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Scotland's Hydrogen Future

Building a Sustainable Economy through Hydrogen and Renewable Energy

Hydrogen – Key to Enabling the Replacement of Oil, Gas and Coal by Renewables?

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Why hydrogen?

A Reminder:

Hydrogen is an extremely flexible fuel.

It can be used in internal combustion engines (ICE), in gas turbines and in fuel cells.

When burnt it releases no greenhouse gases.

If produced by electrolysis using renewable electricity it is a very clean fuel.

But what about safety?

Well actually a case can be made that it is safer that petrol.

1.If released it escapes rapidly away from the point of release

2.It burns with a low radiant heat

3.It cannot get on clothes and catch fire

4.It is non-toxic and its release poses no long-term environmental risk

See for example:
http://www1.eere.energy.gov/hydrogenandfuelcells/education/basics_safety.html

What are our energy demands?

Space heating – about 40%;

Electricity generation - about 25%

Vehicle fuel – about 30%

Electricity is the key fuel as it not only provides power but can be used to produce hydrogen

Table 1 Electricity generation in Scotland

	GWh	%
Coal	14,776	32
Gas	8,847	19
Nuclear	15,863	35
Oil	186	0.4
Hydro	3,693	8
Small hydro and renewables	1,405	3
Small/other fossil fuel	747	2
Total	45,517	

Source: AEA Technology (2006)

Table 2 Electricity - Installed capacity Scotland

Type	MW
Fossil fuel (coal, gas and oil)	5,272
Nuclear	2,410
Hydro (natural flow)	1,161
(pumped storage)	740
Other renewables	44

Source: DUKES (2008)

If electrolysis is used to generate hydrogen what renewable power will generate the electricity?

1. Wind power – well established and Scotland has substantial on-shore and off-shore resources but it suffers from being intermittent.

2. Hydro-electric power - responds rapidly to demand and available at all times but limited sites although there is some potential for small scale hydro.

3. Biomass -if locally available can be used in CHP

4. Tidal and wave are currently under development. Wave power is intermittent (but less so than wind) and tidal, although predictable has a wide range from peak to tough that varies over a couple of weeks

Table 3 Potential renewable generation capacity

	GW
Wind (on-shore)	11.5
(off-shore)	25.0
Wave	14.0
Tidal Stream	7.5
Large hydro	1.5
Biomass	0.6

Source: Garrad Hassan (2001)

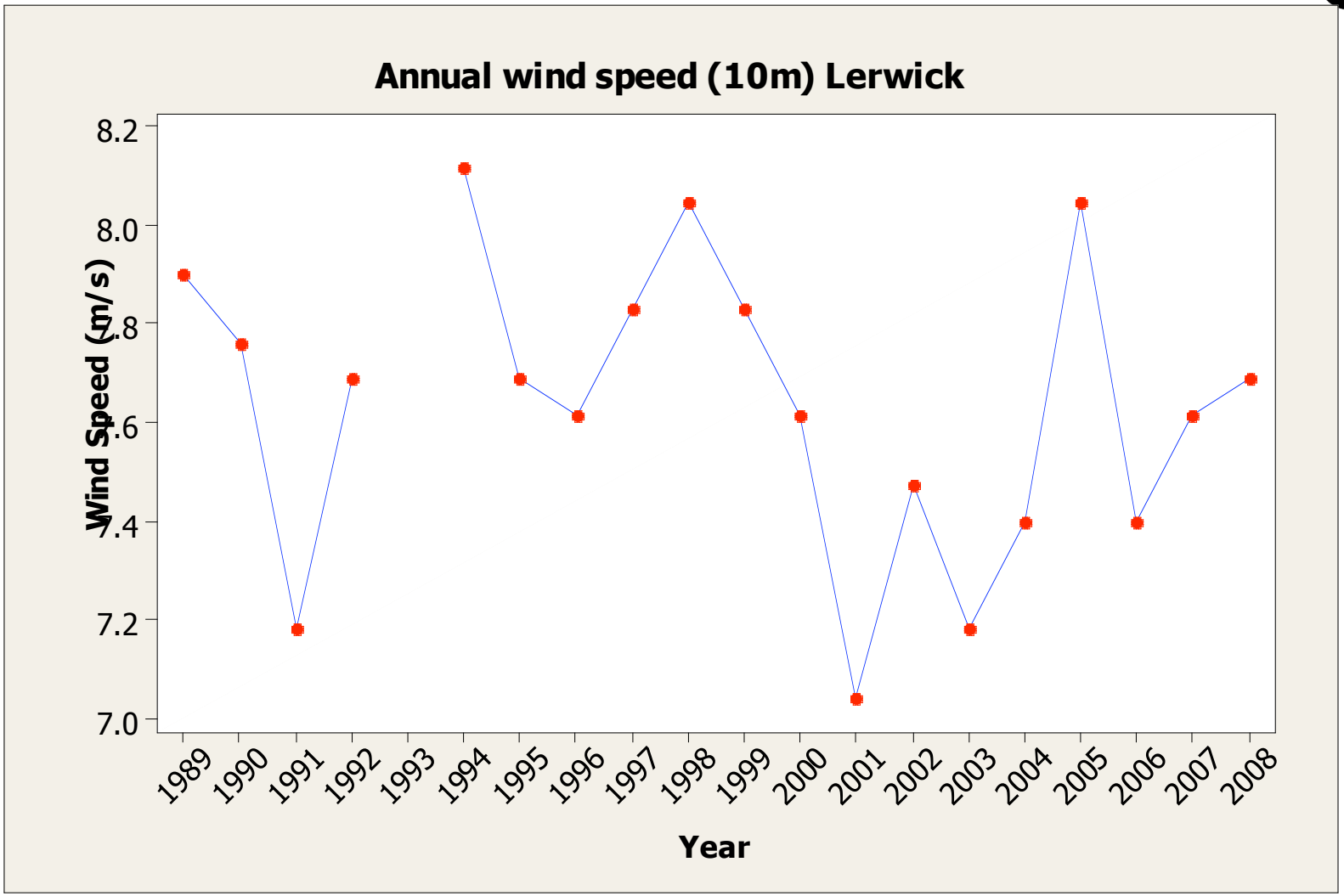
The following work is a case study of the potential production and cost of hydrogen using wind as the renewable energy source.

The work is based on the wind regime in Shetland where the wind power capacity factor is much greater than the UK average of around 28%.

Shetland is of interest as there is currently an application for a 540 MW wind farm but this wind farm will not be built unless there is a interconnector to the Scottish mainland.

The Viking Energy estimate of the TNUoS charge appears to be around 2.5p/kWh (the current charge for the North of Scotland mainland is about is about 0.51p/kWh) which would reduce financial viability.

Figure 1 Annual Wind Speed in Lerwick



Note 1993 did not have a complete run of data so that year was not included in the analyses

Figure 2 Burradale 3.68 MW Wind Farm Shetland (from south west)

Burradale has exceeded a 60% capacity factor (UK average 28%)

The Lerwick anemometer is to the east of the hills above which run N-S along the Shetland Mainland and therefore the wind regime is less extreme than that at Burradale or at most proposed Viking Energy wind turbine sites that will have a 540MW total capacity.

Table 4 Cost of wind turbines for Shetland

(p/kWh)

	Turbine cost (£/kW)		
Cost of capital (%)	800	1000	1481
	Viking Energy Operational Costs		
5	4.23	4.89	7.49
8	4.87	5.62	8.61
12	5.78	6.68	10.03
	Includes TNUoS charge of £22.27/kW		

Assumes:
50% capacity factor for wind and NPV of 0 after 10 years
TNUoS of £22.27/kW – current North of Scotland charge (2008/09)
Land rent 2% of revenue (using wholesale average price of 5.5p/kWh)
Insurance of 1% of capital cost (inflated at 2% pa)
Maintenance of 0.55p/kWh (inflated at 2% pa)
(land rent, maintenance and insurance costs from Boehme et al 2006)

Viking Energy projected operational costs are 1.69p/kWh (assuming 50% capacity factor for the 540 MW proposed installation – www.vikingenergy.co.uk)

A fall in capacity factor to 35% would increase costs by 0.8 - 1.3p/kWh (or by a maximum of 2.5p/kWh

Figure 3 Annual capacity factor in Shetland for Nordex N80 2.5 MW turbine (mean 50.1%)

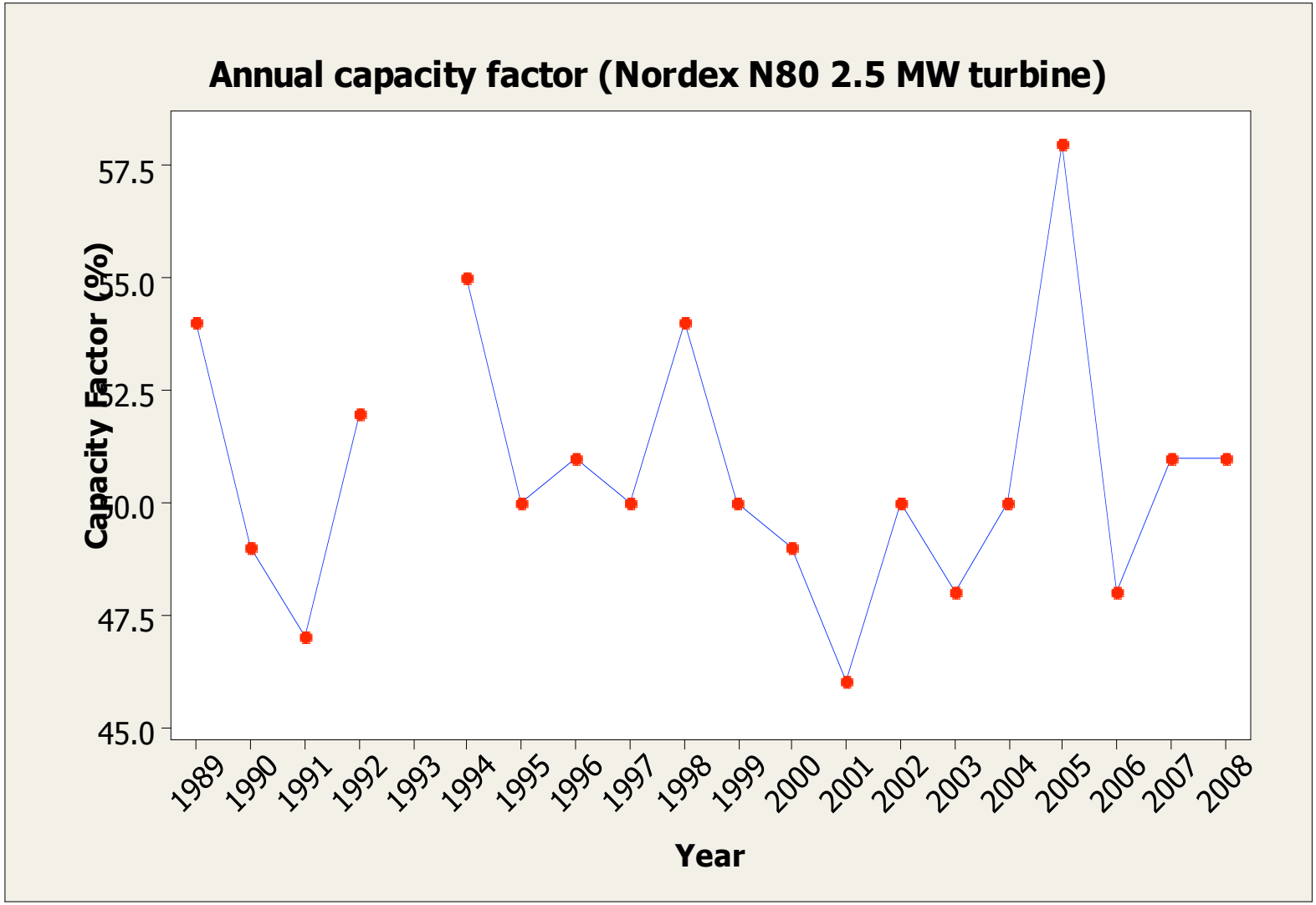


Figure 4 Annual capacity factor REpower 5M (5 MW) turbine (mean 58.1%)

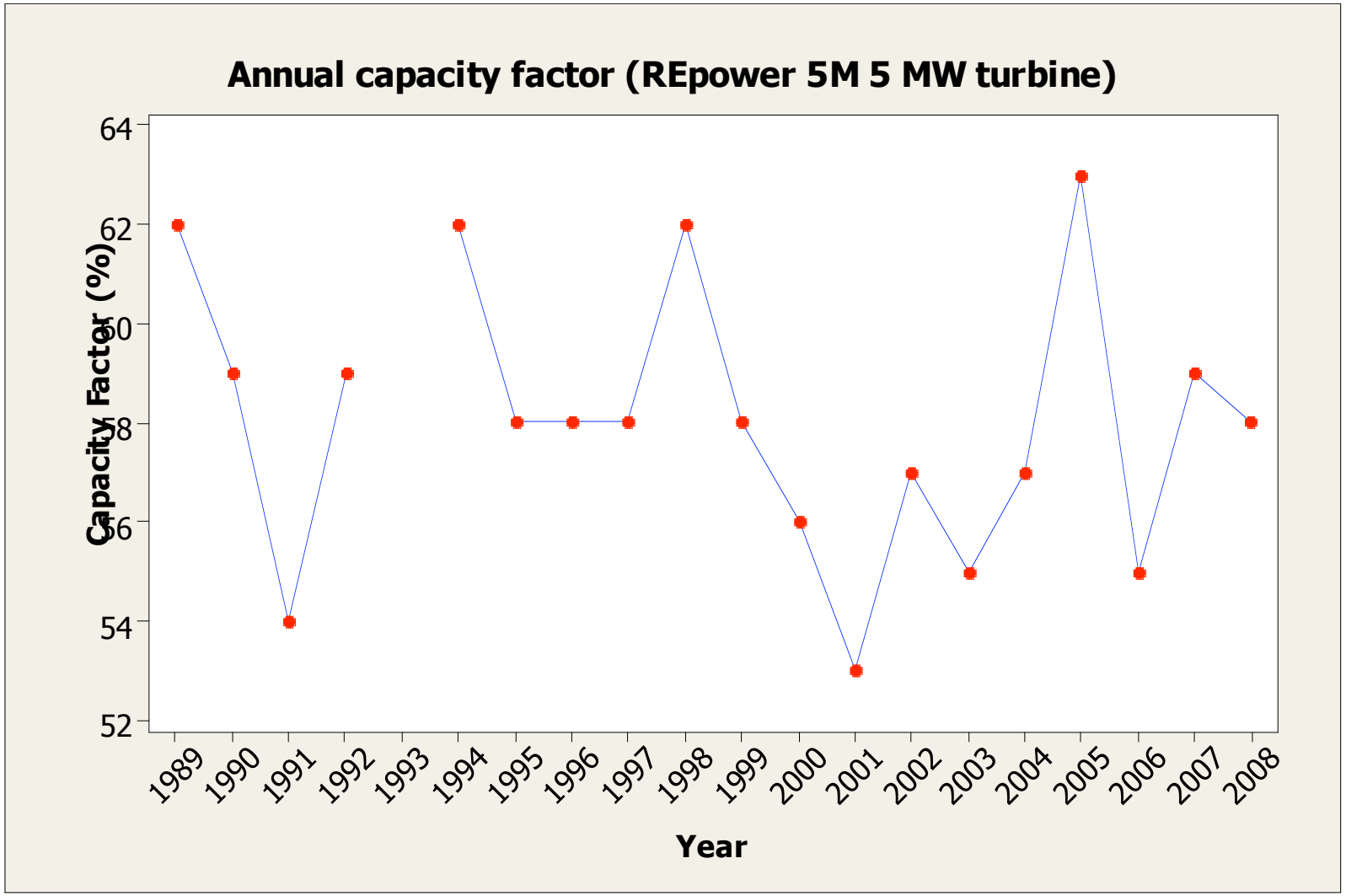


Table 5 Cost of electrolysers (p/kWh of H_2)

	Electrolyser Price (£/kW)			
Cost of capital (%)	200		400	
	(a)	(b)	(a)	(b)
5	1.61	2.36	2.07	3.26
8	1.86	2.71	2.38	3.76
12	2.20	3.22	2.83	4.46

Assumes:
(a) 8760 hour operation cash flow for 7000kWh H_2 (80% efficiency) using wind and other renewable power
(b) 4380 hour operation cash flow for 3500kWh H_2 (80% efficiency) using wind only
Maintenance of 0.8p/kWh (inflated at 2% pa); Insurance of 2% of capital cost (inflated at 2% pa); NPV of 0 after 10 years

Electrolyser prices: Source: Anderson, D. and Leach, M. (2004) *Energy Policy,* 32, 1603–1614

Table 6 Cost of hydrogen (p/kWh)

	Min	Max
Electrolysers cost	1.61	4.46
Electricity for electrolysers (@5.5p/kWh)	8.09	8.09
Total hydrogen cost (p/kWh)	9.70	12.55

Electricity for electrolysers allows for 80% efficiency and 15% for compression and storage.

Table 7 Range of electricity cost (p/kWh) generated in Shetland using a mix of wind power and hydrogen

	Minimum	Maximum
Electricity generation cost (wind)	4.23	8.17*
Using hydrogen fuel for 55 MW of CCGT plant (at 60% efficiency) providing 115 GWh	19.15	25.02
Average cost of combined wind and CCGT power	11.69	16.60
With ROC for wind power this falls to	6.40	11.31

But current electricity prices are at about 5.5p/kWh so this does not look a realistic option.

Note: ROC applied to both CCGT power and wind power as wind power used to generate hydrogen for CCGT plant so ROC would be gained for that power.

*This uses Viking Energy capital cost but operational costs given in Table 4 not Viking Energy estimate.

Other energy demands

Space heating:

While hydrogen could be used in domestic CHP systems or in gas central heating boilers, the costs will again be much higher than ever the cost for oil fired central heating.

In any case the best investment related to space heating is to improve insulation standards which are generally far too low.

So what about the use as vehicle fuel?

Table 8 **Comparison of petrol and hydrogen costs for Shetland (p/kWh)**

	Current	Max in last 2 years
Cost of vehicle fuel (p/kWh)	13.68	15.43
in Shetland (petrol)	119p/l	133p/l)

	Min	Max
Cost of hydrogen (p/kWh) Table 6)	9.70	12.55

If hydrogen is generated using wind power in Shetland, what is the storage required to ensure demand can be met.

This was calculated iteratively assuming that demand for vehicle fuel was essentially constant throughout the year and assuming that ICE vehicles were converted to run on hydrogen.

It was found that about 23 GWh of storage was required.

Two examples shown
a) 62.5 MW of Nordex N80 2.5 MW turbines and,
b) 55 MW of Repower 5M 5 MW turbines

Figure 5 Hydrogen storage range from 62.5 MW installed capacity (Nordex N80 turbines)

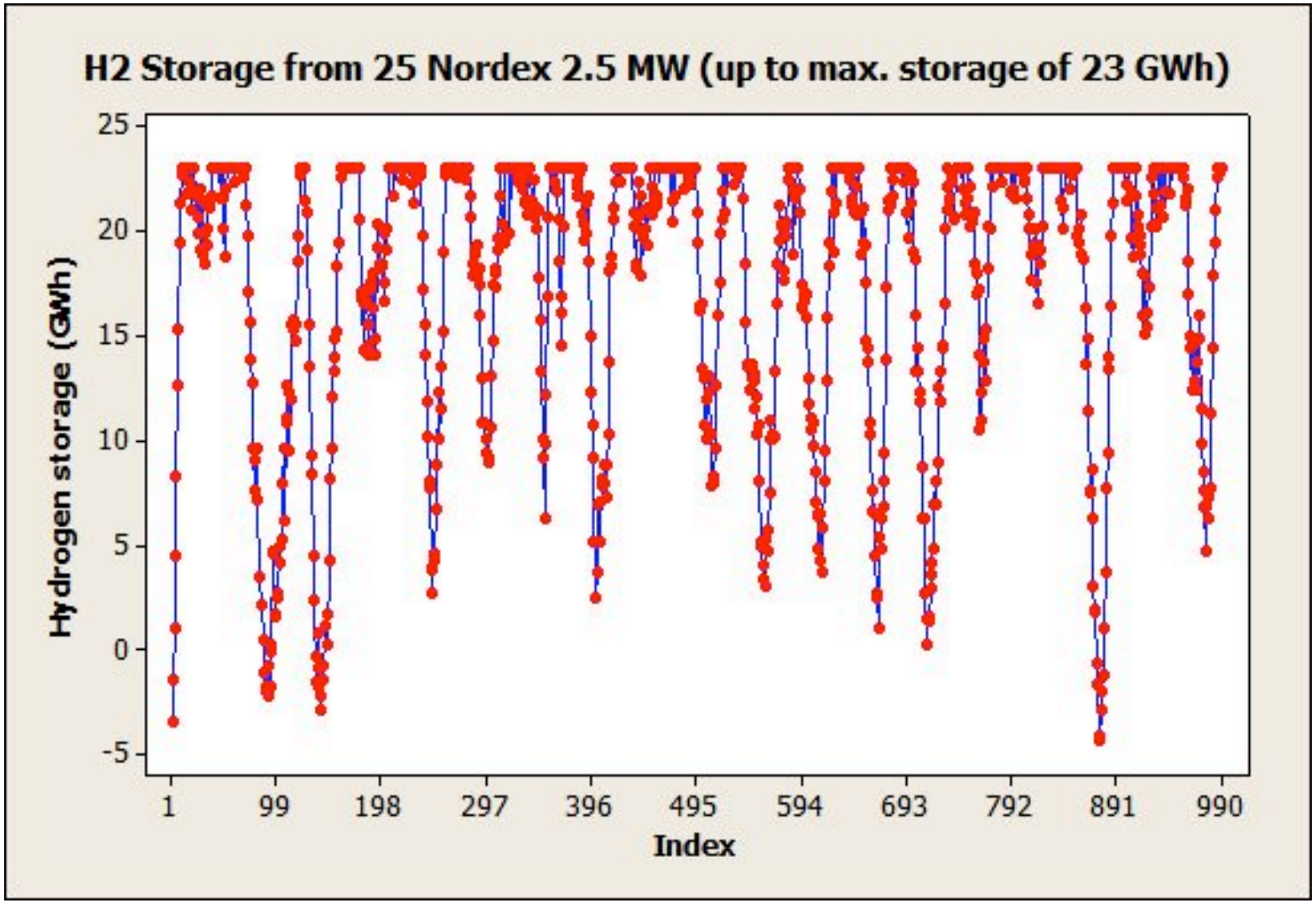
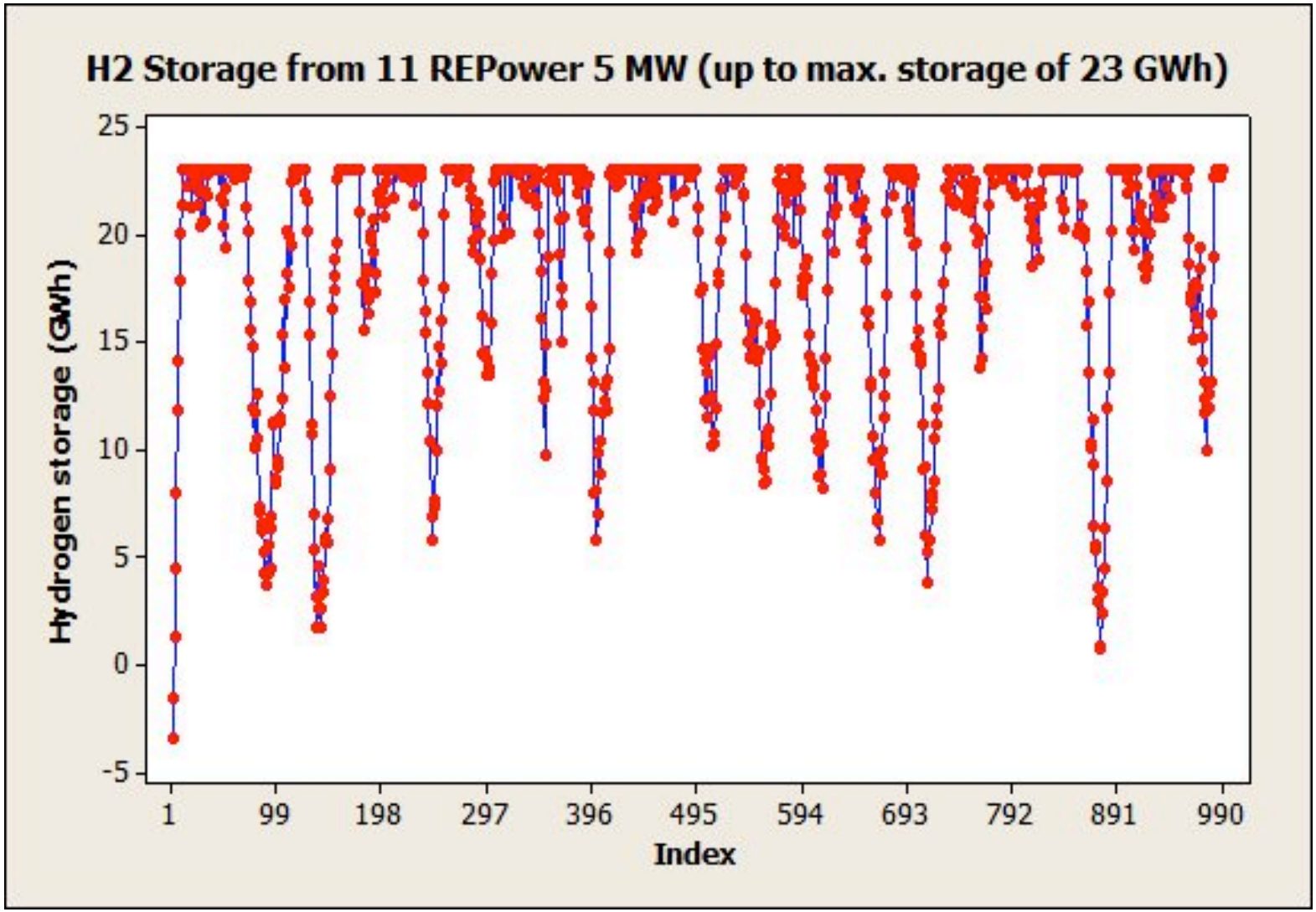


Figure 6 Hydrogen storage range from 55 MW installed capacity (REpower 5M turbines)



Scale of storage requirement

Total maximum storage required for 23 GWh of H_2 at 1 MPa (10 bar) = 817,924m^3 or 40,896m^3 at 20 MPa (200bar)

Comparison with Sullom Voe terminal:
16 crude oil storage tanks, each with a capacity of 80,000t
Four 20,000t LPG tanks (50 m diameter)
Oil storage ~1.15 x10^6 m^3 LPG storage ~0.149 x10^6 m^3

UK Total gas storage = 39,982 GWh and the main Rough storage facility operates at a maximum pressure of 20.5 MPa (205 bar).

Source: Farrington, B 2004 THE VALUE OF GAS STORAGE IN THE UK, Senior Consultant with ILEX Energy Consulting published in Utility Week on 12 March 2004.
http://www.ilexenergy.com/PAGES/Documents/Reports/Gas/StorageThinkPieceUtilityWeek.pdf

Concluding comments:

1. It would appear that hydrogen could be a cost-effective vehicle fuel in Shetland even at the current cost of renewable hydrogen and could be more cost effective in hydrogen fuel cell electric vehicles.

2. However, Bossel (2003) claims an electric fuel cell vehicle has a 22% tank-to-wheel efficiency for compressed hydrogen and 17% for liquid hydrogen battery powered and that electric cars are better.

3. Others suggest tank-to wheel efficiency of fuel cell vehicles is about 45% an about 36% when a driving cycle like the New European Driving Cycle – a comparative NEDC figure for a diesel car is 22%.

Concluding comments (cont.)

4. Honda have released the FCX Clarity which it is claimed gets 60% tank to wheel efficiency.

5. With figures close to 2 or 3 times the efficiency of an ICE vehicle, fuel costs for vehicle owners and the amount of storage required will fall by the same proportion.

6. Of course the case in Shetland compares hydrogen costs with vehicle fuel costs that have a substantial tax element.

7.The analysis shows that although substantial storage is required it is not unrealistic and the amount would reduce using FC vehicles and using less intermittent renewable generation.

Concluding comments (cont)

8. Hydrogen is unlikely to be a cost effective fuel for electricity generation apart from mobile operation, unless fuel cells and renewable electricity fall substantially in price.

9. In the case of space heating attention should be paid to energy efficiency followed by the use of ground or air source heat pumps and solar hot water panels before hydrogen should be considered as an option.

10. Shetland provides a useful case study and further work can be undertaken to consider how tidal power could play also play a role in switching to a local hydrogen economy.