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LINKING DISTRIBUTED EUROPEAN HYDROGEN PRODUCTION SOURCES

PART III: Analysis of Hydrogen as a Storage Device for Renewable Energies

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The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org

ABSTRACT

This report is a deliverable of the Roads2HyCom project, which is studying technical and socio-economic issues associated with the use of fuel cells and hydrogen in a sustainable energy economy. Within the project, several studies have been made related to the question of primary energy sources to produce Hydrogen. This report is one of three that looks at the linking of those primary energy sources, in this case focussing on the use of hydrogen production as an energy storage device for the electricity grid.

Most renewable energy sources supply electricity, which is difficult to store. In addition, the introduction of intermittent renewable sources, e.g. wind energy, to attain the policy targets means further challenges for energy production in Europe. A solution could be to store electricity during peak production times and then supply the grid with electricity at periods of low renewable production. This capability would also help to cope with demand-led fluctuations.

Analysis of fluctuations show that long-term variations can hardly be met by storing energy but small-scale storage can balance the major part of the short-term fluctuations very well. One can distinguish between two storage needs:

- Interim storage, which is needed to reduce short fluctuations or to allow the shift of power supply to peak load hours (midday or early evening).
- Surplus power storage, which is necessary to handle the mismatch between load and power production, thus avoiding an overloading of the grid due to lack of transmission capacity.

It can be shown that surplus power only arises above a penetration level of 25% (wind) or 15% (photovoltaics). Extrapolation indicates that this penetration is rarely exceeded at large-scale, even at a local level. Policy for ramp-up of renewable energy use indicates that storage of surplus renewable electricity will not be required before 2020.

Yet storage will be necessary for balancing fluctuations rather than managing the electrical grid as a whole. Available storage systems include pumped hydro, compressed air, flywheels, batteries, and compressed hydrogen production. Hydrogen offers the advantage of a nearly unlimited size of storage and an instant provision of energy due to a complete decoupling of input and output conversion. As an example, in this report a wind-hydrogen system is described that enables the user to "schedule" wind power production due to a combination of precise forecasts and hydrogen-based electricity production. This eliminates short-term fluctuations and forecast errors. The resulting predictable production could be used to reduce balancing power or could be sold on the spot-market.

The demand for surplus power storage cannot be determined at this moment due to a lack of data for the future development and technical details of new production capacities in power generation and the electricity grid. Also, hydrogen will not be an option for the large offshore installations planned in the North Sea due to the low conversion efficiencies and the costs involved. On the other hand, stored hydrogen, for instance in a wind-hydrogen system, does not necessarily need to be converted back to electricity. It could also be deployed for other uses, e.g. as a transport fuel or as industrial gas, thereby diversifying renewable energies in their end-use.

LINKING DISTRIBUTED EUROPEAN HYDROGEN PRODUCTION SOURCES

PART III: ANALYSIS OF HYDROGEN AS A STORAGE DEVICE FOR RENEWABLE ENERGIES

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1. Introduction

This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project is studying technical and socio-economic issues associated with the use of hydrogen and fuel cells in a sustainable energy economy. Within the project, several studies have been made related to the question of primary energy sources to produce hydrogen. This report is one of three that looks at the linking of those primary energy sources. The three reports are:

- Part 1: Distribution Issues (Document R2H2013PU)
- Part 2: Electricity Grid Development Strategies and Constraints (R2H2014PU)
- Part 3: Hydrogen as a Storage Device (this document)
- The conclusions of these three reports are summarised in document R2H2012PU

The use of renewable energies today is the only means of providing energy for the world's constantly growing demand without depleting natural resources. Therefore their utilisation has a high priority in the European policy agenda. The European Commission set the target for the share of renewable energies in the primary energy consumption to 12% by the year 2010 in its White Paper of 1997 [EU 1997]. This was complemented by the decision in 2001 (Renewables Directive [EU 2001]) to reach a 21% share in the electricity production, also by 2010. More recently these goals have been further augmented by a roadmap with new targets for the year 2020, setting renewables to then provide a 20% average of primary energy in the EU [EU 2006]. Binding legislation on these goals is planned to be adopted by the European Council and Parliament by 2009 and the Member States by early 2010. These plans also include the 10% minimum share of biofuels in the transport fuel market. The contribution of renewable energies to electricity production is not quantified in this document. The IEA, though, expects the share to be far beyond 25% (38% in the OECD countries in 2030) [IEA 2007]. Linear extrapolation from the 2010 figures results in approx. 35% of electricity demand from renewables in 2020.

The integration of increasing amounts of renewable energy into European electricity grids constitutes a challenge for the coming years. Most renewable sources of electricity display natural fluctuations, often at very short time scales. The resulting power fluctuations have to be balanced and overloading of especially peripheral grids (e.g. coastal) can become an issue. A way of managing, controlling and storing fluctuating renewable electricity has to be developed in order to better integrate these resources into the electricity supply system and overcome limitations of grid development. Grid development has been discussed in part 2 of this report. Storage technologies can play their roles in achieving the goal of strengthening the grid by adding flexibility, new degrees of freedom and 'intelligence'. Hydrogen can play a special role here as will be discussed in this (third) part.

2. The Necessity of Storing Renewable Energies

Most renewable energies supply electricity, which again is the type of energy most difficult to store. Table 1 gives on overview. The last 15 years have seen a tremendous growth in renewable electricity production, especially wind energy, in Europe. Renewable electricity in Europe is mainly produced from hydraulic (hydro) energy (Figure 1). This is a rather well developed and controlled resource with a large contribution to base (run-of-river hydro) and peak load demand (reservoirs, even disregarding pumped storage as largely non-renewable). In recent years wind energy has taken over a larger share, thus for the first time introducing a non-controllable, fluctuating electricity source to the European grids. Inspection of figure 2 shows that though a number of European countries display a high fraction of renewables in their electricity supply structure, especially those with a high resource of hydro energy. Attaining the 2010 goals – and assuming proportionally increased electricity targets as compared to the primary energy objectives – will introduce specifically wind and solar, maybe wave energy to the electricity supply systems in vast quantities. All of these will bring new challenges in harnessing the fluctuations in electricity production due to the inherent meteorologic influence on these sources.

Table 1: Types of end-use energy typically supplied by Renewable Energies. Brackets indicate secondary uses, i.e. of the gases produced.

Source	Type	Heat	Electricity	Other
Solar	**thermal**	✹		
	PV		✹	
	tower		✹	
	algae	(✹)	(✹)	H_2
Wind	**repellor**		✹	
Solar/Wind	**thermal flow**		✹	
Geothermal		✹	✹	
Hydro	**stream**		✹	
	dam		✹	
Tidal/ wave			✹	
Biomass	**combustion**	✹	✹	
	fermentation	(✹)	(✹)	CH_4
	pyrolysis	(✹)	(✹)	**syn-gas**

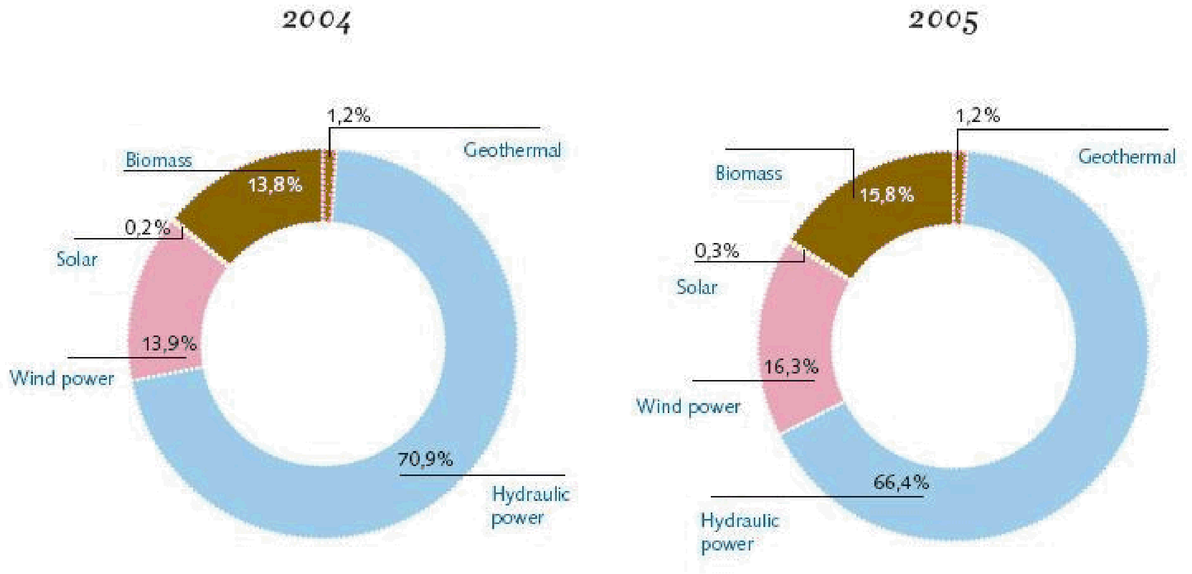

Figure 1: Share of single resources in the renewable electricity generation (in %) 2004 and 2005 [EUR 2006].

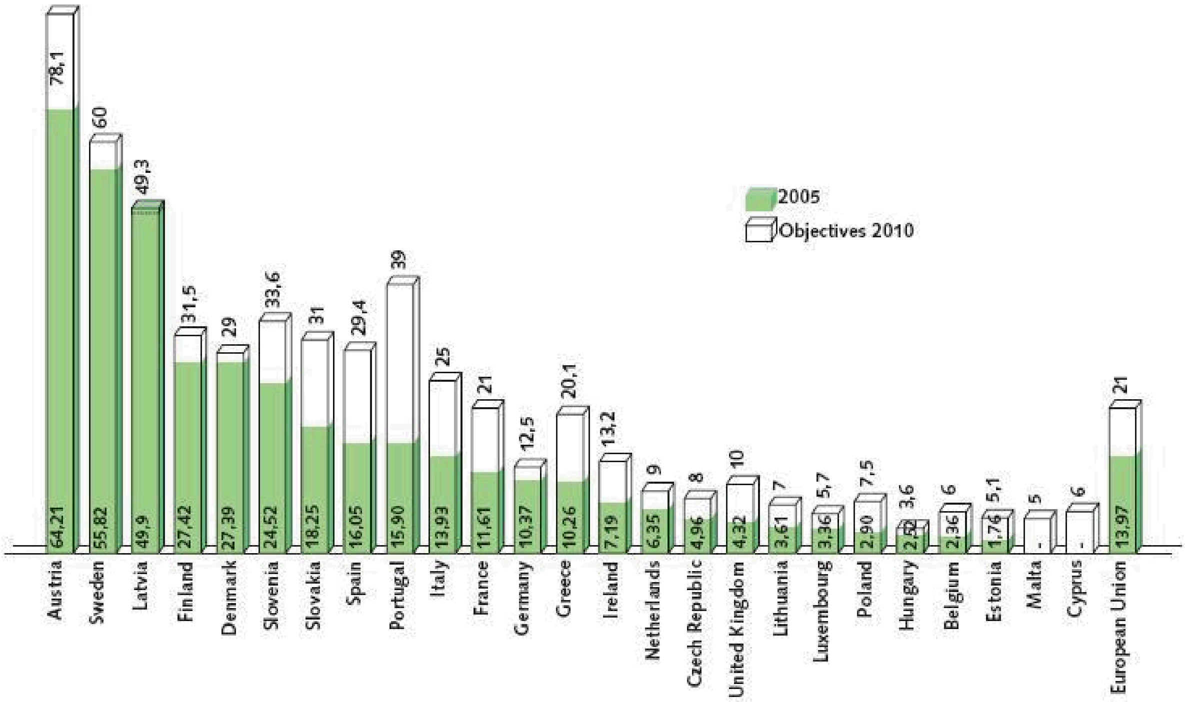

Figure 2: Share of renewable energies in gross electrical consumption in the EU countries in 2005 (in %, solid bars) and the 2010 goals [EUR 2006].

In Germany, for instance, the installed wind energy capacity increased from 68 MW to more than 20 GW between 1990 and 2006 [Nitsch 2004, VDMA 2007]. Plans are currently being pursued to develop the enormous offshore wind energy potential of the North Sea.

Germany has a theoretical potential of 60 GW of which a maximum of 50 % may also be technically exploitable under economical conditions. With increasing contributions of renewable, and especially wind energy in the power supply system problems regarding the renewable electricity integration are expected: regarding the management of renewable electricity production, in making maximum use of the natural resources, the necessary enhancement of grid capacity, creating additional transport lines (for instance connecting the up-to-now little developed coastal regions which are now becoming centres of wind electricity generation) to the centres of electricity demand, and the additional provision of balancing power, in order to compensate the fluctuating input.

It is generally expected that an increasing need for balancing power will result from the advent of large offshore wind parks in the North Sea. To neutralise this effect, it is necessary to adjust the operation of the grid as a whole to the requirements of a modern mix of energy sources. In some regions in Germany, e.g. Schleswig-Holstein and Niedersachsen (Lower Saxony), and in Denmark network operators already experience problems with the management of wind power. In these areas the transportation capacity of the electricity grid will have to be increased and additional (conventional) generating capacity may be required in order to provide backup for the installed wind power resource [Bouillon 2004]. Additionally, a discussion has developed, whether the fluctuations of wind energy will increase the requirements for balancing power in load frequency control [Bouillon 2004, dena 2003, Küffner 2003].

Critics claim that the additional supply of balancing power will induce increased use of fossil fuelled power stations at low capacity factors and thus low efficiencies [Leonhard 2002]. As a consequence, this would cause additional emissions and fossil fuel consumption which contradicts the basic idea of environmentally benign energy production from wind. Today, the grid stabilising system is based on some pumped hydro and in its majority on conventional fuels (mainly hard coal and natural gas); thus additional fuel demand in this sector will reduce the emission reduction potential of fluctuating renewable electricity. In order to avoid additional conventional fuel use and ensuing emissions, ways of controlling and storing renewable electricity in an environmentally friendly manner have to be developed. Hydrogen can be one of these options as will be discussed below.

Seeing the dependence of most renewable electricity generation on meteorological circumstances outside of human control, the necessity for electricity storage is derived from the desire to:

- Store renewable electricity for periods of low renewable production
- Store renewable electricity for peak demand periods
- Reduce fluctuations
- Integrate surplus and/or stranded production

2.1 Fluctuation of Renewable Energy Production

Renewable energies can display a variety of fluctuations. Their time scale ranges from seconds to several months or even years as determined by

- Wind gusts (wind energy) and cloud shadow (PV) (seconds)
- Rapid changes in weather (wind, cloud cover) (minutes)
- Major changes in weather (wind, cloud, waves) (minutes to hours)
- Diurnal variations (wind, insolation, tides) (12 to 24 hours)
- Large-scale changes in weather conditions (wind, insolation, waves, run-of-the-river hydro) (12 hours to several days)
- Seasonal variations (wind, insolation, waves, run-of-river and reservoir hydro, biomass) (3 to 12 months)
- Long-term variations (all) (12 months to several years)

Their integration into the European electricity grids requires means of controlling these fluctuations in order to ascertain a reliable electricity supply that will at all times cover the demand. Research into meteorological variability at a variety of scales [Steinberger 1993] has shown that the short time fluctuations are of a stochastic nature and will cancel out if the bulk power output of large renewable electricity systems is considered. The shorter the time scale, the smaller the area within which these variations will be balanced by the geographical diversity. On the other hand, the long term variations will affect large geographical areas thus for instance impacting the whole European (UCTE) electricity grid. The long term variability of, for instance, rainfall may have an effect on the availability of reservoir hydro. This may vary regionally since the large-scale weather conditions across Europe are rarely uniform, even at long time scales.

Figure 3 shows a sample wind energy production curve from a 15-MW-wind farm in variable weather. Ramps of +/- 2 MW (i.e. approx. 12% of installed power) within few minutes are present under these conditions. Figure 4 shows a sample of daily solar irradiation under extreme cloud conditions with a large number of small clouds. Figure 4 also shows the effect of geographical separation of a few hundred meters. The insolation at the measuring sites is generally in sync but the details vary. Therefore the lumped power output from these sites or the bulk power from an array of this size will not display the short-term variability. Figure 5 finally shows one week of run-of-river hydro power output from a large number of small installations in New Zealand indicating the strong dependence on rain-fall. This would be less prominent in larger installations and in reservoir hydro which supply most of Europe’s hydro electricity resources. The variability of wave energy devices is less documented due to the prototype stadium this technology is still in.

Biomass produced electricity will also show some seasonable variability but this will be less due to immediate variation in energy resources but rather to the general market availability and the price of biomass that will depend on the annual crop seasons and is of no concern here.

A systematic analysis of the amplitude and variability of the renewable electricity supply and the influence storage technologies can have [Steinberger 1993] shows that long-term variations can hardly be met by storing energy. Local wind calms will on average last several days in summer. Economically it is not feasible to store sufficient energy to cover a week's of wind energy production unless major pumped storage capacities are available. On the other hand small-scale storage can balance the major part of the short term fluctuations remaining after geographical balancing has been accounted for.

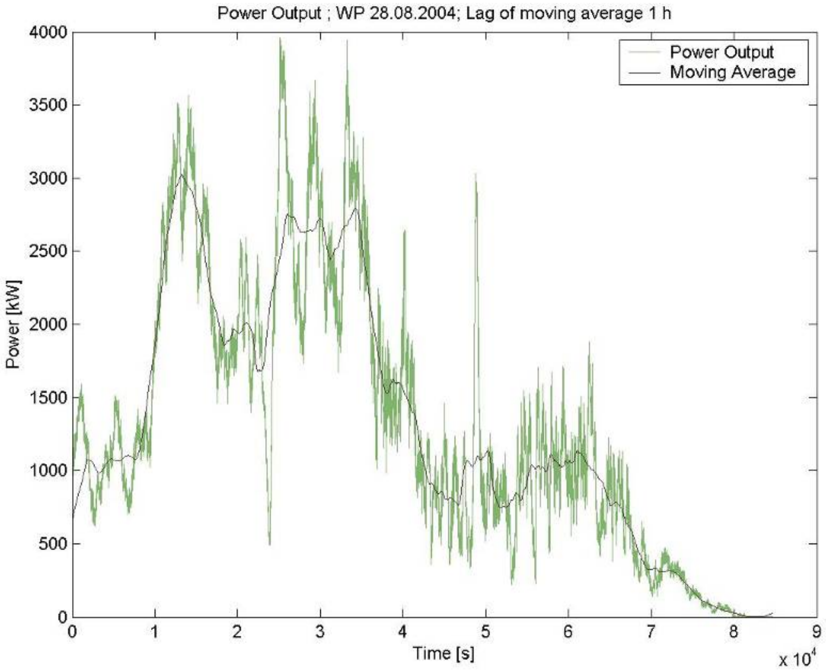

Figure 3. Wind power output from a wind farm in North Germany rated at 15 MW over 24 hours (86 400 sec).

Maximum ramps are +/-2 MW within few minutes. The drawn line indicates the moving average of the data with width of 60 minutes [Mueller 2005].

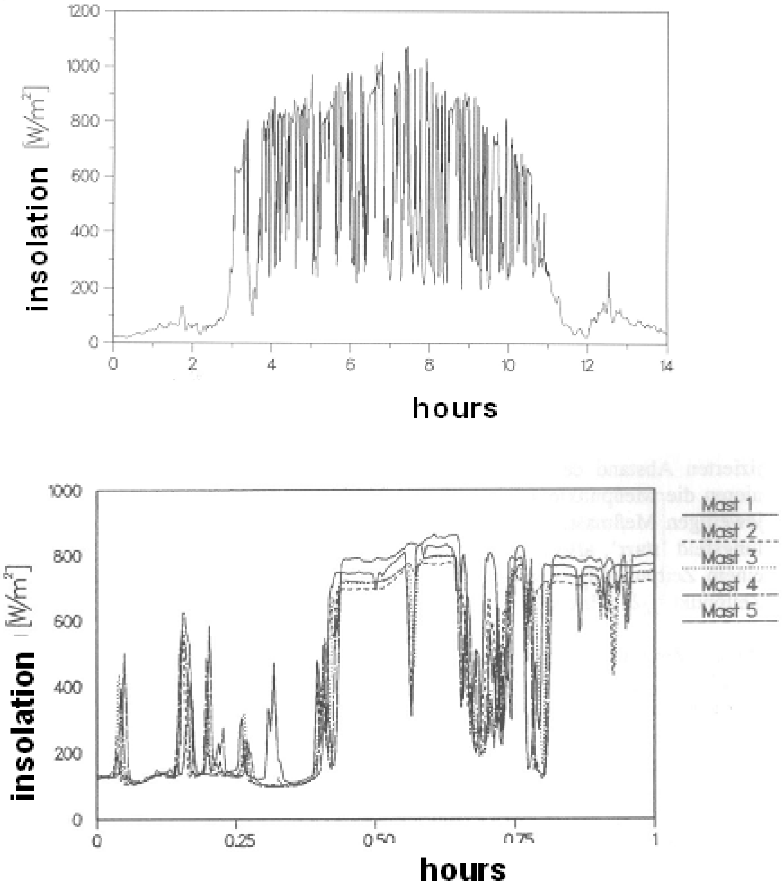

Figure 4: Fluctuation of a single site and an array of five solar irradiation measurements (identical to an assumed PV-array output) [Steinberger 1993]

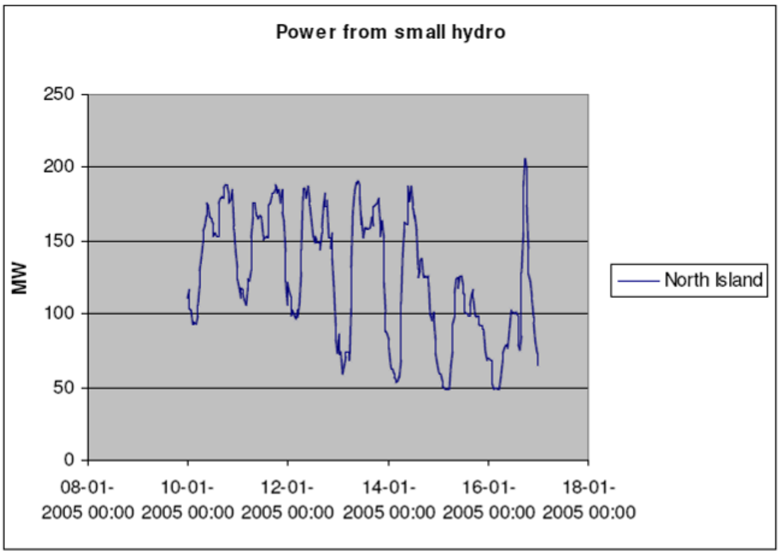

Figure 5: Example of power output from small hydro plants in New Zealand [Windolf 2007].

2.2 Storage Requirements

From the above it follows that a distinct demand for renewable energy storage will ensue from the high penetration levels into the electricity grids that can be expected in the years to come. Nevertheless, levelling power fluctuations is only one of several reasons to implement electricity storage for renewables.

2.2.1 Interim Storage

Interim storage (short term) serves to reduce the (stochastic) fluctuations of power production as seen when cloud cover passes PV arrays or in the turbulence in wind flow. It can also be used to either shift power production in time, for instance typically from day time to night time for PV or as a reserve for peak load hours, typically providing additional power during midday or early evening hours.

Interim storage will typically display a rapid response and have a low to medium storage capacity. The effect can be described as seen in Figure 1: the moving average depicted as solid line could be seen as the result of sufficient storage incorporated in the grid system. Large gradients are avoided while the mid-term diurnal variation remains present.

2.2.2 Surplus (Excess) Power Storage

Surplus power arises from

- A temporary mismatch between load and power production, or
- Overloading of a grid due to lack of transmission capacity,

and results in a momentary shutdown of the renewable generation capacity.

Surplus (or ‘un-usable’) power can also occur where ‚stranded‘ power production is found when renewable energy potential is located in areas with no or very weak grid connection and results in sub-optimal usage of the renewable energy potential. Similarly to the case of excess power production, an existing renewable resource cannot be used appropriately and is lost as a contributor to the electricity supply.

[Steinberger 1993] calculated that for the German national grid a penetration level of 25% of wind electricity or 15% PV electricity into the supply girds will result in temporary production of renewable electricity that will not be able to be integrated into the grid due to overloading. Though the main conventional production capacity may be controlled sufficiently there remain the base load plants (nuclear, lignite and run-of-river hydro) that cannot be adapted to the rapid changes in renewable production. Similar calculations for the whole European grid do not exist to date. It can be reasonably assumed that the conditions will be similar on average, though the situation within single national grids may diverge greatly (for instance the Austrian, Swiss and Norwegian grids with a major contribution from reservoir hydro energy and the French grid with a nuclear-hydro mix etc.). The main body of the European (EU) grid is organised within the UCTE grid and thus acts as one single grid as far as voltage and frequency stabilisation are concerned.

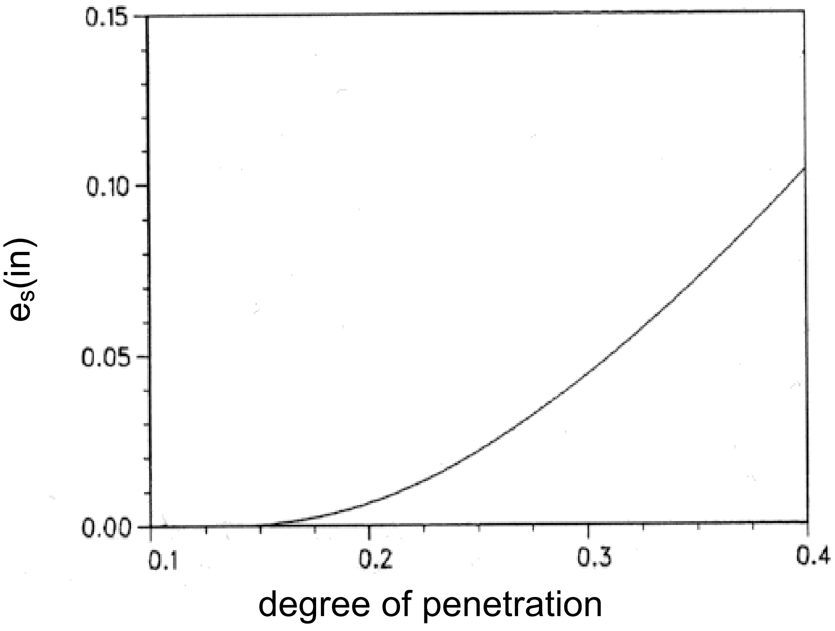

Figure 6: Production of surplus energy above a penetration level of approx. 15% of PV electricity into the German national grid.

The calculations were performed with load data from the 1980ies for solar (PV) electricity production distributed across West Germany [Steinberger 1993].

Given that 21% of electricity consumption are to be covered by renewable electricity in 2010 [EU 2001] and considering the targets for primary energy from renewables in 2010 [EU 1997] and 2020 [EU 2006] a level well above 30% of electricity demand can be expected for 2020. Also assuming that the major part of this will come from wind and hydro energy, Figure 6 would indicate there is a low surplus production. Given that the potential for new hydro energy plants is limited in Europe (also see the report “Potential of Emerging and Future CO_2-Neutral Hydrogen Sources on the European Scale” published as Deliverable 2.2 by the Roads2Hycom project [R2H 2008]), the major part of the increase in generating plant will come from wind, wave and solar generation.

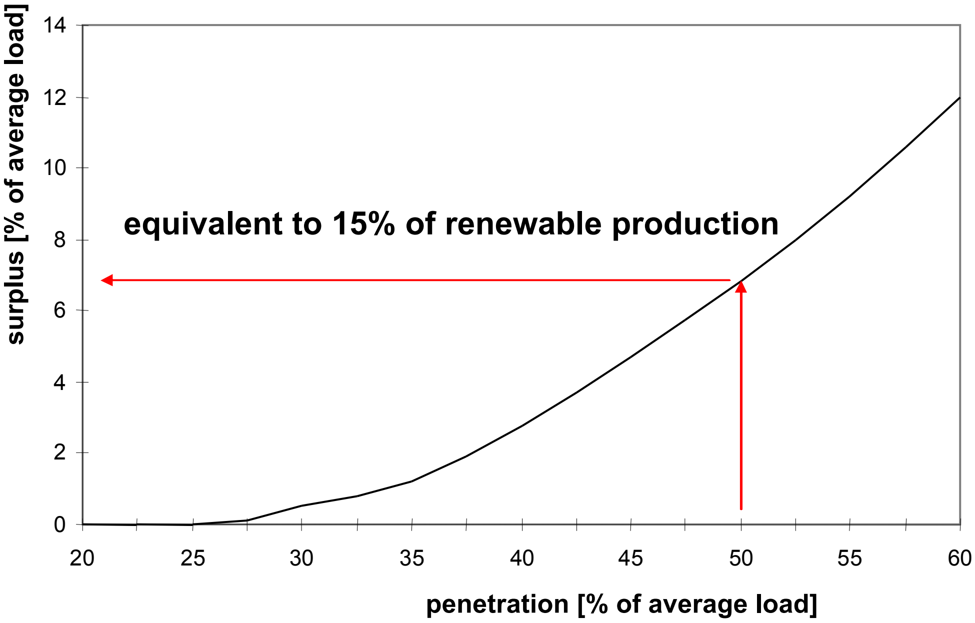

Figure 7: Production of surplus energy above a penetration level of approx. 25% of wind electricity into the German national grid.

The calculations were performed with load data from the 1980ies for wind electricity production distributed across West Germany. At a penetration level of 50% an amount of energy equivalent to 7% of the total electricity demand (load) is lost. This corresponds to 15% of the renewable (wind) production. [Steinberger 1993]

Extrapolating from figure 1 and figure 2, though, indicates that even if the share of renewable electricity is more than doubled to around 35% from the 2005 values, the potential share of wind and solar electricity will hardly surpass the level of 15 to 20%. Therefore the occurrence of excess energy will be limited to situations where the local and regional grids are overloaded as a result of a lack of foresight in planning ahead for the electricity grids of the future.

This means that the major part of storage required for renewable electricity integration in 2020 is necessary for balancing fluctuations rather than managing the electrical grid as a whole.

2.3 Storage Technologies

A brief overview of storage technologies shall be given here as a state-of-the-art report. Today the following technologies for storing electricity are used at more or less large scales:

- Pumped storage
- Batteries
- Flywheels

New developments include:

- Compressed air (CAES)
- Super capacitors
- Hydrogen

The overall efficiency of the storage process is determined by the efficiency of the input and output conversion and any losses during storage (self discharge, loss of gas pressure, leakages, evaporation etc.) (Figure 8).

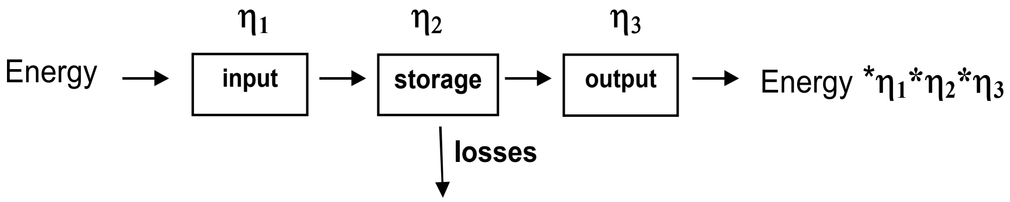

Figure 8: Efficiency chain of energy storage.

The goal is to reduce any losses from conversion or storage to a minimum in order to make best use of the stored energy. Brief discussions of the technologies used today or in near-term development follow.

2.3.1 Pumped hydro

Pumped hydro storage systems have been in use since the 1920s in order to balance the fluctuating electricity consumption and achieve continuous operation for power plants. There are 33 facilities in Germany with an overall power of 6,610 MW [Wagner, 2003].

A pumped hydro storage system consists of two large water reservoirs. During peak demand, water is released from the upper reservoir and flows downward through high-pressure pipelines. It drives turbines and ultimately flows into the lower reservoir. The turbines directly drive electricity generators. Potential energy stored in the water is converted into kinetic energy and subsequently electricity. For charging the storage, the generators are used as electrical engines, driving the water turbines in pumping mode. Typically, this occurs in conventional grid systems when electricity demand is low and cheap excess power is available. Changing the mode of operation may require closing of gates and locks, waiting for water flow to subside and changing the angle of turbine blades and therefore requires some time. As the energy content depends on the difference in elevation, the topographical distance between the upper and the lower reservoir should be as large as possible. In Germany the typical ‘head’ is between 70 and 600 m. Obviously, the potential for installing such plants very much depends on the availability of a suitable site. Coastal regions will often not have access to a topography with sufficient height differences so that storage and generation are naturally separated and only connected via transmission lines, thus not necessarily avoiding grid congestion. Environmental damage (by flooding) is considerable and acquiring a planning permit today is involved.

2.3.2 Compressed air energy storage

Compressed air is a proven and tested energy storage medium based on uncomplicated and robust technology. Compressed air energy storage systems (CAES) again are storage devices for potential energy, where the storage principle is based on compression and expansion of a volume of gas. The amount of energy stored in the system depends on the pressure and the volume of the storage vessel, mostly an underground cavern. The first CAES power plant was installed in 1978 in Huntorf, Germany. According to [Kentschke 2003] the rated power of 290 MW can be delivered over 4 hours. The storage volume is about 3*105 m³.

Generally, a CAES includes a compressor, conditioning of compressed air (dehumidifiers and filters), a pressure vessel and a turbine (sometimes identical with the compressor). The overall efficiency of such a system, though, is rather low. Basically there are two forms of CAES. As a combined energy storage and power plant, the CAES is linked to a natural gas power plant. In such systems the storage is a cavern or a porous rock formation. It is based on the division of a conventional natural gas turbine in a compression unit for the combustion air and an expansion turbine for the exhaust gases [Crotogino 2003]. By using the compressed air as an input to the turbine, fossil fuel use can be reduced. The separate compressed air storage makes it possible to temporally decouple compressor and gas turbine mode. Such power plants can ramp up to deliver maximum energy in less than 10 minutes. It should be noted, though, that this system is not a storage system in the general sense and produces carbon dioxide during unloading. A closer analysis of the implications of this situation is still ongoing.

The second type of CAES corresponds to compressing and expanding air through a compressor/turbine (or separate units), using the potential energy stored. The overall efficiency of modern CAES power plants is only around 55% [Crotogino 2003], since the heat produced from compression is dissipated and the volume flow during expansion is reduced due to the contraction of the gas volume in cooling. This can only be remedied, if sufficient heat can be recuperated from the environment in this process or heat loss from storage is minimal.

2.3.3 Flywheel energy storage

Beginning with work at Lawrence Livermore National Laboratory (LLNL) in the 1970's, the research on fibre reinforced composites forms the basis for fast rotating flywheel rotors, prevalently for mechanical energy storage. In most recent applications however, flywheels are used to store electrical energy. In this case electrical energy is transformed to rotational energy using an electrical motor. De-acceleration, on the other hand, drives the motor in generator mode and reconverts rotation to electricity. One of the main advantages of the flywheel is its simple and effective working principle. The flywheel energy storage can be charged and discharged at high rates for many cycles [Ruddell 2003]. The bottlenecks, however, are the high costs and stand-by (frictional) losses. Uninterruptible power supply (UPS), power quality (PQ) systems, and trackside support in traction (rail) systems are the main applications.

2.3.4 Batteries

The lead-acid battery, one of the earliest battery types, has for a long time been the most important rechargeable electrochemical storage system. Even though the amount of energy that can be stored is rather modest with respect to the high weight of the reacting substances, there are many other reasons that contribute to the outstanding position of this system: the reactants are solid and the reactions are highly reversible.

Although Nickel cadmium (NiCd) batteries (invented in 1899) have been in industrial use almost as long as lead-acid batteries they are a niche product in comparison to lead-acid batteries for industrial applications. Portable, sealed NiMH batteries were introduced in 1991 for the rapidly increasing mobile phone and laptop computer markets. Their specific energy content is about 50% higher than with NiCd batteries. Lithium-ion cells (Li-Ion) were introduced in the late 1990's featuring low weight, relatively high power and lacking the 'memory effect' seen especially with NiCd batteries. Albeit their high performance, these battery types are not used for bulk storage service in electricity supply systems today.

A battery consists of 'cells' connected in series or in parallel according to the desired output voltage and capacity. The cell itself consists of three major components [Lailler 2003]: the anode, the cathode and the electrolyte. In the case of the lead-acid battery storage systems the anode is based on lead, the cathode is based on lead dioxide and the electrolyte is an acid sulphuric solution, either in form of an actual liquid or gel. Each single cell has a voltage of approx. 0.7 V, depending on the materials used. High voltages necessary in efficiently converting direct current to the traditional 220 to 400 V AC therefore require a series connection of a considerable number of cells.

2.3.5 Compressed Hydrogen energy storage technologies

Hydrogen as a storage medium uses chemical processes to store fluctuating electrical energy sources, especially, but not limited to, wind and solar. The storage cycle from transforming electrical energy into hydrogen and then back into electrical energy consists of three steps (Figure 8). The first step is the electrolysis of water to produce hydrogen and oxygen using electricity. The second step comprises drying, compression and storage of the hydrogen (compressed hydrogen energy storage, CHEST). In the third step, hydrogen is transformed back to electricity in a fuel cell (cf. Figure 8, position 1 through 3). Since storage input and output are completely decoupled, switching time is zero. As electrochemical devices, electrolysis and fuel cell have similar reaction times as batteries. It has to be kept in mind, though, that a 'cold start' from low ambient temperatures to regular operating temperature may require a considerable ramp-up time of up to 30 minutes.

The fuel cell is very similar in structure and function as a battery with the difference that fuel can be constantly supplied with no need for 'charging' the device. It can be operated as an independent power generation unit (as long as it can be supplied with hydrogen from storage) and can provide scheduled generation (offering the option of selling wind-based electricity on the spot markets) and balancing power for fluctuating energy. It is noteworthy that hydrogen systems which use renewable energy can provide balancing power free of carbon dioxide (cf. discussion in section 1).

2.3.6 Comparison of selected technologies

In the following section we will discuss results from simulation calculations looking into the total efficiency of storage systems and their response to transients. Renewable electricity production has been described statistically in the frequency regime in order to evaluate the influence of fluctuations and levelling effects of geographical dispersion on the output of large generation systems [Steinberger 1993, Beyer 1993]. Distributing renewable (fluctuating) electricity generation geographically results in an elimination of high frequency contributions. Storage systems constitute low pass filters, if they ideally compensate fluctuations of high frequency, as can be reasonably expected. Nevertheless, they will show 'inertia' in that not all technologies as described in Section 1.3 are instantly available for power storage or production. They may have a limited transient response time or limitations in switching from a 'loading' to a 'discharging' regime. Thus, their function as filters will be limited. Another limiting factor is the total efficiency which prevents full reclamation of the energy stored and thus affords more energy to be stored than can be unloaded. The third effect is the statistical sequence of positive and negative fluctuations from a given target 'signal' (for instance a timetable for production or predicted renewable generation, see below).

2.3.6.1 System Efficiency

The energy balance of a storage system is very simply described as (Figure 8)

$$\eta_{total} = \eta_{input} * \eta_{storage}(t) * \eta_{output} \quad (1)$$

where the input and output converter efficiencies determine the conversion efficiency and the storage 'efficiency' describes losses from storage. The latter can consist of self-discharging, evaporation from a reservoir, frictional losses etc. and could even be negative in the case of rainfall into a water reservoir. Whilst the converter efficiency can be described as an energy balance of energy gained (or converted) divided by energy (or stored medium) input, the storage efficiency is a function of time.

2.3.6.2 Other Performance Indicators

In evaluating the performance of different storage systems a variety of targets can be considered. Table 2 gives some indications of main characterisation parameters of the technologies mentioned in Section 1.3. Table 3 expands this to the specific requirements of transient operation as is necessary in balancing short term fluctuations.

Table 2: Comparison of storage technologies (without hydrogen, since no commercial installation data were available at the time of writing)

	Compressed Air (CAES)	Pumped-Hydro	Flywheel	Lead Acid
Physical / Chemical principle	Mechanical - potential energy storage	Mechanical - potential energy storage	Mechanical - kinetic energy storage	(Electro-)chemical energy storage
System voltage	Low, medium	Medium, high	Low, medium	Variable
Range of capacities [W]	High MW to GW	High MW to GW	Low kW to high kW	Low kW to medium MW
Discharge time	Hours	Hours	Minutes	Minutes to Hours
Energy density [kWh/m^3]	n/a	n/a	10 –20	20 – 80
Lifetime [cycles]	~ 10000	~ 50000	~50000	< 1000
Energy efficiency [%]	~55 for non adiabatic storage	~80	~90	~75 (incl. self discharge)
Capital cost per unit power [$/kW]	<1000	~1000	~300	<900
Capital cost per unit of storage capacity [$/kWh]	<100	~100	~5000	<1000

Table 3: as above but concentrating on the transient properties of the systems discussed and including hydrogen systems

	Compressed Air (CAES)	Pumped-Hydro	Flywheel	Lead Acid	Hydrogen
Response to transients	moderate	moderate	fast	fast	fast
Source of inertia	mechnical (rotation), switching interval	mechnical (rotation), switching interval	mechnical (rotation)	reactant transport (electro-chemical)	reactant transport (electro-chemical)
Inactivity during change in the storage process (e.g. storing – delivering)	Minutes	Minutes	Instant	Instant	Instant

2.3.6.3 Technology conclusions

In balancing power fluctuations (either from load or from production variabilities) the transient behaviour of the storage systems is of vital importance. Table 3 shows qualitative assessments of different storage technologies. Those with a high possible capacity (compare to table 2) mostly show considerable ‘switching’ time from loading to discharging (e.g. pumped hydro and CAES). On the other hand the technologies with rapid response to load changes (flywheel and battery) are those with least capacity. The only exception to this observation is hydrogen technology where both the (principally) unlimited storage capacity of CAES or pumped hydro are combined with the (near-to) instant response of a battery.

The drawback of hydrogen, though, is the limited overall efficiency which is limited both by the electrolyser (approx. 67%) and fuel cell (approx. 40%) efficiencies. Storage loss can be neglected. Overall return is therefore below 30% of the energy fed to the storage. Clearly, effort has to be invested in order to improve this situation. On the other hand the benefits of low storage losses, rapid response and decoupling of input/output converter rating from the actual storage capacity may in the future make good for the overall considerable energy loss.

Another obvious solution could be the combination of a rapid response/low capacity technology with a high capacity/slow response technology. This, of course, inflicts added cost for a more complex system.

3. Hydrogen as a Storage Device for Fluctuating Energy Sources

Hydrogen, as indicated in the previous section, has a very specific potential as a storage device for renewable electricity. It has the advantages of

- complete decoupling of input and output conversion (cf. Figure 8)
- arbitrary size of storage
- negligible storage losses
- quick response to load changes (both input and output)
- multiple use of the storage vector (hydrogen)

A brief comparison of the properties of a hydrogen storage system with other technical options has been shown in Section 1.3.6. The main strengths are the independence of storage size from the conversion to and from hydrogen (other than with batteries, supercaps or flywheels, for example), the comparatively low price of storage, the negligible losses, and the prompt response to load changes only limited by gas diffusion in the electrodes of electrolyser and fuel cells, and by limitations in ramping up in cases of ‘cold start’, before the regular operating temperature has been reached.

Nevertheless, considering Figure 8, it is rather obvious that the total efficiency from electricity to hydrogen and back again is low. Assuming standard values of efficiency for electrolyser (67%) and fuel cell (40%), the total efficiency of storage is as low as 27%. Clearly, there is a need of improving both the efficiency of electrolysis and fuel cell conversion. On the other hand, these circumstances also indicate that rather than re-converting the hydrogen to electricity there might be more efficient ways of using the hydrogen, for instance as an industrial gas or vehicle fuel. A variety of options exist once a hydrogen production and storage facility is available. This aspect is to be expanded in one of the following section.

3.1 Eliminating Power Fluctuations

As shown in section 1 (Figure 4 and Figure 5), it is necessary to balance the fluctuations from renewable electricity generation (as far as wind, solar and wave energy are concerned) in order to avoid excessive demand for conventional, fossil fuelled balancing power in the grids. Even though geographical dispersal throughout Europe will alleviate the problem and eliminate the short term, high frequency fluctuations, large gradients can still occur, especially when large scale weather events like storm fronts hit a high number of energy converters more or less simultaneously.

A strategy of reducing the fluctuations has been presented by the project HyWindBalance [Steinberger 2007]. The analysis uses today’s tools in balancing power generation and demand as a starting point. Weather forecasts have been in standard use in grid management for decades, as have knowledge-based approaches to predicting electricity demand and balancing the short term, statistical fluctuations inherent to electricity demand. The problem of integrating renewable, fluctuating power is then reduced to an optimised network management obeying given, admittedly novel, constraints. The HyWindBalance concept describes solutions to renewable power management (concentrating on wind energy) by ways of electricity storage via hydrogen. The management and economic efficiency of renewable electricity supply is improved by the possibility of supplying wind energy in a controlled manner (“dispatching”).

- This enables scheduling of wind electricity production (bringing increased reliability of wind energy generation and allowing for intermediate storage of excess energy);
- And minimises the use of traditional balancing power (minimising the consumption of fossil fuels).

The concept couples hydrogen production, storage and re-conversion to electricity with an intelligent control unit that incorporates wind as well as load prediction routines. Figure 9 gives an overview of the system modules and their interaction. The main aim of the project is to develop a wind hydrogen system that, in its function as a "virtual power plant", establishes the following options for wind energy (but also any other fluctuating renewable source of electricity)

- Scheduled generation, thus making the wind resource ‘controllable’;
- Reduction of need for balancing power from conventional power plants (secondary balancing power);
- Active (scheduled) sale of wind-based electricity as (amongst others) balancing or peak power on the spot market.

In its simplest form, the system uses a wind power prediction (day-ahead 24 hour prediction) similar in appearance to the solid line in Figure 4. This prediction is introduced to the day-ahead power market as a firm electricity source in the same way as a conventional power plant generating the equivalent power profile. The energy management and storage system is then used to eliminate the short term fluctuations (cf. Figure 4) and the unavoidable prediction errors [Lange 2005]. The layout of the storage system can be adjusted to the typical forecast errors of the predictions which are much smaller than the full fluctuations of the wind power output. In this case the storage content has to be managed in a way that the statistically expected fluctuations can always be compensated for. As a consequence, renewable electricity can be offered to the market in very much the same way as conventional plant. It should be especially noted that wind-hydrogen-systems of this type can provide balancing-power free of carbon-dioxide as a self-contained system with no outside energy input.

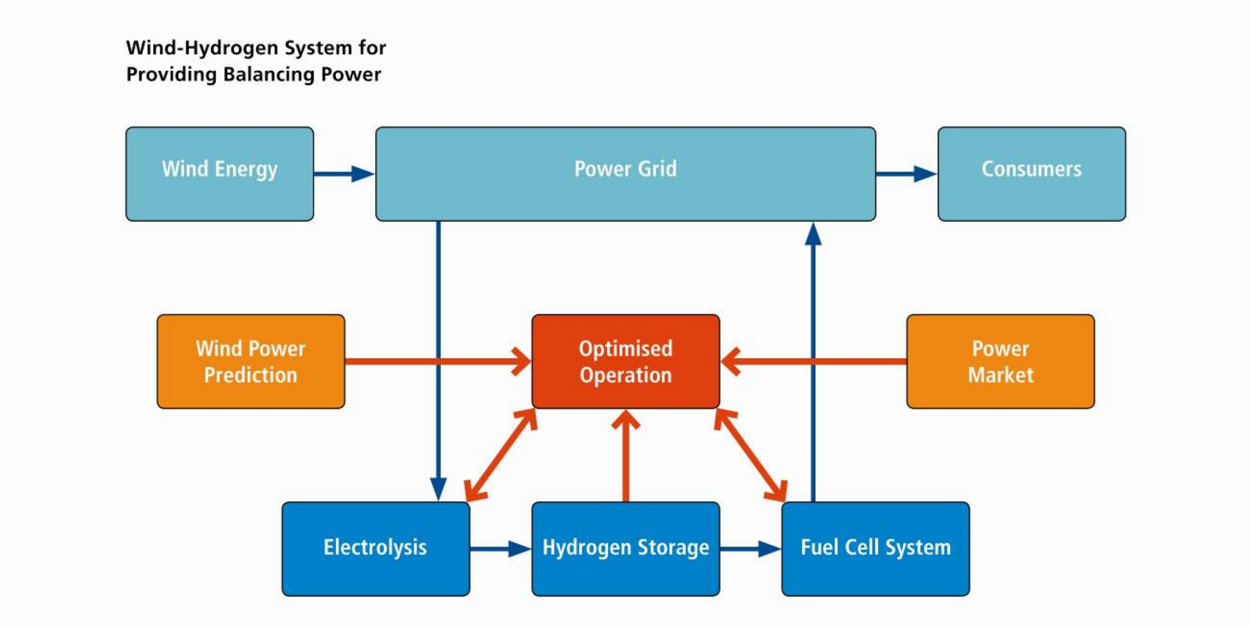

Figure 9: Block diagram of the HyWindBalance wind-hydrogen balancing power system [Steinberger 2007]

Wind power predictions are required for the efficient operation of the wind-hydrogen system, especially with regard to an optimal management of the storage. The predictions provide the information how much wind power will be available in the near future, i.e. over a time horizon from 0 to 48 hours, in more recent times supplemented by an ‘intra-day’ prediction update in the range of 6 hours. Hence, the fluctuations of wind power due to meteorological conditions are known in advance within the uncertainty of the prediction.

Based on various numerical weather prediction (NWP) data the wind power predictions in this case are calculated with the established forecasting system *Previento*. The prediction system delivers forecasts of power output of single or the aggregated output of a number of wind farms in a region up to five days ahead. In addition, *Previento* can provide the uncertainty of prediction depending on the prevailing weather situation. It is a so-called physical system [Lange 2005] and is based on a meteorological description of the atmosphere. The coarse resolution of the NWP is spatially refined to obtain the wind speed for given sites. Different forecast systems vary significantly in their refinement methods and the physical parameterisation to obtain the wind speed in hub height. The wind speed values are plugged into the power curve of the wind turbines and the expected power output is calculated. The advantage of physical models is their deterministic parameterisation based on meteorology and the fact that no measured data are needed to produce a prediction, although they can of course be optionally to improve the forecast accuracy. Figure 10 shows the principal scheme of the forecast system. The main ingredients are the NWP input, site-specific data of the wind farm, and, for aggregated predictions, a database of all wind farms in a given region.

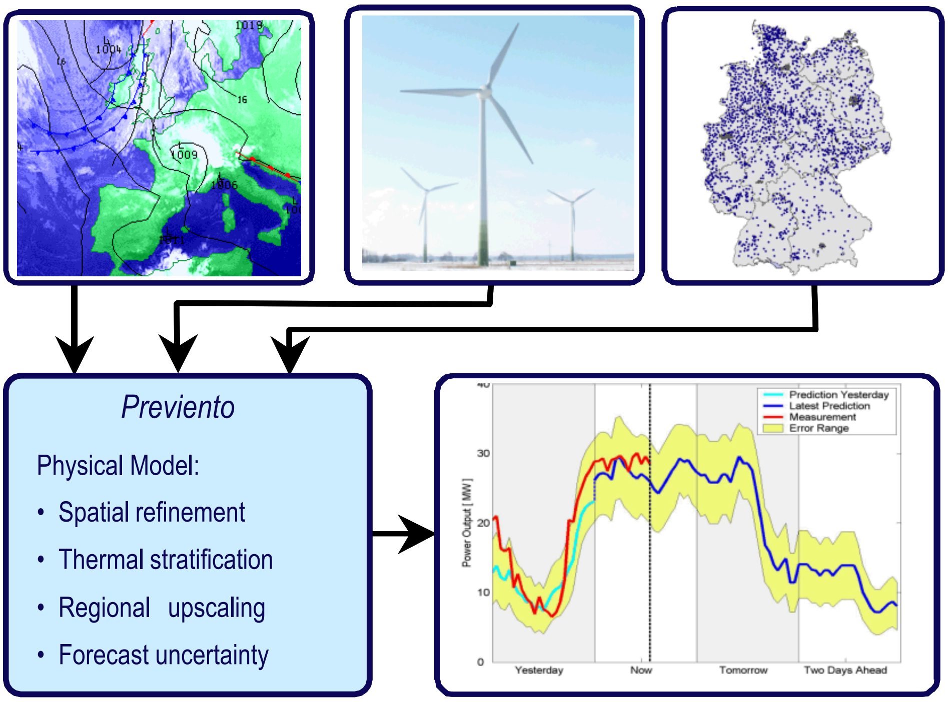

Figure 10: Basic scheme of a physical wind power prediction system.

Based on weather data from several meteorological services and information on all German wind farms, the system uses physical methods to provide a wind power forecast [Lange 2005].

Although the HyWindBalance system could integrate any kind of electricity storage, hydrogen was chosen on the grounds of a higher versatility and large storage capacity coupled with fast response. The concept shows that although single technologies would not be capable of controlling renewable electricity variations, since generation and storage capacities to be installed would be excessive, the combination of measures adapted and integrated into more ‘intelligent’ overall systems can offer competitive solutions that will satisfy the needs of reliable and efficient power generation, while at the same time providing CO_2-free and indigenous energy.

3.2 Storing Surplus Power

As indicated in Figure 6 and Figure 7, excess power production will begin in grids with 15% photovoltaic or 25% wind electricity penetration, based on a grid characteristic as found in Germany. Forecasting that maybe up to 40% of electricity demand will be satisfied by renewable electricity in 2020, and deducing from figures 1 and 2 that hydro energy today covers approximately 10% of European electricity demand and that the potential for new hydro capacity is low, the main body of increased generation capacity will be wind, wave and maybe PV (cf. also report [R2H 2008]). Seen at a European scale, therefore, surplus energy production according to Figure 7 will be negligible. The situation will then rapidly change as renewable generation capacity is further increased towards 2030 and 2050.

Given a 50% share of wind and wave capacity in European grids in the long-term future and also assuming that the characteristics of wave power might be similar to those of wind – which is not totally correct since the ocean potential energy will level out even mid-term fluctuations – a total of 15% of the renewable electricity resource equivalent to 7.5% of overall electricity generation will be produced in excess of immediate load demand and therefore need to be stored. The predictions for European electricity demand development are 3200 to 3500 TWh in 2020 and 3800 to 4200 TWh in 2030 [WETO 2030] [EUSUSTEL 2005]. The lower figure refers to the EU15 countries, the higher to EU25. [WETO 2050] even predicts up to 8000 TWh of electricity demand in the whole of Europe up to the year 2050.

Taking 7.5% of this figure results in an energy amount of approximately 250 to 300 TWh that has to be passed through storage annually. From this figure an actual storage capacity cannot be deduced since this will depend on a variety of other parameters that can only be resolved using power grid simulation, a tool that was not available in this project. For comparison, though, the total energy amount supplied from European pumped storage amounted to 13.6 TWh in 2005 [EUROSTAT]. Comparing these figures indicates a massive increase in storage capacity in the context of integrating very high quantities of fluctuating energy sources into the European electricity supply systems.

Surplus production may also arise if grid access is limited, restricted or underdeveloped. In many cases a large renewable electricity resource will be located at sites with no or low grid density and capacity. This is easily understood since especially wind and wave power will be connected to the grid in areas with traditionally low grid development level, namely the coastal regions. The same goes for large photovoltaic plants that will – due to their high demand for placement areas – tend to be located in areas with low real estate costs, i.e. low development level. In these cases renewable resources might also be ‘stranded’ in that they cannot be developed due to a lack of grid access. Instead of building transmission lines, a hydrogen production facility could be built in order to bypass the electricity grid bottleneck and directly feed into a gas distribution grid.

The discussion on hydrogen as a power transportation vector below will in analogy also cover the case of ‘stranded’ power. Here we can restrict ourselves to the case of limited grid access.

3.3 Power Transportation Vector

Hydrogen has been discussed as an energy transportation vector for offshore wind energy development (the equivalent would also hold for future wave energy development). The motivation was that bottlenecks became visible for cable laying for on-shore connection of the German North Sea offshore projects. On the basis of cable technology available in 2000 to 2005 it was not possible to lay enough cable capacity to shore, taking into consideration the fragile National Nature Resorts along the German coastline and the ensuing limited access points.

Studies were therefore conducted in order to determine whether the electricity transmission could be replaced by hydrogen pipelines or barge transport [Altmann 2001]. Nevertheless, from Figure 8 it can easily be concluded that the energy losses along the conversion chain are too high to justify the offshore hydrogen production coupled with on-shore re-electrification. Apart from the obvious difficulties of operating and maintaining large hydrogen production plants on offshore sites, converting all wind energy to hydrogen necessitates an electrolyser system with the same rating as the wind capacity with the ensuing similarly low load factor of around 3000 to 3500 hours per year. Economically, this setup will not be able to be competitive.

Offshore wind development has today taken a different approach in that plans have been drawn up to install a pan-national ‘super grid’ in the North Sea connecting the offshore wind resources of Germany, Denmark, the UK and the Netherlands [Fairley 2006]. Using advanced cable technologies and a point of access to the on-shore grid at a major industrial development area, for instance in the Netherlands, avoids many of the problems encountered in connecting the wind resource along the German coast with its very few industrial sites with sufficient high-voltage grid capacity.

3.4 Hydrogen Infrastructure Outlook

The upper part of Figure 11 shows a wind-hydrogen system equivalent to the generic structure shown in Figure 8. In this case the direct link between wind resource and grid is also shown. Considering the multiple usage possibilities of hydrogen the storage now serves as a ‘distribution hub’ to a variety of other applications. In the medium term, it will therefore be possible to sell hydrogen produced from excess renewable electricity to other markets than the electricity sector, for example as fuel for road vehicles (lower left) or industrial gas (middle) etc. Such diversification of wind energy could in the future, for instance, relieve the wind electricity market from economical pressure ensuing from excess production.

The system in Figure 11 will also serve as a ‘nucleus’ of a future energy distribution system in which hydrogen will play a major role. It can serve not only as a source of renewables-derived hydrogen but can also collect hydrogen from a variety of other sources, e.g. industrial surplus, biomass gasification etc. The supply of wind-hydrogen as a fuel is especially attractive since the reference efficiency of today’s internal combustion engines is extremely low at around 12 to 15%. Even allowing for further optimisation of combustion technology up to 2020/2030 will still keep the total efficiency according to Figure 8 well above this level.

Therefore fuel cell vehicles operated on wind hydrogen will not only increase energy efficiency but also supply an environmentally neutral means of transport [Feck 2001]. In contrast, the distribution of 'renewable' hydrogen as a fuel for stationary fuel cells as indicated in Figure 11 to the bottom right will not be a reasonable solution unless other sources of hydrogen are also fed into the distribution system since overall efficiency cannot be compared to the adequate reference of grid electricity and conventional heating appliances.

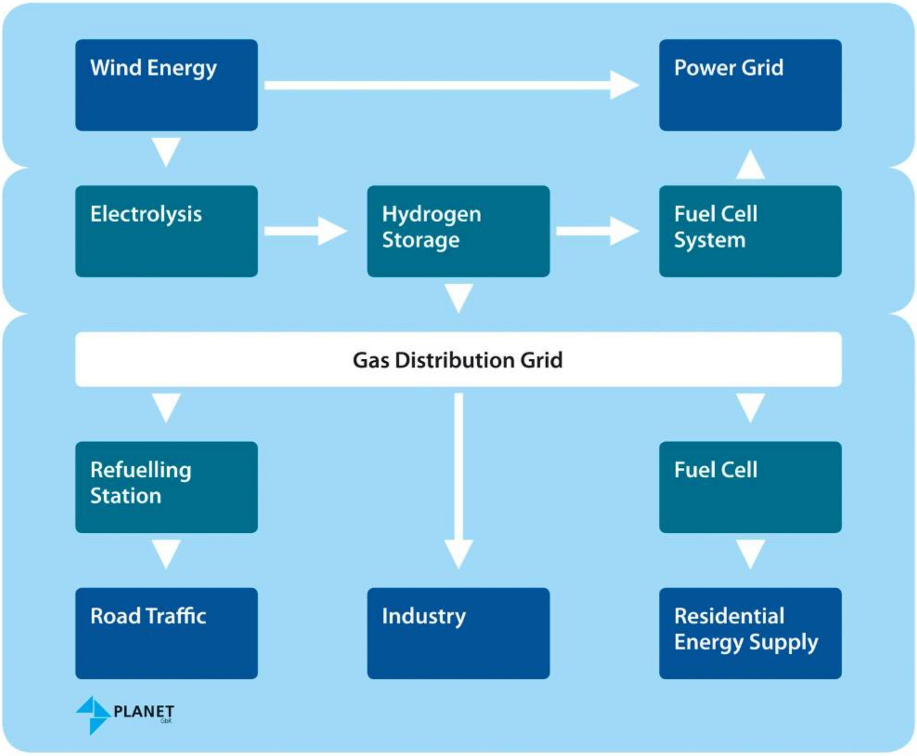

Figure 11: Flow chart of a wind-hydrogen-system with different pathways of hydrogen utilisation [Steinberger 2007].

3.5 Economic Considerations

The assumptions illustrated in this section so fare were economically analysed in [Shaw 2008] where a cost-benefit assessment was carried out for wind-hydrogen systems. Taking into account both in sections 3.2 and 3.4 introduced options of reducing fluctuations, thereby reducing network management costs, as well as the production of gaseous hydrogen with surplus electricity for the use in, for instance, vehicles this study conducts an assessment of different scenarios with varying market prices for wind energy and hydrogen. The results of the analyses suggest that the economic viability will be dependend on the relative value of the wind energy in the electricity market compared to the hydrogen market. It shows that in places where the market value of wind electricity is low due to its excess supply and the incurred high costs for balancing power (and the need for curtailment), the incentive to locally produce hydrogen increases.

For remote locations, however, where there is no grid-access at all, the calculations look clearly different. As diesel fuel is the primary source of electricity in several thousand remote communities, and fuel transport costs represent a significant component of fuel expenditures, in these communities a wind-hydrogen system with storage becomes economically feasible much earlier. Figure 12 shows the comparison of cost of delivered power for a diesel genset (with two transport scenarios) and energy generation based on hydrogen. It can be seen that hydrogen-based energy storage and power systems are competitive with diesel generators already today in many remote power applications.

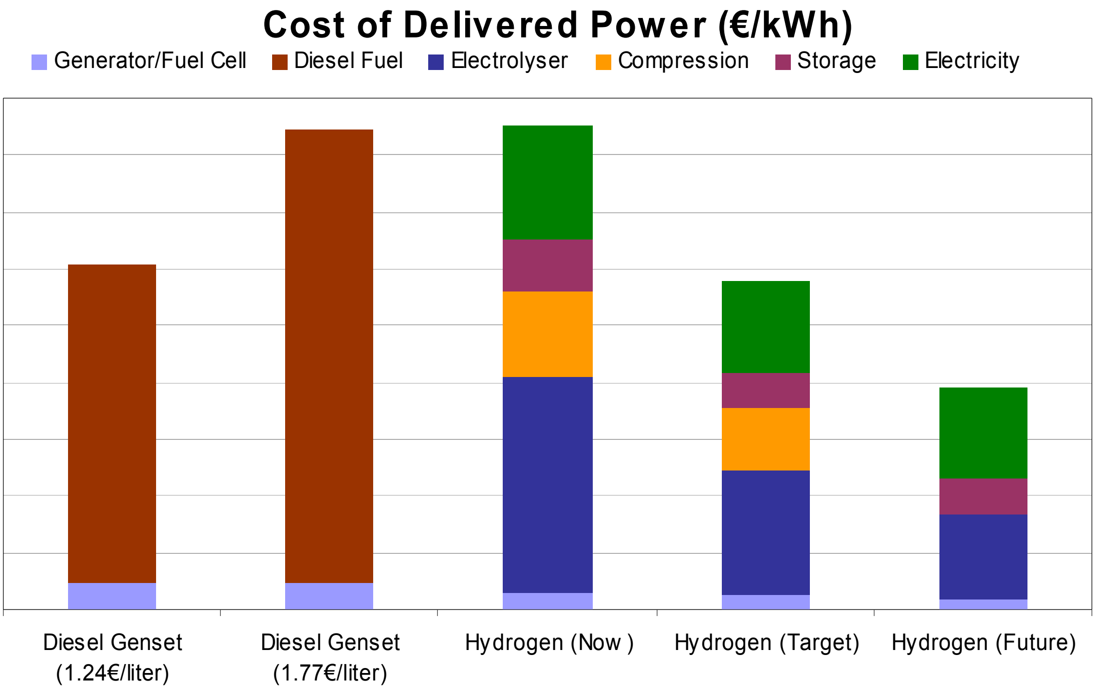

Figure 12: Comparison of cost of delivered power for remote areas, where diesel gensets are used, to a wind hydrogen system.

Key assumptions are diesel power cost of 400€/kW, hydrogen system roundtrip efficiency of 30%, wind power cost of 0.04€/kWh, and hydrogen energy storage (150kWh + 5 days storage). Source: Alteration of [Wilson 2008]

4. Conclusions

As was shown in section 1.3.6 no single storage technology can satisfy the requirements of balancing power for major contributions from fluctuating renewable electricity production. The optimum system supplying balancing power will consist of a number of different technologies, for instance an instant-response low capacity technology like flywheels or supercaps, coupled with a mid- to long-term storage like pumped storage, compressed air or hydrogen.

In contrast to the other long-term storage options, hydrogen offers the advantage of a high flexibility and the possibility for multiple-use, for instance being delivered as vehicle fuel. On the other hand the overall storage efficiency is low, at least when considering today’s technologies. This situation may partly change when development progress is made. The advantages, though, will always be bought at a sacrifice of energy, due to the limited efficiency of the re-conversion to electricity. Even if the heat generated might be put to use, the return on the electrical energy initially fed into storage will remain in the order of magnitude of 50%, which is comparable to today’s CAES systems.

However, even given this conclusion, the use of hydrogen as short term storage still offers the benefit of synergy with its production for other uses, so it is possible to consider in some circumstances a multi-functional plant that both exports hydrogen and supplies emission-free balancing power for wind, wave and tidal energy schemes, thus improving integration of these sources into the European electricity grid. Such a plant would have a high capital cost, because its elements (hydrogen production from electricity, hydrogen re-conversion back to electricity) would be under-utilised by definition, but in some circumstances this could prove to be a favoured solution especially if there were a demand for the (intermittent) waste heat. This situation also applies for remote areas with no grid-access and high fuel transport costs for the local generation of electricity.

The issue of surplus energy on a longer timescale will start to occur at a European scale when the share of renewable electricity is further increased well above the 35% envisaged for 2020. Then, though, hydrogen can play an important role due to the possibilities of long-term, low-loss storage and, again, the ability to integrate this function with what could, by that time, be a substantial transport fuel supply need.

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