IEA-HIA Task 24
Wind Energy & Hydrogen Integration.

2007-2011

Final report
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1 Introduction

1.1 Objective, scope and structure of this report

This final report summarises the work under Task 24 “Wind energy & hydrogen integration”. Task 24 operates under the Hydrogen Implementing Agreement (HIA) of the International Energy Agency (IEA). This task was carried out between spring 2007 and autumn 2011.

The purpose is to provide an overview for technologies which have direct influence on development and implementation of systems integrating wind energy with hydrogen production.

Wind energy is an established technology. In the last thirty years, driven by the rising cost of conventional hydrocarbon fuels, environmental concerns and the need for energy self-sufficiency, there have been some rather impressive developments in the renewable energy field, particularly in wind energy,

A major constraint of wind energy is its intermittent availability, which affects both stand-alone and grid-connected applications. In stand-alone applications, either an energy storage system (e.g. batteries) or alternative power supply systems (e.g. diesel generators) are required to ensure uninterrupted supply of electricity. This adds to wind power costs and defeats some of the advantages of a renewable energy source. In grid connected applications, particularly at high penetration levels, the intermittent nature of wind energy poses a variety of operational problems for the electric system and lessens its economic value.

Factors which may contribute to a low average price of the surplus electricity in a high wind penetration scenario include curtailments enforced by the system operator due to operational limits or transmission constraints, penalties for imbalance in a liberalized market, and a high price differential between off peak and on peak electricity. In certain cases the wind resource is located in remote locations, where a weak grid limits transmission of excess electricity to the more populated regions, where the power is needed. These problems intensify at wind-power penetration levels beyond about 10%.

In the first part of this report the wind power situation in Europe and in some countries with high wind power generation is described. Solving some issues derived from the integration of
wind power into the grid to increase the penetration of wind power without putting in risk the management and stability of electrical network seems challenging.

Different energy storage systems that can compete with hydrogen are also briefly described, as well as the state of the art of other equipment such as wind turbines, electrolysers, and the power electronics necessary to integrate the renewable energy source.

Being the wind to hydrogen systems in a very preliminary deployment status, it is necessary to make intensive use of specific simulation tools to study and understand the behaviour (energetic and economic) of particular systems, as well as to help engineering, consulting and scientific community in designing and sizing elements before the physical implementation of the systems themselves.

Later in the report, current and completed projects, for R&D or demonstration, are described, summarising the learning from these projects.

Finally a closer look is devoted to the regulations on electricity and on alternative fuels in various countries to assess the possible opportunities and obstacles they may generate for hydrogen derived from wind energy.

1.2 Participation in the Task

The following experts have participated in Task 24. The authors acknowledge their relevant contributions and participation in the debates during the meetings:

Ismael Aso (CNH2, Spain), Operating Agent (ex aequo)
Aaron Hoskin (NRCA, Canada)
Kevin Harrison (NREL, USA)
Klaus Stolzenburg (PLANET GbR, Germany)
Raquel Garde (CENER, Spain)
Allan Schroeder (Risoe, Denmark)
Ken-ichiro Ota (Yokohama NU, Japan)
Dennis Krieg (Juelich, Germany)
Rupert Gammon (Bryte Energy, England)
1.3 Disclaimer

Despite the care that was taken while preparing this document, the following disclaimer applies: The information in this document is provided as is and no guarantee or warranty is given that the information is correct or fit for any particular purpose. The user thereof employs the information at his/her sole risk and liability.

The report reflects only the authors’ views. The International Energy Agency is not liable for any use that may be made of the information contained therein.
2 Wind power evolution

Wind power has reached an important technical and economical maturity level during the last decades. This energy source grows rapidly year after year and all over the world. Availability of wind resource, along with electricity transport infrastructure, proper regulation and incentives can considerably boost the installation of new power, so that although having a global magnitude, wind power has regional and local characteristics. Furthermore, as hydrogen from wind seems to potentially add value when saturation of wind turbines gets closer, the chapter focuses especially in some countries in Europe still leading the installed power figures and hence more prone to benefit from the synergies with hydrogen from wind power.

According to the study developed by the EWEA (European Wind Energy Association), Pure Power (1), the current electricity supply structure in Europe maintains the characteristics of the time in which it was developed. Each country has its own energy system, the technologies applied are ageing and the markets supporting it are underdeveloped. Europe needs a good internal market for electricity to face the global challenges of climate change taking into account the depleting of indigenous energy resources, the increasing fuel costs and the threat of supply disruptions.

The estimations are that by 2020, 332 GW of new electricity capacity – 42% of current EU (European Union) capacity - needs to be built to replace old power plants and meet the expected increase in demand. This could represent an opportunity for Europe to build a new, modern renewable energy power supply and grid system capable of meeting the energy and current climate challenges, while enhancing Europe’s competitiveness and creating hundreds of thousands of manufacturing and related jobs, supported all by a well functioning internal market in electricity.

The 2009 EU Renewable Energy Directive aims to increase the share of renewable energy in the EU from 8.6% in 2005 to 20% in 2020 and as the cheapest technology and most developed, onshore wind will be the largest contributor to meeting the 34% share of renewable electricity needed by 2020 in the EU.

EWEA has analysed the wind power market in the 27 Member States to provide estimations about the deployment of wind energy in Europe by 2020 and 2030. EWEA has considered two scenarios, low and high. The first one is more conservative and assumes a total installed capacity in EU by 2020 of 230 GW, producing 580 TWh of electricity. The second one
assumes a total installed wind power capacity of 265 GW by 2020, producing 681 TWh of electricity.

By 2030, in the conservative scenario, EWEA expects 400 GW of wind energy capacity in EU-27, with 250 GW of on-shore and 150 GW of off-shore.

That means that by 2030, wind power in Europe will produce 1155 TWh, meeting between 26% and 34% of the European electricity demand, depending on the demand considered as reference.

The offshore generation will reach 563 TWh due to the higher capacity factor of the offshore turbines. It is assumed that the average capacity factor of all wind turbines in Europe will increase from 24.1% in 2008 to 28.9% in 2020 and 33% in 2030 mainly due to a better design, exploiting resources in more windy areas, technology improvements and a large contribution of offshore wind.

In Table 1 the data about energy generation for the two scenarios predicted for 2020 are collected.

By the end of 2008, there was 64.9 GW of wind power capacity installed in the EU-27, of which 63.9 GW was in the EU-15 and the 62.6% concentrated in two countries, Germany and Spain with 23.9 GW and 16.74 GW respectively.

Regarding the share of wind power, however, is Denmark the first country in Europe with a 20.2% of the electricity consumption covered by wind energy, followed by Spain, Portugal and Ireland with 12.3%, 11.5% and 9.1%, respectively.

If we take into account that the household consumption is expected to increase from 790 TWh in 2006 to 1,114 TWh in 2030 (2), being the 25% of the total electricity demand, and the average household consumption will be 4,787 kWh in 2030, wind power would produce electricity equivalent to more than all the electricity consumed by the 233 million households in Europe this year.
Related to electric cars, we could assume that the average consumption of an electric vehicle is 2,000 kWh/year (0.2 kWh/km, 10,000 km/year\(^1\)), therefore, in 2020 wind energy would power 291 million cars and 577 millions in 2030.

The IEA World Energy Outlook report in 2008 (3) expected 4,528 GW of electricity generating capacity to be installed worldwide in the period 2007-2030, requiring investments of $5,034 billion in generation, $2,106 billion in transmission grids and $4,657 billion in distribution grids. For OECD (Organisation for Economic Co-operation and Development) Europe expects 686 GW to be built, requiring investments of $922 billion in new generation, $187 billion in transmission and $567 billion in distribution grids.

Adjusting the European Commission figures for total generating capacity and new capacity, EWEA has calculated that in 2008, 8.1% of all capacity in the EU was wind energy and the share would increase to 24.2% in 2020 and 37.7% in 2030. Wind power’s share of new generating capacity is forecast to be 32% in 2009-2010, 59% in 2011-2020 and 70% in the decade leading up to 2030.

Regarding the \( \text{CO}_2 \) reductions from wind power, it is assumed that each kWh of wind power substitutes a kWh of coal, oil or gas. It is assumed also that 1 TWh produced by wind energy saved 0.724 Mt \( \text{CO}_2 \)/TWh in 2005 based on 2005 data of generation and emissions. Using this approach it is assumed that wind energy in 2020 will avoid 0.572 Mt \( \text{CO}_2 \)/TWh and 0.518 Mt \( \text{CO}_2 \)/TWh in 2030. In 2008, wind energy avoided 91 Mt of \( \text{CO}_2 \). In EWEA’s reference scenario, annual \( \text{CO}_2 \) avoided from wind energy will increase to 333 Mt in 2020 and 599 Mt in 2030.

A closer look on the three countries in Europe with a higher installed power or share of wind energy will follow.

\(^{1}\) The European Environment Agency (2009) estimates that Electric Vehicles (EV) will consume between 0.11 and 0.2 kWh/km – the lower estimate through likely technology developments in the future. The Brussels-based NGO “Transport & Environment” assumes that EVs have an annual mileage of 8640 kilometres (80% of that of petrol cars).
Table 1. Wind power generation estimated by 2020, low and high scenarios.

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### IEA HYDROGEN IMPLEMENTING AGREEMENT – Task 24 “Wind Energy and Hydrogen Integration”

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2.1 Spain

2.1.1 Wind Energy in Spain

The wind power installed in Spain by the end of 2010 reached 20.7 GW, being the third power generation technology after the combined cycles and nuclear energy. In 2010 wind supplied 16.6% of the energy demand, avoided the emission of more than 25 million of CO₂ tons and the import of fossil fuels valued at more than 1,541 M€. Moreover, wind energy contributes directly or indirectly to the GDP (Gross Domestic Product) with 3,200 M€ or a 0.34%.

Figure 1 shows the evolution of wind energy from 1998 to 2010. It is important to note the increase of wind power installed in 2004, 2007 and 2009 with more than 2,300 MW, 3,500 MW, and 2,400 MW respectively, and the rest of the years from 2001 with an increase of around 1,800 MW/year.

Table 2 shows the wind power installed in the different regions in 2009 and 2010. Castilla La Mancha, Castilla y León and Galicia are the regions with the most wind power installed. It is interesting to note the low increase percentage in some communities as Galicia, Navarra or Aragon which accumulate a big power from the previous years. In some of these regions as in Navarra, the capability of the grid to integrate more wind power is
limited by technical requirements, and in other regions, the emplacements with good wind resource are already exploited so that new wind farms in low resources sites are not cost-competitive.

Table 2. Wind power in regions, 2009-2010. Source: AEE.

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2.1.2 Objectives

According to the Plan of Renewable Energies in Spain 2005-2010, the foreseen wind power installed should reach the 20,155 MW, objective that has been achieved, while the regions (4) intend to accumulate 44,000 MW by 2020 including off-shore wind energy. The revised Plan for 2011 to 2020 sets the target in 38 GW with on-shore as well as off-shore wind power.

REE (Red Electrica Española, Spanish Electric Network agent) has published a report including feasibility studies for installing 44,000 MW of wind energy in Spain. The preliminary results point to the viability of the regions’ plans if the planned electric grid for 2016 (5) is already developed and several technical requirements are also fulfilled.

Amongst all it is essential to satisfy the requirement against voltage dips according to the Operational Procedure 12.3 and version PO 12.2 of certification and new specifications. Moreover, wind energy must provide solutions and services to ensure the stability and security of the electrical system (4).
In Figure 2 we show the distribution of wind and solar energy in the different regions according to their plans.

![Wind/solar energy distribution](image)

Figure 2. Wind/solar energy distribution according to the various regional Plans. Source: REE.

The coverage of electric demand in Spain due to the wind power is collected in Figure 3.

![Electric demand coverage](image)

Figure 3. Coverage of electric demand with wind power, 2009. Source: REE and AEE.
In November and December 2009, wind energy was again the second technology of the system with 4,663 GWh (23.6% more than in 2008) and 20.1% of production ahead of the 4,138 GWh produced by nuclear, which accounted for 17.4% of the total. On the morning of Wednesday December 30th, there was a new wind energy record reaching demand coverage of 54.1% at 3h50. The high wind production that morning, together with the high hydropower generation as a result of the reservoirs from recent rains, forced the REE Control Centre to technically minimize heat production.

These wind records must be added up to the wind energy production highs reached November 8th 2010: 11,620 MW of simultaneous power in operation, 11,429 MW/h of hourly wind production and 251,543 MW/h of daily wind production, being 44.9% of electricity demand that day. That same day, wind energy production covered from 03h00 till 08h30 53 per cent of demand in those hours that ranged between 21,700 and 19,700 MW.

Between 40 and 42.5 GW of wind power capacity are expected by 2020 according to the low and high scenarios of EWEA, 1-1.5 GW of which could be off-shore capacity. These predictions match well with the objectives of the Spanish Government. However, this big potential for wind power generation can lead to problems with power integration into the grid.

2.1.3 Challenges

The challenges to integrate wind energy in the generation and transport of electricity system are coming from the nature of wind. Wind energy is not fully manageable and electricity is not storable, therefore a dynamic and instantaneous equilibrium between generation and demand energy should be accomplished.

To follow the demand, fast-response and safe reserve power generation systems are needed to ensure the consumptions coverage every time. Wind power is not able to satisfy any of these requirements. Sometimes, its profile is opposite to the ramp of the demand curve. Therefore, the availability and reliability to cover peak loads are low. Wind power connects and disconnects to the grid without taking into account the network requirements, its variable behaviour with sharp ramps sometimes, the small reduction of the peak in summer and winter, and forecasts errors in the order of 20% rising with the prediction horizon time, makes very difficult to consider wind power as a firm power generation system but an energy resource.

In spite of all the improvements developed in the wind power systems and in the grid to adjust the increased wind power share, some mismatches can occur. Thus, in Spain in the early morning of November the 2nd 2008, indications were given to lower the wind power
production to maintain system stability near 2,800 MW, due to the inability to integrate all the wind for lack of sufficient demand (Figure 4).

Difficulties arise when large forecast errors occur that are not foreseen, even from updated forecasts. An example in Spain has been the 11th of November 2008 when the wind generation fell by more than 4,000 MW in 8 hours and achieving a minimum when the demand started growing (Figure 5).

These situations do not occur very often, but the system should be prepared anyhow. Other examples of extreme ramp rates recorded during storms are large ramp rates recorded for about 11 GW of wind power: 800 MW (7 %) increase in 45 minutes (ramp rate of 1,067 MW/h, 9 % of capacity), and 1,000 MW (9 %) decrease in 1 hour and 45 minutes (ramp rate - 570 MW/h, 5 % of capacity). Generated wind power between 25 MW and 8,375 MW have also occurred (0.2 %.72 % of capacity).

Figure 4. Disconnection of wind power during the morning, 2 November 2008. Source: REE.

Figure 5. Misbalance between wind power generation and electric consumption, November 11th 2008. Yellow: Real consumption, Green: Forecasts, Red: Committed. Source: REE.
2.1.4 Regulations and Tariffs


According to the Royal Decree 661/2007, owners of facilities operating before January 1st 2008 have a transition period of 5 years and can choose either to:

- remain under a transitional system and make a permanent election before January 1, 2009 to sell at a fixed tariff or at market price plus a premium; or

Wind farm operators which remain under the transitional system and decide to sell at a fixed tariff will be subject to the tariffs under RD 436/2004 for the operating life of the facility and wind farm operators that elect to sell at the market price plus a premium will receive the premiums and incentives established in the RD 436/2004 until December 31, 2012 and will then be transferred to the new regime.

Wind farm operators that fully accept RD 661/2007 may not return to the pricing system established under the transitional system.

Fixed Tariff

- RD 436/2004 - The price is set at between 80% and 90%\(^2\) of the Average Electricity Tariff (TMR) plus complements. The TMR is set annually by the Spanish Government. For instance, in 2007 the Average Electricity Tariff was 76.6 €/MWh.
- RD 661/2007 - The price is set at 73.2 €/MWh (2007 base price), for wind during the first 20 years plus complements reducing to 61.2 €/MWh (2007 base price) after 20 years of operation.

Market Price & Premium

- RD 436/2004 - The price is set at the pool price plus a premium (40% of the Average Electricity Tariff), incentives (10% of the Average Electricity Tariff) and complements.

\(^2\) P< 5 MW, 90% TMR 15 years; 80% rest

5 MW <P< 50, MW 90% TMR 5 years; 85% TMR 10 years; 80% rest
RD 661/2007 – The market tariff option is the sum of the market pool price, plus a market option premium, plus reactive energy remuneration, less any imbalance charges. The market option premium is 29.3 €/MWh (2007 base price). The market tariff option is subject to a cap and floor mechanism ranging between 71.3 and 84.9 €/MWh (2007 base price).

In the wind offshore case the maximum market option premium will be 84.3 €/Mwh with a cap in the market tariff of 164 €/MW.

The fixed tariff option, market option premium, market tariff cap and floor and the reactive energy remuneration are escalated annually by the Spanish consumer price index less 0.25% until the end of 2012 and IPC less 0.5% thereafter.

According to the RD 661/2007, the objective of 20,155 MW of wind power installed in 2012 was established as reference, which had been already achieved in 2010. Nowadays the Royal Decree 1/2012, of January 27th has cut this development, forcing all new Special Regime producers to trade into the electrical market outside the previous incentive mechanisms. The economic downturn is severely affecting also renewable energies. New legislation which has entered into force afterwards limits more and more the profitability of existing wind farms and even the feasibility of new ones, as the Law 15/2012, which sets a special tax on all electricity producers in amount of 7%, and Royal Decree 2/2013, revising the update of the feed-in tariff (to lower values).

### 2.2 Germany

#### 2.2.1 Wind Energy in Germany

The installed wind power generation capacity in Germany amounted to 25.8 GW at the end of 2009 (see Figure 6 and Table 3), being the second power generation after coal which had about twice the capacity in 2007 (sum of hard coal and lignite). Electricity generation from wind power amounted to 37,809 GWh in 2009 which is equivalent to about 6.5% of the gross electricity consumption. Wind energy thereby avoided some 30 million tonnes of CO₂ equivalent emissions.

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More than 42% of all wind power generation capacity is installed in the Federal States bordering the North Sea and the Baltic Sea, respectively (Niedersachsen, Mecklenburg-Vorpommern and Schleswig-Holstein plus the “City States” Bremen and Hamburg, see Table 3). Another 29% are located in Brandenburg and Sachsen-Anhalt, two States in the East with a largely flat topography. The 2009 figures for Niedersachsen in Table 3 include 60 MW representing the first German offshore wind farm, erected some 60 km off the coast.

![Figure 6. Annual and cumulative installed wind power in Germany 1990-2009. Source: (7).](image)

### 2.2.2 Objectives

Being a member of EU, Germany has agreed on the 20-20-20 goal, which includes a 20% share of renewable energy in total energy supply to be accomplished by 2020. In 2009, renewable energy contributed 10% to the final energy consumption (6).

Moreover, the official Government’s target for the share of renewable energy in gross electricity consumption is 30% at least by 2030, compared with 6.5% in 2009, as mentioned. Notwithstanding this target, the Government actually expects to achieve even 38.6% based on extrapolation of the development up to now. The latter figure was published recently when the national renewable energy action plan was agreed upon in August 2010 (8).
The German Renewable Energy Federation (Bundesverband Erneuerbare Energie, BEE) has also published a prognosis for the development of the renewable power. It claims that the renewables can cover 47% (278,000 GWh) of the electricity consumption by 2020. Installed green power is expected to rise to 111 GW, including 45 GW from wind turbines (9).

The Government has published an energy concept for the period up to 2050. It mentions hydrogen as an energy storage medium and emphasises the need for reinforcing the electrical network, respectively creating an efficient grid infrastructure for integrating renewable energy (10).


<table>
<thead>
<tr>
<th>Federal State</th>
<th>Accumulated on 31/12/08 (MW)</th>
<th>Newly installed in 2009 (MW)</th>
<th>Accumulated on 31/12/09 (MW)</th>
<th>Increase in 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niedersachsen</td>
<td>6016</td>
<td>451</td>
<td>6467</td>
<td>7.5%</td>
</tr>
<tr>
<td>Brandenburg</td>
<td>3768</td>
<td>403</td>
<td>4170</td>
<td>10.7%</td>
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<tr>
<td>Sachsen-Anhalt</td>
<td>3014</td>
<td>341</td>
<td>3354</td>
<td>11.3%</td>
</tr>
<tr>
<td>Nordrhein-Westfalen</td>
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<td>157</td>
<td>2832</td>
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<tr>
<td>Schleswig-Holstein</td>
<td>2665</td>
<td>193</td>
<td>2859</td>
<td>7.3%</td>
</tr>
<tr>
<td>Mecklenburg-Vorpommern</td>
<td>1431</td>
<td>67</td>
<td>1498</td>
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<tr>
<td>Rheinland-Pfalz</td>
<td>1207</td>
<td>94</td>
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<tr>
<td>Sachsen</td>
<td>851</td>
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<td>901</td>
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<tr>
<td>Thüringen</td>
<td>692</td>
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</tr>
<tr>
<td>Hessen</td>
<td>509</td>
<td>25</td>
<td>534</td>
<td>4.9%</td>
</tr>
<tr>
<td>Baden-Württemberg</td>
<td>422</td>
<td>30</td>
<td>452</td>
<td>7.0%</td>
</tr>
<tr>
<td>Bayern</td>
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<tr>
<td>Bremen</td>
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<td>95</td>
<td>7.7%</td>
</tr>
<tr>
<td>Saarland</td>
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<td>6</td>
<td>83</td>
<td>7.8%</td>
</tr>
<tr>
<td>Hamburg</td>
<td>34</td>
<td>12</td>
<td>46</td>
<td>35.6%</td>
</tr>
<tr>
<td>Berlin</td>
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<td>0</td>
<td>2</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23860</strong></td>
<td><strong>1917</strong></td>
<td><strong>25777</strong></td>
<td><strong>8.0%</strong></td>
</tr>
</tbody>
</table>

2.2.3 Challenges

So-called feed-in management of wind energy due to bottlenecks in the grid takes place since 2003. At times of high wind, the grid operator reduces the generation of wind farms or, if not part of a farm, individual wind turbines, in order to secure keeping the grid code. Feed-in management became first necessary in Schleswig-Holstein, the northernmost
of the German States with a grid relatively isolated from the rest of the country. Today, wind turbine operators in all States with a high share of wind energy can be affected. Since 2009, the Renewable Energy Act stipulates that the grid operator has to compensate wind energy producers for the electricity that was not produced due to feed-in management.

The challenges due to increasing shares of wind energy were first systematically addressed in a study commissioned by the German Energy Agency (Deutsche Energie-Agentur, dena) published in February 2005 (11). This “dena Grid Study”, commonly known as DENA I, developed scenarios for the expected installed capacities of renewable energy in 2007, 2010, 2015 and 2020 with a focus on wind. The scenarios accounted for the need to transport electricity from areas with high wind energy potential in the North and East to the centers of power consumption in the West and South. Based on the outcomes of the scenarios, requirements for upgrading and extending the grid were derived. An extension of the transmission grid (380/220 kV) by 850 km (corresponding to 5%) in several steps up to 2015 was identified as necessary, for example. It was also found that there was no need for erecting additional power stations for balancing and backup purposes before 2015.

DENA I was a consensus between the parties financing it, including grid operators and wind farm operators. Before it was finalized, there were heated debates, for example regarding parameters for economic calculations or boundary conditions that govern the (assumed) grid capacity4.

The grid extension measures as defined in DENA I are being realized although some of them with delay. On the other hand, the anticipated large offshore wind farms are implemented later than planned as well.

The original time frame of DENA I had been 2020. However, while the study was prepared it became apparent that a number of aspects becoming relevant from 2015 could not be investigated in sufficient detail within its scope. Accordingly, these aspects were only touched upon and a second study, DENA II was commissioned (in 2007) to develop a long-term plan for the integration of renewable energy into the German power grid (12).

4 As a consequence of the latter, temperature monitoring of high voltage lines based on measurements has become a standard procedure in recent year, instead of assuming, for example, 35°C ambient temperature and dead calm along the power transmission lines – limiting their capacity - at times of high wind speeds and thus high electricity generation at the wind farms.
The overall objective of DENA II is to investigate the integration of up to 39% of renewable energy in the German power supply system in the 2020/25 time frame. In its base scenario, 3,600 km of new extra high voltage lines have to be built by 2020/2025, at a cost of EUR 9.7 billion. Alternative scenarios would cost up to EUR 29 billion.

In addition to a base scenario with conventional use of the transmission assets, the study assesses two scenarios using different technologies, one using overhead line temperature monitoring, and the other high temperature conductor cables. The study also assesses high voltage direct current underground power cables. Until 2020, the scenarios lead to the following results:

- Conventional 380 kV scenario: 3,600 km of new lines, at a cost of EUR 9.7 billion;
- Temperature monitoring scenario: 3,500 km of new lines, upgrading of 3,100 km of existing lines, at a cost of EUR 9.8 billion;
- High temperature conductor cable scenario: 1,700 km of new lines, upgrading of 5,700 km of existing lines, at a cost of EUR 17 billion;
- High voltage direct current underground scenario: 3,400 km of new lines, at a cost of EUR 22 to 29 billion.

As a result of its study, DENA makes the following recommendations:

- Thorough assessment and planning of specific network expansion;
- Acceleration of permitting procedures and improvement of the legal framework;
- Measures to increase public acceptance for the necessary network expansion;
- Assessment of alternative transmission technologies in the framework of future network planning;
- Implementation of pilot projects for the use of selected technologies.

### 2.2.4 Regulations and Tariffs

Renewable energy is supported through the Renewable Energy Act (Erneuerbare-Energien-Gesetz; EEG). The EEG has been amended twice, so there are 3 versions according to the year of coming into force: EEG 2000 (13), EEG 2004 (14), and EEG 2009 (15). This section focuses on the latter, i.e. the current situation.
2.2.4.1 The EEG Basic Principles

For each kilowatt-hour that a wind turbine produces over 20 years from installation, a fixed tariff is paid. It depends on the calendar year of commissioning. The tariff has two stages:

- 1st stage: “high tariff”, for at least 5 years for onshore and 12 years for offshore wind turbines
- 2nd stage: “low tariff”, for the remainder of the 20-year period (on- and offshore).

The duration of the 1st stage is extended beyond the first 5 years if the actual yield of an installation falls short of a reference yield. The reference yield depends on the site and the turbine model.

A wind turbine commissioned in 2009 and matching the reference yield (or doing better) would thus earn 9.2 ¢/kWh over the first 5 years and 5.02 ¢/kWh thereafter (see Table 4, columns 2 and 5). A turbine commissioned in January 2010 would earn 9.11 ¢/kWh and 4.97 ¢/kWh, respectively. Inflation is not compensated for.

The extra costs generated by these tariffs are distributed equally among all consumers as a surcharge per kilowatt-hour consumed, except some electricity-intensive industries.

2.2.4.2 Remuneration of Onshore Wind Energy

EEG 2004 comprised adjustments of provisions and tariffs, according to technological progress and market developments. The tariffs for new installations were reduced accordingly from 1 August 2004 (see Table 4). Owing to a massive increase in prices of the wind turbine raw materials and components, EEG 2009 lifted the tariffs again.

EEG 2009 also substantiates the provisions for feed-in management including a clause on compensation, as discussed above (concerning both onshore and offshore generation).

2.2.4.3 Remuneration of Offshore Wind Energy

Tariffs can be found in Table 5. The 12-year duration of the 1st stage is further supplemented according to water depth and distance from the shore:

- 0.5 months for every nautical mile beyond 12 miles from the sea shore
- 1.7 months for every full meter depth increase beyond 20 meters.
2.2.4.4 Bonuses

EEG 2009 stipulates that energy from wind turbines commissioned before January 2014 receives a “system services bonus” of 0.5¢ per kWh if certain requirements regarding fault on the wind turbine side and on the grid side are fulfilled, in particular as regards maintaining voltage and frequency and providing reactive power.

In the past, wind turbines were obliged to disconnect from the grid, for example, in case of excess or low grid voltage. Modern installations have so-called fault ride through capacities that can help stabilizing the grid in critical situations.

EEG 2009 authorizes an ordinance that defines the criteria and financial incentives for “combined renewable energy power plants” that facilitate steady feed-in and/or demand-based feed-in. It is not clear yet when such bonus may be implemented. The next amendment of the EEG is currently planned to come into force at the beginning of 2012.

Table 4. Remuneration for onshore wind energy in Germany. Tariffs are guaranteed over 20 years after commissioning; remuneration depends on the calendar year of commissioning, see text for further explanation. Figures are based on the provisions in EEG 2000, EEG 2004, and EEG 2009.

<table>
<thead>
<tr>
<th>Year of Installation</th>
<th>EEG 2000 from 1 March</th>
<th>EEG 2004 from 1 August</th>
<th>EEG 2009 from 1 January</th>
<th>EEG 2000 from 1 March</th>
<th>EEG 2004 from 1 August</th>
<th>EEG 2009 from 1 January</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>9,10</td>
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<td>8,70</td>
<td>5,90</td>
<td>5,50</td>
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<td>5,60</td>
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<tr>
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<td>8,84</td>
<td>5,00</td>
<td>4,58</td>
<td>4,82</td>
</tr>
</tbody>
</table>
Table 5. Remuneration for offshore wind energy in Germany. Tariffs are guaranteed over 20 years after commissioning; remuneration depends on the calendar year of commissioning, see text for further explanation. Figures are based on the provisions in EEG 2004, and EEG 2009.

<table>
<thead>
<tr>
<th>Year of installation</th>
<th>EEG 2004 from 1 August</th>
<th>EEG 2009 from 1 January</th>
<th>EEG 2004 from 1 August</th>
<th>EEG 2009 from 1 January</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>9,10</td>
<td>6,19</td>
<td></td>
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</tr>
<tr>
<td>2005</td>
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<tr>
<td>2006</td>
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<tr>
<td>2007</td>
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<td>2008</td>
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<tr>
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<td>2018</td>
<td>7,26</td>
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<td>2,71</td>
</tr>
<tr>
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<td>7,12</td>
<td>9,78</td>
<td>4,87</td>
<td>2,57</td>
</tr>
<tr>
<td>2020</td>
<td>6,97</td>
<td>9,29</td>
<td>4,77</td>
<td>2,44</td>
</tr>
</tbody>
</table>
2.3 Denmark

2.3.1 Wind Power in Denmark

The electricity supply system in Denmark has changed dramatically over the last decades. 25 years ago about 15 central power plants supplied the entire demand for electricity in Denmark (disregarding exchange with neighboring countries) whereas today the electricity is generated by numerous wind turbines and local power plants in addition to the conventional central plants. As a result of restructuring the electricity supply in Denmark, wind turbines are now producing about 20% of the electricity demand on average and Danish authorities are planning for 50% in 2025.

After a period of stagnation by the start of the millennium the installation of wind power is now gaining speed again in Denmark. The development is partly illustrated by Figure 7, but a new trend/plan for installation of off-shore wind power is not reflected properly, as the numbers in the figure end by 2009. In 2009 a new wind farm - Horns Rev 2 with a capacity of 209 MW – was inaugurated and new farms have since then been put out for tenders and are now under construction (200 MW at Roedsand 2 + 400 MW at Anholt).

![Figure 7](image-url)

Figure 7. Accumulated installed wind power in Denmark since 1980. The green columns show the installed on-land capacity and the blue parts show the installed off-shore capacity. The red curve shows the share of wind power in the domestic Danish power demand. Source: Danish Energy Authority, www.ENS.dk.

Over the period shown in the above figure still larger wind turbines have been installed and today small old turbines are decommissioned and substituted by modern state-of-the-art turbines of typical size in the range 2-3 MW. This tendency is expected to continue, not the
least considering that more and more new installations will be off-shore wind farms, where large size is not an esthetical issue the same way as on land. Figure 8 shows the development.

![Figure 8. Development of size of installed turbines in Denmark.](image)

Figure 8. Development of size of installed turbines in Denmark. The data shows the general trend that still larger turbines are installed and this tendency is expected to continue. Source: Danish Energy Authority.

### 2.3.2 Objectives for wind power in Denmark

Aside from security of supply, energy savings and green growth, expanding the use of renewable energy in Denmark is central in the Danish energy policy as stated in the parliament agreement “Danish energy policy for the years 2008-2011” from February 2008 (www.ens.dk). As a step towards the long-term goal for a green-growth economy which is independent of fossil fuels, the Danish government is taking pains to deliver the ambitious goal of

- a share of 20% renewables in gross energy consumption by 2011
- at least 30% in final energy consumption by 2020, as stipulated in the EU climate and energy package
- a binding target of 10% renewable energy in the transport sector by 2020.

Furthermore the Danish TSO, Energinet.dk, is planning for 50% wind power in the Danish power supply by 2025 and scenarios are under consideration for 100% supply by 2050. Major contributions to this development should come from off-shore wind power installations, since off-shore locations offer the optimal wind conditions and since on-land locations are not always publicly well accepted in the densely populated regions of Denmark.
The energy agreement from February 2008 strongly improved framework conditions and enhanced support for wind power.

### 2.3.3 Challenges for wind power integration in Denmark

Electricity is a volatile commodity and has to be consumed at the same pace it is produced. In other words: production of electricity must be adapted to consumption at a very short notice if grid stability shall be maintained. Disturbances in production and changes in demand imply frequency deviations in the grid and to prevent such deviations the Transmission Service Operator (TSO – in Denmark Energinet.dk), who is the overall responsible entity for grid stability in the Danish power system, buys services (ancillary services) that can maintain the balance, when changes in demand or supply occur. Energinet.dk buys ancillary services from producers and consumers of electricity. Currently, a substantial part of the services are provided by owners of existing fossil power plants, e.g. conventional central power plants or de-central gas engines, which are active on the market for ancillary services.

One consequence of the increased share of wind power in the electricity supply is that stable, controllable fossil plants are substituted by variable, largely incontrollable generating capacity, which does not hold the same capability to provide (mandatory) ancillary services. Along this line the US Department of Energy has estimated\(^5\) that for every GW of wind power added to a system 17 MW spinning reserve must also be added to account for the system’s variability. In Denmark similar problems are foreseen and therefore an interest has emerged to clarify, which technologies could be suitable – technically and economically – for future provision of ancillary services in a Danish perspective.

In addition to problems about fast reserves and provision of ancillary services, the increasing share of wind power also introduces problems of a larger time scale. This problem is illustrated in Figure 9 where the present Danish wind power production - distributed over calendar months - is shown together with the corresponding electricity demand. The present wind production is based on approx. 3.7 GW installed capacity and if this capacity is multiplied to reach 18 GW (green curve), then the annual production is exactly equal to the annual demand (red curve). However, serious mismatches between the two curves can be

\(^5\) D. Link and C. Wheelock, Energy Storage Systems, Pike Research, 2010

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seen – some lasting for months and indicating a need for balancing means as represented by energy storage technologies like hydrogen technologies.

Ultimately, when Denmark reaches the goals of 100% fossil-free energy supply, also the transport sector of Denmark should be powered by renewable, probably bioenergy or wind energy. Today transport consumes almost 30% the total Danish energy demand and is virtually completely based on fossils. Wind power for transport would require vast application of appropriate storage technologies suitable for mobile purposes (high energy and power density). Here hydrogen or hydrogen-rich chemical compounds are likely to play a prominent role as they possess precisely the sought properties, somewhat in contradiction to battery technologies.

![Graph showing wind production and power demand in DK](image)

**Figure 9.** The graph shows the present wind power production in Denmark (blue curve) distributed over months of a year in addition to the total, national electricity demand (red curve). Furthermore, the green curve shows a projected curve for wind production if all the demand should be supplied by wind.

### 2.3.4 Regulations and tariffs

In the summer of 2008, the level of support for electricity produced from wind turbines was increased (www.ens.dk). The subsidy now varies depending on a number of factors such as the size of the turbine and time of connection to the grid.
New wind turbines - onshore as well as offshore - receive a price premium of 25 øre/kWh for 22,000 full load hours. Additional 2,3 øre /kWh (1 Euro cent = 7.5 øre) is provided in the entire lifetime of the turbine to compensate for the cost of balancing etc.

Household wind turbines below 25 kW receive a fixed feed in tariff of 60 øre /kWh.

For special wind farms at sea the subsidy is settled by a tender procedure. In previous tenders the Horns Rev 2 wind park of 200 MW ended at a fixed feed in tariff of 51,8 øre/kWh in 50,000 full load hours, while Roedsand 2 wind park of 200 MW ended at a fixed tariff of 62,9 øre/kWh for 50,000 full load hours.

Most recently, DONG Energy won the tender for the Anholt Offshore wind farm with a feed-in-tariff of 105,1 øre/kWh in 20 TWh (all data from www.ens.dk).
3 Impact of High Wind Energy Penetration on Power Systems

In the last ten years, wind power has increased its installed capacity dramatically from 5GW in 1995 to the current 280GW of installed capacity in 2012. This means that there are countries with a very high penetration of wind energy and others with very little or none wind. Even within the countries with a big share of wind, the situation can vary depending on the energy mix and the international interconnection capacities. For example, Denmark with a higher level of wind penetration, 20%, is also highly interconnected to its neighbours Norway, Sweden and Germany, being able to export or import 100% of its peak load.

Contrarily, Spain also with 20% of its energy coming from wind, has only round 2,5% of interconnection capacity with the UCTE through France, needing to solve any problem due to wind on its own (in some cases, Spain and Portugal are considered together as a single system, both sufficiently interconnected and both with a high wind penetration).

Depending on its own system characteristics, energy mix and interconnection capacity, each country chooses its own way of integrating wind energy and each case should be studied independently.

Wind energy has some special characteristics that may have a significant effect on the power system, the most important its intermittency and variability. The operation and capabilities of wind energy should be adapted to the system and this one should recognize the specific characteristics of the wind energy and adapt its operation and management rules to better integrate this new major energy source.

The impact of wind energy on the Power System affects to the operational security, reliability and efficiency and could be analysed from a technical and economical point of view. The impacts can be related to three focus areas: balancing, adequacy of power and grid as the IEA WIND task 25 group has shown in some results obtained from this international collaboration(16).

3.1 Balancing requirements

The current system operation is designed to follow load fluctuations at every moment and balancing mechanisms, being different kind of reserves as frequency containment reserves (FCR), frequency restoration reserve (FRR) and replacement reserve (RR), are based on forecasting values of wind power and load. This means that power station outages,
stochastic load variability and fluctuations of wind power injections are the main factors to take into account for controlling and balancing power.

The development of models for dynamical forecast uncertainty estimation as for wind power forecast are prioritised areas due to their applications concerning decision-making problems related to allocation of balancing power and reserve requirements, schedules of power generators and bidding strategies in electricity markets, among other issues. Therefore, the accuracy on forecasting wind energy influences the conventional capacity operation as well as the unit commitment.

### 3.2 Adequacy of Power

To estimate the required generation capacity, mainly during peak load situations, system load demand and maintenance of production units are taken into account with criteria as the loss of load expectation, the loss of load probability and the loss of energy expectation.

In power systems with increasing wind energy penetration and bigger power ratings, wind turbines and wind farms should assure the frequency stability of the system or fulfil the power and frequency control requirements. That means, in the future wind generation should provide ancillary services that includes the provision of primary, secondary and inertial energy (spinning reserve).

### 3.3 Grid

Wind power affects power flow in the grid and has a relevant influence in the voltage stability of the grid. The impact on the transmission network depends on the situation of wind farms relative to load and the correlation between wind power generation and energy consumption.

Wind turbine technology has been adapted to voltage stability requirements from the grid and manufactures provide their systems with power quality filters and FACTS or STATCOMS to control reactive power and to comply with the regulations of voltage quality.

Also wind farms are obliged to provide capabilities against fault ride through to maintain the grid stability in case of faults. Some codes require grid support with voltage dips of 0% for different times and many of the current wind turbines are already equipped with this specification.
In resume, in the last years the increase of wind energy connected to the power grid has been a challenge for Power System Operators and electricity markets. Nevertheless, a major integration of wind energy is possible if a mutual adaptation between system operation rules and new technical and economic capabilities is established.

Wind promoters and manufacturers have hardly worked to overcome most of the handicaps stated by Power System Operators. Thus, wind turbines have fault ride through capabilities, there are forecasting tools that allow wind to participate in markets assuming the balancing costs, the visibility and controllability of wind power generation have been increased and it is working on providing wind farms with voltage and frequency control capabilities or ancillary services.

The system has to be adapted also to the wind energy and so, systems are designed to face variations due to fluctuations of the load demand by means of tools whose capabilities can be improved to manage also variability of wind energy. The System Operator can control a complete collection of RES plants through control centres and improvements in forecasting wind generation can allow a better integration of wind energy in the electricity market.
4 Electricity storage systems

4.1 Introduction

Electricity storage is a well established concept yet still relatively unexplored. Storage systems such as Pumped-Hydroelectric Energy Storage (PHES) have been in use since 1929 (17) primarily to level the daily load on the network between night and day. As the electricity sector is changing, energy storage is starting to become a realistic option for (18):

1. Restructuring the electricity market
2. Integrating renewable resources
3. Improving power quality
4. Aiding shift towards distributed energy
5. Helping networks operate under more stringent environmental requirements

The main applications can be classified as bulk electricity storage, for the purpose of load-levelling or load management, distributed generation (DG) for peak shaving, power quality (PQ) or end-use reliability.

Electricity storage can optimise the existing generation and transmission infrastructures whilst also preventing expensive upgrades. Electricity storage devices can manage the power fluctuations from renewable resources and thus aid the use of several renewable technologies and their large-scale penetration into the network. In relation to conventional power production, energy storage devices can improve overall power quality and reliability, which is becoming more important for modern commercial applications. Finally, electric energy storage devices can reduce emissions by contributing to the transition to newer, cleaner technologies such as renewable resources as well as the hydrogen economy and distributed generation.

The different applications are distinguished by the power level and discharge time required. These specifications determine the stored energy requirements. Short-term, high-power electricity storage provides reliability and power quality for the digital economy where outages of a few cycles can lead to costly downtime. Long-term electricity storage can mitigate the effects of an overburdened electricity grid by peak shaving and load shifting, while reducing energy costs for consumers.

The main requirements for different applications are collected in Table 6.
Nevertheless, a number of obstacles have hampered the commercialisation of energy storage devices including:

1. Lack of experience and development state of technologies.
2. Inconclusive and difficult quantifying benefits in terms of savings and also power quality.
3. High capital costs due, among other causes, to the still small market.
4. Involvement for energy storage by Distribution or Transmission System Operator (DSO/TSO).

However, as renewable resources and power quality become increasingly important, costs and concerns regarding energy storage technologies are expected to decline. This report describes briefly the different types of electric energy storage devices currently available and the parameters used to describe an energy storage device and the applications they fulfil. Finally, a brief comparison of the various technologies is provided.

### Table 6. Requirements for Energy Storage Applications. Source: Sandia National Lab

<table>
<thead>
<tr>
<th>Application</th>
<th>Typical Power rating</th>
<th>Discharge time</th>
<th>Energy delivery</th>
<th>Frequency of use</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Support</td>
<td>100 MW</td>
<td>10 sec</td>
<td>100 MWs per pulse</td>
<td>1/month</td>
<td>$50-150/kW/yr</td>
</tr>
<tr>
<td>Area Regulation</td>
<td>20 MW</td>
<td>Continuous</td>
<td>2 MWh</td>
<td>Continuous</td>
<td>$700-1500/kW/yr</td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>20 MW</td>
<td>15 min.</td>
<td>2 MWh</td>
<td>1/month</td>
<td>$700-1500/kW/yr</td>
</tr>
<tr>
<td>Transmission Facility Deferral</td>
<td>10 MW/15 Mva</td>
<td>&gt;5 hrs.</td>
<td>50 MWh</td>
<td>100-200 days/yr</td>
<td>$50-150/kW/yr</td>
</tr>
<tr>
<td>Renewable Energy Management</td>
<td>5 MW</td>
<td>1-10 hrs.</td>
<td>1-10 MWh</td>
<td>10-20 days/month</td>
<td>$1000-1500/kW/yr</td>
</tr>
<tr>
<td>Commodity Storage</td>
<td>2 MW</td>
<td>3-4 hrs.</td>
<td>3-4 MWh</td>
<td>6/yr to daily</td>
<td>$120-250/kW/yr</td>
</tr>
<tr>
<td>Commercial Following Load</td>
<td>200 kW</td>
<td>3 hrs.</td>
<td>75-100 kWh</td>
<td>Daily</td>
<td>$10-20/kW/month</td>
</tr>
</tbody>
</table>

### 4.2 Electrical Energy Storage Technologies

There are a number of energy storage technologies that can help support the electric power industry. From electrochemical batteries and capacitors, electromechanical systems as flywheels, superconducting magnetic devices, pumped hydro and others, taken together
can support a wide range of electric power applications (19). In Figure 10 we can observe the ratings of energy storage systems (20).

![Figure 10. Ratings of Energy Storage Systems. Source: (20).](image)

### 4.2.1 Pumped Hydroelectric Energy Storage (PHES)

Pumped hydroelectric energy storage is the most mature and largest storage technique available. It consists of two large reservoirs located at different elevations and a number of pump/turbine units (Figure 11). During off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. Once required (i.e. during peak electrical production) the water in the upper reservoir is released through the turbines, which are connected to generators that produce electricity. Therefore, during production a PHES facility operates similarly to a conventional hydroelectric system.

![Figure 11. Pumped Hydro Energy Storage. Source: Hawaiian Electric Co.](image)
Pumped hydro is available at almost any scale with discharge times ranging from several hours to a few days. There are over 150 plants with 22,000 MW capacity in the United States alone and 90,000 MW of PSH installed worldwide, roughly 3% of the world’s global generating capacity. No PSH plant interconnected directly with a wind farm has been constructed to date.

Until recently, PHES units have always used fresh water as the storage medium. However, in 1999 a PHES facility using seawater as the storage medium was constructed (Figure 12). The specifications of Okinawa Seawater Pumped Storage Power Plant operated by Electric Power Development Co., Ltd. (J-POWER) are:

- Location - Okinawa Prefecture
- Output - 30 MW
- Effective Head - 136 m
- Maximum Turbine Discharge - 26 m$^3$/sec.
- Commencement of Operation - 1999
- Reservoir Type - Embankment dam, Rubber sheet lining
- Gross Storage Capacity - 0.59X106 m$^3$

Figure 12. Okinawa Seawater Pumped Storage Power Plant. Source: IEA Hydropower.

Their efficiency lies in the 70% to 85% range. The technology is considered a worthwhile addition to the electrical grid as the most cost effective means to date for storage
of mass amounts of electrical power. One of the immediate benefits of pumped hydro is its fast response to energy demands.

The main application of pumped hydro is the load levelling due to the large storage capacities and fast response. PHES systems can also be used for frequency regulation in both pumping and generation modes which allows PHES units to absorb power in a more cost-effective manner. That not only makes the facility more useful, but also improves the efficiency by approximately 3% \(^{(21)}\) and the life of the facility. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time. Finally, PHES provides a load for base-load generating facilities during off-peak production, hence, cycling these units can be avoided which improves their lifetime as well as their efficiency.

However, PHES facilities have also some disadvantages, due to the design requirements, they depend on specific geological formations, and therefore the facilities have very expensive cost and long times of constructing. Also, running at part load is very limited.

### 4.2.2 Compressed Air Energy Storage (CAES)

Off-peak electricity can be used to power a motor/generator that drives compressors to force air into an underground storage reservoir. This process typically occurs when utility system demands and electricity costs are the lowest. When electric power demand peaks during the day, the process is reversed. The compressed air is returned to the surface, heated by natural gas in combustors and run through high-pressure and low pressure expanders to power the motor/generator to produce electricity.

The main components are: a power train motor that drives a compressor (to compress the air into the cavern), high pressure turbine (HPT), a low pressure turbine (LPT), and a generator.
In conventional Gas Turbines (GT), 66% of the gas used is required to compress the air at the time of generation. Therefore, CAES reduces the natural gas consumption compared to a conventional GT plant since it pre-compresses the air using off-peak electrical power which is taken from the grid to drive a motor and stores it in large storage reservoirs. As a result, instead of using expensive gas to compress the air, cheaper off-peak base load electricity is used.

When the GT is producing electricity during peak hours, the compressed air is released from the storage facility and used in the GT cycle.

However, the air from the cavern must be mixed with a small amount of gas before entering the turbine because the temperature and pressure of the air would be problematic. Nevertheless, the amount of gas required is so small that a GT working simultaneously with CAES can produce three times more electricity than a GT operating on its own, using the same amount of natural gas.

It is difficult to predict CAES efficiency since it uses both electrical energy and natural gas but it is estimated that the efficiency of the entire cycle can reach 64% to 75% depending also of the technologies involved and the configuration (21), (22). Despite only two CAES plants have been built worldwide until now, there are some others planned for next years and their capacities are in the region of 50 MW – 300 MW. The life of these facilities is far longer than existing gas turbines and the charge/discharge ratio is dependent on the size of the compressor used, as well as the size and pressure of the reservoir.
The first and longest operating CAES facility in the world is near Huntorf, Germany (1978). The 290 MWac (2 hours) Huntorf plant functions primarily for cyclic duty, ramping duty, and as a hot spinning reserve for the industrial customers in northwest Germany (Figure 14) and also for peak shaving in the evening, when no more pumped hydro is available (23). This plant has a capacity reservoir of 310,000 m³. The cavern operates between 50 and 70 bar. Recently, this plant has been successfully levelling the variable power from numerous wind turbine generators in the north of Germany.

The Huntorf plant has an efficiency of 42%. It was built when costs for natural gas were low so recuperation of exhaust gas heat was not implemented. Otherwise, it could have achieved 54% (24).

![Figure 14. Huntorf (Germany) CAES plant. Source: (25)](image)

The only CAES facility in the U.S.A., a 110 MWac (26 hours, 500,000 m³, 45 – 76 bar) plant near McIntosh, Alabama, performs a wide range of operating functions; namely, load management, ramping duty, generation of peak power, synchronous condenser duty and spinning reserve duty (Figure 15). This plant has heat recuperation implemented and accomplishes 54% efficiency (26).
Both existing plants do not use the heat that results from air compression then the underground storage is charged. They are of diabatic type. An adiabatic compressed air energy storage facility (ACAES) would store this heat and utilise during air expansion, substituting heat from natural gas burning. Concept studies indicate efficiencies of around 70% (27).

Usually, CAES locations are natural geological formations that include salt-caverns, hard-rock caverns, depleted gas fields or an aquifer so these systems have some concerns regarding the emplacements.

The main application and advantages of CAES are:

- The CAES plant is a technology that can provide significant energy storage (in the thousands of MWhs) at relatively low costs. The plant has practically unlimited flexibility for providing significant load management at the utility or regional levels.

- The CAES technology can be easily optimized for specific site conditions and economics. There are commercial turboexpander units range in large size from 10 -20 MWac to 300-400 MWac.

- CAES consists on several well-known technologies as generators, compressors or gas turbines which can be delivered by a large number of suppliers but the whole system has not yet proved, concretely the new adiabatic designs.

- CAES plants are capable of black start and fast start-up time. If a CAES plant is operated as a hot spinning reserve, it can reach the maximum capacity within a few minutes. The emergency start-up times from cold conditions at the Huntorf and McIntosh plants are about 5 minutes. Their normal start-up times are about 10 to 12 minutes.

- CAES plants have a ramp rate of about 30% of maximum load per minute.
CAES plants also excel at part load. Their heat rate at 20% of maximum load is 80% of the nominal heat rate at maximum load. This is very good and unique, since all other oil, gas, and coal power plants have poor efficiency at 20% of maximum load, making them uneconomical for operation at part load for normal duty. This characteristic of CAES plants make them very useful (and efficient) for ramping, part load, and regulation duty.

A CAES plant can (and does) operate as a synchronous condenser when both clutches are opened (disconnecting the motor-generator from both the compressor train and the expander train), and the motor-generator is synchronized to the grid. VARS (reactive power) can be injected and withdrawn from the grid by modulating the exciter voltages. Since this operation does not require the use of stored air, the plant operator can choose to operate the plant in this mode for as long as necessary.

The main disadvantages are the emplacement availability and specific requirements as large size, close to the grid or able to retain compressed air long time so, capital costs are very high for CAES systems. Also, CAES uses electricity and fossil fuels so the emissions and safety regulations are similar to conventional gas turbines.

### 4.2.3 Electric Energy Storage in Batteries

Electricity is stored as chemical energy in batteries where two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

#### 4.2.3.1 Lead acid battery

Lead acid is one of the oldest and most developed battery technologies. It is a low cost and popular storage choice for power quality, UPS and some spinning reserve applications. Its application for energy management, however, has been very limited due to its short cycle life. The amount of energy (kWh) that a lead-acid battery can deliver is not fixed and depends on its rate of discharge.

Both the power and energy capacities of lead-acid batteries are based on the size and geometry of the electrodes. The power capacity can be increased by increasing the surface area for each electrode, which means greater quantities of thinner electrode plates in the battery. However, to increase the storage capacity of the battery, the mass of each electrode must be increased, which means fewer and thicker plates. Consequently, a compromise must be met for each application.
These batteries can respond within milliseconds at full power. The average DC-DC efficiency of a lead-acid (LA) battery is 75% to 85% during normal operation, with a life of approximately 5 years or 250-1,000 charge/discharge cycles, depending on the depth of discharge. Charge/discharge efficiencies for lead-acid batteries are 60 – 95% with low self-discharge rates. Because of the high density of the materials used in these batteries, the typical energy densities are lower than other batteries at 25 – 45 Wh/kg.

The requirements of new large-scale storage devices would significantly limit the life of a LA battery. Consequently, a lot of research has been directed towards other areas. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi-MW applications.

Nevertheless, there are some examples of large scale applications:

The largest one is a 40 MWh system in Chino, California built in 1988. It contains four million pounds of lead, was put into load-leveling service in 1988 at the Chino substation of Southern California Edison Company, and has a discharge capacity of 10 megawatts over a four-hour period. Since going on-line, the system has proven to be 100% reliable in meeting daily deep cycle requirements.
Figure 17. Chino Battery Facilities, 10 MW, 4 h. Source: Tecnalia Corporación Tecnológica.

The 8.5 MWh BEWAG plant in Berlin, was constructed in 1986 when West Berlin was essentially an ‘electrical island’ in the East. The BEWAG system provided a crucial spinning reserve and frequency regulation functionality.

The 5 MWh Vernon Plant at Exide Technologies’ lead-acid battery recycling facility in California. The $4 million system was installed in 1996 and serves primarily as an Uninterruptable Power Supply (UPS). If the recycling facility loses utility power, the battery energy storage system instantly provides up to 5 MW of power to support critical infrastructure. If necessary, the system can operate the whole plant for up to one hour. The system is also used for peak shaving.

The 1.4 MWh Metlakatle plant (installed in 1997 and operated by Metlakatla Power and Light) was used to condition the hydroelectric current that powers a sawmill in a rural island community. Although the sawmill has now closed, prior to the installation of the battery storage system, the sawmill operators transported diesel fuel by boat to the island to run a back-up generator. During the course of its operation, the battery storage system saved close to 90% of the mill’s annual energy costs.

The Puerto Rico Electric Power Authority currently operates the largest lead-acid Battery Energy Storage System in the world with an output capacity of 20 MW and 14 MWh of stored energy. Due to surging demand from petrochemical industries in the 1960s and 70s, the Puerto Rico Electric Power Authority built new generating capacity in large 400 MW units. Each one of these units represents approximately 10% of the average load on the island system. Automatic load shedding was the only way to reduce overload and control
frequency during an unscheduled outage. The system is now being expanded by another 20 MW module, with an eventual capacity of 100 MW.

4.2.3.2 Nickel-Cadmium battery

Nickel Cadmium (Ni-Cd) batteries use cathodes made from nickel and anodes from cadmium, as the name implies. The positive electrode is made up with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divide. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. They have the capability to withstand a huge number of full charge/discharge cycles, in the range of 500 to 1000, without deteriorating past the point of usefulness. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery.

Ni-Cd batteries have been produced since the early 20th century and formed the majority of the rechargeable battery market in consumer electronics by the 1990s.

Ni-Cd batteries are also relatively lightweight, have a good energy storage density (although about half that of alkaline cells), and tolerate trickle charging when properly designed. Nickel Cadmium batteries have a very low internal resistance - meaning they can create high currents - which changes little as the cell discharges. Consequently, this battery produces a nearly constant voltage until it becomes almost completely discharged, at which point its output voltage falls precipitously.

There are two NiCd battery designs: vented and sealed. Sealed NiCd batteries are the common, everyday rechargeable batteries used in a remote control, lamp etc. No gases are released from these batteries, unless a fault occurs. Vented NiCd batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low-pressure release valve making the battery safer, lighter, more economical, and more robust than sealed NiCd batteries.

The DC-DC efficiency of a NiCd battery is 60%-70% during normal operation although the life of these batteries is relatively high at 10 to 15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1,000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3,500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. At small Depth of Discharge (DoD) rates (approximately 10%) NiCd batteries have a much longer cycle life (50,000 cycles) than other batteries such as LA batteries. They can also operate over a much wider temperature
range than LA batteries, with some able to withstand occasional temperatures as high as 50°C.

NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures. However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems.

These batteries have also some disadvantages since their life can be reduced due to rapid charge/discharge cycles and NiCd batteries suffer from ‘memory’ effects and also lose more energy during due to self-discharge standby than LA batteries, with an estimated 2% to 5% of their charge lost per month at room temperature in comparison to 1% per month for LA batteries. Also, cadmium is a toxic material which creates a number of problems for disposing of the batteries.

One project using this kind of batteries is the Golden Valley Electric Association Saft 40 MW Nickel-Cadmium Battery System. In August 2003, the world’s largest battery energy storage system (BESS) went online in Alaska. Engineered by Swiss-Swedish ABB Ltd. with Saft Industrial Batteries the system is capable of supplying 40 MW of power and should help reduce the risks of blackouts by more than 60%, according to ABB.

The battery, comprised of 13,760 high performance nickel-cadmium cells in four strings, will form the heart of the BESS to provide continuous voltage support during normal operation as well providing energy back-up, known as ‘spinning reserve’, to respond quickly during system disturbances to reduce customer interruptions.

Back-up power is essential to the local population in Fairbanks, due to the extremely low temperatures, which can fall to -51°C in the winter. At -40 °C a dwelling without power for two hours will begin to experience frozen pipes.
4.2.3.3 Lithium ion battery

Lithium Ion (Li-ion) batteries have a cathode of a lithiated metal oxide (LiCoO$_2$, LiMO$_2$, etc) and an anode of graphitic carbon with a layer structure. The electrolyte is made up of lithium salts (such as LiPF$_6$) dissolved in organic carbonates. When the battery is being charged, the Lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. This process is reversed during discharge.

Li-ion batteries have a three-layer structure consisting of an insulating porous separator sandwiched between sheet-like cathode and anode materials, which, in the case of a prismatic cell, are wrapped around in an elliptical form. These materials are impregnated in an electrolyte and sealed in a metal case. This metal case forms the anode pin (or cathode pin in the case of an aluminium case). The top of the battery includes the cathode pin (or anode pin in the case of an aluminium case) as well as a safety vent to protect the battery by releasing gas externally if the pressure inside the cell builds up to extreme levels.
Li-ion batteries have a higher energy density than most other types of rechargeable. This means that for their size or weight they can store more energy than other rechargeable batteries. Li-ion and Li-pol batteries offer high charge densities of 100 – 150 Wh/kg. Nanocomposite electrode systems may offer even higher energy densities.

They also operate at higher voltages than other rechargeable batteries typically about 3.7 volts for lithium-ion vs. 1.2 volts for NiMH or NiCd. This means a single cell can often be used rather than multiple NiMh or NiCd cells.

Lithium-ion batteries also have a lower self discharge rate than other types of rechargeable batteries. NiMH and NiCd batteries can lose anywhere from 1-5% of their charge per day, (depending on the storage temperature) even if they are not installed in a device. Lithium Ion batteries will retain most of their charge even after months of storage. This advantage had led Li-ion batteries to take over 50% of the small portable market in a few years. Charge/discharge efficiencies much higher than of 90% are reported for Lithium batteries.

A Li-ion system’s lifetime should be on the order of 2,000 cycles, or six to ten years but there is no long-range operational information as well as for efficiency that it is estimated on 0.85.

There are some challenges for making large-scale Li-ion batteries. The main hurdle is the high cost (above $600/kWh) due to special packaging and internal overcharge protection circuits. The protection circuits are needed to stop charging when the voltage exceeds the...
specified maximum value in order to prevent the battery from overheating or exploding due to overcharging.

In addition, energy storage requires discharge rates that push the envelope of safe operation of liquid-filled lithium ion batteries. Current densities tolerable in small cells create unacceptable safety concerns in large capacity batteries, particularly at high power levels, because solvent-lithium reactivity, heat, and solvent volatility can generate explosive or pyrotechnic mixtures. Electrolyte conductivity and stability limit safe power levels and remain dominant limitations to battery performance.

There are no large Li-ion battery installations at this time. They are primarily used for laptop computers and a variety of small applications and the largest installation under construction in the U.S. today is a 100 kW, one-minute system. However, several companies are working to reduce the manufacturing cost of Li-ion batteries to capture large energy markets.

4.2.3.4 Sodium-Sulphur battery (NaS)

These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid $\beta$-alumina. During discharge, positive $\text{Na}^+$ ions flow through the $\beta$-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide and electrons flow in the external circuit of the battery producing about 2 volts. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally-insulated enclosure that must keep it above 270°C, usually at 320 °C to 340°C.
NaS batteries have a relatively high energy density, within the range 150 – 240 Wh/kg (28). NaS has significant potential to become a cost-effective, modular, and portable bulk storage medium as it is specifically designed for long discharge cycles (8 hours), but has the capacity to discharge very rapidly and at multiples of rated power with pulse power capability over six times their continuous rating (for 30 seconds). This capability makes NaS batteries very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades.

The cycle life is much better than for LA or NiCd batteries. These batteries have an estimated lifetime of 15 years with a cycle life at 100% DoD of approximately 2,500 cycles. As with other batteries, this increases as the DoD decreases; at 90% DoD the unit can cycle 4,500 times and at 20% DoD 40,000 times. The average round-trip energy efficiency of a NaS battery is 86% to 89%.

The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270 °C. It is not only energy consuming, but it also brings with it problems such as thermal management and safety regulations. Also, due to harsh chemical environments, the insulators can be a problem as they slowly become conducting and self-discharge the battery.

Research and development into NaS batteries has been pioneered in Japan since 1983 by the Tokyo Electric Power Corporation (TEPCO) and NGK. As of 2004 there were 59 NaS energy storage systems with capacities rated greater than 500 kW (29). In total, more than 100 MW of NaS energy storage capacity has been installed, mostly in Japan where this energy storage technology is a commercial reality.
Some examples of facilities based on NaS batteries are:

- A 6 MW, 8 h unit has been built by Tokyo Electric Power Company (TEPCO) and NGK Insulators, Ltd., in Tokyo, Japan with an overall plant efficiency of 75% and is thus far proving to be a success (Figure 21). The NaS battery has the potential to be used on a MW scale by combining modules. Combining this with its functionality to mitigate power disturbances, NaS batteries could be a viable option for smoothing the output from wind turbines into the power grid.

![Figure 21. 6 MW, 8 h NaS energy storage facility in Tokyo, Japan. Source: (18)](image)

- American Electric Power (AEP) conducted the first grid-connected demonstration of sodium sulphur technology in the USA. The project commenced in 2002 and in collaboration with Electric Power Research Institute, the US Department of Energy, TEPCO, NGK and ABB. The system is rated at 100 kW for peak shaving or load levelling over about seven hours and up to 500 kW for short term power quality mitigation. In September 2007 AEP ordered three new NaS battery installations that together will total 6 MW and will be installed in West Virginia and Ohio.

### 4.2.4 Flow batteries

Flow batteries or regenerative fuel cells store and release electricity through a reversible electrochemical reaction between two salt solutions (electrolytes) and can be optimized for either real power (MW) or reactive power (MVAR). Unlike conventional batteries, the redox flow cell stores energy in the solutions, so that the capacity of the system is determined by the size of the electrolyte tanks, while the system power is determined by
the size of the cell stacks. They have a high speed of response, supply real and reactive power and are therefore suited to many different applications on a power system.

There are two main commercial types of flow batteries: vanadium (VRB) and zinc bromine (ZnBr).

The Vanadium Redox Batteries store energy by interconnecting two forms of vanadium ions in a sulphuric acid electrolyte at each electrode; with V$^{2+/3+}$ in the negative electrode, and V$^{4+/5+}$ in the positive electrode. During the charge/discharge cycles, protons are exchanged between the two electrolyte tanks through the hydrogen-ion permeable polymer membrane. The cell voltage is 1.4-1.6 volts.

![Vanadium Redox Battery](source)

Most of the advantages of the vanadium redox battery are due to the use of the same element in both half-cells which avoids problems of cross-contamination of the two half-cell electrolytes during long-term use. This means that the electrolytes have an indefinite life so that waste disposal issues are minimized. Long life is assured even with repeated deep charging/discharging.

Because output (cell section) and capacity (tank section) can be separated, layout can be altered according to the place of installation. Longer-hours charging/discharging are possible by simply increasing the volume of electrolyte.

Charging and discharging can respond within one thousandth second. Since use at high-power output of more than twice as high as standard output is possible for short-time charging/discharging (up to several minutes), stable power quality can be secured against instantaneous voltage sag. Nevertheless, they also can be used for every energy storage requirement including UPS, load levelling, peak-shaving, telecommunications, electric utilities and integrating renewable resources.
Because the electrolyte is supplied to each battery cell from the same tank, the charging status of each battery cell is the same. Therefore, special work such as uniform charging is not required. Also, handling is safe because operating temperature is room temperature, with efficiency as high as 85% and as the same chemical reaction occurs for charging and discharging, the charge/discharge ratio is 1:1.

However, VR batteries have the lowest power density and require the most cells (each cell has a voltage of 1.2 V) in order to obtain the same power output as other flow batteries. For smaller-scale energy applications, VR batteries are very complicated in relation to conventional batteries, as they require much more parts (such as pumps, sensors, control units) while providing similar characteristics.

There are several projects around the world including VRB technology. For instance, in 2004, VRB Power Systems Inc. installed a VRB Energy Storage System (VRB/ESS) in Moab, Utah for PacifiCorp for load-leveling (peak shaving) device. The system consists of a 250 kW times 8h energy storage module connected to a 25 kV rural feeder providing voltage support and power flow control. As a result of the ESS, feeder deviations have improved by 2%, and the power factor improvement has reduced line losses by 40 kW.

![Figure 23. Pacific Corp. Facilities, Vanadium Redox Battery 250 kW, 8 h. Source: Tecnalia.](image)

In ZnBr battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a microporous polyolefin membrane. Unlike VRB, the electrodes in a ZnBr flow battery act as substrates to the reaction.

During charging the electrolytes of zinc and bromine ions (that only differ in their concentration of elemental bromine) flow to the cell stack. As the reaction occurs, zinc is
Electrolyte is added to the electrolyte to reduce the reactivity of the elemental bromine, reducing the self-discharge of the bromine and improving the safety of the entire system. During discharge, Zn and Br combine into zinc bromine, generating 1.8 volts across each cell, the highest energy density of all the flow batteries. This will increase the Zn\(^{2+}\) and Br\(^{-}\) ion density in both electrolyte tanks. The net efficiency of the system is about 75% or 80%.

![Zinc Bromine Flow Battery](image)

Figure 24. Zinc Bromine Flow Battery. Source: ZBB

ZnBr batteries can operate in a temperature range of 20°C to 50°C. Heat must be removed by a small chiller if necessary. No electrolyte is discharged from the facility during operation and hence the electrolyte has an indefinite life. The membrane however, suffers from slight degradation during the operation, giving the system a cycle life of approximately 2,000 cycles. The ZnBr battery can be 100% discharged without any detrimental consequences and suffers from no memory effect. Once again, as the same reaction occurs during charging and discharging, the charge/discharge ratio is 1:1, although a slower rate is often used to increase efficiency.

The zinc/bromine battery offers 2 to 3 times the energy density (75 to 85 watt-hours per kilogram) compared to present LA batteries. The power characteristics of the battery can be modified, for selected applications. Therefore, the zinc/bromine battery has operational capabilities which make it extremely useful as a multi-purpose energy storage option. It is capable of smoothing the output fluctuations from a wind farm or a solar panel, as well as providing frequency control. Installations currently completed have used ZnBr flow batteries for UPS, load management and supporting microturbines, solar generators, substations and T&D grids.
There are several pilot plants in USA and Australia using ZnBr batteries. One interesting project is the one developed in June 2002, when ZBB shipped a 500 kWh system to be installed on a remote utility distribution line of Australian Inland Energy (AIE) in New South Wales, Australia. The storage system operates in conjunction with AIE’s refurbished 20 kW PV concentrator dishes at White Cliffs. The system was designed to sustain a 300-amp discharge at an average 480 volts for 4 hours. The system was able to store electricity generated by the array of PV concentrating solar dishes, tested by AIE. The battery is charged by the solar dishes during the day in order to provide reliable night-time power to remote area property owners.

4.2.5 Flywheel

Flywheels are a mechanical form of energy storage in which electricity is stored as kinetic energy. A FES (Flywheel Energy Storage) device is made up of a central shaft that holds a rotor and a flywheel. Flywheels store energy by accelerating the rotor/flywheel to a very high speed and maintaining the energy in the system as kinetic energy. Flywheels release energy by reversing the charging process so that the motor is then used as a generator. As the flywheel discharges, the rotor/flywheel slows down until eventually coming to a complete stop.

A flywheel energy storage system draws electricity from a primary source to spin the high density cylinder at speeds greater than 20,000 rpm. Modern flywheel systems are typically comprised of a massive rotating cylinder, supported on a stator by magnetically levitated bearings that eliminate wear and extend system life compared with conventional bearings. To increase efficiency, the flywheel is operated in a low pressure environment to reduce friction with the air.

The power and energy capacities are decoupled in flywheels. In order to obtain the required power capacity, you must optimise the motor/generator and the power electronics. These systems, referred to as ‘Low-speed flywheels’, usually have relatively low rotational speeds, approximately 10,000 rpm and a heavy rotor made from steel. They can provide up to 1,650 kW, but for a very short time, up to 120 s.
When the rotor speed is increased, the systems are referred to as 'High-speed flywheels', spin on a lighter rotor at much higher speeds, with the fastest flywheels commercially available spinning at about 80,000 rpm. They can provide energy up to an hour, but with a maximum power of 750 kW.

Flywheels have a quoted energy density of 50 – 100 Wh/kg, an efficiency of around 90%, dependent on the speed range of the flywheel (30) and the charge-to-discharge ratio is 1:1.

These systems have also some disadvantages as they are kept in a vacuum during operation and it is difficult to transfer heat out of the system, so a cooling system is usually integrated with the FES device. Low-speed flywheels may be able to provide high power capacities but only for very short time period, and high-speed flywheels the opposite. Finally, FES devices also suffer from the idling losses but they are usually less than 2% per day.

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. While typical flywheel applications are for standby power, flywheels can also be used for load levelling applications because they can operate through thousands of cycles. Also they can be used to provide ride-through power instantly until a generator or microturbine can assume the load for an extended outage. In general, flywheels are used for power quality enhancements such as Uninterruptable Power Supply (UPS), capturing waste energy that is very useful in electric
vehicle applications and finally, to dampen frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines.

There are no projects with flywheels linked to wind farms in large scale but the concept is being studied. Nevertheless, there are some examples of flywheels as the 100 kW UPT pq management system from Urenco Power Technologies to assess and evaluate it for power quality applications, acquired by Italian CESI corporation. The UPT pq system ensures that the television or lighting relay transmitter is never off-air because of power supply outages due to thunderstorms.

4.2.6 Supercapacitors

Supercapacitors are created by using thin film polymers for the dielectric layer and carbon nanotube electrodes. They use polarised liquid layers between conducting ionic electrolyte and a conducting electrode to increase the capacitance. They can be connected in series or in parallel. Supercapacitors store energy in the electric field between a pair of charged plates.

Supercapacitors (SCES) are capable of very fast charging and discharging times, and are able to go through many cycles without degradation, more than $10^6$ cycles. Supercapacitor systems usually have energy densities of 20 MJ/m$^3$ to 70 MJ/m$^3$, with an efficiency of 95%. In comparison to batteries, supercapacitors have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous substances.

SCES has a very low energy storage density leading to very high capital costs for large scale applications. Also, they are heavier and bulkier than conventional batteries. The self-discharge of the supercapacitor is substantially higher than that of the electro-chemical battery. Supercapacitors with an organic electrolyte are affected the most. In 30 to 40 days, the capacity decreases from full charge to 50 percent. In comparison, a nickel-based battery discharges about 10 percent during that time.
SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load levelling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute.

Ultracapacitor-based energy storage has been primarily used for hybrid electric vehicle applications (31), to provide instantaneous energy during engine acceleration; also in DC traction systems to operate as a shock absorber to reduce voltage sags on the DC bus (32). Recent demonstration projects, e.g. "capacitor-stabilized soft-transfer interface system" conducted by EPRI (33), and "Ultracapacitor EnergyBridge™" technology introduced by Northern Power Systems, (34), have investigated Ultracapacitor-based energy storage applications for distribution systems. However, the sizing issue and design of an efficient energy storage medium for these applications imply that in-depth analysis of the system characteristics is required.

**Palmdale Power System**

Figure 26. Maxwell MC and BC ultracapacitor cells and modules. Source: Maxwell Technologies.

Figure 27. Palmdale Power System scheme. Source: Microgrids group at Berkeley Lab.
Probably the most interesting project is the Palmale Power System (Figure 27) which includes 950 kW of wind power, 1,800 kW of diesel generation, 200 kW of natural gas, and 250 kW of hydroelectric. The load is 1.25 MW with 400 kW critical and the supercapacitors are 450 kW for 20-60 seconds for wind power output smoothing and emergency reserves.

4.2.7 SMES

A Superconducting Magnetic Energy Storage (SMES) system is a device for storing and instantaneously discharging large quantities of power. The SMES systems store energy in the magnetic field created by the flow of direct current in a coil of superconducting material that has been cryogenically cooled.

![Figure 28. 2 MJ SMES developed by ACCEL. Source: ACCEL](image)

In general, when current is passed through a wire, energy is dissipated as heat due to the resistance of the wire. However, if the wire used is made from a superconducting material such as lead, mercury or vanadium, zero resistance occurs, so energy can be stored with practically no losses. Material properties are extremely important as temperature, magnetic field, and current density are pivotal factors in the design of SMES.

The overall efficiency of SMES is in the region of 90% to 99%. SMES has very fast discharge times, but only for very short periods of time, usually taking less than one minute for a full discharge. Discharging is possible in milliseconds if it is economical to have a PCS that is capable of supporting this. Storage capacities for SMES can be anything up to 2 MW, although its cycling capability is its main attraction. SMES devices can run for thousands of
charge/discharge cycles without any degradation to the magnet, giving it a life of more than 20 years.

The most significant disadvantage of SMES is its sensitivity to temperature. A very small change in temperature can cause the coil to become unstable and lose energy. Also, the refrigeration can cause parasitic losses within the system. Finally, although the rapid discharge rates provide some unique applications for SMES, it also limits its applications significantly. As a result, other multifunctional storage devices such as batteries are usually more attractive.

These systems have been in use for several years to solve voltage stability and power quality problems for large industrial customers. SMES systems increase transfer capacity and protect utility grids from the destabilizing effects of short-term events such as voltage dips caused by lightning strikes and downed poles, sudden changes in customer demand levels and switching operations. In many cases, D-SMES is a cost-effective way to reinforce a transmission grid without the costly and environmentally intrusive construction of new lines.

There are some examples of applications of SMES but none of them with renewable energies. One interesting project has been developed by Wisconsin Public Service (WPS), which decided to increase the capacity in existing transmission lines to handle its estimated 15% growth in demand, in lieu of constructing additional lines. Increasing load on the system's northern transmission loop gradually caused the network to experience voltage instability problems, including momentary voltage depressions. Rapidly increasing load conditions in the largely rural region posed significant stability threats as well as the high concentration of paper mills in the region, with large inductive motor loads that give real and reactive power losses over lengthy transmission lines, made voltage recovery more problematic.

A multiple-unit D-SMES system was installed on the WPS power grid in July of 2000. That summer, the D-SMES system provided successful carryover through a variety of two and three phase disturbances, including a lightning strike, that otherwise could have triggered a wide-area blackout. Perhaps more importantly, the installation solved the stability problem at a cost of under $5 million that would have otherwise required a $12 million upgrade spread out over several years. D-SMES provides an effective solution for WPS' instability problem while increasing grid capacity by 15%.
4.2.8 Hydrogen

Hydrogen is one of the most promising energy storage techniques available. Hydrogen, however, is not a system but an energy carrier so it displays numerous applications in addition to the storage of electricity. Hydrogen is a gas, used for long-time as chemical in several industries as petrochemical, food, pharmacological, etc. This gas must be generated, because is not a natural resource or primary energy, stored in different ways and finally, it can be used as chemical, fuel or energy storage system.

There are many options to produce hydrogen from fossil fuels, mainly natural gas, and from renewable energies mainly by water electrolysis from wind power. It is possible to store hydrogen as compressed gas, cryogenic liquid or even in solid state with hydrides and finally, hydrogen can be reconverted into electricity or thermal energy with gas turbines and internal combustion engines (ICE) adapted for hydrogen and with the especially developed technology, the fuel cells.

In this task 24, we have focused our analysis on the hydrogen chain: water electrolysis from wind power (in different scales), storage as compressed gas and reconversion into electricity with internal combustion engines (ICEs) or fuel cells. The application of hydrogen in the transport sector is being also analysed as an option to enhance the added value of the hydrogen. In transport sector, hydrogen with still high prices competes with fossil fuels, very dependent on rising oil prices, whereas fuel cells compared to ICEs, display a higher efficiency despite much higher costs. On the contrary, as electricity storage medium, H₂ competes with electricity (kWh) whose prices are much lower and hydrogen technologies are still expensive compared to other options. Therefore, it could be interesting to join both markets to ensure the competitiveness of hydrogen.

However, the main objective of this task is to demonstrate that hydrogen can be a good system to increase and improve the penetration of wind power into the electrical grids avoiding technical and management concerns. Therefore, it looks reasonable to analyse hydrogen as electricity storage system compared to other ESS which compete in the same conditions, that means in the electrical chain instead of transport applications.

A short description of the necessary technologies will follow although being explained in more depth in other chapters in this report.

An electrolyser breaks water into hydrogen and oxygen. The oxygen usually is vented into the atmosphere and hydrogen is stored so it can be used for future generation. Taking into account some advantages as environmental or economical ones in some occasions, one
very attractive option is integrating electrolyser units with renewable resources such as wind or solar instead of using the generation mix, avoiding this way generation losses derived from the fossil fuel power plants as well as pollution concerns. In order to achieve this, an electrolyser must be capable of operating with high efficiency, under good dynamic response, over a wide input range and under frequently changing conditions.

Recently a number of advancements have been made including higher efficiencies (DC, stack), wider input power capabilities, and more variable inputs. Electrolysers are modular devices so the capacity of a device is proportional to the number of cells that make up a stack and it is possible to connect several stacks in series or parallel. There are commercial systems available which can produce 485 Nm³/h per stack, corresponding to an input power of 2.5 MW. The lifetime of an electrolyser is difficult to predict due to its limited experience operating in these conditions (i.e. variable loads). Nevertheless, standard electrolysers have been revealed lifetimes longer than 20 years.

Hydrogen can be compressed and stored in steel vessels or underground reservoirs. Compression is a relatively simple technology, and the efficiency is quite high (85% to 90%) but the energy density of the compressed hydrogen compared with natural gas and liquid fuels is still low. However, this is at present the most common form of hydrogen storage for the transport industry, with the hydrogen compressed to approximately 700 bar (the higher the storage pressure, the higher the energy density). Industrial steel storages are in the range of 50 – 70 bar, pipelines usually do not exceed 100 bar and 50 litres steel cylinders are available at 200 and 300 bar. Underground storages usually cannot exceed 200 bar.

Regarding the reconversion technologies, it was expected that the ICE would act as a transition technology while fuel cells were improving, because the modifications required to convert an ICE to operate on hydrogen are not very significant, despite a substantial decrease in power output for the same engine fuelled with gasoline or natural gas. However, the FC, due to its virtually emission-free, efficient and reliable characteristics, is expected to be the generator of choice for future hydrogen powered energy applications. Gas turbines as ICEs have been adapted to operate with high share of hydrogen (35). The main applications expected for hydrogen gas turbines are related to large scale power generation while ICEs and FCs could cover medium power ranges.

A fuel cell converts the stored chemical energy as hydrogen, directly into electrical energy. There are several fuel cells which can be classified by the electrolyte used or the operation temperature: PEM Fuel Cell (Proton Exchange Membrane), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid
Oxide Fuel Cell (SOFC). Depending on the source, we can find different data about the fuel cell's efficiencies. According to the Department of Energy of USA (36) the PEMFC have efficiencies ranging from 25%-35% in stationary applications, AFC have efficiencies of 60% and PAFC around 40%. The MCFC have electrical efficiencies ranging from 45-47% and the SOFC around 35-43%. MCFC and SOFC operate at higher temperatures (MCFC: around 650°C, SOFC: 750-1000 °C) and could profit the heat for cogeneration as well as PAFC which works at up to 250 °C, increasing the overall efficiency to around 80-90% while PEMFC and AFC operate at low temperature and the CHP applications are still under development. PAFC, PEMFC and AFC operate with pure hydrogen while MCFC and SOFC are designed to operate with fossil fuels by means of internal or external reformers. Nevertheless, new developments of SOFC to operate with pure hydrogen point to higher electrical efficiencies. The two main drawbacks of these systems today are the high investment costs and the short lifetimes.

4.3 Energy management strategies in energy storage application

As we have mentioned before, hydrogen is an energy vector very versatile and useful in different sectors. In energy applications there are several options since hydrogen can be used in:

- Portable applications, small electronic devices, backup systems, UPS in telecom applications, etc.
- Stationary applications, residential and households systems, distributed generation and smart grids, energy storage, etc.
- Transport sector as fuel for automotive applications.

Focused on electrical energy storage applications linked to wind power, the strategy adopted to manage the electricity in the wind farm or in the wind power system is a main factor to be considered in the analysis.

Taking into account the stationary applications, at the present there are two main systems which can use H\textsubscript{2} as electricity storage system with wind power:

- Off-grid or Isolated systems, whose main objective is to satisfy the load of the community in an "island" configuration (37)(38)(39)(40)(41)(42).
Both approaches must be analysed from different perspectives since the objectives as well as the operation strategies are different. Moreover, the development of this kind of
facilities depends on the countries regulations and the grid capacity regarding the renewable energies and their management.

Nowadays the hydrogen industry is showing a new perspective in large scale hydrogen storage. This kind of system could facilitate the management of renewable energy resources (like wind energy in high penetration scenarios). Multiple final applications have been considered for this kind of hydrogen infrastructure. Some projects like FCH JU HyUnder project are analyzing this energy management topology.

Figure 31. Diagram of a hydrogen-electricity system. Source Ludwig-Bölkow-Systemtechnik GmbH.

4.4 Comparative between electrical Energy Storage Systems

4.4.1 Comparison according to storage capabilities

There are many parameters which describe the characteristics and adequacy of the different electrical energy storage systems to the different energy applications. Amongst them, we can mention the size, time of storage, charge and discharge times, costs, etc. Therefore, it is difficult to compare the ESSs in general, and to assess which is more convenient for a certain application it is necessary to analyse several parameters besides the specific application.
Nevertheless it is possible to categorize the ESSs depending on the range of discharge time on very short-term (<1 min), short-term (< 2 hours), long-term (2-8 hours) and very long-term (days or weeks).

In Table 7 the main energy applications and the adequate technologies to achieve the objectives are collected according to the study developed by Sandia National Laboratories (46) (47) and Figure 32 shows the characteristics of the different energy storage systems according to their energy and power capabilities as a result of this study.

Table 7. Applications and Appropriate Technology

<table>
<thead>
<tr>
<th>Application</th>
<th>Power</th>
<th>Storage Time</th>
<th>Energy Response Time</th>
<th>Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very short-term</td>
<td>kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End-use through, Quality, Starting</td>
<td>≤ 1MW</td>
<td>seconds</td>
<td>~0.2</td>
<td>&lt; 1/4 cycle Flywheel, Supercapacitors, Micro-SMES, Lead-acid battery, Flow batteries, H₂</td>
</tr>
<tr>
<td>Transit</td>
<td>&lt; 1 MW</td>
<td>seconds</td>
<td>~0.2</td>
<td>&lt; 1 cycle Flywheel, Supercapacitors, Micro-SMES, Lead-acid battery, Flow batteries, H₂</td>
</tr>
<tr>
<td>T&amp;D stabilisation</td>
<td>up to 100's MW</td>
<td>seconds</td>
<td>20-50</td>
<td>&lt; 1/4 cycle SMES, H₂, Lead-acid battery, Flow batteries</td>
</tr>
<tr>
<td>Short-term</td>
<td>kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed generation (peaking)</td>
<td>0.5-5 MW</td>
<td>~1 hour</td>
<td>5000 - 50000</td>
<td>&lt;1 minutes Flywheel, Advanced batteries, SMES, Lead-acid batteries, Flow batteries, H₂</td>
</tr>
<tr>
<td>End-use peak shaving (to avoid demand charges)</td>
<td>&lt;1 MW</td>
<td>~1 hour</td>
<td>1000</td>
<td>&lt;1 minutes Flywheel, Advanced batteries, Lead-acid batteries, Flow batteries, SMES, H₂</td>
</tr>
<tr>
<td>Application</td>
<td>Power Range</td>
<td>Time Range</td>
<td>Capacity</td>
<td>Technology Options</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------------</td>
<td>---------------------</td>
<td>----------</td>
<td>---------------------------------------------------------</td>
</tr>
<tr>
<td>Spinning reserve – rapid response within 3 sec to avoid automatic shift</td>
<td>1-100 MW</td>
<td>&lt;30 minutes</td>
<td>5000 - 500000</td>
<td>Flywheel, Lead-acid battery, Advanced battery, Flow batteries, SMES, H₂</td>
</tr>
<tr>
<td>Conventional – respond within 10 min</td>
<td>1-100 MW</td>
<td>&lt;30 minutes</td>
<td>5000-500000</td>
<td>Flywheel, Lead-acid battery, Advanced battery, Flow batteries, SMES, H₂, CAES, Pumped hydro</td>
</tr>
<tr>
<td>Telecommunications back-up</td>
<td>1-2 kW</td>
<td>~2 hours</td>
<td>2-4</td>
<td>Flywheel, Supercapacitors, Lead-acid battery, Advanced battery, Flow batteries, H₂</td>
</tr>
<tr>
<td>Renewable matching (intermittent)</td>
<td>Up to 10 MW</td>
<td>Minutes - 1 hour</td>
<td>10-10000</td>
<td>Flywheel, Lead-acid battery, Advanced battery, Flow batteries, SMES, H₂</td>
</tr>
<tr>
<td>Uninterruptible Power Supply</td>
<td>Up to 2 MW</td>
<td>~2 hours</td>
<td>100-4000</td>
<td>Flywheel, Lead-acid battery, Advanced battery, Flow batteries, SMES, H₂</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Long-term</th>
<th></th>
<th>MWh</th>
<th></th>
<th>SMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation, load levelling</td>
<td>100’s MW</td>
<td>6-10 hours</td>
<td>100-1000</td>
<td>minutes</td>
</tr>
<tr>
<td>Ramping, load following</td>
<td>100’s MW</td>
<td>Several hours</td>
<td>100-1000</td>
<td>&lt; cycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lead-acid battery, Advanced battery, Flow batteries, SMES, H₂, CAES, H₂</td>
</tr>
</tbody>
</table>
Flywheels, supercapacitors and SMES could be better adapted to very short-term and short-term applications while CAES and Pumped hydro could be better for very long-term applications and in some cases for short term high energy applications. The main applications are related to load management and emergency reserves.

Batteries in general are well adapted to any application as well as hydrogen technologies taking into account that electrolysers and fuel cells are also electrochemical devices. The applications go from power quality to load levelling or distributed generation.

According to those findings, hydrogen could cover the whole range of energy applications and even some power applications competing with flywheels or supercapacitors. However, these applications require more development of the FC technology. Nevertheless, the hydrogen use is not broadly spread due to two main factors, the high costs and the low cycle efficiency.

According to Table 7 probably the most appropriate applications for hydrogen are the short-term and long-term applications and linked to renewable energy depending on the energy management strategy selected for the system.
If we take into account the commercial maturity, costs and efficiency of the different energy storage systems we observe that hydrogen today is not well placed compared to some other ESSs. In Table 8 we collect the main data related to these parameters for the different ESSs analysed in the study of National Sandia Laboratory. Most of the costs have been calculated based on a mass production for the system and have been updated according to the study developed by Chen et al. (48).

Regarding to the commercial maturity, hydrogen technologies are at the same level as other competitors like batteries, except for lead-acid batteries which are the only technology completely developed and commercialised. Nevertheless, the integration of hydrogen with renewable energies attracted the attention of many potential investors some years ago and there are many demonstration projects that prove the technical feasibility of these systems despite the designs need yet further improvements mainly on power electronics, control strategies and operation modes of some hydrogen technologies.

Regarding the costs, hydrogen technologies are better suited for energy storage than for power applications, as we can see in the Table 8. However, in both applications, efficiency is a main factor and hydrogen fuel cells and ICEs are much less efficient than batteries in the short-term or pumped hydro in the long-term applications, for instance.
On the other hand, if we take into account also the life time, hydrogen technologies are well placed compared with other competitors mainly, lead-acid batteries. The short lifetime of the lead batteries could compensate the higher costs of other electrochemical systems and, in the case of hydrogen technologies compared to other batteries, the storage time capacity without losses is another advantage to be included in the analysis.

If we consider now the very long-term applications, the main competitors of hydrogen are CAES and pumped hydro systems. Both of them are currently less expensive than hydrogen technologies, the efficiencies are higher than the hydrogen efficiency and PHS are completely developed, in fact, it is the only current electricity storage system widely used.

However, the main drawback of PHS is the environmental concern, since these facilities require natural emplacements which are not always available and generally environmental impact studies and permits are compulsory, which entail long time procedures to obtain. In those cases, hydrogen technologies are easier to install, so that costs and lower efficiency could be compensated.

It is interesting to note the results obtained by VDE (49) in a study about energy storage systems. In this study several evaluations of different energy storage systems according to different scenarios are developed to determine the role which hydrogen can play compared to other ESS in energy applications. Based on several assumptions in the medium term (10 years) and some of them applicable only in Germany, about power and energy capabilities, efficiencies, discharging time, natural reservoirs or caverns available, etc. authors conclude that hydrogen stored in caverns is the feasible option at the lowest costs in the case of weekly storage, that means large-scale and/or long-term storage, and no potential of pumped hydro systems derived from emplacement limits. However, in the case of hourly storage, hydrogen is not a feasible option compared to pumped hydro and adiabatic CAES solutions.

An important advantage of hydrogen as a storage medium is its high energy density relative to CAES and pumped hydro, which is important when considering large amounts of energy. Table 9 compares the technologies in this respect. For the parameters given, the energy density of hydrogen storage is more than 230 times higher than for pumped hydro and still more than 50 times higher than for adiabatic CAES. The case when hydrogen is not used for re-electrification but, for example, sold as fuel for road vehicles, the net specific storage capacity is even higher. This net capacity considers all energy losses during conversion and represents the amount of electric energy available at the end of the storage
chain. In the “hydrogen fuel” case, the net capacity is the energy content of the sold to the customer.

Table 9 also illustrates the absolute amount of usable energy that can be stored in a volume of 8 million cubic metres of geometrical volume. For comparison, the largest pumped hydro power station in Germany (Goldisthal) has an upper reservoir of 12 million cubic metres and a head of almost 350 metres. One of the largest underground storage systems in Germany (Nüttermoor), consisting of 16 caverns, has a geometric volume of more than 7.5 million cubic metres.
Table 8. Comparison of different parameters for Energy Storage Systems. (48)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy related cost ($/kWh)</th>
<th>Power related cost ($/kW)</th>
<th>Balance of Plant ($/kWh)</th>
<th>Electrolyser ($/kW) &amp; compressor ($/scfm)</th>
<th>Cost Certainty</th>
<th>Commercial maturity</th>
<th>Discharge Efficiency</th>
<th>Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid batteries</td>
<td>200-400</td>
<td>300-600</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.85</td>
<td>6</td>
</tr>
<tr>
<td>Advanced batteries</td>
<td>100-2500</td>
<td>150-4000</td>
<td>40</td>
<td>3-4</td>
<td>2-3</td>
<td>0.70</td>
<td>2-3</td>
<td>10</td>
</tr>
<tr>
<td>Flow batteries</td>
<td>150-1000</td>
<td>600-2500</td>
<td>30-50</td>
<td>2</td>
<td>2-3</td>
<td>0.7</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Micro-SMES</td>
<td>72000</td>
<td>300</td>
<td>10000</td>
<td>2</td>
<td>2</td>
<td>0.95</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>SMES</td>
<td>1000-10000</td>
<td>200-300</td>
<td>100-1500</td>
<td>2</td>
<td>2</td>
<td>0.95</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Flywheels (HS)</td>
<td>25000</td>
<td>350</td>
<td>10000</td>
<td>3</td>
<td>3</td>
<td>0.93</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Flywheels (LS)</td>
<td>300</td>
<td>280</td>
<td>80</td>
<td>1</td>
<td>2</td>
<td>0.90</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>300-2000</td>
<td>100-300</td>
<td>10000</td>
<td>3</td>
<td>3</td>
<td>0.95</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>CAES</td>
<td>2-5</td>
<td>400-800</td>
<td>50</td>
<td>2</td>
<td>2-3</td>
<td>0.79</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>5-100</td>
<td>600-2000</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.87</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>H₂ FC/Gas Storage (Low)</td>
<td>15</td>
<td>3000-6000</td>
<td>50</td>
<td>300+112.5</td>
<td>2-3</td>
<td>2-3</td>
<td>0.59</td>
<td>10</td>
</tr>
<tr>
<td>H₂ FC/Gas Storage (high)</td>
<td>15</td>
<td>4500-7500</td>
<td>50</td>
<td>600+112.5</td>
<td>2-3</td>
<td>2-3</td>
<td>0.59</td>
<td>10</td>
</tr>
<tr>
<td>H₂FC/Underground Storage</td>
<td>1</td>
<td>3000-6000</td>
<td>50</td>
<td>300+112.5</td>
<td>3</td>
<td>3</td>
<td>0.59</td>
<td>10</td>
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<tr>
<td>H₂ICE/Gas Storage</td>
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<td>2000-2500</td>
<td>40</td>
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<td>2</td>
<td>2-3</td>
<td>0.44</td>
<td>10</td>
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</tbody>
</table>
Legend for the Table

<table>
<thead>
<tr>
<th>Number</th>
<th>Commercial maturity</th>
<th>Cost certainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mature products, many sold</td>
<td>Price list available</td>
</tr>
<tr>
<td>2</td>
<td>Commercial products, multiple units in the field</td>
<td>Price quotes available</td>
</tr>
<tr>
<td>3</td>
<td>Prototype units in the field</td>
<td>Costs determined each project</td>
</tr>
<tr>
<td>4</td>
<td>Designs available</td>
<td>Costs estimated</td>
</tr>
</tbody>
</table>
Table 9. Comparison of Storage Capacities of Pumped Hydro, Adiabatic Compressed Air Energy Storage and Hydrogen Storage. Based on (50).

<table>
<thead>
<tr>
<th>Storage Method</th>
<th>Net specific storage capacity</th>
<th>Storage capacity assuming 8 million geometric cubic metres</th>
<th>Round-trip efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydro power station, 300 m head</td>
<td>0.7 kWh/m³</td>
<td>5.6 GWh</td>
<td>80%</td>
</tr>
<tr>
<td>Adiabatic CAES, pressure differential 20 bar</td>
<td>2.9 kWh/m³</td>
<td>23.2 GWh</td>
<td>70%</td>
</tr>
<tr>
<td>Hydrogen energy storage system (electrolysis, underground storage and fuel cell), pressure differential 130 bar</td>
<td>163 kWh/m³</td>
<td>1304 GWh</td>
<td>40%</td>
</tr>
<tr>
<td>Hydrogen energy storage system without re-electrification (electrolysis and underground storage), pressure differential 130 bar</td>
<td>272 kWh/m³</td>
<td>2176 GWh</td>
<td>67% (no &quot;round trip&quot;)</td>
</tr>
</tbody>
</table>

Another study has investigated the storage capacities that will be required for a full renewable power supply system in Europe. It comprises figures for the geometrical volumes needed to store 2% of the annual electric energy consumption in Europe. The study also compares pumped hydro, ACAES and hydrogen, and employs parameters similar to those in Table 9. It finds that with pumped hydro 106 km$^3$ for water storage would be required. Assuming that this was realised as one system and that the upper water reservoir had a depth of 20 m, this reservoir would cover some 5,184 km$^2$ which is about twice the area of Luxembourg.

With adiabatic CAES, 29.46 km$^3$ storage volume would be required and with hydrogen storage merely 0.41 km$^3$ or 410 Mm$^3$ (51). The largest underground gas storage system in Europe is located in Epe (Germany). It currently consists of 57 caverns, operated by five different companies. The gross geometrical volume amounts to about 22 Mm$^3$.

These figures illustrate the competitiveness of hydrogen storage underground as regards energy density and geometrical volume required, respectively. They also indicate that only hydrogen could be feasibly when it comes to large-scale storage, including strategic reserves.

### 4.4.2 Comparison according to the energy management strategy

In the previous analysis, we have compared the different energy storage technologies according to their capabilities to store energy in the short, medium and long term. Hydrogen can also compete with other technologies depending on the energy management strategy.
chosen which could give to hydrogen an added value in comparison with other systems. In the next sections we compare hydrogen and other ESS according to this factor to determine which energy applications are the most promising.

4.4.2.1 Load levelling

We have described above the main applications of electrical energy storage systems and depending on the scale, hydrogen technologies can be applied associated to wind power for load levelling (peak shaving) at small (wind farm) and large scale (global grid), for reduction of forecasts deviations, peaking plants and repowering.

The load levelling in the wind farms or at the substation level (for a local group of wind farms) basically consists in managing the wind power according to the electrical demand profile at this point. That means, when the demand is low and there is an excess of wind power production, hydrogen is produced and stored. When the demand is high, it is covered by the wind power and the hydrogen if necessary (52). This kind of systems are usually isolated systems at small scale and when the scale is higher, generally wind power is supported by other power generation systems and the size of the hydrogen system needed is a few percent of the installed wind power capacity.

It can be also applied in distributed generation systems based mainly on renewable energies and connected to distribution grids which basically should satisfy the load curve in a medium scale of several MWs maximum.

The main competitors in these systems are the batteries which can follow the load profile as hydrogen technologies because are also electrochemical devices but their efficiencies are higher. In the medium scale systems we can also include as competitors the pumped hydro in small plants with artificial reservoirs.

The load levelling at large scale could be described as a demand management or virtual energy storage. Electrolysers can be considered as simple loads placed in different sites and with different sizes, in gas stations for vehicle refuelling, in substations, in houses or in centralized plants (53) (54). Depending on the wind power generation available, the rest of the foreseen demand and the rest of the power generation system, the electrolysers will work or not, absorbing the excess of energy to produce hydrogen but, in this case, the gas would not later be used to produce electricity but as fuel for transport applications or even as complement in natural gas pipelines. The final application of this hydrogen will depend on the price of the competitors, the kWh, the gasoline litre or the natural gas Nm$^3$ price.
In this kind of application, transport, electric vehicles might constitute a very important competitor for hydrogen, as EV can be charged during valley hours (night) and used during the day for transport and, even in the V2G concept as support during peak hours giving back electricity to the grid. However, we can also consider hydrogen vehicles not as competitors but complementary technologies since the autonomy of H2 vehicles is higher and the charge time is much shorter than the EVs.

If we consider EV as an electricity storage system since they permit a load management and therefore an increase and improvement of the wind energy penetration, hydrogen production by water electrolysis can be considered in the same way and then, electric vehicles in the short-term and hydrogen vehicles in medium-long term can substitute a large percentage of fossil fuels for transport increasing the wind power penetration in the grid and the contribution of renewable energies in the transport sector.

4.4.2.2 Forecast deviation correction

The forecast deviation reduction is another application for hydrogen. In that case, the operator of the wind farm acquires some commitments on energy sales based on the wind forecasts. If the commitments are not satisfied because the wind power is not enough, the operator must pay some penalties. To avoid that, hydrogen is produced when the generation exceeds the compromises and is transformed into electricity to cover the deficit when the wind generation is below the compromises. In this application the size of the hydrogen plant can be quite reduced but it depends on the deviation average of the farm, taking into account that in some regions even (short) deviation peaks of more than 20% can occur (55).

According to the Spanish Tariffs Regulation, the wind power promoters have two options to sell the energy: a) with a regulated tariff but the deviation penalties are subtracted from the final price of the kWh or b) the usual way, in the electricity market thorough an operator who manages several wind farms reducing the deviations among them. The penalties are defined depending on the final tariff of the electricity achieved according to the power generation planning.

In Spain the penalties are not enough high to compensate the energy losses due to the low efficiencies and the high costs of the hydrogen technologies. Moreover, there is no regulation about the tariff of the electricity produced by ICEs or fuel cells from the renewable hydrogen, which should be higher with bonus to make the systems cost-competitive.

The main competitors in this application are also the batteries, and more concretely the flow batteries, due to their high capability of cycling and efficiency and as for hydrogen technologies, the power and energy capacities are independent.
4.4.2.3 Peaking plants

The peaking plant is a very interesting application for hydrogen, in which the gas is produced during the night (valley hours when electricity is cheaper) and used as electricity during one or two peak hours per day when the electricity price is higher. The higher the gap between the prices per kWh of peak and valley hours is, the more cost competitive this strategy will be.

Depending on the country and its generation mix, the gap between prices will be higher or lower. Thus, the Nordpool is a market based mainly on hydropower, unlike the EEX (European Energy Exchange) which is largely based on fossil fuels. As we can see in Figure 33, the variation in prices in the Nordpool are not very significant compared to other markets. Usually when the hydropower share in generation capacity is high, the prices stabilize and there is a reduction of the gap between the peak and the valley tariffs. Therefore, the hydropower generation, due to its flexibility of management, contributes to the stabilization of market prices.

Therefore, the peaking strategy is more cost-competitive in fossil fuel based markets with more temporary fluctuations in the electrical tariffs. In Spain, the power generation is based mainly on fossil fuels and this strategy is well suited for hydrogen. However, the growing wind power penetration in the market is also stabilizing the tariffs (as hydropower) and the gap between prices is not enough to compensate the low efficiency and high costs of the hydrogen technologies, by now.

![Figure 33. Average Europex tariffs in different markets. Source: APX: electricity and natural gas markets in the Netherlands, the United Kingdom and Belgium; NORDPOOL: Nordic electricity market; EEX: European Energy Exchange; Powernext: energy markets in France, the Netherlands and Belgium; OMEL: Energy market in Spain and Portugal; GME: Italian Electricity Market](image-url)
Nevertheless, hydrogen is well suited to this application since the capabilities of the electrolyser and the reconversion systems are independent. That permits to design a hydrogen plant with medium size electrolysers, large size fuel cells or ICEs and the hydrogen storage quite small because the system has a daily cycling operation.

In this application, mainly medium size systems and with a daily cycle, the only main competitor could be the flow batteries since the power and energy capabilities are also independent. However, in flow batteries the stack used in the charge and discharge is the same and in despite of the possibility to discharge twice or three times the rated power, the time of discharge in these conditions is limited. In large scale CAES and PHS are also other options to take into account.

### 4.4.2.4 Repowering / Grid bottlenecks

Finally, the repowering application (56) is not strictly an energy management strategy but the increase of wind power installed in some nodes of the grid could lead to grid bottlenecks which will need a good energy management to avoid any concern related to energy supply or stability. This application has sense in countries as Spain, Germany or Denmark where many existing outdated wind turbines and some of the best emplacements are underexploited.

In Spain for example, the rated power of the wind farms cannot overcome the 5% of the power at the PCC (point of common coupling). Therefore, the rated power of the wind farm will be as high as this value. Most of the best emplacements are now exploited with wind turbines of rated power lower than 1 MW while the new technologies are all over this value. If we want to increase the wind farm capacity factor in the PCC, we can increase the rated power of the wind farm but several hours per year the generation will excess the PCC limit and the wind farm will be disconnected losing energy and benefits. Hydrogen can be produced by electrolysis during these hours, stored and finally used to produce electricity during low wind generation increasing the capacity factor or used as fuel for transport if possible.

In this application the competitors can be batteries and also CAES and pumped hydro depending on the size of the wind farm (off-shore wind farms are much larger than on shore wind farms with rated power up to 800 MW).
5 Technologies

5.1 Wind Energy

The produced electrical power from wind has dramatically increased in the last years. Therefore today's wind turbines, which typically are centralized in wind farms, have a significant influence on the power production. Besides the integration of several turbines into bigger units in farms for increasing the production from wind energy, the turbine itself has developed in size and technology rapidly in order to extract more energy from the wind and reduce the cost per kWh produced. During these developments the wind turbine has to overcome various kinds of issues and master new challenges.

There exists a huge range of possible wind turbine configurations. Most commonly wind turbines are sorted into the two major categories of "fixed speed turbines" and "variable speed turbines".

The most commonly used concepts are depicted in the figure below:

![Figure 34. A-Direct grid connected asynchronous generator with short circuit rotor.](image)

![Figure 35. B-Grid connection via converter of an asynchronous generator with short circuit rotor.](image)
Figure 36. C-Dynamic slip control with slip ring generator.

Figure 37. D-Grid connection via converter and synchronous generator with excitation system.

Figure 38. E-grid connection via converter and synchronous generator with excitation system.
Fixed speed wind turbines equipped with asynchronous or induction generators directly connected to the grid is one of the oldest and simplest concepts, which was first used in Denmark, and therefore known as the "Danish concept" (see Figure 34).

Variable speed turbines with induction or synchronous generator, directly or indirectly connected to the grid have become more and more important in recent years. Possibilities such as mechanical load reduction and more efficient energy production, due to intelligent control strategies, make these concepts a beneficial economic solution. Furthermore these types are better grid compliant compared to the fixed speed turbines. The possibility to independently control the speed decoupled from the grid, gives the possibility to decouple frequencies resulting from the wind fluctuations from the grid, which reduces flicker contribution. The converter integrated in variable speed wind turbines gives the possibility to actively control the power output of the wind turbine, which is increasingly important for the integration of wind turbines into the grid.

The fixed speed wind turbine is a self controlled concept. With increasing wind speed the laminar wind current flow around the fixed blade profile breaks and, as the turbine loses the possibility to obtain energy from the wind, the turbine stalls. The squirrel cage induction generator which transforms the obtained mechanical energy into electrical energy is directly connected to the grid. The speed of the generator may differ from the grid frequency due to the slip variation of the generator, which is up to 1%.

The variable speed wind turbine is usually equipped with a pitch control, where the blade can be turned to increase or decrease lift forces on the blade profile and thereby continuously control energy absorption from the wind. The active pitch control is designed to optimize the power obtained from the wind by changing the rotation speed of the rotor and the pitch angle and there with gain an optimum current flow around the blade. The therewith achieved variable speed range at the turbine shaft or generator axes is different from the
fixed frequency of the power system to 50Hz or 60Hz. A direct coupling of asynchronous generator to the grid is therefore not possible, and a squirrel cage induction machine is too small in speed variation possibilities (<1%), which would limit power production only in a synchronism of the shaft speed and grid frequency. To enable an efficient power production at a huge range of different wind speeds the mechanical speed has to be decoupled from the grid frequencies. One method to decouple the two systems is to use a full scale power converter between the generator and the grid. This may give a speed variation up to 120%. The success of this concept has been limited over many years due to technical development in the area of power electronics and associated costs.

Another way to connect a variable speed wind turbine to the grid is to use a double fed induction generator (DFIG). Wind turbines equipped with DFIG have become more and more common during the last years. It combines the advantages of pitch control with an efficient transmission of the power to the grid and the possibility of dynamic control of active and reactive power. Wind turbine technology benefits from the developments in the area of drive control.

In a system with DFIG the converter is placed to feed into the rotor of the machine while the stator is directly connected to the grid. Through the converter it is possible to control the supply, or extract the energy to the rotor of the induction machine. Thereby the machine can be controlled to run between sub synchronous speed and over synchronous speed (speed higher than synchronous speed). Usually a variation from -40% to +30% of synchronous speed is chosen. The total speed variation is between 60% and 70%. Under these conditions the power converter has only the size of a thirty, maximum a forty percent of the rate power, which is beneficial both economically and technically.

### 5.2 Electrolysis

Once the electricity has been produced, the next step in the technology chain of a wind-hydrogen system is the electrolyser. There are a number of variations of electrolyser technologies, all of which have strengths, and weaknesses which may make them more or less suitable for a wind-hydrogen application. These technologies will be discussed in the following sections.

#### 5.2.1 Introduction

The basic concept of electrolysis entails passing an electric current through an electrolyte solution to split water into hydrogen and oxygen (Figure 40):
Hydrogen is produced at the anode, and oxygen at the cathode as outlined in the following reactions:

**Cathode:** Hydrogen Evolution \[ H_2O + 2e^- \rightleftharpoons H_2 + 2OH^- \]

**Anode:** Oxygen Evolution \[ 2OH^- \rightleftharpoons \frac{1}{2} O_2 + H_2O + 2e^- \]

**Cell:** Overall Reaction \[ H_2O \rightleftharpoons H_2 + \frac{1}{2} O_2 \]

The cathode and anode compartments are separated by a membrane which ensures the separation of the product hydrogen and oxygen, which can then be collected and stored. Electrolysis plants with normal or slightly elevated pressure usually operate at electrolyte temperature of 70-90°C, cell voltage of 1.85-2.05 V and consume 4-5 kWh / Nm³ of hydrogen, which is obtained at a purity of 99.8% and more.

There are three main types of electrolyser technologies, which are named for the electrolyte they employ: liquid alkaline, proton exchange membrane (PEM) and high temperature solid oxide. Each of these technologies will be described in more detail below.

### 5.2.2 High Temperature Solid Oxide

A high temperature solid oxide electrolyser acts on the same concept as a Solid Oxide fuel cell operating in reverse. High temperature electrolysers consume less electricity than traditional room-temperature electrolysis because the free energy input decreases with
temperature. This is illustrated in Figure 41 which shows the free energy required for dissociation of water as a function of temperature.

![Energy demand for H₂O Electrolysis](image)

Figure 41. Electrical and total energy input required to split the water molecule Source: (57).

Higher temperatures also give better performance, due to a decrease in the electrical overpotential required, increased gas diffusivity, and increased kinetics (with non-precious metals). The high temperature required can be supplied by a relatively high temperature heat source such as concentrated solar. The necessity for the high temperatures, and relatively long start-up and shut down times, hampers this electrolysis technology from utilization in some industrial energy to hydrogen production applications. However, if the solid oxide electrolyser is allowed to work steadily, it has very attractive properties.

A special feature of high temperature electrolysis technology its ability to split not only H₂O but also CO₂. If a mixture of water and CO₂ is subjected to electrolysis in an SOEC it has been shown that a mixture of hydrogen and carbon monoxide is formed. From such mixtures (sometimes referred to as “synthesis gas”) it is possible to synthesize hydrocarbons, including liquid synthetic fuels, which may be immediately utilized in existing car engine technology. Thus, SOE may provide the strongly demanded link between sustainable electricity produced from wind energy and fuels for transportation. Furthermore this concept would not require expensive investments in new traction technologies for cars nor in new fuel distribution systems. It would, though, require sources for CO₂, which may eventually be extracted from atmosphere.

5.2.3 Proton Exchange Membrane:

One of the most promising technologies for hydrogen production and utilization is the proton exchange membrane (PEM), which is can be used as a part of a fuel cell, or an
electrolyser. In PEM electrolysis, when a voltage is applied to the membrane and the water is fed in, the hydrogen ions are allowed to pass through the membrane, but the oxygen is not and therefore the elements are separated. The efficiency of such systems is currently lower than that of alkaline electrolysis, but a possible contemporary increase of the operating temperature of the membrane could raise the system efficiency from levels of around 85% to as high as 95%. PEM electrolysis uses similar materials as a PEM fuel cell. Ultrapure water is fed to the anode structure of the electrolysis cell which is made of porous titanium and activated by a mixed noble metal oxide catalyst. The membrane conducts hydrated protons from the anode to the cathode side. Appropriate swelling procedures have led to low ohmic resistances enabling high current density of the cells. The standard membrane material used in PEM water electrolysis units is Nafion™ 117 and is manufactured by DuPont. The cathode of such an electrolyser consists of a porous graphite current collector with either Pt or, in more recent designs, a mixed oxide as electrocatalyst. Individual cells are stacked into bipolar modules with graphite based separator plates providing the manifolds for water feed and gas evacuation. The operation of the cells leads to electroosmotic water transport through the membrane from the anode to the cathode side.

The first commercial scale PEM electrolyser was installed in 1987 at Stellram SA, a metallurgical specialty company, in Nyon, Switzerland. The unit was designed to produce up to 20 Nm³/h of hydrogen at a pressure of 1-2 bar. The plant consisted of 120 cells of 20 x 20 cm² active area each, grouped into four modules of 30 cells, and electrically connected in series. The modules were arranged into two vertical stacks which were compressed individually by a hydraulic system with a force of 350 N/cm². The individual cells were composed of a sheet of Nafion™ 117, which was coated by a thin layer of Pt on one side. The anode catalyst for oxygen evolution was a Ru/Ir mixed oxide, applied as a PTFE-bonded powder to the surface of a porous Ti current collector, which consisted of a graphite-PTFE composite bonded to a brass wire mesh. The nominal operating conditions for the plant at start-up were: 400 A (i.e. 10 kA/m²) at 80 °C. Cell voltages at these operating conditions were typically of the order of 1.75 V. The plant was operated at variable load, according to the hydrogen needs of the metallurgical process, for approximately 15,000 hours before it had to be shut down completely in 1990, because the hydrogen concentration in the oxygen had exceeded the safety limit (3%).

Since this initial commercial scale PEM electrolyser, there have been significant progresses in membrane and electrode technologies. As it can be understood, any advancement in PEM fuel cell technology is also advancement in PEM electrolysis.
There are a few international research groups and commercial manufacturers, who are developing PEM electrolysers specifically for use in renewable energy systems

5.2.4 Liquid Alkaline

Liquid alkaline electrolysis has a number of advantageous characteristics including, lower cost, the ability to turndown output over the full range of power, and the ability to operate intermittently, all of which make it the preferred process for the application of wind energy to hydrogen production. The process uses a liquid electrolyte, which assists in heat transfer and allows the units to be scaled up to multi mega-watt sizes. The cell chemistry is basic (alkaline) thereby precluding the necessity for noble metal materials, lower cost nickel based electrode materials can be used rather than the platinum materials required in PEM. This ensures the overall system costs are lower.

This is also the most mature of the technologies, with large scale (MW) plants having 20-40 year lifetimes. One such plant was operated for over 20 years, and for the last 8 years it was operated intermittently. The process was shut down daily during high cost/peak-electricity demand periods, and restarted once peak electricity demand dropped. This outlines the robustness of alkaline technology, and suggests how a similar alkaline electrolyser would react under an intermittent operating regime as would be the case in a wind-electrolysis plant.

5.2.5 Alkaline Electrolysis Process

In liquid alkaline electrolysers a direct electrical current is applied between two plate electrodes in a concentrated KOH solution. As with all electrolysis techniques, hydrogen is produced at the cathode and oxygen at the anode. A membrane separates the two electrodes, ensuring the two product gases remain separate, maintaining their purity. The cell efficiency can be determines by the product of voltage efficiency (the voltage drop between electrodes at a given rate of hydrogen production compared with the thermodynamic equilibrium cell voltage) and being the same hydrogen production rate compared with the theoretical maximum rate based on the current flow measured in the external circuit. There are two basic cell designs for alkaline electrolysers; the first generation systems which employ a unipolar design, and the bipolar systems which are becoming more common.
5.2.5.1 Bipolar Design

In the bipolar design, sometimes referred to as the filter-press, alternating layers of electrodes and separators are held together (Figure 42). This results in the cells being relatively thin, thus the overall stack size is less than that required for the unipolar system, making cell pressurization practical. Pressurization of the cells further reduces the necessary cell volume, due to decreased gas void (bubble) volumes. On the other hand, the reduced cell volume means there is less liquid electrolyte, making fluctuations in electrolyte circulation, brought about by fluctuations in input power, more acute.

![Bipolar Electrolysis Cell Design](image)

**Figure 42. Bipolar Electrolysis Cell Design. Source: NREL.**

The cell bank in a bipolar system is made up of a stack of cells, connected in series. Due to the bipolar design, the electrodes are electrically connected to each other via the electrolyte they share; therefore the current can flow between any electrode pair in the stack. The current efficiency is reduced below 100%, because current does not flow through every cell in the stack, which reduced the overall energy efficiency. Also, the current flow can be reversed between electrodes in different cells, resulting in the generation of gas impurities, caused by reversal of the electrolysis process. This is a concern, if it causes small amounts of oxygen to be mixed in the hydrogen. These effects are most pronounced at low cell currents when IR voltages for different current paths in the cell are relatively low compared to the cell voltage, hence the proportion of bypass currents to total current are greatest and gas impurities are highest on a percentage basis. Another problem can arise when reverse currents occur, when the unit is shut down, resulting in the electrode material experiencing reverse polarity, which in turn can cause corrosion of electrodes and degradation of system performance.
5.2.5.2 Unipolar Cell Design

The unipolar cell design differs from the bipolar design, in that the anodes and cathodes are separate, and are alternatively suspended in a tank filled with the alkaline solution (Figure 43). Each cell is connected in series composing the cell bank. This configuration necessitates external connections between cells (usually copper bus bars) making the cell bank significantly larger than the bipolar systems.

![Unipolar Electrolysis Cell Design](image)

Figure 43. Unipolar Electrolysis Cell Design. Source: NREL.

One advantage of the unipolar design arises because the electrolyte in each tank is isolated, meaning bypass current cannot flow between cells, making the overall current efficiency 100%. This increased current efficiency means that the unipolar cell bank can operate over the entire range of currents, and makes it less susceptible to polarity reversals upon shut-down, decreasing electrode degradation. This would be a significant advantage in intermittent operation, as would be the case for large scale wind-hydrogen integration. However, cell voltages required are higher than for the unipolar design, due to the increased distance between electrodes and voltage drop through the bus bar that connects the individual cells together.
5.2.6 Challenges to Wind Hydrogen Systems

There are a number of challenges directly related to the integration of wind energy systems to hydrogen production via electrolysis, including:

- Controlling electrolyte circulation and mixing
- Long-term electrode stability under intermittent operating conditions
- Reducing By Pass Currents
- Maintaining cell pressurization

These challenges will be further explained in the following section.

5.2.6.1 Controlling Electrolyte Circulation and Mixing

The circulation of electrolyte is important for a number of reasons including, ensuring good mixing of byproduct anolyte and catholyte, maintaining the level of electrolyte which ensures the separator is not exposed to mixing hydrogen and oxygen, and ensuring heat management/transfer out of the stack. Usually, electrolyte circulation is driven internally by the gas lift in the cell. Gas generation reduces the density of the electrolyte, which pushes the liquid and gas toward to top of the cell. At the top of the cell, gas leaves the electrolyte, which falls back into the cell, thereby propagating circulation. As the current between the cells increases, the rate of gas generation is also increased; this in turn increases the flow velocity of the circulating electrolyte. If the current increase accelerates the flow of electrolyte to a point that the flow out is faster than the flow into the cell, the electrolyte level can fall below the top of the electrode in the cell, thereby exposing the separator. This could potentially cause gas mixing between the hydrogen and oxygen sides. If the power surge is very large, the volume of electrolyte pushed out of the stack can exceed the capacity of the gas liquid separator, and electrolyte can flow into the suction volume of the compressor. Electrolyte flow is a less critical issue in unipolar electrolyser design than it is in the bipolar stacks because circulation is far simpler, being around one electrode, and the electrode gap and electrolyte volume are generally larger.

Fluctuating power levels have the largest effect on electrolyte flow when the system is started from rest. An electrolyte pump can be employed with a bipolar system to continuously circulate electrolyte when the system is on stand-by overcoming the problem, though overall process efficiency would decrease. Another option is to use larger gas-liquid separators to accommodate excess electrolyte outflow, however, if the electrolyte leaves the cell it can provide a conductive pathway for current bypass to occur, which would contribute to the generation gas impurities. Recently, designs such as the Hydrogencics IMET cell stacks avoid
current bypass in the gas liquid separators by locating the gas outlets in the middle of the cell stacks, ensuring the anolyte and catholyte gas liquid separators can be grounded by the same potential.

5.2.6.2 Electrode Materials

As mentioned previously, intermittent operation can cause activated high surface area electrodes to degrade due to stresses induced by the gas evolution reaction. This is particularly problematic to the hydrogen producing cathode, and impacts both unipolar and bipolar cell design. Electrode degradation is also expedited in bipolar systems, due to polarity reversal on shut down.

5.2.6.3 Reducing Bypass Currents

Bypass currents reduce current efficiency in the cell and hence the process efficiency is also impacted. These bypass currents can be reduced by increasing the electrical resistance if the electrolyte channels in the cell. Good cell design involves making tradeoffs between reducing the cross-sectional area and increasing the length of electrolyte channels to increase resistance (Ohm law) and keeping channels large enough to provide adequate circulation to supply electrodes, for heat transport and electrolyte mixing. The bypass currents that occur in some bipolar designs can limit the turndown of the cells to greater than 20% of maximum output.

5.2.6.4 Maintaining Cell Pressure

The key to the intermittent operation of cells (as would be the case in wind to hydrogen applications) is maintaining cell pressurization and the pressure balance across the cell membrane. Electrolysis systems must incorporate an automated process for purging before resuming production, in the case where cells lose pressure. In pressurized systems, the cell membranes must be sufficiently robust to maintain full pressure of the cell in the event pressure on one side of the cell is released.

5.3 System integration

Perhaps the biggest challenge facing full scale hydrogen production from wind energy is the integration of the two core technologies, namely wind turbine generators and electrolyzers. There are a number of power controls, and conditioning electronics which must be employed to ensure that the operation of the electrolyser occurs in conjunction with electricity generation from the turbine.
Dutton et al. (38) studied autonomous wind powered hydrogen production systems. Their study of the effects of intermittent electrolyser operation showed that power fluctuation had no significant effect on the stability of the electrolyser. Moreover, power fluctuations on the scale of minutes, not seconds, affected gas purity. This affection was influenced by the magnitude of the fluctuation; the higher the fluctuation, the more the gas purity was decreased. Operation under variable load factor reduced overall system efficiencies by a few percent. The overall conclusion of the study suggested that there were no technical problems which would preclude the possibility of long-term hydrogen production from wind powered water electrolysis.

Aspects which pertain to the wind speed and size of the electrolyser relative to the wind turbine have also been studied by Dutton (76). Their modelling concluded that at low speeds, when the wind turbine rated power was equal to that of the electrolyser, the electrolyser was underutilized, because it had to be shut down and vented due to H₂ impurities in the O₂ stream which were higher than the safety limit of 2.0 vol. %. Over sizing of the wind turbine improved electrolyser utilization. It was also noted that an increased in the annual wind speed from to 10 m/s from 4 m/s increased the electrical energy generated by a factor of 6.2 and the volume of hydrogen produced by a factor of 7.4. This harkens to the need of good wind forecasting and site selection for wind energy to hydrogen production. It was also noted that in the absence of hydrogen storage options, the excess power was better utilized elsewhere.

In 2001 researchers at the Université du Quebec a Trois Rivières, in Canada developed a standalone Renewable Energy system, utilizing hydrogen production. It became quickly apparent that the system components had substantially different voltage-current characteristics. These components were integrated through a power conditioning device on a 48 V DC bus, which allowed power to be managed between input power, energy storage and load. DC-DC converters were used as power conditioning devices, to connect the fuel cell and the electrolyser (which have different voltage ratings) on the DC bus. It was found also, that the DC-DC converters gave high flexibility to control power flow, and operation of both fuel cell and electrolyser. Compared to the DC bus voltage, the fuel cell output voltage is low, and hence the DC-DC boost converter was used to transfer the power effectively to the DC bus. Similarly, the DC-DC buck converter was needed between the electrolyser and the DC bus to transfer the excess power effectively to the electrolyser. Current from the DC bus bar was used to keep batteries charged (as short term energy storage) fed power to the load bank, via an inverter, and also powered the electrolyser via the aforementioned power conditioning device.
More recently, researchers at the National Renewable Energy Laboratories, in Golden Colorado, have developed very sophisticated power conditioning electronics, in conjunction with the ongoing WindH2 project (described in detail in this report). Part of this involves the development of AC-DC converter which allows the output from a variable speed wind turbine to be utilized by an electrolyser. A similar DC-DC converter has been developed for integration of a fixed speed turbine and an electrolyser. A third aspect of this integration work is the ongoing development of the power conditioning which would be needed to directly couple a variable speed turbine with a commercially available electrolyser.

5.4 Hydrogen Compression and Storage

Once the wind turbine and the electrolyser have been integrated, and hydrogen is being produced, there is a need for technologies which would enable large scale storage of the hydrogen. There are two types of hydrogen storage technologies which have been used in existing wind-hydrogen demonstrations: hydrogen storage in metal hydrides, which is effective for smaller scale (kg) applications, and compressed gas storage which can be effective for a variety of scales, from kg to tonnes. Both of these technologies will be discussed in the following section, as will the relevant hydrogen compression technologies.

5.4.1 Metal Hydrides

One option for storage of hydrogen is in metal hydride based materials. Chemical or physically combined storage of hydrogen in other materials has potential advantages over other storage methods. Intensive research has been done on metal hydrides recently for improvement of hydrogenation properties. The disadvantage of having relatively unfavorable hydrogen storage densities, which, for the time being precluded metal hydrides for hydrogen storage in transportation systems, is not a disadvantage for wind-hydrogen systems, given their large physical footprint. A group of Mg-based hydrides stand as promising candidate for competitive hydrogen storage. Efforts have been devoted to these materials to decrease their desorption temperature, enhance the kinetics and cycle life. Kinetics has been improved by adding an appropriate catalyst into the system and as well as by ball-milling that introduces defects with improved surface properties. The studies reported promising results, such as improved kinetics and lower decomposition temperatures. However, the state-of-the-art materials are still far from meeting the aimed target for their transport applications. Therefore, further research work is needed to achieve the goal by improving development on hydrogenation, thermal and cyclic behavior of metal hydrides.
5.4.2 Compressed Hydrogen Storage

The second, and by far the most common, means of hydrogen storage which has been used in wind-hydrogen systems is compressed gas cylinders. Hydrogen can be stored as a compressed gas, with pressures ranging from 30 bar to 700 bar. There are several technologies which are used to compress the hydrogen, outlined in brief below:

5.4.2.1 Piston-Metal Diaphragm compressor

Piston-metal diaphragm compressors are stationary high pressure compressors, 4 staged water cooled, 11~15 kW 30~50 Nm³/h 40 MPa for dispensation of hydrogen. Since compression generates heat, the compressed gas is to be cooled between stages making the compression less adiabatic and more isothermal. The default assumption on diaphragm hydrogen compressors is an adiabatic efficiency of 70%.

5.4.2.2 Guided rotor compressor

The guided rotor compressor (GRC) is a positive displacement rotary compressor based upon an envoluted trochoid geometry which utilizes a parallel trochoid curve to define its basic compression volume. It has a typical 80 to 85% adiabatic efficiency.

5.4.2.3 Hydride compressor

In a hydride compressor, thermal and pressure properties of a hydride are used to absorb low pressure hydrogen gas at ambient temperatures and then release high pressure hydrogen gas at higher temperatures; the bed of hydride is heated with hot water or an electric coil.

5.4.2.4 Electrochemical hydrogen compressor

A multi-stage electrochemical hydrogen compressor incorporates a series of membrane-electrode-assemblies (MEAs), similar to those used in proton exchange membrane fuel cells, this type of compressor has no moving parts and is compact. With electrochemical compression of hydrogen a pressure of 5,000 psi is achieved. Pressure is believed to go beyond 10,000 psi to the structural limits of the design.

5.4.2.5 Ionic liquid piston compressor:

An Ionic Compressor is working like conventional piston compressor. The solid piston is replaced by an Ionic liquid. An ionic liquid differs from a normal liquid in that it has no vapour pressure and no solubility for gases. These characteristics make ionic liquids
favourable for compression, because no liquid is faded into the gas phase. During compression there are no higher hydrocarbons (like oils) in the system, yet the liquid behaves like a hydraulic oil. Ionic compressors have the following advantages over traditional mechanical compressors:

- No cylinder clearance
- Nearly isothermal compression
- Best conversion of hydraulic energy
- Low Energy consumption
- High efficiency

5.5 Hydrogen to Electricity conversion options:

To close the loop in a wind energy and hydrogen integration system, it becomes important to discuss how to re-convert the hydrogen back into electricity. There exist 2 main methods which are currently being utilized in wind to hydrogen systems (Hydrogen Internal Combustion Engines, and fuel cells). Each of these will be discussed briefly in the following section. Hydrogen microturbines, which are an emerging technology, will also be discussed.

5.5.1 Hydrogen Internal Combustion Engines

Internal combustion engines (ICEs) convert the energy contained in a fuel into mechanical power, which is used to turn a shaft. In power generation, a generator is attached to convert the rotational motion into electrical power. There are two methods for igniting the fuel: Spark ignition (SI) for fast-burning fuels, like gasoline and natural gas, and compression ignition (CI) for slow-burning fuels, like diesel. ICEs are also classified as high-speed, medium-speed, or low-speed: High-speed units (1,200-3,600 rpm) are derived from automotive or truck engines, generate the most output per unit of displacement, have the lowest capital costs, and the poorest efficiency. Medium-speed engines (275-1,000 rpm) are derived from locomotive and small marine engines, have higher capital costs and better efficiency. Low-speed units (58-275 rpm) are derived from large ship propulsion engines and are designed to burn low-quality residual fuels.

ICEs are the most commonly used technology for distributed generation. They are a mature technology, inexpensive, and are manufactured in large quantities. ICE generators for distributed power applications (‘gensets’) are made in sizes from about 5 kW to 7 MW. Gensets are frequently used as a backup power supply in residential, commercial, and
industrial applications. Large ICE generators are also used as base load, grid support, or peak-shaving devices.

With proper maintenance, large ICEs can last for 20-30 years, while smaller engines (<1 MW) tend to have shorter lifetimes. Efficiencies range from 25% to 45%, with diesel engines being more efficient than natural gas ones. Ongoing R&D, such as the US Advanced Reciprocating Engine Systems and the Advanced Reciprocating Internal Combustion Engines programs, aimed to achieve shaft efficiencies of up to 50-55% in large engines (>1 MW) by 2010. Other objectives of ongoing R&D include emissions and cost reduction, fuel flexibility, and improved reliability and maintainability. ICEs emit NOx and hydrocarbons in varying amounts depending on fuel, engine type, and manufacturer. Various catalytic systems are used to reduce such emissions.

Other performance-related characteristics of reciprocating engines include:

- Start-up times range between 0.5 and 15 minutes;
- Reciprocating engines have a high tolerance for starts and stops;
- Compared with combustion turbines, a lower amount of waste heat can be recovered;
- ICE heads and blocks can be rebuilt after about 8,000 hours of operation;
- Regular oil and filter changes are required for every 700 – 1,000 hours of operation. In general, maintenance costs of gas and diesel ICEs range between 0.007-0.015 $US/kWh and 0.005-0.010 $US/kWh, respectively.
- The capital cost of basic gas-fueled generator sets range from 300-900 $US/kW, depending on size, fuel and engine type. In general, engine cost per kilowatt increases with size. Additional costs include balance of plant (BOP) equipment, installation fees, engineering fees, etc. which can add 50-100% more to the cost of the engine itself. For example, a 550 kW natural gas ICE has an installed cost of about 1,075$US/kW, of which only about 55% is associated with the engine itself.

There are a large number of companies worldwide that manufacture reciprocating engines and/or complete generator sets for various applications, e.g. Aircogen Ltd, Caterpillar, Cummins, Deutz Corporation, Generac Power Systems, Hess Microgen, Honda Power Equipment, Pacific Power Solutions, Kohler, and Waukesha Engine.
5.5.2 Hydrogen Fuel cell

Fuel cells are electrochemical systems which convert the energy of a fuel such as hydrogen directly into electric power. A fuel cell is based on three key components: the anode, to which the fuel is supplied; the cathode, to which the oxidant is supplied; and the electrolyte, which permits the flow of ions (but no electrons and reactants) from anode to cathode. The fuel is oxidized at the anode, liberating electrons which flow via an external circuit to the cathode. The circuit is completed by a flow of ions across the electrolyte that separates the fuel and oxidant streams. A proton exchange membrane fuel cell (PEMFC) schematic is shown in Figure 44. In this case, at the anode, with the aid of the platinum catalyst, the hydrogen molecules give up electrons and form hydrogen ions. The electrons travel to the cathode through an external circuit producing electrical work. The hydrogen ions migrate through the proton exchange membrane to the cathode, where they combine with oxygen and with the electrons from the external circuit, to form water molecules. Water is the only by-product of the overall reaction.

![Proton Exchange Membrane Fuel Cell Diagram](image)

Figure 44. Proton Exchange Membrane Fuel Cell.

A fuel cell typically generates a voltage of around 0.7-0.8 V and a power output of a few tens or hundreds of watts. Individual cells are assembled into modules (stacks) and connected electrically to provide a larger voltage and output. Energy not converted into
electricity is liberated as heat, which makes fuel cells operating at high temperatures suitable for combined heat and power generation (CHP) for buildings and industry.

The different fuel cell types are listed in Table 10. They operate at different temperatures and are generally distinguished by their electrolytes. Fuel cells are a technology under intense development to improve performance and lifetime, whereas cost does not yet meet market expectations. The status of development differs widely for each type. The most common types of fuel cells are the alkaline (AFC), phosphoric acid (PAFC), solid oxide (SOFC), molten carbonate (MCFC), and proton exchange membrane (PEMFC), also known as solid polymer (SPFC) types.

Most fuel cell activity is focusing on the development of PEMFCs and the two high temperature cells, SOFCs and MCFCs, as well as the demonstration of PAFCs. Apart from AFCs, most fuel cell technology is still at the development or demonstration stage, and there are still technical issues to be resolved, including cell stack lifetime, presently about five years, long-term reliability, except for PAFCs, performance, efficiency and optimization of balance of plant (BOP) components, such as compressors and high temperature heat exchangers. In addition, high production costs are making them less competitive with established technologies, e.g. diesel motors for CHP applications less than 5 MWth and gas turbines for applications more than 5 MWth.

Table 10. Summary of common fuel cell characteristics.

<table>
<thead>
<tr>
<th>Fuel Cell / Electrolyte</th>
<th>Temp.(°C)</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC / alkaline</td>
<td>60</td>
<td>High current and power density, high efficiency</td>
<td>Carbon dioxide intolerance, corrosive liquid</td>
<td>Space and terrestrial power, military</td>
</tr>
<tr>
<td>PEMFC / perfluorinated polymer membrane</td>
<td>80-100</td>
<td>High current and power density</td>
<td>High current and power density, water management, expensive catalyst</td>
<td>Transportation, cogeneration</td>
</tr>
<tr>
<td>PAFC / phosphoric acid</td>
<td>200</td>
<td>Technologically well advanced</td>
<td>Low efficiency, limited lifetime, expensive catalyst</td>
<td>Combined heat and power plants</td>
</tr>
<tr>
<td>MCFC / molten carbonate salts</td>
<td>650</td>
<td>High grade waste heat</td>
<td>Electrolyte instability, short lifetime</td>
<td>Power production, cogeneration</td>
</tr>
<tr>
<td>SOFC / solid</td>
<td>1000</td>
<td>High grade waste heat, long</td>
<td>High operating temperature, low</td>
<td>Power production,</td>
</tr>
</tbody>
</table>
Currently, fuel cells cost about 3,000 $US/kW to 5,000 $US/kW and have efficiencies in the range of 35-45%. Continuing R&D is expected to reduce cost to about 1,000 $US/kW to 1,500 $US/kW, in the near-term, and increase their efficiency. It is estimated that for fuel cell powered sources to become competitive with internal combustion their costs must be reduced to about 500 $US/kW for CHP applications and about 50 $US/kW for transportation.

Besides mobile applications, stationary applications comprise small-scale, on-site, non-utility power generation (3 kW-1 MW); commercial CHP (up to 1 MW); distributed power generation (1-30 MW); and centralized power generation (>100 MW). In this sector, fuel cells will be in competition with current technologies such as gas turbines, steam turbines, combined cycles and diesel engines. Initial markets are expected to be in small-scale applications like on-site generation and combined heat and power (CHP) applications, and small district heating systems. The tendency towards decentralized electricity production, increased energy efficiency, and deregulation are expected to contribute to fuel cells role in this sector.

The application areas differ for the various fuel cell types. The market for low temperature fuel cells (PEMFC) is in transportation, as well as the small scale stationary CHP and decentralized areas. High temperature fuel cells can be used for centralized power generation because these types of fuel cells reject their heat at temperatures suitable for a steam bottoming cycle. Industrial CHP could be an important application area for high temperature fuel cells (SOFC and MCFC), as there are a relatively large number of companies with a steam demand between 10 to 30 tonnes/hour. Presently, gas turbines are the prime mover; however, this market area could well be served with fuel cell CHP systems with electrical capacities in the range of 6 to 20 MW. The main advantages of fuel cells in centralized power production are high efficiency, favourable environmental impacts, and lower capital risk through smaller installed capacity additions. Nevertheless, the use of fuel cells for centralized electricity generation is unlikely to materialize within the next ten years. However, it is expected that beyond 2015 the USA, Europe, and particularly Japan, where power generation costs are high, could all have significant installed capacity.

5.5.3 Microturbines

Microturbines are combustion turbines which produce both heat and electricity on a relatively small scale, in the power range of 25 kW to 500 kW. The combined thermal electrical efficiencies of microturbines in cogeneration applications can be as high as 85%, while the electrical efficiencies are in the range of 20 to 30%. Microturbines are usually
single-stage, radial flow devices with high rotating speeds of 90,000 to 120,000 rpm. They burn natural gas, propane, hydrogen or diesel fuels and have low emissions (9-50 ppm NOx). Microturbines are in the early stages of commercialization and many are still undergoing field tests or large-scale demonstrations. Most have systems which recover heat from the exhaust gas in order to boost the temperature of the air stream supplied to the combustor. Additional exhaust heat recovery can be used in a cogeneration configuration.

Microturbines can be used for stand-by power, peak shaving, and cogeneration applications. They are well-suited for small commercial building establishments such as: restaurants, hotels/motels, small offices, retail stores, and many others. Also, because microturbines are being developed to utilize a variety of fuels, they are being used for resource recovery and landfill gas applications. Microturbine technology for transportation applications is also under development and focuses on light weight and efficient fossil-fuel-based engines for hybrid electric vehicles, especially buses.

Microturbine capital costs range from 700 $US/kW for larger units to about 1,100 $US/kW for smaller ones. The addition of a heat recovery system adds between 75 and 350 $US/kW. Future market expansion and sales volume increases are expected to drive microturbine capital costs below 650 $US/kW. It is also expected that, with fewer moving parts, microturbines will be more reliable and require less maintenance (every 5,000-8,000 hours) than conventional engine generators. Development is ongoing in a variety of areas, including heat recovery/cogeneration, fuel flexibility, vehicle applications, and hybrid systems with fuel cells and flywheels.

Several development, test and demonstration projects, funded by utilities, governments and industry, are under way and are expected to lead to improved designs, higher efficiencies, and lower capital and operating costs.
6 Categorisation of Wind-Hydrogen Systems

Task 24 partners discussed ways of classifying wind-hydrogen systems with respect to their main purpose and in terms of relevant system sizes. Their market perspectives, drivers and hurdles were investigated. This chapter compiles the findings.

Hydrogen production\(^1\) and usage in the context of wind-hydrogen systems can involve a wide range of elements. Figure 45 provides a generalised schematic. Re-electrification\(^2\) can take place in gas turbines, fuel cells or internal combustion engines. Other end uses are possible, such as water desalination. If hydrogen generation is not located next to a wind farm but further “downstream”, electrical energy for electrolysis will be taken from the grid, unlike indicated in Figure 45.

![Generalised schematic of generating hydrogen from wind energy and using it.](image)

Figure 45. Generalised schematic of generating hydrogen from wind energy and using it. Not all elements need to be present in individual systems, in particular as regards hydrogen usage. Source: IEA Hydrogen Implementing Agreement Task 22.

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\(^1\) Hydrogen production throughout this report means the generation of molecular hydrogen (H\(_2\)) from hydrogen-containing chemical compounds, in particular splitting water by electrolysis.

\(^2\) Re-electrification throughout this report stands for the conversion of hydrogen into electrical energy whereas re-powering means the replacement of old wind turbines by new and usually larger units.
Three main categories of wind-hydrogen systems were established which are discussed in the following sections of this chapter:

- Mini Grids
- Electricity Storage
- Fuel Production.

As regards the number of elements, facilities under the “Electricity Storage” category are the simplest ones. They comprise just the upper two rows in Figure 45, i.e. hydrogen is produced, stored and re-electrified. “Mini Grids” can involve any of the elements displayed in Figure 45. In the case of “Fuel Production”, hydrogen may be produced and stored at the garage forecourt (small units, as defined in Table 11) or compressed or liquefied for transportation to the individual refuelling stations on trailers. Long distance hydrogen pipelines will only become available in the medium to long-term future.

Table 11 sketches expected system sizes for each of the three categories. Note that the rated power relates to different components for each category, i.e. load size, wind farm rated power, and rated size of hydrogen generation, respectively. The power range that is stated for “Large” systems under “Electricity Storage” could refer to one large wind farm (likely to be located offshore) or several farms, either on- or offshore.

The debate among Task 24 partners revealed that the perception of the individual categories and their anticipated market perspectives varied significantly from country to country. This is accounted for in the following sections.

Table 11: Expected sizes of wind-hydrogen plants for the three categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mini Grids</strong></td>
<td>~ 300 kW (load size)</td>
<td>~ 5 MW (load size)</td>
<td>~ 10 MW (load size)</td>
</tr>
<tr>
<td><strong>Electricity Storage</strong></td>
<td>~ 500 kW – 5 MW (wind turbine rated power)</td>
<td>~ 10 – 100 MW (wind farm rated power)</td>
<td>~ 100 MW – 1 GW (wind farm rated power, possibly several farms)</td>
</tr>
<tr>
<td><strong>Fuel Production</strong></td>
<td>~ 500 kW – 5 MW (electrolysis rated power, 100 – 1,000 Nm³/h)</td>
<td>~ 10 – 50 MW (electrolysis rated power, 2,000 – 10,000 Nm³/h)</td>
<td>~ 50 – 400 MW (electrolysis rated power, 10,000 – 80,000 Nm³/h)</td>
</tr>
</tbody>
</table>
6.1 Mini Grids

The Mini Grids category refers to fully or partially islanded systems that include wind energy and typically other (decentralised) power generation. Partially islanded systems in this context are those that have significant constraints with respect to their link to the main grid. The main purpose of hydrogen production is the storage of temporary surpluses of energy from renewables and the provision of a demand side management solution for energy supply (the electrolyser serving as a controllable / dispatchable load).

The hydrogen thus produced could be used for any purpose, including as a transport fuel, for re-electrification at times of low renewable generation, water purification and in industry (see Figure 45). Typical sizes are expected to be as in Table 11 and are defined in relation to the maximum load in the respective Mini Grid.

6.1.1 Market Perspectives and Drivers

Mini Grids serve as a solution to the perennial problem of (reliable) energy supply in remote areas (matching of supply and demand) and are, therefore, typically on a small scale. They are expected to become relevant in Canada, Greece, Greenland, Spain and in the UK where the market already exists, so there is a “market pull” for this kind of facility.

Fully islanded systems in remote locations will face a less challenging economic environment thanks to high fuel prices (costs for delivery), high grid connection costs, and – in some cases – tolerance to lower availability. They will also be less affected by energy price variation in markets.

Standard systems could include:

- Small:
  - Remote telecom systems, remote monitoring, other infrastructure (e.g. rail)
  - Residential and small community level.

- Medium and large:
  - Communities (towns)
  - Emergency relief hospitals.

1 The grid constraint is the dominant feature under the Mini Grids category. Hydrogen as a fuel and re-electrification of hydrogen are possible elements of a system under the “Mini Grids” category but should not be mistaken with the “Electricity Storage” and “Fuel Production” categories below.
Environmental legislation related to landscape conservation areas or remote regions in general can be a driver in favour of wind-hydrogen systems but also against them (due to possible bird/bat collisions with wind turbines, etc.). Environmental benefits include less pollution and less noise, elimination of fuel delivery miles, avoided risk of fuel spillages, and low-carbon energy supply.

6.1.2 Challenges and Hurdles

Mini Grid systems are seen as future technologies as they are not yet mature. Components require improvements (efficiency, reliability, and costs of technology) and system integration needs to be tackled. Since there is a market potential for many units to be installed, standard and modular platforms can be expected to be beneficial, providing economies of scale.

Stand-alone systems in truly remote locations could face the challenge of feed water supply, as experienced at high altitudes in some places in Spain. This can be mitigated by water recycling within the system if fuel cells are employed for re-electrification. Possible issues concerning the protection of wildlife have already been mentioned.

6.1.3 Siting

Siting relates to the question of the best location for a plant, from an economic point of view. No decision for upstream electrolysis (near wind power generation) or downstream electrolysis (near hydrogen utilisation) is needed under this category as Mini Grids, by definition, “cover” a small region.

Relevant Projects

- HARI, UK
- HARP, Canada
- Hydrogen-Oxygen-Project
- ITHEN, Spain
- Prince Edward Island, Canada
- RES2H2, Spanish test site
- Utsira, Norway
6.1.4 Competing Technologies

Among the competing technologies are diesel generators, battery systems and pumped hydro\(^1\). Diesel systems and batteries could also serve as complementary systems.

In Denmark, there are many district heating systems. In this situation, surplus wind power could be converted to heat (hot water), stored and utilised in heating applications instead of choosing storing the energy as hydrogen.

6.2 Electricity Storage

The main purpose of systems under this category is “smoothing out” short-term fluctuations in wind power, i.e. negative and positive balancing, and producing hydrogen at times of surplus power production and re-electrifying it during periods of underproduction. Such devices could facilitate wind power integration at large scale, independent of support from fossil-fuel power stations.

The system sizes as displayed in Table 11 (small, medium and large) are based on wind power generating capacity.

Figure 46 exemplifies a system configuration.

6.2.1 Market Perspectives and Drivers

Balancing can include:

- Short-term power balancing to ensure grid stability and power quality (voltage, frequency);
- Energy balancing, to manage supply and/or demand;
- Relieving temporary grid bottlenecks;

Increasing penalties for deviations could create market opportunities here. A wind-hydrogen system will have to compete with conventional (fossil) power plants. However, unlike these, it can provide both negative and positive balancing.

Large amounts of hydrogen could also be stored in underground caverns to bridge longer-term (seasonal) variations of wind power production.

\(^1\) Relatively small pumped hydro units exist on the Canary Islands and in Greece.
Re-electrification of hydrogen could take place in internal combustion engines (ICE’s), fuel cells or gas turbines, always with the option of combined heat and power production (CHP).

![Figure 46. Possible configuration of a system under the “Electricity Storage” category. Blue arrows depict the flow of energy and red arrows the flow of information. Courtesy of the HyWindBalance partnership.](image)

Technologically mature and cost-competitive systems (see “Challenges” below) are likely to find their earliest application in Denmark, Germany and Spain with their large potential for offshore wind power, and possibly in the UK if significant grid re-enforcement is not carried out.

For the UK though, re-electrification of hydrogen is not anticipated to be a large market. The gas produced for grid-negative balancing is likely to be employed predominantly as a vehicle fuel or for other purposes.

### 6.2.2 Challenges and Hurdles

Balancing power plants have a low number of annual full-load hours (i.e. a low capacity factor). This is typical of conventional units, which are usually fuelled by natural gas. Simulations carried out in the HyWindBalance project indicate a similar situation for the “matching a day-ahead forecast” case (see point 8.1 and (55)). This will have a negative effect on economic viability. Costs for electricity fed back into the grid could be higher than 1 €/kWh. The electrical efficiency of a power-to-hydrogen-to-power cycle (round trip efficiency) is unlikely to exceed 40% in the future.
Combining “Electricity Storage” with “Fuel Production” (see next section) could help to overcome the issue of low capacity factor. On the one hand, the operating strategy of such a plant will become more complex, since it includes additional functionality and hardware. On the other hand, the “tightrope walk” of grid balancing is somewhat eased by the flexibility of operation that the addition of fuel production can offer. Carefully designed criteria will be required for allocating priority to re-electrification or to fuel supply under a given set of circumstances. Therefore, it is hardly feasible to define “standard systems” at present.

The relevance of (large) Electricity Storage systems awaits the development and maturity of components such as appropriate electrolysers and gas turbines that are suitable for hydrogen. With respect to electrolysers, this refers to cost reduction, efficiency improvement (regarding both stack and balance of plant, including AC/DC conversion) and meeting the requirements of a high degree of intermittency (low capacity factor, stand-by losses) and potentially a requirement to follow rapid power changes in the sub-second range. The latter could be solved or mitigated by combining with ultracapacitors or battery systems.

### 6.2.3 Siting

Technically and/or economically optimal siting will depend on the structure of the grid that the wind-hydrogen system is intended to support (i.e. to stabilise). In a closely meshed system, electrolysis and re-electrification could take place virtually anywhere. In the case of significant bottlenecks between renewable generation and centres of consumption, energy buffering would have to take place upstream of such points.

Plants under the Electricity Storage category potentially require the accumulation of huge amounts of hydrogen. Storing hydrogen in underground caverns, as is already the practice for bulk storage of natural gas thus seems advisable and – in particular – cost-efficient for such quantities. This would limit such wind-hydrogen systems to regions with the appropriate geological structures.

### 6.2.4 Relevant Projects

- Hychico, Argentina
- Hidrólica, Spain
- HyWindBalance, Germany
- RES2H2, Spanish test site
- Sotavento, Spain
6.2.5 Competing Technologies

Among the competing technologies are (adiabatic) compressed air systems and pumped hydro.

A study by the Association of Electrical Engineers in Germany (49) investigates a number of reference cases. They include:

- Long-term energy storage (0.06 cycles per day, i.e. about 16 days per cycle; 500 MW power; 100 GWh energy content of the storage); the resulting storage costs are:
  - Pumped hydro: between 4 and 10 ¢/kWh, depending on the location
  - Hydrogen: about 23 ¢/kWh today and about 10 ¢/kWh in ten years
  - Adiabatic compressed air: about 38 ¢/kWh today and about 22 ¢/kWh in ten years

  Since pumped hydro systems of this energy capacity do not seem to be feasible in Germany, hydrogen appears to be most favourable option.

- Load levelling in the high-voltage power transmission grid (1 cycle per day; 1,000 MW power; 8 GWh energy content of the storage); the resulting storage costs are:
  - Pumped hydro: between 3 and 6 ¢/kWh, depending on the location
  - Hydrogen: about 24 ¢/kWh today and about 11 ¢/kWh in ten years
  - Adiabatic compressed air: about 6 ¢/kWh today and about 3 ¢/kWh in ten years

  In this case, hydrogen can hardly compete with the other options. The above specifications closely match the Goldisthal (Germany) pumped hydro power station, one of the largest ones in Europe.

  Heating with electricity is sometimes mentioned as an option for negative wind energy balancing (compare “Competing Technologies” part in the previous section).

6.3 Fuel Production

The main purpose of facilities under this category is in supplying hydrogen fuel to (road) vehicles. The most simple mode of electrolysis operation would be to produce and store hydrogen continuously on a 24 hours a day / 7 days per week basis to satisfy a the average fuel demand. However, this plays no role in the management of wind power, as it does not respond to the variable output of either local or distant wind turbines.
In terms of energy security and climate change, significant benefits are gained in operating electrolysers in a more responsive, grid-balancing mode that enables more effective and wider deployment of renewables, particularly wind power. In this case, the electrolysers are switched on and off\(^1\), or modulated, in order to respond to the supply and demand balance of the grid. This is rewarded through flexible tariffs and price signals on the spot market, e.g. at times of surplus renewable power. Due to the considerably lower capacity factors that this entails, a larger electrolysis plant and hydrogen storage facility is needed, as is a more complex operational control. From a commercial point of view, the electrolyser must be much cheaper than one operating at high capacity factor, since the return on investment will be so much slower.

In practice, a mixed approach that incorporates both re-electrification and fuel production may be advantageous, as is outlined in the preceding section. One option, or niche market, in this context could be that of “hydrogen cities” or “hydrogen communities”, where hydrogen is also used in CHP units and for industrial purposes, with the fuel transported in local hydrogen pipeline networks.

The option of taking electrical energy out of the grid to stabilise it (negative balancing) and using the hydrogen thus produced entirely outside the power sector, is a scenario that has been explored for the UK above.

The system sizes in Table 11 are based on electrolyser capacities.

### 6.3.1 Market Perspectives and Drivers

Large systems for fuel production as defined in Table 11 will only become relevant in the far future when a substantial share in the car fleet is based on hydrogen-powered vehicles.

Small systems will be dominant for the time being. Currently, development is driven by demonstration projects for car and bus fleets, such as the CHIC project, with nine sites in Europe and Canada (58), and the Clean Energy Partnership in Germany (59). Fuel supply for forklifts is another niche market for the introduction of hydrogen as a fuel (60)

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\(^1\) Assuming a plant with several electrolysis stacks installed in parallel.
Four sites in the HyFLEET:CUTE project\(^1\) and its predecessor projects CUTE and ECTOS operated an electrolyser of 60 Nm\(^3\)/h capacity (Amsterdam, Barcelona, Hamburg and Reykjavik) to serve a fleet of three fuel cell buses each (The Hamburg fleet was later increased to nine buses, pushing the installation to its capacity limits). Although wind power was used in the hydrogen production, its energy was delivered via the grid from distant locations. The electrolysers were not run responsively and therefore did not have to withstand fluctuating input power generated by changes in wind power output. On the other hand, they often encountered start-stop cycles when the on-site storage of the refuelling station was full and a similar pattern would be expected of an electrolyser used as a grid-balancing load. The electrolysis units proved to operate reliably in this environment (61).

Reference (62) has determined the costs per kilometre driven when employing hydrogen derived from wind power in a plant of 60,000 Nm\(^3\)/h production capacity. They amount to about three times those of using a corresponding diesel vehicle (prices of 2004, including taxes). This difference can be considered as non-prohibitive for the introduction of “green” hydrogen as a fuel for road vehicles. In the light of rising crude oil prices on the one hand (although currently mitigated by the financial and economic crisis), and technological progress and cost-reduction potential in hydrogen and fuel cells on the other hand, cost parity in terms of kilometres driven appears to be a realistic perspective in the not too distant future.

6.3.2 Challenges and Hurdles

The build-up of hydrogen-based mobility faces the typical “chicken and egg” problem, i.e. “vehicles first” vs. “infrastructure first”. It is therefore important that hydrogen refuelling stations, once built and operated in demonstration activities, remain in service beyond the timeline of such projects. This was the case for the HyFLEET:CUTE installations in Berlin and Hamburg (project ended December 2009), which continue operation as part of the CEP.

Such facilities should be publically accessible and, ideally, integrated into conventional refuelling stations to make them as visible as possible.

They can serve as nuclei for infrastructure implementation. The next step would therefore to be linked via intermediate sites, as is planned for the motorway between Berlin

\(^1\) In the HyFLEET:CUTE project, hydrogen-powered buses and their refuelling infrastructures were operated in ten cities on three continents from 2006 to 2009 (120). CHIC bases on the lessons learned in HyFLEET:CUTE.
and Hamburg, and down to the Ruhr Region, for instance. International “hydrogen highways” – for example, from Norway to Italy – should also be connected.

Infrastructure build-up requires political incentives and a reliable framework. Equally, a clear commitment from industry, such as that made recently by car manufacturers and energy companies in Germany is essential.

Underlying all this must be the unambiguous understanding that, in the medium to long term, hydrogen (for mobility) must be derived from renewable energy, even though today hydrogen is almost entirely based on fossil primary energy, particularly through the steam reforming of natural gas. Otherwise, the environmental benefits of hydrogen-powered transportation are likely to be questioned, as was encountered during the introduction of biofuels.

### 6.3.3 Siting

Downstream electrolysis, near the main areas of hydrogen fuel consumption, would be beneficial during the early stages of market development. Small and medium-sized units (see Table 11) will most likely be built at this stage. The “last mile” could be covered by truck transport of hydrogen or by de-central pipelines if generation does not take place on the refuelling station site.

Assuming that the electrolysers do not merely produce hydrogen at a steady rate but contribute to grid balancing, downstream siting will ease the need for highly dynamic responses due to averaging effects across the electric network. However, downstream electrolysis will not disburden the grid in terms of capacity.

Upstream electrolysis could be combined with “Electricity Storage”, as discussed. Up to the point in time when hydrogen pipelines become economically feasible, hydrogen liquefaction and trucking could be favourable in this application. As a potential alternative to liquefaction, work on high-pressure tube trailers (about 500 bar) is ongoing.

### 6.3.4 Relevant Projects

- Hydrogen-Oxygen-Project
- IATHER, Spain
- Prince Edward Island, Canada
- RES2H2, Greek test site
6.3.5 Competing Technologies

Technologies that potentially compete with wind-hydrogen include battery-electric vehicles, biofuels and synthetic liquid fuels. None of them is mature yet, therefore their potential is, in practice, difficult to assess. A few points are worth mentioning:

- In terms of range, speed of refuelling and potential for long-period time-shifting of electrical loads (for grid balancing), battery electric vehicles are unlikely to ever compete with hydrogen-powered vehicles.

- Additional hydrogen is required in converting hydrocarbon feedstocks from biological sources or the gasification of fossil fuels (with carbon capture and sequestration) and this can be produced by the methods discussed above.

- An advantage of synthetic liquid fuels would be that they do not bring about the need for investment in a (fundamentally) new infrastructure. Synthesis gas for generating liquid fuels could come from solid oxide electrolysis cells that convert H₂O and CO₂ (63).

6.4 Conclusions and Outlook

The main findings of this chapter comprise:

- System under the “Mini Grids” category are likely to become economically feasible once the challenges in the technical domain have been met, given the market pull.

- Although devices for “Electricity Storage” and “Fuel Production” were initially considered individually in the framework of Task 24, actual future systems are likely to serve both purposes to some extent, due to economic and technical benefits.

- Given the low round-trip efficiency, but high energy density, compared with competing technologies, “Electricity Storage” is expected to be most promising in the domain of long-term (up to seasonal) bulk storage of hydrogen in underground salt caverns.

This chapter also touches upon the diversity of options that were discussed during the work of Task 24 with regard to the three categories. Partners often expressed significantly different expectations concerning the perspectives and potentials for their home country and even for particular regions therein.

“Fuel Production” opens up new markets for energy harvested by wind turbines. With respect to this opportunity, additional opportunities have been discussed recently in the light of rising fossil energy prices. This includes the use of hydrogen in industrial processes, as raw material, as a substitute for natural gas and even its methanisation.
Under the headline “Power to Gas” it is also considered to inject hydrogen into transmission pipelines of the natural gas system as an alternative to re-electrification. Given the vast amounts of energy that are stored and transported in such networks, this could be a simple option in technical terms while staying within the boundaries set by the established codes and standards (grid codes) for natural gas systems (as regards energy density and Wobbe Index\(^1\), in particular).

\[1\] The Wobbe Index is the ratio of the higher heating value and the square root of the specific gravity of a gas. It is used as an indicator of the interchangeability of fuel gases in terms of technical boundary conditions.
Simulation tools

Simulation tools are computer programs that implement in a series of mathematical models which represent the behavior of different equipment existing in reality. These applications are useful to study and understand the behavior (energetic and economic) of a particular system, as well as to help engineering, consulting and scientific community in designing and sizing elements before the physical implementation of system itself. The objective of this chapter is hence to describe specific simulation tools that are used to analyze wind-hydrogen systems.

Currently there are several software applications used to simulate systems based on renewable energy (64). In this report, only tools that implement mathematical models to study wind-hydrogen facilities will be considered.

The next sections entail the description of the tools, indicating: general information (year of creation, developers, etc.), purposes of tool, type of mathematical model used for the wind turbine and electrolyzer, and references in the bibliography about studies and analysis of wind-hydrogen systems realized with these tools.

Tools considered are:

- HOMER
- HOGA / GRHYSO
- WindHyGen
- THESYS
- H$_2$RES
- Hydrogems
- ESSFER

Other generalists' simulation tools, also potentially useful for analyzing wind hydrogen systems, could be considered as PSCAD, Simulink and InterPSS. These tools, featuring dynamic simulation, are beyond the scope of this report and will not be analyzed.

7.1 HOMER

The tool "Hybrid Optimization Model for Electric Renewables (HOMER)" was created in 1992 and developed by the National Renewable Energy Laboratory (NREL, www.nrel.gov) dependent of Department of Energy of the United States. This software has been
implemented in C programming language, and it is a free tool that can be downloaded from the following reference (65). Since its inception, there have been more than 42 patches/updates of it.

HOMER is used for analysis of systems based on renewable energy and storage systems and their optimization when they are isolated or connected to the grid. The tool can make energy and economic calculations, where the size of the components of the facility can be varied and optimized.

Time step for simulations, by default, is one hour, but it can be reduced to minutes. Simulation time horizon is usually one year. Results obtained can be seen on screen, or can be exported to a data processor, such as Excel. Due to the information shown in simulations this type of tool is most suitable for economic studies.

From an energy perspective, the mathematical model to describe wind turbine is based on its characteristic curve (electric power generated versus wind speed). Input parameters to calculate the electrical power generated are wind speed at time step and power curve of turbine according to UNE-EN 61400-12.

Electrolyzer is implemented simply with an average efficiency between electric power consumed and hydrogen volume produced. Electrolyzer performance depends on several factors (temperature, load, etc), therefore, assuming an average efficiency could add uncertainty to the energy and economic results obtained with this tool.

NREL has reported one document about the analysis of wind-hydrogen using HOMER, called “Wind Energy and Production of Hydrogen and Electricity - Opportunities for Renewable Hydrogen” (66). Other documents about integration of renewable energy and storage systems like do also refer to this software as: potential of wind energy in Ethiopia (67), isolated systems consisting of wind and diesel generators in Saudi Arabia (68), and a study of isolated systems based on integration of renewable energy and hydrogen in Newfoundland (Canada) (69) and Leicestershire (70). All this studies are theoretical and results reported have not been validated with experimental data.

7.2 HOGA

Simulation tool HOGA (Hybrid Optimization by Genetic Algorithms), has been developed using programming language C++, the developers of this tool belong to Department of Electrical Engineering at the University of Zaragoza (www.unizar.es), the first results with it dating from 2005. This tool is free and can be downloaded from (71).
HOGA is software developed for the optimization of hybrid renewable energy system with or without storage (hydrogen, batteries, etc.). Eminently economic optimization can be done (called mono-target tool), but multi-objective optimization also can be performed, where in addition to the search for the best economic option, other optimization criteria can be set, for example: minimum CO₂ emissions from energy supply to demand. In Figure 47, the elements implemented in the tool are schematically shown and its connection mode depending on the electric current (AC or DC).

This tool has the particularity of use genetic algorithms (72) for optimization of system components (main genetic algorithm) and control strategy (secondary genetic algorithm). Genetic algorithms allow obtaining satisfactory solutions to problems with a high level of complexity with a low time of calculation. These techniques have been applied to a lot of problems in the industry, obtaining sometimes better solutions in less time than other optimization methods (73).

Figure 47. Equipment's implemented in HOGA tool. Source: Universidad de Zaragoza.

Time step often used for simulations is an hour, although this option can be changed. Simulation time horizon is one year.

Wind turbine model is based on its characteristic curve. Wind data can be entered through window, with monthly average data or can be added from text file (with a time step of one hour).

Electrolyzer model is defined by a curve that related electricity consumed and hydrogen produced for different power loads. The curve is characterized with two parameters: initial point and the slope of curve. This linear behavior of hydrogen production with respect to current is an approximation to real behavior. Hydrogen flow produced in the
electrolyzer depends on temperature and the relation between cell voltage and current density in stack.

In literature, there have been several studies of systems that integrate renewable energy and hydrogen in which HOGA has been used (74)(75).

Considering wind-hydrogen systems, a techno-economic study for the management of these facilities (76) was published.

In 2008, a specific tool was created for studying wind-hydrogen systems called GRHYSO (Grid-connected Renewable Hybrid Systems Optimization). This is based on the same mathematical models and genetic algorithms of HOGA tool. GRHYSO is used for analyzing wind-balance systems and takes into account sell price of electric energy to the grid during the period of simulation. HOGA is used for stand-alone renewable-energy systems.

7.3 WindHyGen®

This tool, created in 2006 by CENER (National Renewable Energy Center, www.cener.com) in Spain, is programmed using Java. It is proprietary software and being under testing and debugging.

The purpose of this tool is performing techno-economic studies of large-scale wind farms with hydrogen technology, to couple the electricity production of wind farm with grid demand.

As in the previous tools, the economic model is more relevant that the energy model when the system is analyzed. Time step considered for simulations is one hour, and time horizon of the studies is variable, normally one year.

Mathematical models for wind turbine and electrolyzer are static. As in previous software, wind turbine model is based on its characteristic curve, and electrolyzer model is based on voltage-intensity characteristic curve. CENER is currently working on these mathematical models, introducing dynamic aspects, including variation of electrolyte temperature and specific times of start and stop (77). Also, a wind speed prediction model is been developed. With this, the development team wants to extend its use as a tool for the management of wind farms in real time.

Considering hydrogen production, as proportional to electric power consumed by the electrolyzer without taking into account the effects of temperature, causes errors in the results of hydrogen production.
This tool has been used to conduct a study on an increase of installed capacity in wind farms, and its economic benefits using hydrogen as energy storage for different scenarios (77).

7.4 THESIS

THESIS, Tyndall Hydrogen Economy Scenario Investigation Suite is software developed by Rutherford Appleton Laboratory using Visual Basic. First version dates from 2004, and currently is a proprietary software tool.

The aim of the software is to study the impact in terms of energy, economy and greenhouse gases emission when a combination of different energy sources is considered for providing energy for transportation, electricity production and applications of cold and heat production with energy storage as hydrogen. Generally, each energy consumption sink is considered separately, but with the future hydrogen economy, and the use of fuel cells, the consumption of different applications will be related (transport, electricity and heat generation) (78).

The models used for hydrogen technology and renewable energy are simple, based on the average energy transformation efficiency.

In literature, a paper discussing a scenario with a high penetration of hydrogen in 2050 for the UK (79) can be referenced. Although the tool can be used to analyze wind-hydrogen systems, no specific study has been found in references.

7.5 H₂RES

H₂RES is a simulation tool that analyzes the inclusion of renewable energy in different energy systems. This application was developed in 2000 by the Instituto Superior Técnico de Lisboa (Portugal), together with the School of Mechanical Engineering and Naval Architecture in Zagreb (Croatia). The software has been developed in C++. Currently, the tool is currently under testing and is not distributed to external customers.

H₂RES, studies the coupling between generation and energy demand hourly during a period of time defined by user. The application has been specifically designed to increase the presence of renewable energy using hydrogen technology in islands which have a stand-alone grid. H₂RES can study: simply one renewable primary energy source (wind, hydro, solar, etc.) and various types of sources coupled to the same grid. They have been implemented various energy storage systems, but for the transport sector only hydrogen is considered.
Calculations are purely energetic, whereas economic models are currently under development. For performing simulations time step is one hour and time horizon is at least one year.

Mathematical model of wind turbine is based on its characteristic curve. For the electrolyzer an average efficiency is used like in HOMER tool.

H2RES has been used for creating a methodology to analyze various energy scenarios in islands (80) (81), analyzing various energy scenarios in Malta and Mljet island (82) and investigating the role of hydrogen in future energy systems of islands (82).

### 7.6 Hydrogems

Hydrogems, is a set of modules used to simulate systems based on renewable energy and hydrogen technology in the simulation software TRNSYS. These have been developed by the Institute of Energy Technology in Norway, since 1995, first as part of a PhD (83) and later as part of various projects. Since 2006, these modules are integrated into the kernel of TRNSYS (version 16). The programming language used is FORTRAN.

This application does not respond to the outline of the tools discussed above, since the user is responsible for defining the lay-out of system to be simulated. In addition, it requires the user to have previous knowledge of TRNSYS for simulations. The parameters to enter for defining components are preferably energetic, but they may introduce economic aspects of each of the equipment as: cost, operation and maintenance costs (fixed and variable). TRNSYS as such does not perform optimization studies; it is the user who must define the objective function of optimization and the number of simulations.

Simulation step and time horizon of the tool is configurable. The first can be from seconds to an hour, and the second from one year to several years.

Mathematical model used to define the wind turbine is based on its characteristic curve provided by the manufacturer. For the electrolyzer, the mathematical model used is based on the cell current-voltage curve, and hydrogen production is calculated considering the current flowing through the stack. This model is explained in detail in (84). Experimented users can simulate the system dynamically taking into account transient behavior of electrolyzer in starts and stops.

This tool has been used for the analysis of stand-alone integration of wind power and hydrogen (85) (86).
Mathematical models of the electrolyzer have been validated with experimental results of an integrated PV-hydrogen system (84). Model results show a good approach with experimental data.

In Ulleberg et al. (87) experimental results obtained in Utsira project are used to improve the mathematical models of Hydrogems. The paper does not indicate which the models improvements are, though.

These modules are valid for the study of hydrogen production from wind energy taking into account the temperature variation of the electrolyte in electrolyzer, but are closed modules that cannot be modified. To change them it is needed to recompile the kernel working TRNSYS GUI.

### 7.7 ESSFER

Tool ESSFER (Environment Simulation Tool for Renewable Energy Sources Systems) is a library of components, with which it is possible to simulate and analyze systems based on renewable energy and hydrogen technology. It has been developed in several stages by various departments of the Engineering School of University of Seville (www.us.es) since 2002. Currently, the tool is a proprietary software of the Thermal Engineering Group (Department of Energy Engineering). The modules have been developed for using them in the simulation environment Matlab Simulink.

The tool has a library of modules to evaluate several integrated systems with renewable energy sources and hydrogen technology from an energy point of view. The system configuration is completely definable by user. The tool incorporates economic calculations. Time step can change from seconds to hours and time horizon is open to user preferences (88).

Modules used are improvement modules of TOPIC tool developed in Task 11 of the Hydrogen Implementing Agreement of the International Energy Agency.

Mathematical model of wind turbine is based on its characteristic curve. Electrolyzer is based on cell current-voltage characteristic curve, and hydrogen production is proportional to current flowing through stack. Temperature and operating pressure of electrolyzer are defined by user and remain constant throughout simulation period.

A paper can be referenced on an analysis of the increase in the rate of penetration of wind energy in the electrical system of Andalusia by integrating hydrogen technology in wind farms (89).
7.8 Conclusion on the software tools

The state of the art for simulation tools for sizing and designing integrated systems can conclude that most of tools are based on simplified mathematical models of main equipment for hydrogen production from wind: wind turbine and electrolyzer.

In all tools analyzed, wind turbine is modeled by its characteristic curve (wind speed versus generated electric power) supplied by the manufacturer.

On the contrary, the electrolyzer is modeled in different ways:

- Using an efficiency coefficient defined as the ratio of the chemical energy of hydrogen produced versus energy consumed by the electrolyzer (HOMER, H₂RES and THESIS).

- Using a linear relationship (with a minimum efficiency, greater than zero) which relates hydrogen production with electric power consumed (HOGA and WindHyGen).

- Using the cell current-voltage characteristic curve of electrolyzer and Faraday's Law to calculate the hydrogen production (TRNSYS-HYDROGEMS and ESSFER).

In all tools, except Hydrogems, the electrolyzer model is static in which the efficiency is constant and independent of the operating conditions of the electrolyzer. In order to perform simulations closer to reality, it is necessary to consider dynamic models with more emphasis when the electrolyzer is connected to renewable energy sources, like wind energy. Also, improvements in auxiliary equipment modeling (electrolyzers converters, compressors, etc.) need to be realized.

Table 12 shows a summary with the main characteristics of the simulation tools considered in this report.

<table>
<thead>
<tr>
<th>TOOL</th>
<th>Energy Calculations</th>
<th>Economic Calculations</th>
<th>User Interface</th>
<th>Type</th>
<th>New Component Addiction</th>
<th>Different system configurations</th>
<th>Expert User</th>
<th>Result Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOMER</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Free</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>HOGA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Free</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>WindHyGen</td>
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<td>Yes</td>
<td>Yes</td>
<td>Own</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>THESYS</td>
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<td>Yes</td>
<td>Yes</td>
<td>Own</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>H2RES</td>
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<td>No</td>
<td>Yes</td>
<td>Own</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>HYDROGEMS</td>
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<td>Yes</td>
<td>Licensed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>ESSFER</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Own</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 12. Summary of tool characteristics.
8 Evaluation of Wind-Hydrogen System Projects

This chapter introduces an overview on completed R&D and demonstration projects. In some cases, only partial information is available. Not all projects discussed in this chapter employ wind as the source of primary energy. Corresponding ventures that rely on hydro power and photovoltaics have been considered to illustrate the range of options in terms of energy sources but also the possible use of “by product” oxygen.

The projects mentioned hereinafter are sorted by alphabetical order (country and name of the project).

8.1 Hychico (Argentina)

The project objective is to maximise wind utilization by producing hydrogen, which is admixed to natural gas and used as fuel in a genset. High-pressure oxygen will be supplied to the local market.

The project has two phases: Phase 1 is the “Large Scale Clean Hydrogen Production in Patagonia Argentina” pilot project. Phase 2 will be the start-up of a 6.3 MW wind park which will feed 0.8 MW to the hydrogen plant, the remaining output being sold to the national interconnected electric system.

In Phase 1, two 325 kW electrolysers produce a total flow of 120 Nm³/h of hydrogen and 60 m³/h of oxygen at max. 10 bar. For re-electrification, the hydrogen is mixed with natural gas from an oil field. The 1.4 MW genset supplies the oil field with power. Oxygen is compressed to 200 bar and stored.

The genset has an ICE designed to operate with gases from biomass, pyrolysis, etc., and has been specially adapted to operate with rich and/or poor gas – hydrogen mixtures. It is worth mentioning that gases used are raw gases extracted from the field with no previous treatment. The rich gas has a 90% methane content and the poor gas has a ~40% CO₂ content.

It is planned to use 3 years wind resource data as input signal to the electrolysers, in order to simulate wind park behaviour.

8.2 HARP, Bella Coola (Canada)

The Hydrogen Assisted Renewable Power Project (HARP) aims at facilitating the use of renewable power and reducing greenhouse gas emissions in remote communities.
Surplus of renewable energy from the run-of-river generator at Clayton Falls, isolated from BC Hydro’s main electricity grid, is stored in a flow battery and is used to produce hydrogen from water (60 Nm³/h electrolyser, hydrogen compression and 200 bar storage). Then, during peak periods, the stored hydrogen is fed into a 100 kW fuel cell to generate electricity. At the same time, the flow battery can produce up to 125 kW of electricity.

The project includes a microgrid controller with advanced optimisation and management software, which optimises the operation and dispatch of all these elements together. It is anticipated to enable significant efficiencies leading to the reduction in the use of diesel and related greenhouse gas emissions.

8.3 Ramea Island (Canada)

Ramea Island is a small island located in the Atlantic Ocean, off the eastern coast of Canada. It was the site of Canada’s first wind-diesel demonstration project, in 2004. In an attempt to move away from utilizing the diesel genset to smooth electrical output, from the turbines, a wind-hydrogen project was initiated. The system consists of six 65kW wind turbines, a 90 Nm³/h alkaline electrolyser, with 2,000 m³ hydrogen storage (200 bar). The stored hydrogen will be converted back to electricity via four 62.5 kW hydrogen internal combustion engine generators, as need be. There have been a number of delays, in getting all system components to the remote location.

8.4 Prince Edward Island Wind Hydrogen Village (Canada)

Prince Edward Island is home to Canada’s Wind Energy Institute, and boasts one of the strongest wind regimes in Canada, with 44 MW installed and another 30 MW planned. As such, it is well positioned to host a wind to hydrogen demonstration project (or suite of projects). The Wind Energy Institute is located on North Cape area of the island, is the site of one of the wind to hydrogen projects, with systems components as shown in the figure below (Figure 48). Aside from providing back-up/ auxiliary power, the hydrogen produced will also be used to fuel two hydrogen internal combustion engine 12 seat buses. These buses will be used as part of the public transit system in Charlottetown (the provincial capital).
8.5 University of Quebec (Canada)

Being pioneers, a standalone renewable energy system based on hydrogen production from wind and solar energy has been in operation at the Hydrogen Research Institute (HRI) of the University of Quebec a Trois Rivieres (UQTR) (37). The system consists of a 10 kW wind turbine generator and a 1 kW (peak) solar photovoltaic array as primary energy sources, a 5 kW electrolyser, a 5 kW fuel cell, as well as short-term (batteries) and long-term (hydrogen) energy storage devices. The renewable electricity that is produced in excess of the load demand is stored as hydrogen produced using the electrolyser. The hydrogen is stored and later used to produce electricity with the fuel cell when there is insufficient wind and solar energy to meet the demand. Autonomous operation of the system is achieved with an improved power control system designed to maximize the direct energy flow from the RE sources to the electrolyser and the load in order to avoid draining the batteries. When energy is not available from the RE sources, due to local climatic conditions, a 10 kW programmable power source is used to simulate typical RE patterns. The RE system performance was recorded for long-term operation from 3 December 2001 to 17 April 2002 for daily operation of six hours.
In a recent publication the HRI group use the above system to measure round-trip efficiencies (electricity→hydrogen by electrolysis→electricity by a fuel cell). They measured round-trip efficiencies of 13.5%, when compressed air was used as an oxidant, and 18%, when electrolytic oxygen was recovered and used as an oxidant in the fuel cell instead of compressed air. The ideal round-trip efficiencies calculated by the authors amounted to 26% without and 38% with oxygen recovery. The authors conclude that, because of electrochemical irreversibility and the gas handling aspects of such a system, round-trip efficiencies of hydrogen storage without oxygen recovery are likely to remain below about 30%.

8.6 Fachhochschule Stralsund (Germany)

Fachhochschule Stralsund established in the 1990s a Multi-component Laboratory for Integrated Energy Systems, which includes a variety of energy conversion devices that can convert renewable sources of energy, such as wind and solar energy, to thermal or electrical energy.

The wind turbine has a nominal power output of 100 kW. However, depending on the wind speed, the two-speed asynchronous generator can be operated at either 1,000 or 1,500 rpm, producing 20 kW or 100 kW of electricity, respectively. Nominal power of 100 kW is reached at a wind speed of 12 m/s. The 20-kW alkaline pressure electrolyser was developed by ELWATEC GmbH Grimma, that later became Hydrogen Systems GmbH. It can deliver hydrogen at up to 25 bars. The system comprises 40 cells characterized by a very compact bipolar design. The hydrogen storage tank has a geometrical volume of 8 m³; however, because the system works without a compressor, the tank is only used to the maximum pressure of the electrolyser. Under 25 bars, the tank is filled within 50 hours and contains 200 Nm³ hydrogen. A two-stage compressor with an output pressure of 300 bar is available for filling up tanks or bottles. The static and dynamic behaviour of the electrolyser has been investigated in this facility. The efficiency of the electrolyser stack reached about 80% on a HHV basis. The electrolyser was controlled according to the power output of the wind turbine.

8.7 Hydrogen-Oxygen-Project (Germany)

The project was initiated by the need for oxygen. The municipal sewage plant in Barth needed an upgrade of its ventilation system of the aeration basin, in order to keep the biological decomposition processes stable during the summer period. Using oxygen instead of air for this purpose can improve efficiency by about 30%. In this way, the construction of a
second basin could be avoided. Trailer supply of oxygen was not considered a suitable option given the remote location of Barth on the Baltic coast and the relatively small amounts required. Instead, the decision was in favour of on-site water electrolysis based on power from a PV system. The “by-product hydrogen” could be utilised in a bus.

Erecting wind turbines was not possible due to restrictions set by planning law. Since a key aim was to employ renewable energy, PV was chosen.

Following a design study completed in 2000, the project started in 2001 and the oxygen part of the installation and the hydrogen filling station including electrolysish were complete in September 2003. The PV installation followed and the bus started into the field tests in 2006.

A PEM electrolyser (HOGEN 380, 60 kW, and 10 bar) was installed with a capacity of generating 10 Nm$^3$ hydrogen per hour at 99.999% purity and 5 Nm$^3$ oxygen at 97% purity. Electrical energy is supplied mainly by a photovoltaic field (97 kW peak) erected on the site, with dual-axis tracking. Two membrane compressors facilitate oxygen storage at 60 bar in a steel vessel and hydrogen storage at 280 bar in cylinders (90) (91).

The oxygen is fed into the sewage basin via a pressure reduction valve and an aboveground pipeline. The midi-hybrid-bus for 24 passengers with a battery and fuels cells (originally 6 stacks at 6.5 kW by Proton Motor Fuel Cell GmbH, Type PM-600) serves local transport and tours into the nearby national park.

After problems with both the fuel cells and the electrolyser, new units were installed. Heliocentris integrated two 16 kW stacks supplied by Hydrogenics (Type HyPM HD16) into the bus in 2008. In summer 2009, the company also delivered and commissioned an alkaline electrolyser that can generate 10 Nm$^3$ H$_2$ and 5 Nm$^3$ O$_2$ per hour, as before.

8.8 HyWindBalance (Germany)

The overall goal of the HyWindBalance consortium is to develop wind-hydrogen systems that establish new options for wind energy, such as scheduled generation, thus making the wind resource “controllable”, reduction of the need for balancing power from conventional power plants, and active (scheduled) sale of wind electricity as balancing or peak power on the spot market.

Figure 46 provides a schematic of the envisaged system configuration and interaction of the components. In the medium term, it also expected to sell hydrogen from excess wind energy to other markets than the electricity sector, namely as fuel for road vehicles.

The objectives of the research phase up to March 2008 were:
Gaining experience with the operation of a research system (5 kW electrolyser and 1.2 kW fuel cell)

Developing operating strategies for different meteorological, technical, and market conditions,

Building a simulation tool that can map out the behaviour of system components and plant management,

Assessing the feasibility of this technology at a large scale.

The electrolyser of the research system was not coupled to a real wind turbine but received its input power signal from the control unit. The same applied for the signal that drove the electronic load and the fuel cell, respectively. The advantage of this approach was that the same time series of power supply and load could be imposed on the system several times while employing different operating parameters. Such time series were generated by scaling measured wind power and load data to the size of the research system.

8.9 RES2H2 (Greece)

The RES2H2 project ("Cluster project for the integration of renewable energy sources into European energy sectors using hydrogen") implemented two wind-hydrogen prototype systems, one in Greece and one in Spain. The former is discussed here, the latter in the next section.

For the Greek test site of RES2H2 a Casale Chemicals 25 kW electrolysis unit operating at a pressure of up to 20 bar has been connected to a 500 kW gearless, synchronous, multipole Enercon E40 wind turbine. The electrolysis unit has been developed with special cells to be able to withstand rapid changes of input power (15-100% capacity in 1 sec). The electrolyser will operate in various modes (percentage of wind turbine production, "peak-shaving", etc.), with excess energy from the wind turbine being fed to the grid. The electrolytic hydrogen will be purified prior to entering a buffer tank. Part of the produced hydrogen will be stored in novel metal hydride tanks of approximately 40 Nm$^3$ H$_2$ capacity. The rest of the produced hydrogen will be compressed to 220 bar and fed to cylinders at a filling station.

8.10 ENEA wind- hydrogen (Italy)

The "Hydrogen Generation from stand-alone wind powered electrolysis systems" EC project (contract number JOU2-CT94-0413) took place between 1994 and 1997. It aimed to
study the integration of wind energy technologies with electrolysers, in order to complement the numerous studies investigating PV-based hydrogen production. The project sought to determine how best to control a wind turbine to produce a smooth power output, to examine the tolerance of an electrolyser to fluctuating power inputs, and to design and build a small scale (<10 kW) stand-alone wind hydrogen production system. The main components of the system are listed in the following table:

The plant comprised the wind turbine, the electrolyser unit complete with its built-in controllable power supply, battery storage, a DC-DC controllable converter, and two dump loads (0.5 and 2 kW) controlled by two voltage-actuated relays. The auxiliary equipment (electrolyser pumps, valves, control equipment, and water demineralization unit) for the demonstration plant were supplied by the grid for convenience.

8.11 Utsira (Norway)

The world’s first stand-alone, full-scale application of wind/hydrogen was inaugurated in July 2004 at Utsira, a remote island in Norway. The Utsira project, shown in Figure 49, involved a partnership between Hydro, a hydroelectric power producer in Norway, and Enercon, a German wind turbine producer, and was supported by public funding. The Utsira project supplied energy to ten households, whose entire energy demand was namely provided by renewable sources. It was powered by two 600 kW wind turbines operating at wind speeds in the range of 2.5-25 m/s, which at optimum performance provided more than enough energy to supply the whole Utsira community. Hydrogen produced by a 48 kW, 10 Nm³/h electrolyser is compressed and stored in a container that can hold up to 2,400 Nm³ of hydrogen gas, sufficient for two full days of energy supply to Utsira. The stored hydrogen is used to produce power by a 10 kW fuel cell and a 55 kW hydrogen ICE, when there is insufficient wind energy. These units were supported by a 5 kWh flywheel and a 35 kWh battery and a 100 kVA master synchronous machine to ensure power quality. The components were connected via a 400 V AC mini grid. A 22 kV transformer connected to the cable that supplied the residential houses some 1.5 km away from the wind-hydrogen unit. The houses have their own 230 V sub-station. They could also be connected to the public grid if necessary.

In general the system worked well. Only the fuel cell caused major problems, in particular rapid degradation from the beginning of the operating phase.

After more than three years of operation, the hydrogen ICE ran into technical problems. The issues may have been caused by hydrogen leaking into the crank case and reacting with the lubricating oil or by water emulsifying the oil.
The Utsira system has demonstrated that it is feasible to supply communities in remote areas with wind power using hydrogen as the energy storage medium. Technical improvements and cost reductions need to be made, though, before wind-hydrogen systems can compete with existing commercial solutions, such as wind-diesel units.

![The Utsira, Norway wind/hydrogen plant](source)

**Figure 49. The Utsira, Norway wind/hydrogen plant. Source: Hydro Oil & Energy.**

### 8.12 Hidrólica (Spain)

This project involved a Wind-Hydrogen Pilot Plant located near Cadiz (Spain) which is a part of a research project led by ENDESA Generation with Green Power Technologies, AICIA, and INERCO as partners. After a preliminary study of the electricity production of the wind farm where the pilot plant is located (by comparing the production and prediction curves of the last 3 years), simulations were made in order to optimize wind energy generation by means of an integrated system of hydrogen and electric energy generation. This system, whose main components are an electrolyser, a fuel cell and a hydrogen tank, allows the generation of hydrogen by using part of the energy produced by a variable-speed wind turbine.

The system is located on site at an 80 MW park located on the south of Spain (1,900 equivalent production hours per year, “MADE 800” wind turbines). It is composed of an
electrolyser with a maximum electricity consumption of 41 kWe. Once the hydrolysis is complete the resulting oxygen is vented and the hydrogen is stored at medium pressure, 15 bar, in a storage tank. The system also has a compressor, for storage at 200 bars and a fuel cell capable of generating 12 kWe.

8.13 IITHER (Spain)

The aim of the IITHER Project is the start-up of an installation that allows tests of hydrogen generation by electrolysis, with electricity obtained from renewable sources, with the most diverse available technologies. The project tries to cover all the hydrogen chain (production, management and efficient use), obtaining the primary energy from renewable sources by means of processes currently available (photovoltaic and wind). The secondary goal of the mentioned installation will be the learning of integration at real scale of renewable sources and temporary hydrogen storage, dissemination, training and public awareness, "green" hydrogen generation from renewable sources for their consumption in stationary or portable applications, and evaluation of the efficiency and functionality of the whole system, all that in an operation frame that guarantees an economic return by the sale of the excess of electricity by feed-in tariff that facilitates the financing of the project and covers its operation and maintenance costs.

It consists of three turbines, each one with a type of technology and on an average rank of powers (80, 225 and 330 kW) and 100 kW PV either integrated in a parking roof (60 kW) and in four double axis trackers (20 kW + 10 kW + 5 kW + 5 kW), featuring different kinds of panels. Produced electricity can be derived to the local grid or to the pressurized alkaline electrolyser (10 Nm$^3$/h capacity, manufactured by IHT, formerly Lurgi technology). The system includes also the power electronics, the control system and supervision (SCADA), the connection to the electrical grid to derive the excess of production, and the additional devices to improve the electrical power quality. The elements of the balance of plant must also be considered: water demineralisation, hydrogen purification, compression and storage, both by metal hydride (capacity of 100 kWh of energy) and compressed hydrogen gas at 30 bar in a buffer tank and at 350 bar for dispensing to vehicles. Hydrogen not delivered to vehicles can be used in a variety of applications at the Foundation main premises, such as an off-grid hybrid application (PV + batteries + 1 kWe fuel cell), distributed generation (10 kWe), a back-up power system for the IT server, and a residential CHP fuel cell.
8.14 RES2H2 (Spain)

The RES2H2 project implemented two wind-hydrogen prototype systems, one in Greece and the second Spain. The latter is discussed here, the former in the previous section.

The system was inaugurated in 2007. Electrical energy generated by a wind turbine is partly converted to hydrogen (55 kW electrolyser) and stored at 25 bar when electricity supply exceeds demand. Hydrogen is re-electrified through six 5 kW PEM fuel cells, when power from the wind turbine does not cover demand from the electrical loads connected to the system, including a reverse osmosis plant for water desalination.

The system was nevertheless not directly connected to a wind turbine. Power production data of a 225 kW wind turbine installed close to prototype are recorded and scaled appropriately to generate times series that are used as input power signal to the system for “hardware simulations”.

Stationary and dynamic tests of all components have been performed to obtain the efficiency, range of operation, power consumption, transient response and especially the operating curves of fuel cells and electrolyser. The response of the components to power variation typical from wind energy resources and the interaction of each component with the rest of the system have been analysed. The performance data will allow defining the appropriate wind turbine capable of satisfying the demands of the prototype and the load profiles in stand-alone operation. An initial topology of the stand-alone system has been designed.

8.15 Sotavento (Spain)

This project took place at the premises of the Experimental Wind Farm Sotavento, comprising a storage plant of wind energy using hydrogen at a scale that, without being the one that solves the variability of generation, allows making experiences in real operations which may easily be extrapolated to design full scale solutions.

The production of hydrogen was obtained by an electrolyzer of 60 Nm³/h capacity, which works on electricity from wind turbine generators. The electrolyzer produced hydrogen at low pressure, which was later compressed to reduce the volume of storage in steel cylinders at about 200 bar. For the following conversion into electrical energy, a motogenerating equipment of 60 kWe was used.
The facility used surplus electricity generated by the wind farm to produce hydrogen, in other words it utilised energy available in excess of what has been expected based on the forecast for the wind farm. When wind energy production fell short of the predicted level, the genset tried to compensate this.

Figure 50. Schematic of Sotavento Wind to Hydrogen Project. Source: Parque eólico experimental Sotavento.

8.16 HARI (United Kingdom)

The Hydrogen And Renewables Integration (HARI) project was established on site of an existing renewable energy system at West Beacon Farm, in Leicestershire. The two main objectives of this project were to demonstrate and gain experience in the integration of hydrogen energy storage systems with renewable energy systems, and to develop software models which could be used for the design of future systems of this type.

Prior to the installation of the hydrogen energy system, the existing renewable energy systems at the site included two 25 kW wind turbines, 13 kWp photovoltaics and two micro-hydroelectric turbines with combined output of 3 kW. The addition of a hydrogen energy storage system to the existing RE supply network was seen as a means of balancing the intermittent supply with the fluctuating demand, enabling the evaluation of the feasibility of a stand-alone RE system. Three key components were added to the existing network were a
36 kW alkaline electrolyser (with 25 bar output pressure), 2856 Nm$^3$ of pressurized (137 bar) hydrogen storage, and 2 fuel cells (2kW and 5kW).

### 8.17 PURE Project (United Kingdom)

The Stand-Alone Small Size Wind Hydrogen Energy System (PURE) Project was a joint project of Unst (community of the Shetland Islands), siGEN (system integrator), AccaGen SA for the PURE Community of Shetland-Islands, and supported by EU funds. The project aimed to demonstrate how wind power and hydrogen technology can be combined to provide the energy needs for a remote rural industrial estate. PURE was conceived to test and demonstrate safe and effective long-term use and storage of hydrogen produced by renewable energy using wind powered electrolysis of water and to regenerate the stored energy into electric energy with a fuel cell. The key components of the system are listed below:

- Wind turbines: two 15 kW (Proven Ltd)
- Electrolyser: 15 kW Alkaline operating at 55 bar (Acca Gen SA)
- Hydrogen storage: 44 Nm$^3$ in H$_2$ cylinders
- PEM fuel cell 5 kW (Plug Power)

The electrolyser section consisted of an AccaGen electrolyser unit assembled with advanced cells specifically designed and manufactured for wind applications, capable of operating up to 55 bar. Apart from high energy efficiency and good dynamic performance in intermittent operation, a particularly important requirement for wind operated water electrolyser is the possibility of operating the electrolyser over a wide range with high current yields and sufficient gas purities.

### 8.18 NREL (USA)

The National Renewable Energy Lab (NREL) located in Golden Colorado has been investigating a wind to hydrogen project, with the goals of examining the optimal wind/hydrogen through systems engineering, characterizing and controlling the wind turbine and H$_2$-producing stack, evaluating the synergies from co-production of electricity and hydrogen, and comparing alkaline and PEM electrolyser technologies when linked to wind turbines. System-wide efficiency of devices (Electrolysers, Compression, Storage and H$_2$-fueled ICE genset) were also examined. The system includes both a 100 kW Northern Power Systems fixed speed wind turbine, and a 10 kW Bergey variable speed turbine, the power conditioning electronics mentioned above in Section 3, three electrolysers (two HOGEN 40
RE PEM electrolysers, and a Teledyne HM-100 Alkaline electrolysers) a hydrogen compressor (to 3,500 PSI and hydrogen storage).

8.19 On-going related projects

8.19.1 Elygrid

ELYGRID Project aims at contributing to the reduction of the total cost of hydrogen produced via electrolysis coupled to renewable energy sources, mainly wind turbines, and focusing on megawatt size electrolysers (from 0.5 MW and up). The objectives are to improve the efficiency related to the complete system by 20% (10% related to the stack, and 10% electrical conversion) and to reduce costs by 25%. The work will be structured in 3 different parts, namely: cell improvements, power electronics, and balance of plant (BOP). Prototype electrolysers will be tested in facilities which allow feeding with renewable energies (photovoltaic and wind).

There is moreover a special interest to adapt the technology to wind energy, because this one of the most developed and extended renewable sources, especially in two countries which take part in this proposal (Spain and Germany).

8.19.2 HyUnder

In the 4th call of the European FCH JU (AIP 2011) a project has been approved to map out the relevance of hydrogen underground storage. The focus being on large scale energy storage, the potential, application profile, impact of and schedule to implement this concept may differ across Europe. In recent studies a clear profile for various large-scale storage concepts / technologies has been elaborated for Germany and here specifically the northern regions, with involvement of the public sector and industry.

Utilizing this knowledge, also actors in other regions have started to assess the individual geographic hydrogen underground storage potential in their respective region such as in Spain and the UK, and show interest to commercially deploy this concept. The idea behind the project is to establish a European initiative supporting the deployment of hydrogen energy storage in underground storage caverns at large scale, benchmark their storage potential in relation to the energy market and competing storage technologies, and to identify and assess application areas, stakeholders, safety, regulatory framework and public acceptance.
The general concept of the project foresees case studies for five representative European countries (France, UK, Spain, the Netherlands and Romania) benchmarking against the results from ongoing German industry projects. Each of these case studies will consider the competitiveness of hydrogen storage against other large scale energy storage concepts, the geologic potential for hydrogen storage in the region, and how to embed the hydrogen energy storage in the energy market. The perspective of the case studies is potential business cases for each region and the development of an Implementation Plan at European scale.

The key issue here is to make the best possible use of insights already available internationally. For that reason, the goal of the project as proposed here comprises the following aspects:

- document and evaluate the existing know-how on a comparison of hydrogen storage with other large-scale energy/electricity storage concepts,
- describe the relevant storage options for underground storage of hydrogen with respect to injection and production performance, storage capacity, safety, and possible impacts on the environment,
- assess geological implications, i.e. the possible influence by the host rock and any in situ water/brine and microorganisms on hydrogen held in a storage system,
- evaluate actual operating experience, also with respect to permitting and public acceptance,
- document the state-of-the-art of technology and operations in detail, with a specific focus on the learning from natural gas underground storage (safety),
- provide a highly visible overview of the regional potentials for hydrogen underground storage in Europe and identify/involve relevant players,
- assess how to embed large scale hydrogen storage in relevant regional energy structures, specifically with a view to unlock synergies between energy sectors in various European economies,
- analyse the need for policy support to kick-start regional industry activities and
- compare regional approaches to draw conclusions and provide recommendations towards a European implementation plan.
Figure 51. Diagram of a subterranean hydrogen storage. Source: KBB Underground technologies.
9 Lessons learned

Several demonstrations of electrolytic hydrogen production linked to renewable energy sources have proven technical feasibility under certain circumstances as well as potential for economic viability under conditions which could be met in the near future. Though the early demonstrations were dominated by photovoltaic/hydrogen systems, there has been several wind to hydrogen demonstration projects.

As summary of the investigations and internal debate among the Task 24 partners, there were a number of conclusions reached from this undertaking:

9.1.1 Incumbent technologies and benchmark

- Hydrogen is less expensive and has a smaller footprint when compared to batteries for large capacity, long timescale electricity storage.
- Hydrogen allows dissociation of charge rate, discharge rate and energy store capacity, which is beneficial to renewable energy because charge rates are typically high and discharge rates low.
- Hydrogen is less efficient than batteries for the storage of electricity, typically losing some 70% of the initial energy available (in round trip comparison) compared to 20% in batteries.
- Due to these losses incurred in electricity storage applications, hydrogen is better suited to transport uses than to re-electrification. As fuel for transport, it allows rapid refuelling, energy balancing over longer timescales and greater range than batteries, which are limited to short-range vehicles. Batteries are not a threat to hydrogen, but they are complimentary to.
- Biofuels are not a threat to hydrogen markets. In the long term, they will find greater value in stationary power generation due to their dispatchability or, when combined with hydrogen, in the production of synthetic aviation fuel.
- In a low-carbon energy system, hydrogen production via electrolysis provides a controllable load for use in grid management. Hydrogen thus produced is closer to marketability as a transport fuel and in the longer term for re-electrification or blended with natural gas. Nevertheless Power-To-Gas concepts can boost interest in hydrogen from excess renewable energy in the medium term.
• Hydrogen still ranks low in the merit order of demand-side management measures (e.g. grid reinforcement, smart metering, flow cells, etc). These do not threaten hydrogen markets, but are complimentary to them.

9.1.2 Applications and markets

• Besides meeting technical and cost targets and addressing safety issues, the design of a hydrogen energy system must be done in relation to what is market ready – no point to optimise a system specifying units whose capacity is not available or that are still at early development phases.

• Hydrogen energy technology deployment follows on from the high penetration of renewable energy into an energy system. It does not logically precede it; this would bring no climate change or energy security benefits. There is little point in seeking ways to make hydrogen, as it will naturally result from high proportions of renewable generation anyway.

• A battery-hydrogen hybrid energy storage system is required for stand-alone operation of a renewable energy system. Batteries carry out micro-balancing (instantaneous) of supply and demand, while hydrogen undertakes macro-balancing (on the scale of days or longer).

• There is considerable scope for improvements in the cost and operation of hydrogen energy technologies; however urgent action is required to enable this in time for mass market demand.

9.1.3 Electrolysers

• Downstream operation of electrolysers enables greater efficiency in the operation of low-carbon energy systems, because this exploits the smoothing of system dynamics that greater system-wide aggregation affords.

• In grid balancing applications, electrolysers run at low capacity factors, therefore their capital cost must be dramatically reduced for operators to have a viable rate of return on investment.

• Current electrolyser technology needs to be optimised for the variable and intermittent power input that is typical of renewable energy generators.
• The election between pressurized or atmospheric electrolysers is not yet clear. Some claim atmospheric ones are better suited to renewable energy (92), whereas pressurized ones reduce compression costs depending on the storage downstream.

• It is important to improve power electronics of electrolysers.

• The need for balancing the pressures on hydrogen and oxygen sides of the electrolyser complicates system operation. A precise regulation is needed because only a very small differential pressure is tolerated.

9.1.4 Power electronics

• Hardware, as the electrolyser, inverters and fuel cells, are not designed to be used with this type of wind turbines standalone system and the fluctuating grid and control communications.

• Delayed component and system response to rapid changes of power input (electrolysis) and power demand (fuel cells) is also blamed on power electronics and inappropriate operating software.

• Inverters must be carefully selected to meet the requirements of a (weak) mini grid.

• As regards the question of how quickly electrolysers and fuel cells must/can really be able to react, the suggestion from some projects is that ultracapacitors and/or batteries should carry out micro-balancing (instantaneous) of supply and demand, while hydrogen undertakes macro-balancing. A hybrid ultracapacitors/batteries/hydrogen system can hence help supporting the grid on different time scales: use of ultracapacitors in the range of milliseconds, batteries in the minutes range, and hydrogen for the hours time scale.

• Filters (electronics) are necessary to reduce the harmonics content caused by current rectification.

• It has proven out to be useful to install a dummy load for carrying out tests and experiments that cannot be performed when connected to the household consumers.

9.1.5 Design, erection and commissioning

• The sizing of the preliminary design usually is based on engineering considerations made by technical models, but it may change due to restrictions in budget and availability of suitable components.
• It is important to have a well-defined design basis and operational philosophy that takes into account climate, signal quality, communication (as regards control and regulation), and interfaces.

• Purity requirements are a cost driver and they reduce system efficiency. It is important to keep the hydrogen purity requirement as loose as possible, in order to increase the overall efficiency of the plant.

• The selection of the right project partners is key since wind-hydrogen systems are far from “plug and play”.

• Co-operation with local companies may help reducing the costs for designing and installing the more conventional facilities and even some specific ones, as for instance a downstream hydrogen refuelling station.

• The cost of equipment depends on the size and engineering services required. It is also important to consider the risk of changing exchange rates.

• To be on the safe side, an ample provision for extra costs should be considered for calculating the costs of large systems.

• Civil works were an important part of the cost of the project, and may be increased due to the safety regulations, as big concrete walls to be erected between the areas for storage and generation.

• Delivery time for specific materials and components is long.

• The logistics required for transporting the components to remote sites pose a challenge. All equipment must be kept as simple and as robust as possible and redundancy needs to be accounted for.

• Transportation and installation of hardware is something to be considered for such installations that are in many cases remote and with poor access. The capacities of the systems involved can put a challenge on the limit of conventional trucks and lifting equipment in terms of size and weight in combination with the poor access road quality.

• Standardised protocols for communication between the individual components should be improved.

**9.1.6 O&M**

• Some of the component distributors tend to underestimate the effort (and therefore the costs) for regular maintenance.
• Gas connections between components have to be carefully checked for leaks. Even when all connections appeared to be tight when first checking with nitrogen, sometimes small leaks are detected when the system is filled with hydrogen subsequently.

• High extra costs for nitrogen (for purging) need to be taken into account.

• For outdoor installations, care must be taken to keep animals such as rats away, because they can eat any plastic tubing or wire. Other problems related to installations on “remote areas”, in the absence of permanent personnel on-site, are an increased cost for maintenance, theft and transport issues.

9.1.7 Permitting and safety

• The bureaucratic process associated with obtaining the necessary approvals for the installation proves long, complicated and expensive.

• There is a lack of regulations, codes and standard which made the permitting processes complex and very dependent on the exact site. To obtain the support and involvement of local and regional authorities is crucial.

• A strong focus on safety, health and the environment is recommended. One reason for this was the expected considerable number of (unskilled) visitors.

• High extra costs may arise because of hard security requirements, as for piping and instrumentation with redundant security elements (valves, sensors, etc).

• Costs for approvals should not represent a major hurdle, but in large plants they may be a hard obstacle to overcome.

• Another cost factor can be the strictness of safety requirements, which are may result in unnecessarily over-engineered systems if unduly stringent, and require considerable time and effort in following approval procedures. In current research projects, these issues are often not so pronounced, but could severely affect ventures that are more commercial.

9.1.8 Miscellaneous

• More research on integrating electrolyser, wind turbine and grid will be helpful.

• Oxygen as a by-product can contribute to the profit margin. It seems likely that such oxygen can only be marketed locally, which would affect site selection.
- The system proves quite difficult to model. It turned out to be problematic to reproduce the behaviour of the “electrolyser + compressor” subsystem under the scheme of work involved in the operation with renewable energy.

- Installation of a dispenser to supply a hydrogen vehicle with fuel would be an option to increase the capacity factor of the system.

- Tradeoffs between component lifetime and operational burdens have to be established and optimised in the future.
10 Countries Perspectives

This chapter investigates the present situation and the potential for wind-hydrogen systems in some Task 24 member countries.

It first looks into current regulations and support schemes for renewable electricity and for alternative fuels, in order to identify incentives regarding wind energy and hydrogen.

For selected countries, an overview of on-going and planned activities relevant to the scope of Task 24 is provided. Projections of the evolution of renewable energy are summarised.

The objective was to establish, as far as possible at present, market opportunities and obstacles for future commercial wind-hydrogen systems and for hydrogen derived from wind energy, respectively

10.1 Canada

10.1.1 Support for renewable energy

The federal government has instituted a number of programmes to promote the development of some types of renewable energy. In general, these programmes fall under three headings: market assistance, fiscal measures, and research and development.

Federal Market Assistance Programmes

In 2007, the federal government announced a number of ecoENERGY Initiatives. These programmes provide almost CAD 4 billion in funding to assist the development of a more sustainable energy system. The initiatives include a four-year, CAD 1.5 billion investment² to increase the supply of renewable energy from a number of sources.

It includes the ecoENERGY for Renewable Power programme, which offers eligible renewable energy projects (those commissioned before March 2011) a production incentive of CAD 0.01 per kWh for up to 10 years. This represents an investment of approximately

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¹ Most entries reflect the situation in 2010 when Task 24 initially was scheduled to end. Only major changes that occurred in 2011 and 2012 are considered in the chapter.

² 1 CAD is about 0.75 €, as of September 2010.
CAD 1.48 billion over 14 years, and will support the installation of up to 4,000 MW of new capacity.

**Fiscal Measures**

There are two principal fiscal measures that provide support for investment in the production of electricity from renewable sources. First, under the Federal Income Tax Act, equipment that is designed to produce energy from renewable sources is eligible for an accelerated capital cost allowance (ACCA) at 50% on a declining basis. Secondly, for projects using these renewable energy technologies, many start-up expenses qualify as Canadian Renewable and Conservation Expenses (CRCE) that may be deducted in full in the year incurred, carried forward to future years or transferred to investors using flow through shares.

**Support for Research and Development**

Canada’s energy research and development activities are focused towards increasing the efficiency of emerging technologies and reducing their cost. The ecoENERGY Technology Initiative provides CAD 230 million to fund research, development and demonstration to support the development of next-generation clean energy technologies. The initiative provides funding towards the development of technologies for producing and using renewable energy from clean sources such as wind, solar, tidal, and biomass. In addition, the federal government sustains two funds to support the development and demonstration of innovative technological solutions operated by Sustainable Development Technology Canada (SDTC), a not-for-profit foundation that supports the development of clean technologies. The Sustainable Development Tech Fund is a CAD 550-million scheme aimed at supporting the late stage development and pre-commercial demonstration of clean technology solutions: products and processes that contribute to clean air, clean water and clean land, which address climate change and improve the productivity and competitiveness of Canadian industry.

**Renewable Electricity in the Provinces and Territories**

Ontario has conducted three competitive procurements of large-scale renewable energy projects, which yielded a total of 1,600 MW of renewable electricity generating capacity. In November 2006, the Ontario Power Authority announced a Renewable Energy Standard Offer Program (RESOP) that offers 20-year contracts to projects of 10 MW or less. For wind, biomass and hydro, prices are CAD 0.11 per kWh with 20% of the price indexed to the Ontario Consumer Price Index. For photovoltaic projects, the price is CAD 0.42 per kWh.
Projects that demonstrate that they can operate reliably during peak hours will be paid an additional CAD 0.0352 per kWh for electricity delivered during peak hours.

A net metering programme is in place, which allows electricity generated from small-scale renewable installations to be exported to the electrical network in return for a credit towards the producer’s electricity bill. In May 2009, the Ontario legislature passed the Green Energy and Green Economy Act, 2009, a significant piece of legislation intended to attract new investment, create new green economy jobs and better protect the environment. The legislation was the result of consultations with stakeholders, including public comment on its provisions through both legislative hearings and posting on Ontario's environmental registry.

Key elements of the legislation (and related policy) include:

- Streamlined approvals for renewable energy projects, encouraging investment in renewable energy while working with municipalities and ensuring strong protection for health, safety and community consultation.

- Opportunities for municipalities, First Nations and Métis communities to build, own and operate their own renewable energy projects.

- New programmes for municipalities, communities and aboriginal groups to ensure that some project costs associated with community renewable energy projects can be recovered.

- Establishment of an academic research chair to examine potential public health effects of renewable energy projects.

- Important responsibilities for the Ontario Energy Board and other entities in achieving the province’s objectives of conservation, promotion of renewable generation, and technological innovation through the smart grid.

- A feed-in tariff system, which will provide guaranteed prices for renewable energy projects, including a focus on helping companies, farmers, co-ops and other groups navigate the approvals process, creating Ontario jobs, and developing a smart grid which, among its benefits, will support this new energy supply.

- The feed-in tariff, based on successful European schemes, will introduce a new power purchasing programme with guaranteed 20-year pricing and no upper limit on project scale. The tariff will replace the existing RESOP and is the first of its kind in North America. The feed-in tariff also includes a price adder for aboriginal and community projects to encourage greater participation.
In an effort to add renewable electricity capacity to British Columbia’s generation portfolio, BC Hydro is purchasing power from independent power producers whose projects meet detailed green criteria. To date, these projects have involved well-established technologies utilising resources such as small-scale hydro and biomass.

Since 2000, BC Hydro has issued four Calls for Power for varying amounts of renewable energy, wherein independent power producers bid into a generation process. By November 2008, BC Hydro had received 68 proposals from 43 registered proponents in response to the most recent Clean Power Call. In aggregate, the 68 proposals represent a total firm energy output of approximately 17,000 GWh per year from 45 hydro projects, 19 wind projects, two waste heat projects, one biogas project, and one biomass project. In November 2009, BC Hydro short-listed 47 proposals and decided to advance with post-proposal discussions with the 13 proponents whose projects have been identified as the most cost-effective. BC Hydro contacted the proponents of the other 34 short-listed proposals in November 2009 to afford them an opportunity to make their proposals more cost-effective.

In another scheme, BC Hydro is implementing a Standing Offer Program to encourage the development of small and clean energy projects throughout the province. The programme is a mechanism to purchase energy from small projects with a nameplate capacity between 0.05 MW and 10 MW. BC Hydro will pay for each megawatt-hour of energy delivered a tariff based on a number of different factors. The programme does not have an initial target volume or quota and the need for total or annual volume caps will be reviewed after the first two years of the programme, sometime in the first half of 2010.

Manitoba is implementing a policy to develop 1,000 MW of wind within the next decade assuming the economic feasibility of future wind projects. Manitoba Climate Change legislation restricts the operation of the province’s only remaining coal-fired generating facility for emergency use only.

Québec released its Energy Strategy in 2006. With approximately half of its total energy consumption coming from renewable, Québec is planning to go even further. Jointly with its Plan Nord objectives, more than 7,500 MW of hydroelectric power and 4,300 MW of wind power will be implemented on the grid before 2035.

The Atlantic Provinces – Prince Edward Island, Nova Scotia, and New Brunswick – are the only jurisdictions to have implemented legislated Renewable Portfolio Standards. Prince Edward Island has set a 30% standard to be achieved by 2016; Nova Scotia has set a standard of 5% of new emerging renewable energy by 2012 and 10% by 2013; and New
Brunswick a 10% standard by 2013. In October 2008, the government of Prince Edward Island announced the province’s wind energy strategy entitled Island Wind Energy, Securing Our Future: The 10-Point Plan. The province’s goal is to establish 500 MW of wind power, installed in the province, by 2013. The 10-Point Plan sets clear ground rules and establishes a fair, open and transparent process for developers.

10.1.2 Support for alternative fuels

There is no specific support for the use of “green” hydrogen or hydrogen fuel in general.

10.2 Denmark

10.2.1 Support for renewable energy

The Danish political agreement on energy from February 2008 sets the goal for renewable energy at 20% in 2011. This will include all kinds of renewable energy like incineration of waste, wind power, biomass etc. and a number of initiatives have been taken in order to reach this goal.

In the Danish Law to Promote Renewable Energy of December 2008, the subsidies for wind power in general are set to 0.25 DKK/kWh (about 3.3 ¢/kWh) for the first 22,000 hours (full capacity) (93). In addition 0.023 DKK/kWh (0.3 ¢/kWh) is paid for the expenses of balancing. The subsidies for large offshore wind farm projects are defined independently for each wind farm. For example, the wind farm Rødsand II receives a fixed tariff of 0.63 DKK/kWh (8.4 ¢/kWh), independent on the power spot price (93). All these extra prices are in turn paid by the consumers, who are forced to accept a certain amount or fraction of expensive “prioritized” power on their bills.

In addition, the legal framework allows neighbours of new wind turbines to demand compensation or to become part owner of the turbine. These possibilities have been opened after numerous protests from wind turbine neighbours, who see the value of their private properties decline, when the turbines are raised.

The present support for renewable electricity in Denmark is hardly sufficient to imply a strong market penetration for wind hydrogen solutions over the next two decades. Hydrogen systems are still very expensive and the public acceptance is doubtful for economic reasons, particularly considering the recent economic recession in Denmark as in many other countries.
10.2.2 Support for alternative fuels

The Danish tax on cars of 180% is the highest in the world. Under the present legislation (presently agreed until 2015), electric and hydrogen cars are tax-free. This, however, does not include hybrid cars with combustion engines. Considering the high tax rate for normal cars, the tax exemptions constitute a strong economic motivation to introduce hydrogen (or electrical) cars in Denmark.

The Danish TSO, Energinet.dk is supporting a demonstration and test program for electric vehicles where a number of companies and institutions has received support of 33 million DKK (about 4.5 million €\(^1\)) for gaining experience. The aim of the project (called the EDISON project - Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks) is to develop optimal system solutions for EV system integration, including network issues, market solutions, and optimal interaction between different energy technologies. The total budget is 49 million DKK (6.5 million €) (94).

Authors judge that fossil energy will be the predominating source for transport fuels in Denmark for several if not many decades ahead. Only for local transport operation in urban areas a market opportunity is foreseeable for hydrogen/electric vehicles in a near term future.

10.2.3 Prognosis on the evolution of renewable energy

There is no official prognosis for the evolution of renewable energy in Denmark.

The declared goal for 2011 is 20% renewable energy (all kinds) and 1,300 MW additionally installed (new) wind power capacity by 2012 (leading to wind power penetration of 25-30%).

The Danish TSO operates with a goal of 50% wind power penetration in the power system by 2025 and the present plans in Denmark for off-shore wind installation strongly support that this goal will indeed be reached.

As member of the EU, Denmark has agreed on the 20-20-20 goal, which includes a 20% share of renewable energy in total energy supply by 2020. However, as indicated above it is expected that Denmark will increase its share even further.

The Danish government has declared the ambition to make Denmark independent of fossil fuels in the future, however without indicating a year for this to happen. A strong driving

\(^{1}\) 1 DKK is about 0.13 € as of October 2010.
force for this ambition is the declining prospects for the Danish fossil resources in the North Sea.

10.2.4 Prospects for wind-hydrogen systems

There are no dedicated wind-hydrogen installations in Denmark, but a number of projects on utilization of hydrogen are being carried out, where electricity (not directly linked to wind power) is converted to hydrogen either for domestic use or for use as a transport fuel:

Electricity Storage

In the CFT project at Lolland an electricity storage system using hydrogen has been built and is currently being tested. The system included a 9 kW electrolyser, 150 Nm³ hydrogen storage (at 6 bar) and 9.5 kW of PEM fuel cells. The system has been storing electricity from the grid, i.e. there was no direct connection to wind turbines.

Since September 2008 households in the village of Vestenskov on the island of Lolland have been connected to a local hydrogen network, which provides the households with electricity and heat based on renewable energy sources via electrolytic production of hydrogen and re-electrification in fuel cells. A consortium of nine companies called Dansk Mikrokraftvarme (Danish Micro Combined Heat and Power) is carrying out the 6-year project to develop the required technology and deploy the ideas to obtain valuable, practical experience. Initially 5 households were connected to the network and the goal is that Dansk Mikrokraftvarme should provide heat and electricity to 35-40 households in 2012. Each household has a 2 kW fuel cell which supplies sufficient heat and power for Danish conditions throughout the year. No data on economy or technical measures are yet available. For more information, visit www.h2-lolland.dk.

Fuel production for transport

Figure 52 shows the present and planned hydrogen fuelling stations in Denmark. Two hydrogen fuelling stations on public roads are available (in western Jutland and in Copenhagen). 10 smaller fuelling stations are used by companies and public/private institutions to fuel small, special vehicle, typically for off-road applications like forklifts. More information can be found in www.hydrogenlink.net.
The filling station in Copenhagen delivers hydrogen at 350 bar (the aim is 700 bar by the end of 2010). The station is operated by a private company and is able to fill 5-10 cars per day. The station is mainly used by the municipality of Copenhagen, who bought 8 cars at a price of 100,000 € each in 2009. The cars are used for every-day-functions and have maximum speed of 110 km/h, accelerate 0-50 km/h in 5 sec. The anticipated hydrogen price, when the station was launched in 2009, was 138 DKK (18.5 €) per kg of hydrogen. For the vehicles serviced in the project 1 kg of hydrogen implies a driving range of approx. 100 km and with the 350 bar tank the cars have a driving range of approx. 195 km. The fuel cells are at least designed for 2,000 service hours before service (corresponding to about 100,000 km) and Copenhagen Municipality has a service agreement securing fuel cell life of 5,000 hours.

10.3 Germany

10.3.1 Support for renewable energy

Renewable energy is supported through the Renewable Energy Act (Erneuerbare-Energien-Gesetz; EEG).
The EEG basic principles

For each kilowatt-hour that a wind turbine produces over 20 years from installation, a fixed tariff is paid. It depends on the calendar year of commissioning. The tariff has two stages:

- 1\textsuperscript{st} stage: “high tariff”, for at least 5 years for onshore wind turbines (offshore see below)
- 2\textsuperscript{nd} stage: “low tariff”, for the remainder of the 20-year period.

The duration of the 1\textsuperscript{st} stage is extended beyond the first 5 years if the actual yield of an installation falls short of a reference yield. The reference yield depends on the site and the turbine model.

A wind turbine commissioned in 2003 and matching the reference yield (or doing better) would thus earn 8.9 c/kWh over the first 5 years and 6 c/kWh thereafter (see Table 13, columns 2 and 5). A turbine commissioned in January 2004 would earn 8.8 c/kWh and 5.9 c/kWh, respectively. Inflation is not compensated for.

The extra costs generated by these tariffs are distributed equally among all consumers as a surcharge per kilowatt-hour consumed, except some electricity-intensive industries (95).

Changes with EEG 2004 and EEG 2009: Onshore

The major changes established by EEG 2004 comprised adjustments of provisions and tariffs, according to technological progress and market developments. The tariffs for new installations were reduced accordingly from 1 March 2004 (Table 13, columns 3 and 6).

Owing to a massive increase in prices of the wind turbine raw materials and components (96), EEG 2009 lifted the tariffs.

Changes with the EEG 2004 and 2009: Offshore

EEG 2004 introduced separate and higher tariffs for offshore wind. The duration of the 1\textsuperscript{st} stage was increased to twelve years for all turbines installed before 31\textsuperscript{st} December 2010. This 2010 deadline was dropped in EEG 2009. The duration of the 1\textsuperscript{st} stage is further supplemented according to water depth and distance from the shore:

- 0.5 months for every nautical mile beyond 12 miles from the sea shore
- 1.7 months for every full metre depth increase beyond 20 metres.

Table 13. Remuneration for onshore wind energy in Germany. Tariffs are guaranteed over 20 years after commission.
System service bonus

EEG 2009 stipulates that energy from wind turbines commissioned before January 2014 receives a “system services bonus” of 0.5 c per kWh if they fulfil certain requirements regarding fault on the wind turbine side and on the grid side, in particular as regards maintaining voltage and frequency and providing reactive power.

Table 14. Remuneration for offshore wind energy in Germany. Tariffs are guaranteed over 20 years after commission.
In the past, wind turbines were obliged to disconnect from the grid, for example, in case of excess or low grid voltage. Modern installations have so-called fault ride through capacities that can help stabilising the grid in critical situations.

**“Combined renewable energy power plant” bonus, including energy storage**

EEG 2009 authorises an ordinance that defines the criteria and financial incentives for “combined renewable energy power plants” that facilitate steady feed-in and/or demand-based feed-in. This can be accomplished by combining fluctuating and dispatchable renewable energy sources, for example wind-based and biomass-based power generation (97), or by energy storage. The idea is to promote market integration of electricity from renewable sources with growing shares in total electric energy supply. Several models have been suggested in this respect.
A recent study assesses these models. For energy storage, it suggests a bonus of 2 c/kWh of stored energy (technology component). The response to feed this energy into the grid on demand would earn the storage operator another 2 c/kWh. Under direct marketing (on the spot market, for example), only the technology component would pay off (98).

It is not clear yet when such bonus may be implemented.

**Conclusion**

The support mechanisms for renewable energy are starting to be adjusted in order to account for the implications of fluctuating sources, such as wind energy, in the light of growing market penetration and grid stability concerns. This could make energy storage in the form of hydrogen attractive in the medium to long-term future.

10.3.2 **Support for alternative fuels**

An alternative fuel strategy was drawn up in 2004 that suggested support for biofuels and hydrogen derived from renewable energy (99), including tax incentives, research and development, and the development of technical and legal standards.

To date, though, hydrogen is subject to the same amount of energy tax as natural gas. This amounts to 31.80 €/MWh in general but is reduced to 13.90 €/MWh until the end of 2018. There are no exceptions for “green” hydrogen, possibly since hydrogen in Germany still is mainly produced from natural gas.

Research and demonstration projects can be exempted from energy taxation anyway. A tax incentive for hydrogen will be required only when the fuel pathway is ready for the market.

A review of the alternative fuel strategy started in June 2011.

The “National Innovation Programme for Hydrogen and Fuel Cell Technology” (NIP, 2007 - 2016) is running under the auspices of the Federal Ministry of Transport, Building and Urban Development, while involving also the Ministries for Economics and Technology (BMWi), for Education and Research (BMBF) and for the Environment, Nature Conservation and Nuclear Safety (BMU).

Hydrogen as a fuel for road vehicle has been a focus of the NIP from its beginnings (see for example the Clean Energy Partnership below). Hydrogen derived from wind energy has received more attention recently.
10.3.3 Prognosis on the evolution of renewable energy

The government finalised its energy concept for up to 2050 in September 2010. One of the key goals is to reduce greenhouse gas emissions by at least 80% and to increase the share of renewable energy in gross electricity consumption to 80% by 2050. See Table 15 for more detail.

Measures planned to foster renewable energy include simplifying the approval procedures for offshore wind farms and for repowering onshore, and creating an efficient grid infrastructure for integrating renewable energy. A section on energy storage mentions compressed air, hydrogen, hydrogen-derived methane and battery vehicles. It is intended to facilitate access to the balancing power/energy markets for storage plants. The relevance of fuel cell vehicles is highlighted in the context of “green” hydrogen (100), (101).

16.1% of the gross electricity consumption was derived from renewables in 2009, of which about 40% came from wind, 30% from biomass and 20% from hydro power (6).

The German Renewable Energy Federation (Bundesverband Erneuerbare Energie, BEE) published a prognosis for the development of the renewable power up to 2020 (9). It claims that 47% (278 TWh) of the electricity consumption can be covered by renewables in 2020. Installed green power is expected to rise to 111 GW compared with some 45 GW at the end of 2009, almost 26 GW of which were wind turbines (6).

A study commissioned by the Federal Ministry for the Environment, published in 2007, predicts some 155 TWh renewable electricity for 2020, about 250 TWh in 2030 and some 430 TWh by 2050 (102). This corresponds to about 27%, 45% and 75% of the gross electricity consumption in the respective years.

Table 15. Key target figures of the German energy strategy up to 2050. Source: (10)

<table>
<thead>
<tr>
<th>Year</th>
<th>Reduction of greenhouse gas emissions relative to the level in 1990</th>
<th>Share of renewable energy in gross electricity consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>40%</td>
<td>35%</td>
</tr>
<tr>
<td>2030</td>
<td>55%</td>
<td>45%</td>
</tr>
<tr>
<td>2040</td>
<td>70%</td>
<td>60%</td>
</tr>
<tr>
<td>2050</td>
<td>80% – 95%</td>
<td>80%</td>
</tr>
</tbody>
</table>
10.3.4 Prospects for wind-hydrogen systems

The installed wind energy generation capacity in Germany amounted to 25.8 GW at the end of 2009. More than 42% of this is installed in the Federal States bordering the North Sea and the Baltic Sea. Another 29% are located in Brandenburg and Sachsen-Anhalt, two States in the East with a largely flat topography. These areas are thus the main focus in exploring the needs-based potential for wind-hydrogen systems.

Near the coastline, there is also high capacity for repowering, thereby increasing the installed power, and of course, for offshore wind farms. In Germany, some 46 GW are expected to be installed by 2020, 10 GW of which will be offshore (8). Some 25 GW of offshore wind power capacity are foreseen by 2030.

The National Organisation Hydrogen and Fuel Cells (NOW) that executes the NIP (see above), presented the results of a study on the state-of-the-art and prospects of water electrolysis in May 2011.

NOW has recently commissioned a study on the integration of wind-hydrogen plants into the energy system with a focus on technical and economic viability. Results are expected for autumn 2012.

A study commissioned by the Governments of Hamburg and Schleswig-Holstein on the potentials of wind-hydrogen technology in these Federal States was published in autumn 2010 (103).

In May 2011 three federal ministries launched the “Energy Storage Funding Initiative” to promote research and development in this field, making up to 200 million € of support available (104). It is known that proposals concerning wind-hydrogen systems have been submitted. Decisions on the allocation of funding are pending.

Mini Grids

All parts of Germany are connected to the national grid, including the islands, so there is no immediate potential in the Mini Grid context.

Electricity Storage

Electricity Storage is most likely to take place in the main regions of wind energy generation as outlined above. First, because in doing so, bottlenecks in the power lines towards the main areas of consumption in the west and south of the country could be managed. Second, the geological conditions in the northern regions are beneficial for underground gas storage in salt caverns (105). Today some 170 caverns exist that can hold some 8 billion normal cubic metres of natural gas. The capacity has been increased
continuously in recent years; an additional capacity of 1 billion normal cubic metres is planned for in the near future.

A number of research activities have taken place related to Electricity Storage via hydrogen, in particular carried out by the Universities of Applied Sciences in Stralsund and Lübeck, and by the HyWindBalance consortium.

Developers and operators of wind farms have started relevant activities as well:

The company WIND-projekt is going to combine a wind farm (of up to 30 turbines, 160 – 180 MW) with a 1 MW electrolyser. In the RH₂® (Renewable Hydrogen) project, hydrogen will be stored at 300 bar (9,500 Nm³) and re-electrified in a 250 kW CHP unit with an ICE motor. Electricity from the CHP plant will be supplied to the wind turbines at times of low/no wind instead of drawing energy from the grid, to operate controls etc. CHP heat will be supplied to a farm near the wind-hydrogen site. Apart from fostering the integration of wind energy, the RH² project also aims at serving as a starting point for a hydrogen infrastructure in the State of Mecklenburg-Vorpommern. Hydrogen could be delivered to the HyPort project (inland ships and buses) by trailer and used for tractors, for example. Options to market also the oxygen generated will be studied. The project started in 2009 and will run until 2014. Construction started in the second quarter of 2011.

The wind farm developer ENERTRAG in cooperation with the University of Applied Sciences Stralsund are implementing a wind-hydrogen-biomass hybrid power plant with three 2 MW wind turbines, a 500 kW alkaline atmospheric electrolyser, hydrogen storage at 25 bar, two 350 kW CHP units (ICE) that can run on mixtures of biogas and hydrogen at variable rates. The hydrogen will also be used in road vehicles. It is further planned to utilise the oxygen. The idea of the project is to match exactly a day-ahead forecast for wind power. Other modes of operation will be studied, too. The project is seen as a first step towards wind energy as a base-load supplier (106). Construction is planned to be complete by end of 2011.

Fuel Production

The GermanHy study has investigated energy sources that hydrogen fuel for road vehicles can be derived up to 2050. It identifies wind energy as a major contributor from around 2025. In fact, the study expects wind energy to be the most important resource for hydrogen fuel generation due to its high potential. In 2025, around half a million passenger cars and some 70,000 light duty vehicles powered by hydrogen are expected to be in operation. Around 2,000 refuelling stations (of today roughly 15,000) may offer hydrogen by that time. Delivery to the refuelling stations will be dominated by liquid hydrogen trailers with
at least one liquefier close to the coastline, until hydrogen pipelines become economically feasible from 2025/30 onwards (107).

At about 25 stations in Germany it is currently possible to refuel hydrogen. This includes stations from project such as HyFLEET:CUTE and from the Clean Energy Partnership. Several new sites are in preparation. A “CO₂-neutral hydrogen refuelling station” will be integrated into the new Berlin Brandenburg International Airport. The entire station including hydrogen generation will be powered by a nearby wind farm. It is planned to open in 2013 (108).

10.4 Greece

10.4.1 Support for renewable energy

According to Annex I, part A to Directive 2009/28/EC, the Greek national target for energy from RES in gross final consumption of energy in 2020 is 18%, starting with a share of 6,9% in 2005. In the new Greek Law 3851/2010 (OG A/85/4 June 2010), which came into effect on 4 June 2010, an even more ambitious national target is set for RES, namely 20% in final energy consumption, with specific targets of 40% for RES electricity share, 20% for RES heating and cooling share and 10% in RES transport share. Law 3851/2010 aims at simplifying the licensing procedure, rationalizing the feed-in-tariff scheme, addressing existing barriers at local level and establishing specific regulations for the use of RES in buildings, in accordance with the “Energy Performance of Buildings Regulation” (OG 407/B/2010).

At the beginning of 2010, the installed capacity of wind was only 1,180 MW and that of PV about 70 MW, generating approximately 4% of electricity, in addition to 9% by large hydro plants. A “National Renewable Energy Action Plan in the scope of Directive 2009/28/EC” was released in mid-2010. It has been compiled under the supervision of the National Committee for meeting 20-20-20 targets and other requirements, established by decision of the Minister for Environment, Energy and Climate Change. The document includes a comprehensive overview of policies and measures concerning the support for renewable energy.

Since the first legislative effort that considered alternative forms of energy for power generation (Law 1559/1985), the regulatory framework for renewables was gradually established through the adoption by the Greek Parliament of several laws and the issue of several ministerial decisions, among which:
• Law 2244/1994 “Regulation of power generation issues from RES and conventional fuels and other provisions”, which introduced feed-in-tariffs for RES and the obligation for the Public Power Corporation to buy the energy produced from the RES unit.


• Law 3468/2006 “Generation of electricity from renewable energy sources and through high-efficiency co-generation of electricity and heat and other provisions”, which differentiated the previously unique feed-in-tariff regime, amended by Law 3734/2009

The grid operator is obliged to buy the RES energy as per Power Purchase Agreement signed with the producer for 10 years, extendable for another 10 years. The remuneration of RES electricity production, as set in article 13 of Law 3468/2006 is reported in the upper section of Table 16. The feed-in tariffs were adjusted in the following years by Ministerial Decrees, reaching the levels as reported in 2009, see middle section of Table 16.

According to the new Law L3851/2010, the state will determine areas where offshore wind farms are environmentally acceptable and will open a public tender for the exploitation rights of the selected sites. Furthermore, L3851/2010 foresees increased tariffs for wind farms installed in areas with low wind potential, on islands that are electrically connected to the mainland system by the farm owner and a compensation for up to 30% of eventual curtailment. As from June 2010, the feed-in tariffs are set to the values as in the lower section of Table 16.

<table>
<thead>
<tr>
<th></th>
<th>c / kWh</th>
<th>Mainland</th>
<th>Non-interconnected islands</th>
</tr>
</thead>
<tbody>
<tr>
<td>According to Law 3468/2006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind energy</td>
<td>7,3</td>
<td></td>
<td>8,46</td>
</tr>
<tr>
<td>Off-shore wind energy</td>
<td>9,0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valid in 2009</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind energy</td>
<td>8,784</td>
<td></td>
<td>9,944</td>
</tr>
<tr>
<td>Off-shore wind energy</td>
<td>10,484</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As set be Law 3851/2010</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind energy &gt; 50 kW</td>
<td>8,785</td>
<td></td>
<td>9,945</td>
</tr>
<tr>
<td>Wind energy &lt; 50 kW</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10.4.2 Support for alternative fuels

In Greece, there is no specific support for the use of “green” hydrogen as fuel.

10.5 Norway

10.5.1 Support for renewable energy

The Norwegian renewable policy is based on support given in the form of direct capital subsidies to the construction of new renewable capacity through the public agency, Enova. Since 2004 Enova’s budgets have increased substantially, as shown Table 17. 2009 was an extraordinary year because an extra €1.2 billion NOK\(^1\) was allocated to Enova as a mean to limit the effects of the economic downturn.

Table 17. Budget allocations to the Energy Fund 2004 – 2010. Figures given as million Norwegian krones (NOK); 1 million NOK is about 127,000 €, as of September 2010.

<table>
<thead>
<tr>
<th>Year</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income from the levy on the distribution tariff</td>
<td>470</td>
<td>717</td>
<td>735</td>
<td>734</td>
<td>723</td>
<td>735(^2)</td>
<td>760(^3)</td>
</tr>
<tr>
<td>Interest on the Energy Fund (from previous year)</td>
<td>13</td>
<td>14</td>
<td>29</td>
<td>54</td>
<td>88</td>
<td>105</td>
<td>84</td>
</tr>
<tr>
<td>State budget allocations: Ordinary budget allocation</td>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Transfer of return from the Grunnfond</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>399</td>
<td>391</td>
<td>756</td>
</tr>
<tr>
<td>Fiscal Measures to Limit the Economic Downturn</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.190</td>
<td>0</td>
</tr>
<tr>
<td>Total allocation</td>
<td>543</td>
<td>731</td>
<td>764</td>
<td>788</td>
<td>1.410</td>
<td>2.621</td>
<td>1.800</td>
</tr>
</tbody>
</table>

Green certificates market

The first negotiations between Sweden and Norway on a common green certificates market failed in 2006 due to disagreements on the burden sharing. The negotiations resumed in 2008.

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1 Norwegian Crown is about 0.127 €, as of September 2010.

2 Estimate for 2009.

3 Estimate for 2010.
A memorandum of understanding (MoU) between the two countries establishing the principles for a common green electricity certificates market was signed 7 September 2009.\(^{(110)}\)

The MoU establishes some key principles: equivalent ambitions in both countries, the time of implementation and non-discrimination between technologies. The goal is to start the common green electricity certificates market from 2012 onwards. The two countries are currently negotiating the details and workings in order to realise this plan.

The Norwegian government has established that all hydro power plants with an installed capacity below 1 MW (micro plants) where construction started after 1 January 2004, and all other renewable energy plants where construction started after 7 September 2009, are eligible to take part in the green electricity certificates scheme.

**Enova’s programmes for promoting renewables**

Programmes include:

- **Renewable electricity production**

  The renewable energy production programme is based on investment subsidies. The objective of the programme is to increase the production of wind power and further develop the Norwegian wind power market. The investment support must be the triggering factor for construction of the facility.

  The programme is launched once or twice a year by Enova. Market players need to apply within a given deadline and those who apply have to compete for the available pre-announced amount of funding. Applications are ranked according to the support required per kWh of expected annual production. The cheapest projects are granted support. The maximum permitted support is calculated on the basis of the following assumptions:

  - Required rate of return: 8% actual pre tax
  - Lifetime: Construction time + 20 years of production
  - Power price: Last 6 months' average of 3 years forward observed on Nord Pool as of the application deadline date
  - Revenues: Power price multiplied by the expected energy production

- **Demonstration of renewable energy technologies**

  The purpose of the programme is to demonstrate and hence to improve the deployment of new renewable energy technologies, such as offshore wind, tidal, wave, solar
and projects that combine solar heating with other energy sources except for electricity. The programme also addresses new technologies within energy efficiency. Enova can contribute up to 50% of the total project cost.

Hydro power projects, including small, micro and mini hydro power plants, are currently not covered by Enova’s grant schemes.

10.5.2 Support for alternative fuels

There is no specific support for the use of “green” hydrogen or hydrogen fuel in general.

10.5.3 Prognosis on the evolution of renewable energy

In an agreement between the Ministry of Petroleum and Energy and Enova, which was signed in 2008, Enova is to support/trigger off (i.e. to contract new projects and/or complete projects) new products that adds up to 18 TWh per year of new renewable energy production and energy savings by the end of 2011 above the level in 2001). Enova also has a long-term working target of 40 TWh/year by 2020.

10.5.4 Prospects for wind-hydrogen systems

Mini Grids

The Utsira project, demonstration of an autonomous wind-hydrogen system off the west coast of Norway, operated from 2004 to 2010. The system consisted of two wind turbines, one of which was connected to a hydrogen energy storage system. Excess wind power was converted to hydrogen by water electrolysis. In periods with little or no wind, hydrogen was used to supply energy from a hydrogen engine. Through this project, the technical feasibility of the concept was demonstrated. However further development is needed to drive costs down to a competitive level.

Electricity Storage

Hydro power accounts for nearly all electricity production in Norway and a large proportion of the hydro power stations have reservoirs. In 2009 Norway had 30,789 MW of installed capacity, with more than 98% being hydropower, and the rest fossil fuels and wind generation. Norway has significant wind resources on land as well as offshore and there is a strong interest to increase the use of wind energy in Norway. Wind power is seen as a good match for hydro power as the latter can be used for energy balancing. The potential for storing energy in the hydro power installation is great, with a capacity of 137 TWh in 2009.
The Norwegian power system is thus fairly flexible. Hence, in most regions grid integration of relatively large quantities of intermittent production such as wind power does not pose a major challenge to the balancing of the system. Despite the flexibility of the system not being a significant limitation, the grid capacity itself is a limitation to wind power development in some areas of Norway. In 2008 NVE (Norges vassdrags- og energidirektorat / Norwegian Water Resources and Energy Directorate) and Enova conducted a feasibility study on wind power and grid capacity. They highlighted the amount of new installed capacity of wind power that may be integrated in the grid in each region of Norway in the period up to 2015 and 2025. The result shows that it is possible to install between 5,800 MW (17.4 TWh) and 7,150 MW (21.5 TWh) of wind power.

Fuel Production

The HyNor project is a joint public-private partnership initiated to demonstrate real-life implementation of hydrogen energy infrastructure along a 580 kilometre route from Oslo to Stavanger. In 2009 two new filling stations were opened in Oslo and Drammen on 11 May as part of EVS 24 conference and the Viking rally. The four existing filling stations are operated by Statoil and use different resources and technologies for production and supply of hydrogen.

The hydrogen filling station concept developed by Statoil operates with three different sizes. The Station at Økern in Oslo is the smallest and can supply 10 – 15 cars with hydrogen. The station in Porsgrunn which opened in 2007 can supply 40 – 50 cars per day, and if the demand increases, the station can be expanded. The Økern station is built into a container and can be moved and replaced with a larger one if the demand for hydrogen changes.
The HyNor Lillestrøm station is planned to open in 2011. The hydrogen sources in this project are solar and biogas – both of which are local and renewable energy sources. The goal is to create a grid-neutral hydrogen filling station. This means that the station will deliver the same amount of electricity to the grid as it uses. Figure 53 shows a concept sketch of the production building which is covered with 50 m$^2$ of solar panels on the roof.

Lillestrøm has enough local landfill gas to produce about 2,000 kg hydrogen per day. This is sufficient to cover the average demand of 4,000 light duty vehicles. The filling station will use 1% of the local biogas for hydrogen production. This share will provide 10 Nm$^3$/h to the filling station. The rest of the biogas will be used for district heating. The reformer employed in the project is the ZEG Power reformer technology developed by the Institute for Energy Technology (IFE). This method is called Sorption Enhanced Steam Methane Reforming (SE-SMR). In parallel with production of biogas, hydrogen will be produced by electrolysis from solar generated electricity. A 250 m$^2$ solar panel will be built that has a max power of 50 kW, or sufficient to run a PEM electrolyser capable of producing 10 Nm$^3$ of hydrogen per hour. When the solar panels produce surplus electricity, this will be fed into the grid. Another novel technology demonstrated in this project is the metal hydride compressor. One of the most energy-demanding elements in the hydrogen chain is decompression. In order to reach 450 or 800 bar, electric energy is required that amounts to 10 and 15% of the
energy of the hydrogen being compressed. As a step to reduce costs related to compression, HyNør Lillestrøm will demonstrate one of the first full scale metal hydride (MH) compression systems. Instead of electricity, heat will be used to power the compression and steam at 150°C is sufficient to compress the hydrogen up to 200 bar, thereby potentially reducing the costs connected to compression with 50%.

In addition to the Lillestrøm station, three more stations for vehicles and one for hydrogen buses are planned to open in 2010 – 2011, one for light duty vehicles, one in the harbour of Stavanger and the other three Oslo.

10.6 Spain

10.6.1 Support for renewable energy

Royal Decree 1/2012, of January 27th, which is applicable to the suspension of pre-allocation procedures and the removal of economic incentives for new plants producing electricity from cogeneration sources renewable energy and waste.

Fixed Tariff

- RD 436/2004 - The price is set at between 80% and 90% of the Average Electricity Tariff (TMR) plus complements. The TMR is set annually by the Spanish Government. For 2007, the Average Electricity Tariff was 76.6 €/MWh.
- RD 661/2007 - The price is set at 83.7€/MWh (2013 base price), for wind during the first 20 years plus complements reducing to 69.9 €/MWh (2013 base price) after 20 years of operation.

Market Price & Premium

- RD 436/2004 - The price is set at the pool price plus a premium (40% of the Average Electricity Tariff), incentives (10% of the Average Electricity Tariff) and complements.
- RD 661/2007 - The market tariff option is the sum of the market pool price, plus a market option premium, plus reactive energy remuneration, less any imbalance charges. The market option premium is 33.5 €/MWh (2013 base price). The market tariff option is subject to a cap and floor mechanism ranging between 81.5 and 97.1 €/MWh (2013 base price).

In the offshore wind case the maximum market option premium will be 93.5 €/MWh with a cap in the market tariff of 182 €/MWh.
The fixed tariff option, market option premium, market tariff cap and floor and the reactive energy remuneration are escalated annually by IPC (Spanish consumer price index) less 0.25% until the end of 2012 and IPC less 0.5% thereafter.

10.6.2 Support for alternative fuels

There is no specific support for the use of “green” hydrogen or hydrogen fuel in general.

10.6.3 Prognosis on the evolution of renewable energy

Before the economic downturn, the electrical consumption expected in Spain in 2016 was around 362 TWh, of which around 17.8% could be covered by wind power. That means a wind power generation increase from about 20.7 TWh in 2005 to 64.6 TWh in 2016. To support this generation, the installed wind power needed would be around 29 GW (capacity factor of 25.35% or equivalent to 2,221 full load hours per year).

In June 2010, the National Renewable Plan for the period 2010 – 2020 was approved (111). Installed wind power was expected to reach 38 GW by 2020 (Table 18) with electricity generation rising from around 41 TWh in 2010 to more than 78 TWh in 2020 (Table 19).

Table 18. Planned development of renewable power in Spain in terms of installed capacity. According to the National Renewable Plan 2010 – 2020. Figures for 2005 and 2010 are actual data. (111)

<table>
<thead>
<tr>
<th>Year</th>
<th>Hydro</th>
<th>Solar</th>
<th>Wind</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PV</td>
<td>Concentrating</td>
<td>Onshore</td>
</tr>
<tr>
<td>2005</td>
<td>18.200</td>
<td>60</td>
<td>0</td>
<td>9.918</td>
</tr>
<tr>
<td>2010</td>
<td>18.687</td>
<td>4.021</td>
<td>632</td>
<td>20.155</td>
</tr>
<tr>
<td>2012</td>
<td>19.909</td>
<td>4.921</td>
<td>2.028</td>
<td>23.555</td>
</tr>
<tr>
<td>2014</td>
<td>19.999</td>
<td>5.553</td>
<td>5.861</td>
<td>26.416</td>
</tr>
<tr>
<td>2016</td>
<td>22.109</td>
<td>6.319</td>
<td>3.381</td>
<td>29.278</td>
</tr>
<tr>
<td>2018</td>
<td>22.229</td>
<td>7.246</td>
<td>4.149</td>
<td>32.139</td>
</tr>
<tr>
<td>2020</td>
<td>22.362</td>
<td>8.367</td>
<td>5.079</td>
<td>35.000</td>
</tr>
</tbody>
</table>

Table 19. Planned development of renewable power in Spain in terms of generated electricity. According to the National Renewable Plan 2010 – 2020. Figures for 2005 and 2010 are actual data. (111)
### Prospects for wind-hydrogen systems

#### Mini Grids

In Spain, two categories of mini-grid system must be developed. One of them is related to the peninsula area, where very few electrically isolated areas exist, but where they do, energy supplies are usually provided by diesel generators or really small hybrid renewable installations (wind/photovoltaic) with batteries for storage. Islands are the other application in which hydrogen mini-grids are appropriate, an example of which is the RES2H2 project situated in Canary Islands.

#### Electricity Storage

Around 2,400 MW reversible hydro power plants and, as of 2010, 20,000 MW wind power capacity is installed in Spain. Basically, Spain is an isolated electrical area. The interconnections with France are equivalent to 2% of total grid capacity, whereas around 10% would be desirable.

The aim of the reported Sotavento project was to gain experience with managing the fluctuating output of wind farms. Its key objective consisted in acquiring knowledge from operating a small hydrogen system (60 Nm$^3$/h electrolyser, 55 kW genset).

#### Fuel Production

Today, three hydrogen refuelling stations exist in Spain, all based on electrolytic hydrogen generation on the site:

<table>
<thead>
<tr>
<th>Year</th>
<th>Hydro</th>
<th>Solar</th>
<th>Wind</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWh</td>
<td>PV</td>
<td>Onshore</td>
<td>Offshore</td>
</tr>
<tr>
<td>2005</td>
<td>35.503</td>
<td>41</td>
<td>20.729</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>34.617</td>
<td>6.417</td>
<td>40.978</td>
<td>0</td>
</tr>
<tr>
<td>2012</td>
<td>34.960</td>
<td>8.090</td>
<td>47.312</td>
<td>0</td>
</tr>
<tr>
<td>2014</td>
<td>36.559</td>
<td>9.256</td>
<td>53.906</td>
<td>75</td>
</tr>
<tr>
<td>2016</td>
<td>36.732</td>
<td>10.565</td>
<td>59.598</td>
<td>975</td>
</tr>
<tr>
<td>2018</td>
<td>38.443</td>
<td>12.222</td>
<td>64.925</td>
<td>3.727</td>
</tr>
<tr>
<td>2020</td>
<td>39.593</td>
<td>14.316</td>
<td>70.502</td>
<td>7.753</td>
</tr>
</tbody>
</table>
• The station in Zaragoza has been running since the EXPO 2008. A 50 kW electrolyser is connected to the grid and the hydrogen is consumed by two minibuses, each able to carry 22 passengers.

• In the Hercules station, situated in Seville, a 50 kW electrolyser is supplied by photovoltaic panels.

• The Walqa Station is situated in Huesca and promoted by the Aragon Hydrogen Foundation. 10 Nm³/h can be produced with electricity from a 635 kW wind park.

In the past, there were hydrogen refuelling stations in Barcelona and Madrid as part of the CUTE and HyFLEET:CUTE demonstration projects for hydrogen buses and refuelling infrastructure.

10.7 United Kingdom

10.7.1 Support for renewable energy

The Office for Renewable Energy Deployment (ORED) is responsible for accelerating the deployment of renewable energy and ensuring the UK meets its targets. It works across 3 sectors and covers at least 22 technologies. ORED has 3 key functions:

i) Financial support for renewables – The main financial incentives in the UK are:
   (1) Renewables Obligation
   (2) Feed in Tariff
   (3) Renewable Transport Fuel Obligation
   (4) Renewable Heat Incentive

ii) Green Investment Bank

iii) Unblocking barriers to delivery – ORED aims to identify and address issues that affect the rate of renewables deployment:
   (1) Planning system
   (2) Supply chains
   (3) Connection to the grid
   (4) Availability and use of sustainable bio-energy
   (5) Communities benefits (e.g. community-ownership)
   (6) Bringing forward technologies that are still at relatively early stages of development and demonstration, but expected to be important in achieving 2050 goals, with the aim of developing UK leadership in key technologies.
The Feed In Tariff (and its predecessor, the Low Carbon Buildings Programme), supports small-scale wind installations, but not large-scale ones as these are already commercially viable, especially after Renewables Obligation Certificates (ROCs) have been applied.

The Renewables Obligation was introduced in 2002, stating that suppliers must generate a certain proportion of renewable electricity each year rising to 9.7% by 2010 (Table 20). Failure to do so results in a buy-out fine. These fines are recycled through ROCs, which reward those generating renewable electricity. Since there is a current shortfall in renewable generation, ROCs are trading at greater than their face value (112), (113).

Table 20. Development of the Renewables Obligation in the UK.

<table>
<thead>
<tr>
<th>Obligation period</th>
<th>%age of Supply</th>
<th>ROC Price (£1/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 April 2002 to 31 March 2003</td>
<td>3.0</td>
<td>30.00</td>
</tr>
<tr>
<td>1 April 2003 to 31 March 2004</td>
<td>4.3</td>
<td>30.51</td>
</tr>
<tr>
<td>1 April 2004 to 31 March 2005</td>
<td>4.9</td>
<td>31.39</td>
</tr>
<tr>
<td>1 April 2005 to 31 March 2006</td>
<td>5.5</td>
<td>32.33</td>
</tr>
<tr>
<td>1 April 2006 to 31 March 2007</td>
<td>6.7</td>
<td>33.24</td>
</tr>
<tr>
<td>1 April 2007 to 31 March 2008</td>
<td>7.9</td>
<td>34.30</td>
</tr>
<tr>
<td>1 April 2008 to 31 March 2009</td>
<td>9.1</td>
<td>35.76</td>
</tr>
<tr>
<td>1 April 2009 to 31 March 2010</td>
<td>9.7</td>
<td>37.19</td>
</tr>
<tr>
<td>1 April 2010 to 31 March 2011</td>
<td>11.1</td>
<td>36.99</td>
</tr>
</tbody>
</table>

The way energy is traded will be critical to the development of hydrogen energy markets. Currently, trading mechanisms in the UK neither are well suited to accommodating variable renewable input nor to encouraging the use of hydrogen in grid balancing. Electricity transmission is carried out by one company, the System Operator, called National Grid. Since April 2005 electricity has been traded under The British Electricity Trading and Transmission Arrangements (BETTA). Electricity is bought and sold in ½ hour blocks. The Final Physical Notification (FPN) of each unit must be declared by “Gate Closure”, which is 1 hour before the start of the block in question. If a generator or supplier deviates from the agreed FPN level, they will be charged by the System Operator for any shortfall or excess. Differences in the charges for oversupplying and undersupplying tend to lead to an excess

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1 Pound Sterling is about 1.14 €, as of September 2011.
being available. Such oversupply can conveniently and flexibly be managed by dispatchable heating (hot water) and transport (BEV charging and hydrogen fuel production by electrolysis), while simultaneously reducing the commercial risk of supply mismatches and creating a high value end product. This reinforces the argument that grid balancing in a low carbon system is facilitated, rather than impeded, by integration of heat and transport sectors with the power sector. Recognition of this is gaining currency, as evidenced by projects such as the Low Carbon Network Fund, which includes an investigation of the importance of smart grids to the roll out of electric drive vehicles and a recent report from the influential political think-tank, the Bow Group, entitled ‘Rescuing Renewables – How Energy Storage Can Save Green Power’ makes a strong and convincing case for the use of hydrogen in grid balancing and fuel production (114).

10.7.2 Support for alternative fuels

As of March 2011, about 58 – 60% of the retail cost of petrol and diesel in the UK is taken up by taxes, consisting of VAT at 20% and Fuel Duty, which currently stands at 42 – 44% of the total retail cost.

Fuel Duty used to be higher when the Fuel Price “escalator” was in place, which was a mechanism that increased the percentage of Fuel Duty year on year. The percentage of petrol retail price taken up by taxes reached 81.5% before the escalator was abandoned in 1999 due to political pressure (e.g. “fuel protests”). Bowing to further pressure, the Government cancelled a planned Fuel Duty increase in the 2011 Spring Budget and, instead, aims to introduce a “Fair Fuel Stabiliser” to smooth out fluctuation in prices at the pump.

A key question is, how much of this heavy tax burden is being channelled into the support of alternative fuels and low carbon vehicles? The Government recently announced that over £400 million will be spent on supporting the uptake of a next-generation of ultra-low emission vehicle technologies before 2015. This includes electric, plug-in hybrid, and hydrogen fuelled vehicles, but the vast majority will be spent on battery-electric (BEVs) and plug-in hybrid vehicles. Approximately £80 million will go to R&D, £20 million for the installation of (mainly charging) infrastructure and around £300 million to support consumer incentives, such as grants on vehicle purchases.

The Office for Low Emission Vehicles (OLEV) is an inter-departmental team (from the Departments for Transport; Business, Innovation and Skills; and Energy and Climate Change) set up to take forward a national policy on this shared agenda and manage a programme of measures, including technological and regulatory development, to drive down emissions from road transport. Recently, the main focus has been on the deployment of
Battery Electric Vehicles, but there now appears to be a growing resurgence of interest in hydrogen. For example, the CABLED project was intended primarily to support the deployment of 110 BEVs, but it did include 2 fuel cell powered Microcabs.

- Since the new Coalition Government came to power in 2010, there have been promising signs of a readiness to embrace hydrogen energy more enthusiastically than the previous Labour Government. Discussions between the Chief Scientific Adviser to the Department of Energy and Climate Change (DECC), Prof David McKay, and the newly formed UK Hydrogen and Fuel Cell Association (UK HFCA) have been productive.

- Likewise, dialogue with the leading Japanese car makers has revealed their enthusiasm for the early deployment of FCEVs in the UK, which is seen as a “fast follower”, behind Germany, California and Japan in hydrogen potential hydrogen and fuel cell markets. Recognising the importance of the motor industry to the UK, despite it having no major OEMs of its own, the Government is showing signs of taking seriously the strategic role of hydrogen in securing its future sustainability.

- The recent report entitled “A Portfolio of Power-trains: A Fact Based Analysis”, published by McKinsey (115) has also been highly influential in boosting the prospects for hydrogen in the UK. It concludes that FCEVs are ready for commercialisation and are critical to meeting energy security and climate change targets. It suggests that, by 2020, FCEVs and BEVs could be cost-competitive with internal combustion engine vehicles. It describes the implementation of hydrogen refuelling infrastructure as “justified and doable” and comparable in cost to BEV charging infrastructure, with initial investment “relatively low”.

- Previously, the King Review of October 2007, which examined vehicle and fuel technologies for decarbonising road transport over the next 25 years, was unenthusiastic about hydrogen and fuel cells (116). However, the Committee on Climate Change (CCC), of which Prof King is now a member, is far more upbeat about hydrogen – albeit with some concerns over infrastructure provision (117).

- Of course, proof of this apparently positive trend will only be demonstrated if, during these austere times, the Government backs up such sentiments with significant funding, clear and consistent vocal support and various practical, legislative and regulatory measures. Thus far, the UK’s progress in this field has been impressive, given the scant support and relative antipathy it has received in recent years.

- All this has culminated in the recent announcement from the Technology Strategy Board that it will open a funding call in January 2012 for collaborative projects in hydrogen and fuel cell systems that, crucially, must take a fully integrated approach to link the whole
energy supply chain, from well-to-wheels – or rather, wind-to-wheels. This marks a significant shift in the understanding of hydrogen’s central role in multi-sectorial low carbon energy systems.

The Technology Strategy Board (TSB) is one of the routes by which the Government channels funds into supporting low carbon energy and transport, along with other priority sectors, through competitions and other programmes. The TSB is independent of Government, but sponsored by the Department for Business, Innovation and Skills (BIS).

The Renewable Transport Fuels Obligation (RTFO) requires suppliers of fossil fuels to ensure that a specified percentage of the road fuels they supply in the UK is made up of renewable fuels. The target for 2010/11 is 3.5% by volume. However, the term ‘renewable fuels’ is used to refer to bio-fuels and no acknowledgement is yet given to hydrogen’s potential role.

The Hydrogen and Fuel Cells Carbon Abatement Technologies (HFCCAT) demonstration programme was launched in 2006, initially allocating £5 million to Hydrogen and Fuel Cell (HFC) programmes and £10 million to Carbon Abatement Technologies (CAT) in the 1st of 2 planned calls. A total spend of £50 million over both calls was anticipated, but in the end, only 3 HFC projects were funded, receiving £3.7 million over a four year period. The scheme is no longer in operation.

The Mayor of London had a strategy to deploy 150 hydrogen vehicles in the capital in time for the London Olympics in 2012. These would include 8 hydrogen buses and 15 taxis with the remainder expected to be a mixture of taxis, motor scooters, passenger cars, fork-lift trucks and airport ground vehicles. A bid was prepared in collaboration with other European partners to partially fund this through the Fuel Cell & Hydrogen Joint Technology Initiative (JTI), but the 8 buses have already been fully funded and in operation by the end of 2011.

10.7.3 Prognosis on the evolution of renewable energy

Currently, 3% of the UK’s electricity is generated by wind (a further 4% is generated by other renewables). There are 5.2 GW of installed wind capacity in the UK, of which 3.9 GW is onshore and 1.3 GW is offshore.

A further 3.8 GW (1.6 GW onshore, 2.2 GW offshore) are under construction, 5.4 GW (3.6 GW onshore, 1.8 GW offshore) are consented and 8.6 GW (6.6 GW onshore, 2 GW offshore) in planning. This indicates an almost exponential growth in capacity in the relatively short term. While renewable energy generation, at 7%, fell some way short of the 2010 target of 10%, the burgeoning activity in this sector suggests that the 2020 target of 15% renewable energy
energy generation by 2020 may just be achievable. Representing a sevenfold increase on 2008 levels, this is the most challenging growth target in Europe. Looking at electricity generation alone, the target is for 30% from renewables by 2020, with the assumption that around 2/3rds will come from offshore wind.

Based upon analysis from Pöyry Energy Consulting (118) and Bryte Energy (119), it will be sometime between this point and 2030 that the UK will need significant Demand Side Management (DSM) to cope with the grid balancing challenge imposed by high renewable penetrations. Production of hydrogen by electrolysis, operating as a dispatchable electrical load, will be one of the key methods of DSM. Electrolysis is particularly important for grid balancing over longer periods (typically days or more) than is achievable by most other energy storage or load management techniques.

Whether the UK’s 2050 target for an 80% CO₂ emission reduction (compared to 1990 levels) is likely to be realised is hard to guess, but Bryte Energy’s models suggest that it would be very difficult without a major contribution from hydrogen.

10.7.4 Prospects for wind-hydrogen systems

With most activity in the UK driven by regional hydrogen and fuel cell stakeholder organisations, recent changes in the political and economic landscape are moving the hydrogen energy sector towards consolidation and commercialisation. The new Coalition Government has cut back public sector funding and, in particular, abolished the Regional Development Agencies (RDAs) that supported, for example, the British Midlands Hydrogen Forum (BMHF) and Centre for Process Innovation (CPI). However, the semi-autonomous administrations (devolved parliaments) of Scotland and Wales continue to support the Scottish Hydrogen & Fuel Cell Association (SHFCA), and the hydrogen projects of Glamorgan University / H2 Wales for the time being. Similarly, the semi-autonomous London Mayor’s Office continues to support the London Hydrogen Partnership (LHP).

A growing recognition that the UK could only compete in this field by aggregating its regional efforts culminated in the emergence of the UK Hydrogen Network (UK HyNet) initiative and the merger of the UK Hydrogen Association (UKHA) and Fuel Cells UK (FCUK) to create the UK Hydrogen and Fuel Cell Association (UK HFCA).

Mini Grids

Strictly speaking, there are no fully autonomous hydrogen mini grids operational in the UK; however there is some interest shown in the concept, especially in Scotland where there are numerous island and remote communities for which they would be relevant.
The closest the UK has got to a true mini grid system is the Hydrogen and Renewables Integration (HARI) project. It achieved autonomous operation for a matter of a few days at a time, but not for sustained periods. This lack of reliability was due primarily to problems of electrical system integration rather than shortcomings in the hydrogen energy storage system. Since HARI was commissioned in 2004, it has been followed by a number of semi-autonomous systems that allow import and export from and to the grid, the majority of which also include hydrogen vehicle refuelling capabilities.

Electricity Storage

The UK has a target of producing 15% of total energy demand from renewables by 2020 (32% of electricity, 14% of heat) and there is growing recognition that, as renewables penetrations reach these levels, the need for hydrogen to contribute to the resulting grid balancing challenge starts to becoming increasingly likely.

Scotland, in particular, has a very large renewable energy resource (wind, wave, tidal, hydro). A 2007 report to the Scottish Hydrogen and Fuel Cells Association (SHFCA) by Orion Innovations and Bryte Energy looked at the Scottish Government’s targets of 50% electricity supply from renewables by 2020 and 80% by 2050 (requiring 7.7 GW and 14.5 GW respectively). This indicated that 0.03 TWh/y of hydrogen would be produced in 2020 and 4.3 TWh/y in 2050 as a result of grid management requirements in its base case scenario. With higher renewables penetrations, these would be 0.39 TWh/y and 26 TWh/y. A total of 141 TWh/y would be available if all the renewable resource of Scotland were used. In all cases, hydrogen only starts playing a significant role from around 2030. Scottish CO₂ reductions targets of 80% by 2020 will not be met by the base case, which only delivers 60% reductions, so bolder renewables deployment targets are required.

In Scotland’s northernmost island, the Pure project is investigating the storage of electricity using hydrogen, as is the Hydrogen office in Fife. Likewise, in Wales the Hydrogen Centre at Baglan Energy Park and, in central England, the AMP Technology Centre, Rotherham, are exploring this role for hydrogen.

In all these cases, the hydrogen is also used as a transport fuel, or is awaiting this application subject to the availability of funding and/or suitable vehicles. This is because, both practically and economically, the business case for using hydrogen for electricity storage only is seen as significantly less viable than integrating both electricity storage and transport fuel aspects within one system. Furthermore, Bryte Energy’s studies (119) suggest that, in the UK at least, there will be little need for re-electrifying hydrogen, due to the overall energy balance created by integration of heat, power and transport sectors in a low carbon environment.
economy. Only the Wings Law Wind Farm Project, proposed for Scotland by Wind Hydrogen Ltd, aims to implement a straightforward electricity storage system, but this project is still yet to be realised.

**Fuel Production**

The UK target is for 10% of transport energy demand to be derived from renewable sources by 2020, but this assumed to be almost entirely biofuels. However, interest in hydrogen as a transport fuel is gaining momentum.

London has 5 fuel cell powered buses in operation and, by the end of 2011, there will be 8 of them. Thus, in time for the 2012 London Olympics, the RV1 route will be entirely served by hydrogen-powered buses in regular commercial operation. This is the route that passes many of the city’s most famous landmarks and is therefore particularly popular with tourists. In addition, there will be 15 fuel cell powered “black cabs”, plus another 127 hydrogen powered vehicles in the capital in time for the Games. At the time of its construction, the bus refuelling facility was the largest hydrogen refuelling station in Europe.

At various locations around the UK, the Hydrogen On Site Trials (HOST) programme is being undertaken by ITM Power, who are developers of electrolyser and fuel cell technologies. HOST allows potential customers to familiarise themselves with the technology. Each of the 21 participating companies gets a week’s free trial of ITM’s hydrogen production and refuelling modules and use of an HICE Ford Transit van. Having had a chance to gain confidence in the technology, it is hoped that those taking part in the trial will make a commitment to full commercial implementation.

At Baglan in Wales a hydrogen refuelling facility currently serves a “tribrid” bus (incorporating fuel cell, battery and supercapacitor) minibus. Here, hydrogen is used in balancing the output from onsite photovoltaics and an offsite wind farm. Plans to create a hydrogen highway along the M4 from Wales to London received a recent boost with the opening of the UK’s first full-scale, publically accessible, dual pressure (350 and 700 bar) refuelling station at Nissan’s plant in Swindon. Unlike the previously deployed units at various UK test facilities, this unit does not require a recovery period of several hours between vehicle refuelling operations. Also on the “M4 corridor”, a project to operate hydrogen-powered ferries is underway in Bristol.

Scotland, too, has plans for a “Hydrogen Corridor” along the A90, linking Aberdeen with Peterhead. Hydrogen buses will operate along the route and refuelling stations will be located at either end. A Revolve HICE Transit van is used in the H2Seed project in the Hebrides Islands. In time, the hydrogen refuelling station for this project will use wind-
generated electricity, but currently it uses electricity from a waste-to-energy plant. In Unst, the Pure Project uses a small, medium pressure refuelling unit for charging a metal hydride store in their range-extended electric vehicle.

In the Midlands, a cluster of hydrogen refuelling stations is developing known as the Midlands Hydrogen Ring (MHR). Currently, it includes 5 small units at Birmingham, Loughborough, Coventry, Rotherham and Sheffield, plus a mobile unit at the Millbrook vehicle testing centre. A further facility will be added in 2011/12 at Nottingham and various other sites are under consideration, including airports, logistics centres, vehicle testing centres, tourist attractions and research facilities. The FCEVs and HICE vehicles currently using these hydrogen refuelling facilities are largely in captive fleets under field trial, including: motorbikes and scooters, cars, vans, taxis, and canal boats. Plans are under development to link the MHR with other regions, particularly Wales and London.

Ultimately, such a network could extend north to link with Scotland and, indeed, the UK Hydrogen Network (UK-HyNet) initiative aims to create a nationwide network of infrastructure that would enable a hydrogen-powered vehicle to travel the whole country without ever being out of range of a refuelling facility. Since this would initially require around 60 small units, the cost to implement it would be far lower than to implement an equivalent fleet of BEVs and their recharging points. Using small, re-locatable refuelling units enables the network to be expanded organically with growing demand at low risk and low cost. UK-HyNet has developed a rollout plan for hydrogen vehicle and refuelling infrastructure by 2015, as shown in Figure 54, with further deployment targets set out to 2050.
Figure 54. The UK-HyNet plan for deployment of hydrogen refuelling infrastructure up to 2015. Courtesy of Bryte Energy Ltd.
11 Conclusions

Wind energy is an established technology, which has seen some rather impressive developments in the last thirty years, as a result of environmental concerns and the need for energy self-sufficiency. Worldwide, the technology has improved tremendously; installed capacity has grown exponentially to about 280 GW in 2012 (120). Overall, wind energy is the most advanced renewable energy technology for generating electricity.

The wind/hydrogen alternative appears to be an attractive storage option for overcoming a major drawback, the intermittent availability of wind energy, which affects both stand-alone and grid-connected applications. In stand-alone wind-power applications it can be used to stabilize the availability of electricity by converting wind into hydrogen during periods of surplus capacity and, during periods of low or no wind availability, the hydrogen can be used to generate electricity.

The hydrogen option is also important in grid-connected applications, particularly at high (>10%) wind-electricity penetration, where it can be used to manage the flow of electricity to the grid. Of course, in the long anticipated “hydrogen economy” of the future, hydrogen would be the transportation fuel. Hydrogen is an ideal fuel particularly when generated by environmentally sound, non-polluting renewable (e.g. wind, photovoltaic) energy sources.

In the near future, the use of hydrogen must be associated with established technologies, like natural gas (see Figure 55). Feed into natural gas grid, base of power to gas, permits hydrogen distribution using an existing network.

Figure 55. Wind-hydrogen alternative into hydrogen systems. Source: Ludwig-Bölkow-Systemtechnik GmbH.

Power to gas allows electricity to be held in reserve in the megawatt range. Natural gas network can be utilized by involving existing power and natural gas grids. This allows seasonally adjusted storage of significant amounts of power. It represents a complete system
solution to the problem of surplus energy reserves on the way to a new renewable energy age. Hydrogen and methane are produced from surplus wind energy by a process of electrolysisation, and methanation. The hydrogen produced can be stored in the existing natural gas network for later use.

The technologies associated with hydrogen production, storage and distribution are fairly well established and, largely as a result of environmental concerns and the anticipated hydrogen economy, are benefiting from continuing research and development. Demonstrations of associated wind/hydrogen technologies in isolation, as well as in integrated systems, have generated a wealth of experimental data and, more important, have demonstrated that there are no insurmountable problems with the use of wind power to produce hydrogen by the electrolysis of water.

Thus, one can conclude that hydrogen production is an attractive option for improving the availability of wind-generated electricity, especially so for stand-alone applications of wind energy. The associated technologies are well advanced and are benefiting from continuing research, development and demonstration driven by environmental issues and the anticipated “hydrogen economy”.

Three main categories of wind-hydrogen systems defined are:

- Mini Grids
- Electricity Storage
- Fuel Production.

Installations under the Mini Grids category have a local, perhaps regional, character and can serve a number of purposes and ways of utilising hydrogen in (somewhat) isolated areas.

Large systems under the Electricity Storage and Fuel Production categories are of countrywide, perhaps inter-regional, character. This analysis, however, revealed that the two types should not be considered as limiting cases, but rather with several options between them. Economic viability of such “mixed case” ventures is expected to be better than when serving only one particular application.

Since hydrogen is so versatile in its potential utilisation, future commercial wind-hydrogen systems may address other applications (in parallel), such as supplying hydrogen as a raw material for industry or injecting it into the natural gas grid. The economic viability of wind-hydrogen systems can benefit from this adaptability even more. “Pure” Electricity Storage plants are expected to be rare.
The different situations in individual Task 24 countries add complexity to this matter. The mechanisms for supporting renewable energy in general, and for alternative fuels, differ immensely, even between EU Member States. The sections on the prospects for wind-hydrogen systems, again, show significant diversity.

Concurrently, the demand for energy storage, arising from growing penetration of fluctuating renewable power into the electricity sector, is hardly addressed yet in Task 24 member countries. In this respect, incentives have been emerging slowly, if at all, up until now.

Therefore, the conclusion for the time being is that “bottom-up” work at national level is required.

In conclusion, we can say that hydrogen can be compared with other energy storage systems according to different parameters as size and time of energy storage but also according to energy management strategies. Hydrogen could compete with other ESSs, as pumped hydro or ACAES as some studies have shown for long and very long-term storage. Also it could compete with batteries, mainly in energy applications of short and long term and linked to renewable energies as wind power, depending on the strategy applied.

There are still several disadvantages and technical problems to be solved as low efficiency and high costs that makes hydrogen less suitable for electricity storage applications than other technologies by the moment.

Most of the management applications that have been discussed result in a rather low number of annual operating hours, respectively full load hours. This puts the economic feasibility of wind-hydrogen systems into questions since the result are high specific costs.
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