# Techno-Economics of Distributed Generation and Storage of Solar Hydrogen

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**Abstract**

For hydrogen to become a truly sustainable energy vector, low carbon generation technologies need to be developed and brought to market. Hydrogen from solar energy is a promising approach, capable, if successfully developed, of producing hydrogen from an abundant source with greatly reduced carbon emissions.

At present fundamental research on a wide range of solar hydrogen technologies is being investigated, including thermal, biological and electrochemical methods. The techno-economic properties of these technologies differ significantly. Some are best suited to large-scale centralised applications, whereas others may be employed on a smaller scale as part of a distributed energy resource strategy.

This work focuses on understanding the commercial potential of distributed generation and storage of hydrogen for stationary applications within a future energy system. Of particular interest is the combination of different generation approaches with appropriate storage technology and capacity. The choice of each depends on a number of factors, including electricity price fluctuations and the temporal mismatch between solar generation and demand profiles.

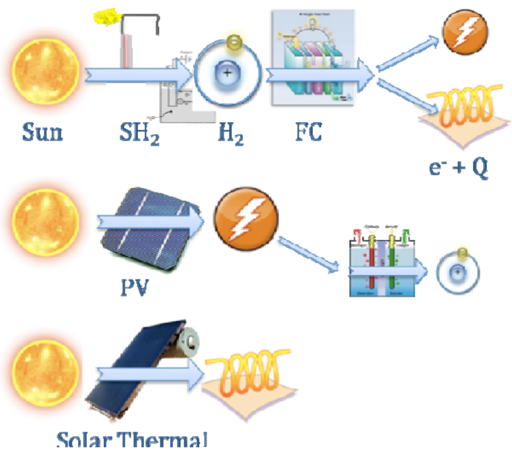


**Figure 1: Conversion pathways for solar energy.**

## 1 Energy Storage in a Low Carbon System

Low carbon energy sources tend to be either intermittent (wind, PV, wave) or inflexible (nuclear). For a future energy system this is expected to make system balancing more difficult and UK electricity prices even more volatile than they already are.

A recent Monte Carlo simulation by Pöyry on a future energy scenario has resulted in periods of high electricity prices (> 1000 £ MWh-1), as well as periods of excess electricity, which has low or even negative prices as shown in Figure 3 (Cox, 2009). The price spikes are said to be necessary for plants with low load factors to be kept on the system to meet demand peaks.

Given the potential for arbitrage between peak and trough prices, it appears interesting to question the role storage may play in such a future energy system. Despite over 3 decades of successful large scale storage applications in the UK and abroad, many of the future scenarios envisaged today do not consider storage as a significant part of the system. Instead, the ECCC recently stated that "[…] excess electricity could be channelled into domestic water and space heating thermal storage that would otherwise use gas". (ECCC, 2010)

Hydrogen storage in particular has widely been dismissed as `too inefficient'. Schaber claims, when comparing storage technologies, that "[…] if all other considerations are equal, efficiency is paramount […]" (Schaber, 2004). This is certainly true for limited and precious resources. But how important is efficiency, when we are dealing with `excess electricity', as seen in Figure 2?

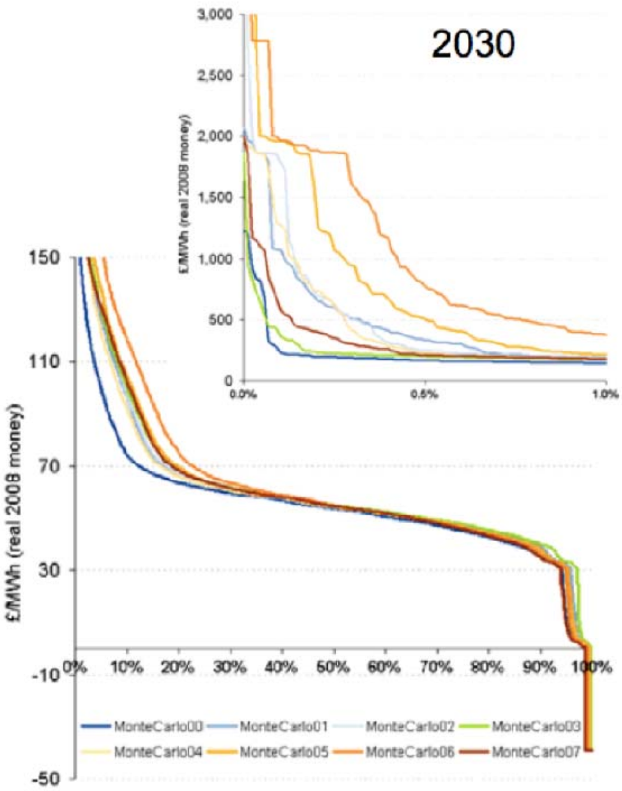


**Figure 2:** **Monte Carlo simulation results of electricity prices in a 2030 UK energy scenario. Periods of electricity valued in excess of 1000 £/MWh contrast with negative dump load prices. (Cox, 2009)**

## 2 Residential Storage

Distributed solar generation tends to suffer from low capacity credit, since the time of generation does not coincide with peak demand. A conveniently storable form of energy would therefore be desirable. The benefit of such a storage pathway has been modelled based on the structure shown in Figure 3. Solar energy can be converted into electricity, heat or hydrogen. A time series of storage is built up from hourly generation and demand profiles. Introducing storage raises the utilisation and adds value by displacing grid supply.

The best results have been achieved through a combination of all three forms of energy, suggesting that solar hydrogen may complement a highly renewable generation strategy. However the costs of local storage and conversion facilities are seen as prohibitive. Regional or national storage and distribution facilities are needed to support solar hydrogen generation.

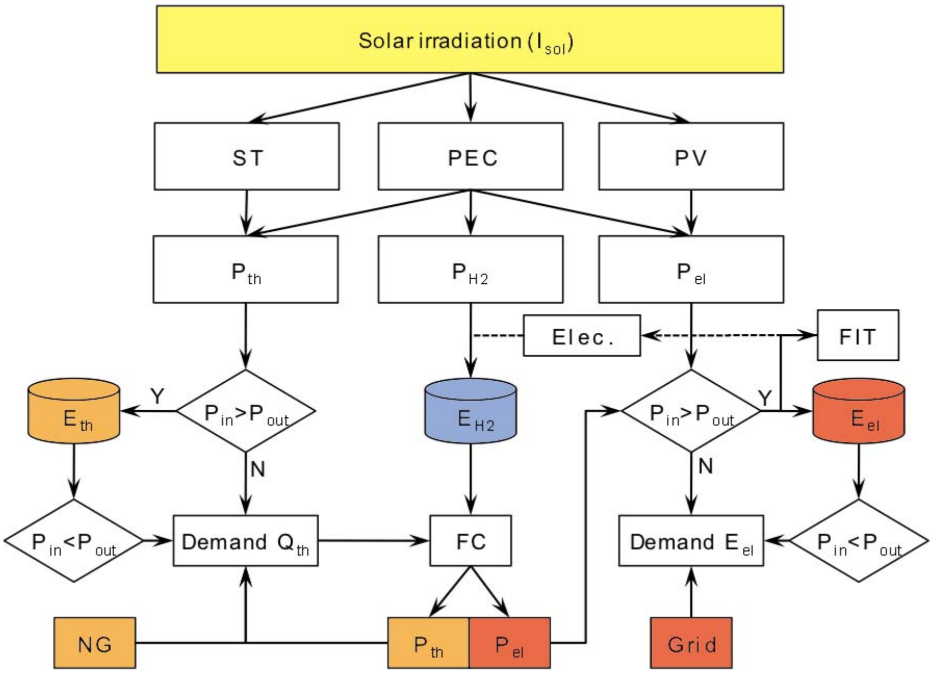


**Figure 3: Model for temporally resolved energy flows in a residential application.**

## 3 UK Storage

The model for a UK wide use of storage follows a similar basic principle to the residential model by building up a time series of generation resource and demand profiles. The choice of energy sources has been expanded to include wind, nuclear and a generic class of fossil fuel plants. Data for the wind and solar resource is based on historical data over the previous 6 years, measured mostly in 1-hour intervals and interpolated to match the 30 min resolution of the National Grid energy consumption data. (National Grid, 2010; UK Meteorological Office, 2006)

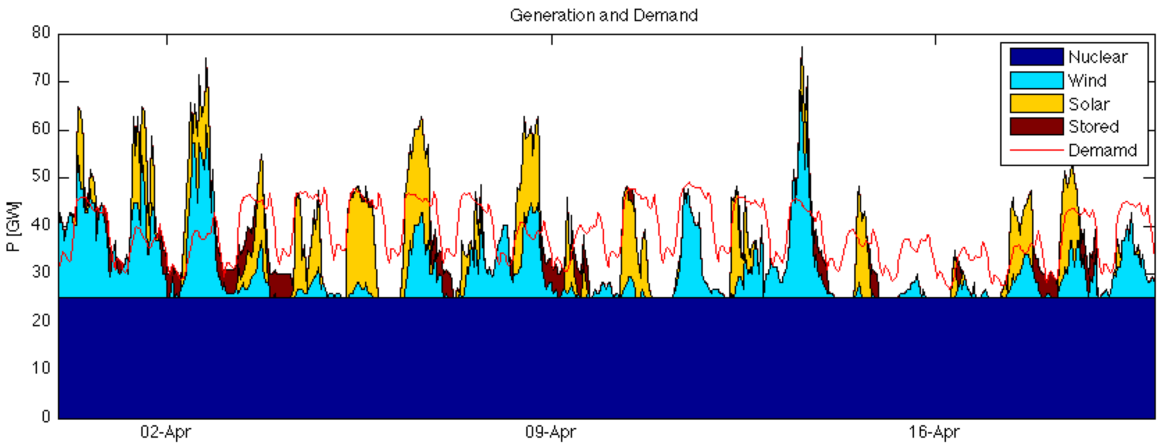


**Figure 4:** **Extract of time series of generation and demand. At times of excess generation energy is stored. Once demand exceeds generation from the low carbon sources, stored energy is released back into the system. Data based on National Grid (2010); UK Meteorological Office (2006).**

Heat demand is not considered in this model, to allow direct comparison with pure electric storage pathways, such as batteries. In practice, inclusion of CHP applications may shift the results in favour of hydrogen storage.

The dispatch order is kept deliberately simple, to avoid any technology bias arising from inaccurately estimated merit orders. Nuclear power is delivered as base load, which does not respond to demand. Solar power and wind are dispatched whenever possible or else stored, if storage is available. Should demand not be met by nuclear, wind and solar energy, stored energy is used. Fossil fuel plants only operate to meet the remaining demand (see Figure 4). In terms of merit order, this strategy could be described as highly carbon price dominated, but not necessarily economically or strategically optimal.

The resulting time series for flows in and out of storage gives an indication of the characteristics that are desirable in a large-scale storage system. If run unconstrained (i.e. infinite storage capacity and power) the power and storage capacity that would ideally be available can be estimated. Further, some typical usage patterns can be established from FFT plots and a storage duration histogram.

With the inclusion of costs for energy storage capacity and power, a solver finds the most cost effective storage configuration for any given generation mix (see Figure 5). The exact electricity prices a storage operator could negotiate in practice are the result of several complex factors that are beyond the scope of this study. Fixed electricity prices have therefore been assumed for off-peak periods and times when stored energy is released.

It has been found that large scale storage, providing arbitrage services in an energy system with more than 30 GW of renewable energy, can be economically viable. For the production of solar hydrogen to be competitive at the residential level, is more challenging. Large installations and a dynamic operation, delivering electricity, heat or hydrogen, are required, whilst meeting ambitious manufacturing cost targets of less than 1$/W$_p$.

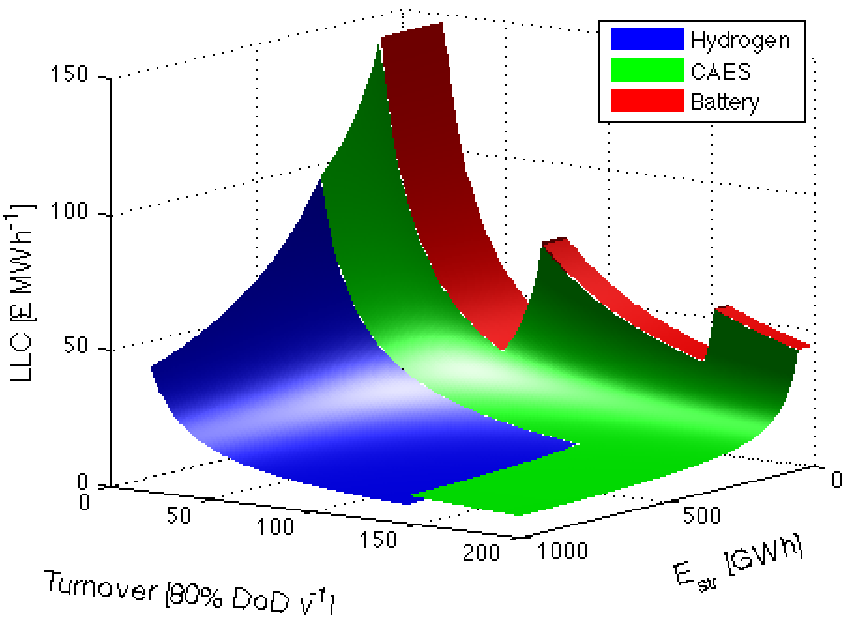


**Figure 5:** **Example of optimum storage technologies for a range of system storage capacities and utilisation.**

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