-cycle costs vary with different O&M, fixed, variable, and periodic replacement costs that, at present, are highly uncertain; the site/location and application specific details will also result in varying cost impacts.

Session 2: Hydrogen Energy Storage for Mitigating the Variability of Renewable Electricity Sources – Moving from RTD to Implementation

Presentation 1 addressed the use of hydrogen gas, derived from electrolysis, as a storage medium that could provide capacity for several days or weeks. This “Power-to-Gas” approach allows for multiple use; options for the hydrogen produced include the transmission of hydrogen mixed with natural gas through the existing pipelines or use as a transport fuel. This makes the hydrogen route unique in terms of high capacity and flexibility. A demonstration plant in Germany will have a 2 MW power-to-gas capability, producing hydrogen which will be fed into the natural gas grid; another demonstration, the EU funded project “INGRID”, planned for operation in Italy will have a 1 MW electrolyser and metal hydride storage with a hydrogen capacity of 33 MWh. Cost reduction is still required and steps are underway to address these issues but in the near term, Government support will be needed if companies are to see a return on investment. Suggested roles for Government include developing policies in support of renewable portfolios and simplification of regulatory frameworks, complemented by energy storage incentives and co-funding of the next step power-to-gas demonstrations (scale 10-50MW).

Presentation 2 addressed some early challenges faced by PEM electrolysers and showed how these have now been overcome. Efficiency is now 87% (HHV) at 1500 mA/cm2 with high differential pressures being possible. There is a wide operating range, which allows a balance to be drawn between capital cost and efficiency; improved manufacturing techniques and reduction in catalyst loadings have allowed significant cost reduction and further reductions are foreseen. Durability has been improved, with stacks being qualified to 30,000 hours and scalability has been addressed with modules up to 100 kW; no barriers are foreseen for further increases to 5 MW. The conclusion from this is that today’s PEM electrolysers fulfil all of the needs for commercial deployment into energy storage systems.

Presentation 3 described a hybrid energy plant designed to be coupled to wind turbines such that electricity, heat and fuel can be supplied at all times irrespective of the wind conditions. At times when there is insufficient demand from the grid, the electricity from the wind turbines is used to produce hydrogen, using alkaline electrolysers, which is stored in gaseous form. This hydrogen is then used in the following ways: (i) in two 350 kW high-efficiency combined heat and power (CHP) plants using gas mixtures with a maximum of 70 %

hydrogen and a minimum of30 % biogas; (ii) fuel for fuel cell electric vehicles (FCEVs); (iii) blending with natural gas and fed into the gas grid. This allows the plant to operate in several different modes allowing carbon neutral hydrogen production and decentralised supply of hydrogen as well as the integration of renewable sources into the market, adjustment of the generation to the requirements of the grid and active grid support. The project has shown that there are still a number of technical (e.g. cost reduction, balance of plant sizing, load range, full automatic energy control system) and non-technical (e.g. energy tax costs, lack of storage reimbursement regulations, no experience by the licensing authorities, etc) challenges that need to be overcome for this technology to enter the market.

Presentation 4 described Areva's MYRTE project, operating on the island of Corsica. This has seen the coupling of a hydrogen energy system consisting of an electrolyser (10 Nm3/h), storage tanks (1400 Nm3) and a 100 kWe fuel cell to a solar photo-voltaic (PV) plant of 560 kWe. The aim is to improve energy management for electricity grid stabilisation by peak shaving and PV load smoothing. The current phase is designed to test durability and tank material stability, to improve thermal management and to optimise system management for increased efficiency. Phase 1 should provide 100 kW of fuel cell power and 1.75 MWh of stored energy; Phase 2 aims to see this increased to 200 kW and 3.5 MWh respectively. A further objective for Phase 2 is to package the system in a product form to be known as a "Greenergy Box". Total cost of ownership calculations have shown that, for an autonomous, island station where diesel power would normally be used, the inclusion of this concept can result in a significant cost reduction.

Session 3: The Economics of Hydrogen Energy Storage Systems

Presentation 1 put forward the case that energy storage in the US can make renewable energy more valuable by reducing transmission costs for remote wind resources, taking advantage of arbitrage opportunities, allowing base loading with renewable resources and providing grid services such as spinning reserve. The focus for this presentation was on an analysis of the potential for hydrogen energy storage in energy arbitrage. The analysis, performed using the publicly available 'HOMER' model developed by NREL, looked at a number of hydrogen scenarios including above and below ground storage, fuel cell or gas turbine power generation and end use for grid electricity or road vehicles. Levelised cost of electricity (LCOE) calculations showed that hydrogen is competitive with battery technologies and could be competitive with CAES or pumped hydro in locations that are not favourable for the latter technologies. The major disadvantage of hydrogen energy storage is capital cost; this could be reduced by increasing the cycle efficiency. In this respect, an increase in fuel cell system efficiency brings a greater cost benefit than an equivalent increase in electrolyser efficiency. The further development of reversible fuel cells, again with increased cycle efficiency, would also provide significant reductions in capital cost with the attendant reduction of LCOE.

Presentation 2 provided an insight into a very recent study sponsored by NOW looking to establish the conditions that would facilitate an economically viable operation of large wind-hydrogen plants by 2030 in Germany. The concept focuses on the surplus electricity in the transmission grid and on longer term hydrogen storage. Two applications for the hydrogen are modelled: as a fuel for road transport and for re-electrification using a combined-cycle plant equipped with a hydrogen-fed gas turbine. The main conclusions from the analysis work, which is still on going, are as follows:

(i) For surplus-driven operation of electrolysis there is a positive economic perspective, even if the power for electrolysis does not come "for free"

(ii) Hydrogen provides the flexibility of use for both the fuel for road transport and electricity markets, providing additional synergies but the former will be affordable and more advantageous than the latter

(iii) The flexibility in operation improves the economic situation.

Presentation 3 looked at a Kawasaki Heavy Industries' initiative to produce hydrogen from brown coal in Australia and ship this to Japan for power generation. While this is more expensive than fossil fuel and nuclear energy, it is possibly cheaper and provides significantly more grid stability than renewable energy. To complete the carbon free chain, the brown coal gasification process is supplemented by a carbon capture and storage (CCS) scheme. The plan envisages the operation of a pilot supply chain from 2017 with full commercial operation by 2030 and would see a production and liquefaction capacity of 770 tonnes per day with a hydrogen supply to Japan of 225,400 tonnes per annum, enough to power 3 million hydrogen vehicles and 650 MW of electricity generation. Other demands for hydrogen in Japan include the steel making process and desulphurisation of crude oil in the refinery process.

Session 4: Policy and Regulatory Frameworks – Towards a Shared Vision

Panel discussion 1 took the form of presentations and debate around the theme of policy and regulatory frameworks as a catalyst for the implementation of energy storage and particularly for the introduction of hydrogen and fuel cells into that arena. In 2009 the European Union adopted a set of legislation (known as "Climate and Energy Package"), which sets a series of key energy objectives for 2020 (known as the "20-20-20" targets) related to the share of renewable energy, the improvement in energy efficiency and the reduction of GHG emissions, with binding commitments from the Member States. These are challenging targets and some Member States are experiencing difficulty but the European Commission is working with those countries to help them get back on track. To aid the process of carbon reduction, the EC has developed a European Energy Roadmap 2050; this recognises that as the level of RES increases, major infrastructure changes will be necessary and an increase in energy storage will be an essential part of that process.

This raised the issue of the need for a sharing of experiences, both across Europe and worldwide so that the impacts of policy measures can be understood and mistakes not repeated; it is recognised in Germany for instance that changes in its internal energy policy will have an impact on its neighbours. This also applies to energy storage but different national regulations often mean that storage cannot be shared between member states; this is where policy change can make a real difference.

In Germany, government and industry is working together to prepare the market, specifically for hydrogen and fuel cells. This is being undertaken under the National Innovation Programme and is focusing on R&D combined with field demonstrations; government is providing 500M€ for the demonstrations and 200M€ for R&D with industry providing matching funds to make a total of 1.4 billion €. Hydrogen and fuel cells are seen as key technologies in an integrated energy system, building upon an increasing share of RES including the transportation sector. Large scale hydrogen storage is linking the stationary energy sector with sustainable mobility solutions.

In the US, portfolio standards are driving the take-up of renewable energy with 29 States having binding goals and a further 7 with non-binding. These have helped to increase the contribution of wind and solar energy in the US dramatically in the last ten years with wind growing by almost 1,800% and solar up by more than 300%. California, in recognising the importance of energy storage, has recently completed the first phase of a requirements assessment and is shortly to embark on the second and final phase of this work. This is to support a Bill, passed by the California Assembly, which directs the California Public Utilities Commission (CPUC), by October 1 2013, to adopt an energy storage procurement target, if it determines such a target to be appropriate, to be achieved by each investor-owned utility by December 31 2015, with a second target by December 2020. This also directs the CPUC to consider a variety of possible policies to encourage the cost-effective deployment of energy storage systems.

The importance of high level techno-economic modelling to help in energy policy and regulation was also highlighted. Electricity systems have imperfections such as non-manageable generation (e.g. wind and PV), unreliable feeders and variable generation prices. These imperfections create opportunities for the cost effective utilisation of energy storage, but determining the value of a given application is non-trivial because electricity markets are diverse and contrived. Government innovation tends to support piecemeal development of components rather than large scale systems because the latter is subject to much greater uncertainty and results in less tangible solutions. Advanced real-time models, allowing the techno-economic benefits and implications to be understood, would help these system issues to be addressed more comprehensively and progress to be accelerated.

The impact of policy and regulation was also discussed since it is recognised that there have already been unintended consequences of specific measures in some countries. European countries that were the first to introduce tariffs to support the introduction of PV technology, for instance, bore the brunt of the expense that helped the technology to achieve large cost reductions and achieve grid parity, while late entrants reaped much of the benefit. This raises the question of how Europe might achieve a suitable energy storage capacity but without one or two member states taking a disproportionate share of the cost. Trans-national issues such as this are best addressed perhaps by policy drawn up and implemented at the EU level.

Session 5: Financing Energy Storage Projects – Opportunities for Hydrogen Energy Storage Systems

This proved to be the most problematic session of the workshop to organise and probably reflected the attitude of the investment community towards energy financing. Much of the discussion centred upon the issues of access to finance and incentives to invest while other topics were:

(i) The main sources of financing for renewable energy projects (government agencies, private sector entities, multilateral organizations, international organisations).

(ii) Best practices for funding energy storage projects

(ii) Investment opportunities for energy storage applications in global markets - competition for capital with more conventional incumbent technologies

(iv) Opportunities for bankable hydrogen storage projects.

In explaining the role of the European Investment Bank (EIB) it was stated that its AAA rating allowed it to take credit risk on its own shoulders, which makes it more attractive for other investors to become involved with a project. The EIB's credit rating also allows it to raise money at low interest rates and lend to projects that otherwise might not attract this AAA rating. However, it is clear that more needs to be done to attract the attention of the investment community for energy storage in general and hydrogen in particular. The EIB is currently undergoing a period of public consultation to elicit views on the role to be adopted in the energy sector.

The timescale for the development of new technologies such as hydrogen was also cited as a challenge; it takes an average seven years for developments to move from R&D to proof of concept and another seven to develop a product/application before mass rollout begins. Although there are many sources for the late stage funding, few options for seed/start-up funding are available. Venture capitalists and other investment institutions find this development process too long to meet their financial criteria. One suggestion from the Panel was that the tax regime could be changed to make it more attractive for institutions and high net worth individuals to invest in start-up companies; another suggestion was for the EU to set priorities for technology development.

The utilities believe that market prices should send adequate signals to determine the most efficient way to provide the flexibility required by the grid. They are also of the view that only investment in mature generation technology should be made by the industry; immature technologies should be co-financed with public funds.

Regulatory measures, such as the proposed new taxation frameworks in Spain that could bring about a reduction in the operating hours of hydro pumping stations, might lead to the abandonment of some current projects and could result in adverse changes to the generation mix.

The large scale introduction of RES means a shift in the traditional energy models – from low CAPEX / high OPEX (excluding nuclear) to high CAPEX / low OPEX. This implies competition of both mature and developing technologies for access to capital markets but with higher market risks for those innovative ones requiring new business models. Although the versatility of hydrogen is a key advantage for energy storage “hydrogen business cases” are not bankable today because they have to compete with other efficient, mature technologies such as grid extension, conventional back-up generation and wind curtailment.

Some of the key factors for a “bankable” project are: (i) provide a market structure for ‘zero-emission’ technologies stabilising the grid, (ii) support technology development and demonstration projects through joint public-private schemes and (iii) develop direct applications of hydrogen for mobility.

Messages to be taken away from this session are:

> There is a need to de-risk investment through public sector funding, EIB support for loan guarantees, co-financing, insurance or low interest loans.
>
> Incentives are needed to make it attractive to invest at the early, high-risk stage rather than the late entrant, low risk phase of technology implementation; these could include favourable tax regimes.

Public/private collaborations can share the early development costs and risks.

Conclusions

Overall Conclusions

This workshop provided a unique opportunity for different communities to come together to discuss the future need for energy storage in a renewable energy environment and, in particular, the role to be played by hydrogen and fuel cell technology. The event saw contributions from all stakeholders including representatives of power generators, grid operators, system and equipment developers and energy policy makers thus ensuring that all facets of this complex subject were included in the deliberations. The panel sessions provided a good opportunity to debate some of these important issues and facilitated lively interactions both during the formal sessions and at the informal networking opportunities.

It is commonly agreed that storage must be an important part of any future energy strategy if RES is to be successfully integrated into an electricity grid and that hydrogen and fuel cells will play an important role in widening the scope and providing energy flexibility. The role to be played by energy storage and the correct choice of options is a complex process however and specific actions will be necessary if electricity grids are to be suitably prepared for the necessary increase in RES capacity. These actions are highlighted in a series of specific messages from the workshop, as follows:

Technical

- Balancing of a grid system with high levels of RES becomes a challenge due to their low load factor, variability and dependence for production on the availability of the primary resource. Energy storage systems will be necessary to overcome the challenges of balancing off-peak availability against high peak demands in grid systems with high levels of RES. In order to identify the optimal energy storage technology, a number of factors must be taken into account, in particular the total cycle efficiency (from charging to re-electrification), the storage capacity and the economic boundary conditions of the specific application.

- Factual based cost benchmarking and related value analysis will be essential to support potential business cases for the specific applications.

Economic/Financial

- Energy storage should be deployed where it is most valuable; this is often where there is a need to address the imperfections of the power system. These imperfections can be spatial, for example a congested infrastructure, or dynamic, for example rapid changes in demand, or both.

- Utilities take the view that energy storage systems must follow the same market access rules as other energy technologies.

- Utilities also take the view that public sector support for energy storage should only be for those technologies that need further time to show their full economic potential, as is the case for hydrogen and fuel cells. Energy prices should only cover the cost of the electricity and not include a levy for the R&D.

- Energy storage has not yet captured the interest of the European investment community; the business case has so far, not been presented convincingly.

- Linking the power sector with the energy needs of transportation increases the flexibility of RES and offers innovative business models.

Hydrogen and Fuel Cells

- There is no single energy storage system that satisfies all of the technical and economic criteria but hydrogen presents a flexible option that encompasses the range from kilowatts to Gigawatts of power and hours to months of capacity. This makes hydrogen, electrolysers and fuel cells an attractive option from both a grid management and an economic perspective; the greatest potential in this respect is for wind to hydrogen systems.

- The main advantages of hydrogen energy storage over competing technologies are its high energy density (170 kWh/m3 compared to 2.4 for CAES and 0.7 for pumped hydro), its potential for distribution as an addition to natural gas in existing pipelines (also reducing the carbon footprint of the gas) and its versatility. This versatility is exemplified by the multitude of potential end uses such as re-electrification, CHP, heating, industrial processes and as a transport fuel.

- The main disadvantage of hydrogen energy storage is cost; this can be reduced by both research and deployment. Research is needed to improve the total cycle efficiency, to reduce materials costs and to develop manufacturing processes while deployment will show the potential of the technology and provide economies of scale.

Policy

- Market preparation for hydrogen storage requires a better alignment of the transport and energy sectors and close cooperation between a wider body of policy makers, regulators, grid operators, energy suppliers and researchers. Public perception and the reaction of the media must also be a consideration in the formulation of policy.

- The hydrogen and fuel cell community must work together to deliver key messages about the potential for the technology to both user communities and policy makers.

- National and trans-national governments must take a long-term view of energy policy; this includes an understanding of the need for energy storage and the role of hydrogen and fuel cells in the mix of storage technologies.

- Energy policy must be transparent, consistent and stable if investment is to be forthcoming. Sudden dramatic changes in policy do not make for a good investment climate.

- Instruments to facilitate an integrated energy system combining power, heat and transportation fuel demand are needed.

Acknowledgements

The workshop was organised by the European Commission under the patronage of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). The sponsorship of Abengoa Hydrógeno is gratefully acknowledged. The organisers would also like to thank all of the workshop presenters and participants for their time and thoughtful contribution to the discussion.

Appendix A: Agenda

Thursday, November 15th 2012

9:00 – 9:30 Welcome by regional authorities and host organisation

- **Javier Brey**, General Manager of Abengoa Hidrógeno
- **Elías Atienza Alonso**, General Manager, Corporación Tecnológica de Andalucía
- **Juan M. González Mejías**, Secretario General de Innovación, Industria y Energía. Consejería de Economía, Innovación, Ciencia y Empleo. Junta de Andalucía

9:30 – 9:45 Introduction to and goals of the workshop

- **Wiktor Raldow**, Head of Unit "Energy conversion and distribution systems". DG Research and Innovation, European Commission.

9:45 – 10:45 Keynotes

1. ***"Challenges and opportunities related to large-scale integration of renewable energies into the electric system"***

   Miguel de la Torre - Coordinator of the Operational Support Area of the National Electrical Control Centre (CECOEL) and Renewable Generation Control Centre (CECRE), Red Eléctrica de España S.A. (REE)

2. ***" Energy storage for the integration of renewable electricity"***

   Andreas Hauer - Operating Agent of Annex 28 of the IEA Energy Conservation though Energy Storage Implementing Agreement (IEA ECES)

3. ***"The potential of hydrogen and fuel cell technologies for energy storage"***

   Monterey Gardiner - U.S. Department of Energy – Fuel Cell Technologies Program, Technology Development Manager

10:45 – 11:15 Coffee break

11:15 – 13:15

1st Session *"Electric energy storage options for variable renewable energy sources – Today's situation"*

Chairman: **Tim Karlsson** Director, Emerging Technologies, Industry Canada

Presentations:

Flexible large-scale pumped hydroelectric energy storage” – **Olivier Teller**, Product Director Pumped (Hydro) Storage Plants, Alstom Hydro.

“Energy Storage Compressed Air Energy Storage – one promising technology in the future energy storage business” – **Andrei Zschocke**, Technology & Innovation Manager, E.ON Innovation Center

“Battery Energy storage technologies for power system” – **Vincenzo Antonucci**, Project leader in Distributed Energy Systems of CNR, Department of Energy and Transportation

“Electricity Energy Storage Technology Options: System Cost Benchmarking” – **Dan Rastler**, Manager Strategic Initiatives and Demonstrations, Electric Power Research Institute (EPRI),

Questions and answers (30 minutes)

13:15 – 14:30 Lunch

14:30 – 16:15

2nd Session *“Hydrogen energy storage for mitigating the variability of renewable electricity sources – Moving from RTD to implementation”*

Chairman: **Klaus Bonhoff**, Managing Director of the German National Organisation for Hydrogen and Fuel Cell Technology (NOW)

Presentations:

“Hydrogen Energy Storage: Technology & Business Model Progress” – **Daryl Wilson**, Chief Executive Officer and President of Hydrogenics Corporation

“The Energy Storage Puzzle: the Electrolyzer Stack Piece” – **Tim Norman**, Vice President of Engineering, Giner Inc.

The “Hybrid” Power Plant – **Werner Diwald**, Director of ENERTRAG AG

“The MYRTE project: implementing hydrogen energy storage through the GreEnergy Box” – **Jérôme Gosset**, EVP Hydrogen & Storage BU of AREVA Renewables

Questions and Answers (20 minutes)

16:15 – 16:45 Coffee break

16:45 - 18:00

3rd Session *"The economics of hydrogen energy storage systems"*

Chairman: **Stathis Peteves**, Joint Research Centre – Institute for Energy and Transport (JRC-IET)

Presentations:

***"Analysis of Hydrogen and Competing Technologies for Utility-Scale Energy Storage"* – Kevin Harrison**, Senior Engineer, US National Renewable Energy Laboratory (NREL)

***"Techno-economic analysis of large wind-hydrogen plants in Germany"* – Klaus Stolzenburg**, Managing Director, PLANET GbR Engineering and Consulting

***"Feasibility study of CO2 free hydrogen chain"* – Kenji Yoshimura**, Manager, Energy & Environment Project, Kawasaki Heavy Industries Ltd

Questions and Answers (15 minutes)

Friday, November 16th 2012

9:00 – 10:30

4th Session *"Policy and Regulatory frameworks – Towards a shared vision"*

Moderator: **Bernard Frois**, Director, Technological Research, CEA

Panellists:

- **Andy Reynolds**, General Manager of the Energy, Mining and the Environment Institute, Canada's National Research Council
- **Jean-Marie Bemtgen**, Project Officer, Energy Technologies and Research Coordination, DG ENER, European Commission
- **Dirk Inger**, Director Climate Change, Energy and Environmental Policy, Federal Ministry of Transport Building and Urban Development (Germany)
- **Joseph Eto**, Leader, Electricity Markets and Policy Group, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory (LBNL)
- **José Arceluz**, Head of Regulated Electricity Markets, Regulation Direction, Iberdrola

In this round table involving energy policy makers, regulators and energy and electric services providers, the panellists will make 4-5 statements or short presentations that will be followed by a moderated debate. Main topics expected to be addressed:

- National energy and transport goals: role of renewables on energy security, transport and climate change
- Role of hydrogen and fuel cells in the future energy and transport policies
- Regulatory framework and market incentives and stimulus for renewables – impact on energy storage's value
- Regulatory measures for utility adoption of energy storage technologies that facilitate the integration of renewable energy sources into the electric grids

10:30 – 11:00 Coffee Break

11:00 – 12:30

5th Session *"Financing Energy storage projects – Opportunities for hydrogen energy storage systems"*

Moderator: **Cordelia Sita**, Chief Director 'Hydrogen & Energy', Department of Science and Technology of South Africa

Panellists:

- **Nicola Pochettino**, Senior Energy Economist, European Investment Bank (EIB)
- **Pierre Etienne Franc**, Technologies of the Future Director at Air Liquide and chairman of the Governing Board of the European Fuel cells and Hydrogen Joint Undertaking (FCH JU)
- **Stephen Voller**, CEO, Cella Energy Limited
- **Michael Salomon**, CEO, Clean Horizon
- **César Martínez Villar**, Expert in Regulatory Affairs, Endesa (TBD)

In this round table involving public and private financing entities and clean technologies suppliers the panellists will make 4-5 statements or short presentations that will be followed by a moderated debate. Main topics expected to be addressed:

- Main sources of financing for renewable energy projects: government agencies, private sector entities, multilateral organizations, international organisations.
- Best practices for funding energy storage projects
- Investment opportunities for energy storage applications in global markets - competition for capital with more conventional incumbent technologies
- Opportunities for bankable hydrogen storage projects

12:30 – 13:00

Closure – Summary, closing remarks and reflections on the workshop

by **Nilgün Parker**, Chair of the IPHE Steering Committee

13:00 – 14:30 Lunch

14:45 - 18:30 Visit to Abengoa’s Solucar Solar Complex

Abengoa’s Solucar Complex is the largest solar complex in Europe. Located just outside of Sanlúcar la Mayor (30 km far from Seville), this solar thermal and photovoltaic installation complex currently has 183 MW in operation. The Complex covers over 2,471 acres (1,000 hectares) and supplies clean electricity to approximately 94,000 households, while eliminating 114,000 tons of CO2 emissions each year. Since its construction began in 2004, this plant has been boosting local industry and services, and has been a catalyst for technological investment in the region. Also, the Complex features a research and development site, where a variety of new technology demonstration plants are under construction. At the Solucar site Abengoa Hidrógeno has also built the first hydrogen service station in the south of Spain (known as “Las Columnas”) where hydrogen gas is produced in an electrolyzer powered by electricity from photovoltaic panels and a reflective parabolic dish concentration system fitted with a Stirling engine.

Appendix B: List of Participants

Last Name	First Name	Company	Country
Antonucci	Vincenzo	CNR-ITAE "Nicola Giordano"	Italy
Arceluz	José	Iberdrola	Spain
Arxer Ribas	Maria del Mar	CARBUROS METALICOS (AIR PRODUCTS)	Spain
Atienza Alonso	Elías	Corporación Tecnologica de Andalucía	Spain
Bandyopadhyay	Bibek	Ministry of New and Renewable Energy, Government of India	India
Bemtgen	Jean-Marie	European Commission, DG Energy	
Benhamou	Khalid	Sahara Wind	Morocco
Bianchin	Alvise	Matres scrl	Italy
Bonhoff	Klaus	NOW GmbH	Germany
Borglum	Brian	Versa Power Systems	Canada
Borzenko	Vasily	Joint Institute for High Temperatures RAS	Russian Federation
Brey	Javier	Abengoa Hidrogeno	Spain
Bünger	Ulrich	Ludwig-Bolkow-Systemtechnik GmbH	Germany
Cao	Xuejun	Department of High Technology and Industrialisation, Ministry of Science and Technology	China
Carreira	Edvaldo	Coppe/UFRJ	Brazil
Castro	Africa	Abengoa Hidrógeno SA	Spain
Chahine	Richard	Hydrogen Research Institute at UQTR	Canada
Cordaro	Joseph	Savannah River National Laboratory	United States
Correas	Luis	Fundacion Hidrogeno Aragon	Spain
Crema	Luigi	Fondazione Bruno Kessler	Italy
Daza	Loreto	Instituto de Catálisis y Petroleoquímica (CSIC)	Spain
De la Torre	Miguel	Red Eléctrica de España	Spain
De Leyva	Maria	Junta de Andalucia	Spain
Decourt	Benoit	Schlumberger - SBC Energy Institute	France
Delplancke	Jean-Luc	Fuel Cells and Hydrogen Joint Undertaking	Belgium
Dorda	Andreas	Austrian Ministry for Transport, Innovation and Technology	Austria
Eeaton	Raymond	Department of Energy & Climate Change (DECC)	United Kingdom

Ekins	Paul	University College London Institute for Sustainable Resources	United Kingdom
Esteban	Daniel	Centro Nacional del Hidrógeno	Spain
Eto	Joseph	Lawrence Berkeley National Laboratory	United States
Everett	Anderson	Proton On Site	United States
Florisson	Onno	DNV KEMA Energy & Sustainability	Netherlands
Franc	Pierre-Etienne	NEW-IG, Industry Grouping for a Fuel Cells and Hydrogen Joint Undertaking	Belgium
Frois	Bernard	CEA-DRT	France
Gammon	Rupert	De Montfort University	United Kingdom
Garche	Juergen	Advisory board NOW GmbH	Germany
Garcia	Daniel	DLR	Germany
Garcia-Conde	Antonio G.	INTA - Spanish Institute of Aerospace Technology	Spain
Gardiner	Monterey	U.S. Department of Energy, Fuel Cell Technologies Program	United States
Georgelin	Lénaïc	European Commission - DG RTD	
González Mejías	Juan	Consejería de economía, Innovación, Ciencia y Empleo - Junta de Andalucia	Spain
Gosset	Jerôme	HELION - AREVA Group	France
Guzy	Christopher	Ballard Power Systems	Canada
Harrison	Kevin	National Renewable Energy Laboratory	United States
Hashimoto	Michio	New Energy and Industrial Technology Development Organization (NEDO)	Japan
Hauer	Andreas	Bavarian Center for Applied Energy Research, ZAE Bayern	Germany
Heap	Richard	Energy Research Partnership	United Kingdom
Hebling	Christopher	Fraunhofer Institute for Solar Energy Systems	Germany
Heggem	Per S.	Hexagon Composites/Lincoln Composites	Norway
Hustadt	Daniel	Vattenfall Europe Innovation GmbH	Germany
Inger	Dirk	Federal Ministry of Transport, Building and Urban Development	Germany
Jiang	Shuhua	Department of International Cooperation, Ministry of Science and Technology	China
Karlsson	Tim	Industry Canada	Canada
Kattenstein	Thomas	Fuel Cell and Hydrogen Network NRW	Germany

Keller	Jay	Zero Carbon Energy Solutions	United States
Kim	Joong-hoo	SK E&S	Republic of Korea
Korobtsev	Sergey	Joint Institute for High Temperatures RAS	Russian Federation
Kout	Wiebrand	HyET BV	Netherlands
Langmi	Henrietta	HySA Infrastructure	South Africa
López	Germán	CTA	Spain
Lucchese	Paul	CEA	France
Lymberopoulos	Nikolaos	UNIDO-ICHET	Turkey
Marquardt	Roland	RWE Power AG	Germany
Martin Bermejo	Joaquin	European Commission - DG RTD	
Martínez Villar	César	Endesa	Spain
Maruta	Akiteru	Technova Inc	Japan
Mauberger	Pascal	McPhy Energy SA	France
Maza	Hector A	Giner Inc	United States
Meng	Qingyun	Beijing Peric Hydrogen Technologies Co., Ltd	China
Menzen	Georg	Federal Ministry for Economics and Technology	Germany
Miguel Montawa	Sagrari	Ariema Energia y Mediambiente S.L	Spain
Mills	Michael	U.S. Department of Energy	United States
Moreno	Angelo	ENEA	Italy
Mori	Daigoro	New Energy and Industrial Technology Development Organization (NEDO)	Japan
Mortensgaard	Aksel	Danish partnership for Hydrogen and Fuel Cells	Denmark
Nissing	Steffi	NOW GmbH	Germany
Norman	Tim	Giner Inc	United States
Oliveira	Sergio	INMETRO - National Institute of Metrology, Quality and Technology	Brazil
Pan	Xiangmin	Tongji University	China
Parker	Nilguen	Federal Ministry of Transport, Building and Urban Development, Germany	Germany
Peteves	Stathis	European Commission, JRC	
Pimenta	Newton	UNICAMP	Brazil
Pochettino	Nicola	European Investment Bank	
Prastaro	Massimo	eni refining & marketing division	Italy

Pütz	Konrad	Transnova	Norway
Raldow	Wiktor	European Commission	
Rastler	Dan	Electric Power Research Institute	United States
Reynolds	Andy	NRC	Canada
Romero	ManueL	IMDEA Energia	Spain
Rosa	Felipe	University Of Seville	Spain
Salomon	Michael	Clean Horizon	France
Santarelli	Massimo	Politecnico di Torino	Italy
Seier	Jochen	Projektträger Jülich	Germany
Serra	Eduardo	CEPEL - Electric Energy Research Center	Brazil
Seymour	Clive	Private	United Kingdom
Shul	Yong-gun	Yonsei University	Republic Of Korea
Sita	Cordellia	Department of Science and Technology	South Africa
Sousa	Samira	Ministry of Science, Technology and Innovation of Brazil	Brazil
Steen	Marc	Institute for Energy and Transport, Joint Research Centre, EC	Netherlands
Stolzenburg	Klaus	PLANET GbR	Germany
Tagle	Jose A.	IBERDROLA SA	Spain
Teller	Olivier	Alstom	France
Voller	Stephen	Cella Energy Ltd	United Kingdom
Weber	Adam	Lawrence Berkeley National Laboratory	United States
Wilson	Daryl	Hydrogenics Corporation	Canada
Yoshimura	Kenji	Kawasaki Heavy Industries, Ltd.	Japan
Zheng	Jinyang	Zhejiang University	China
Zschocke	Andrei	E.ON	Germany