

Article | Received 3 July 2023; Accepted 17 November 2023; Published 29 December 2023
<https://doi.org/10.55092/rse20240001>

Economic green hydrogen for UK refueling stations and buildings

Kevin Kendall

Research, HydrogenUnited.org, Birmingham, UK

E-mail: kevin.kendall@adelan.co.uk

Abstract: The UK seeks solutions to planning and implementing green hydrogen applications. Competition with Germany, Scandinavia and several Asian countries is concerning because only four UK vehicle refueling stations are operating at present, with several closing down in 2022. The key city is Birmingham together with its surrounding Midlands region which has traditionally been the source for UK vehicle manufacture and use. This paper first summarizes the problems found in the biggest UK hydrogen refueling station opened by ITM Power in 2021 at Tyseley near Birmingham airport. Then the ideal green hydrogen refueler design is proposed, together with heat and power for nearby buildings. Finally, experiments on a private site are described with calculations to test the design criteria proposed. The conclusion is that economic UK green hydrogen for vehicle stations and local buildings is possible in 2023, allowing private communities to compete with fossil-diesel fuel and natural gas while making profits along the supply chain.

Keywords: electrolysis; green hydrogen; compression; storage; refueling stations; hydrogen fuel cell electric vehicles; renewable electricity; wind turbines; solar farms; replacing natural gas and diesel

1. Introduction

There were about 800 hydrogen refueling stations worldwide in 2022 [1] and the numbers are growing fast with China leading the way as shown in Figure 1 with UK in fourteenth place, a factor of 62 behind.

The interesting thing about China's rapid growth is that there was only one station in 2015, a relic from the 2008 Beijing Olympic Games, but the Chinese 2016 plan for new energy vehicles [2] began their leading thrust in battery electric cars and hydrogen electric buses/trucks such that Sino-industries now dominate both battery and hydrogen vehicle types worldwide, though their hydrogen is not green. By contrast, the Japan and USA stations have grown slowly since 2005 when the first two Japanese installations were built. Also, the Los



Copyright©2023 by the authors. Published by ELSP. This work is licensed under Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium provided the original work is properly cited.

Angeles cluster started in 2005 and showed steady rise year on year after initiation in April 2004 to promote Californian hydrogen refueling stations, but not green at first.

The UK is different because the first green hydrogen station was installed by Kendall in 2008 [3] at University of Birmingham. The UK Government with industry predicted that there would be 65 by 2020 but failed. In fact, the numbers grew to 12 by 2020, but have since fallen back to 4 operational in 2023, behind small countries like Denmark, Norway and Switzerland. The original Birmingham University station has since closed due to high maintenance costs and lack of demand. There is no plan in the UK, because market forces are expected to apply, but capitalism has been retarded because market leaders BP and Shell have both rejected the move to green hydrogen vehicles, though Shell is building hydrogen stations in the USA. Shell closed UK stations in 2022 [4] because around £2M/a was being lost and the design was too small for future needs.

Also, the UK Government has no plan of action for British manufacturing of hydrogen vehicles nor refueling stations but suggests securing capital investment [5]. This vague situation is reinforced in the UK Infrastructure Commission annual report 2023 which does not mention hydrogen in the transport section [6].

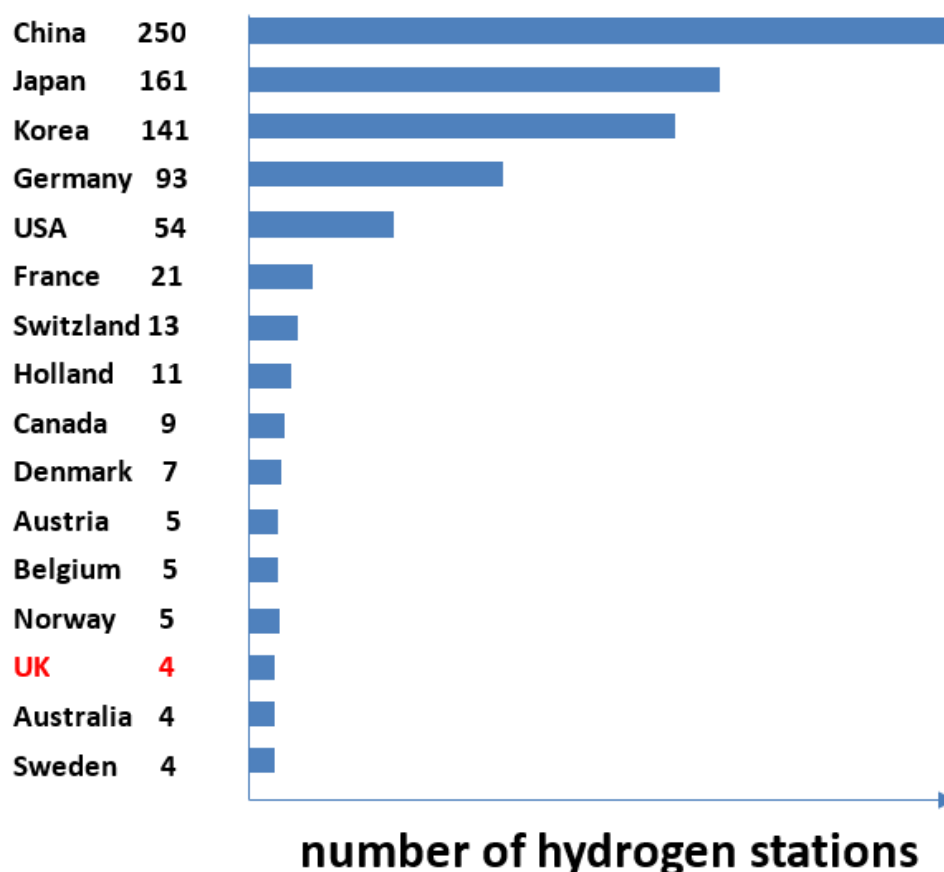


Figure 1. 2023 list of hydrogen refueling stations worldwide showing UK ranking [1].

The purpose of this paper is to explain such difficulties of hydrogen refueling stations in the UK, to propose a competitive economic hydrogen solution, then to test this model experimentally on a small private site, both for hydrogen refueling stations and surrounding buildings.

2. Problems

Three key difficulties may be illustrated by analyzing the construction of the largest UK hydrogen refueling station, a 3MW plant designed to deliver around 1000 kg each day, that was opened at Tyseley Energy Park, Birmingham in 2021 [7]. It was a European Union 5Meuro funded project that started in 2017 aiming to refuel 20 hydrogen buses with approximately 400 kg/day, a modest demand below profitability levels. This lack of demand was a prime issue, since the buses' delivery was delayed for 12 months, and few other hydrogen vehicles existed in Birmingham. Ideally, 1000 Mirai hydrogen cars should have been procured to ensure that daily demand was appropriate and economic. The Cordis definition of this Birmingham City Council JIVE project was published in 2022 [8] when the project was set to finish. A final report has not yet been made public.

Figure 2 shows the first hydrogen bus arriving in Birmingham and the Tyseley station refueling a Toyota Mirai. National Express bus company was contracted to run the 20 buses by demonstrating daily services but made the mistake of locating the hydrogen bus depot 19 miles from the Tyseley hydrogen station. Travelling two hours per day to refuel each bus was not ideal for the drivers, nor the economics of the project.



Figure 2. (a): Hydrogen Bus made by Wrightbus, run by National Express, arriving in Birmingham centre in July 2021; (b): Tyseley hydrogen station refueling a Toyota Mirai.

Only one city, Foshan in China, has managed to match the number of hydrogen stations to the vehicle demand. Foshan installed 10 hydrogen stations while building over 1000 hydrogen buses to utilise this supply in 2021. But China's present 250 stations (Figure 1) would require at least 25,000 hydrogen vehicles to fully utilize the supply, which is the aim by 2025, illustrating the difficulties of matching supply and demand across the whole country. In addition, China is the world's biggest manufacturer of hydrogen, but it is only 20% green. Germany has experienced a similar mismatch by installing almost 100 stations but finding only a few thousand hydrogen vehicles to use the hydrogen, again merely 30% green. Running these stations, the company H2 MOBILITY [9] has big industrial investors plus Government subsidies but loses money on sales of hydrogen.

A second problem in Birmingham was that maintenance difficulties emerged in 2022 and the Tyseley station was closed down for over 3 months. There was no back-up plan to

bring hydrogen in to refuel the buses and cars. Normally, tube trailers ship hydrogen in when a station breaks down. The company contracted to deliver the station, ITM Power (now Motive Fuels Ltd) refused to do this, leading to discontent among customers.

However, the most significant problem that has emerged was the decision to utilize National Grid electricity to power the 3 MW electrolyser. Although the station was located in Tyseley Energy Park where energy from waste and biomass was predicted to be plentiful, the station depends on Grid electricity. First, this electricity is not green, at best 50% renewable, so that the main benefit of running on zero emission hydrogen is missed; second, the price of grid electricity in the UK [10] is among the highest in Europe, with a large tax burden, shown in Figure 3. Bulgaria electricity is three times cheaper than the most expensive EU country and would be better placed to make economic green hydrogen by grid powered electrolysis.

The outcome was that ITM Power lost money on Tyseley hydrogen sold at £12/kg and consequently raised the price to £23/kg in 2023. ITM Power therefore set up a new company in 2022 named ITM Motive Ltd (branded as Motive Fuels [11]) to run their several hydrogen stations, bringing in Vitol Holdings as investor to build the business and supply green electricity. This economic problem coincided with the closing of hydrogen stations in the UK, dropping from 12 to 4 during 2023.

The Tyseley grid-based hydrogen was neither green nor competitive with fossil fuels. Germany, with a high subsidy for the H2 MOBILITY company running their stations, first set the price at 9.5 euro/kg, now risen to 12.85 euro/kg in 2022, and China near £6/kg (but not green). These hydrogen retail prices must be compared with the UK diesel pump price of £15 for 8 kg of diesel which gives similar combustion bus range to 1 kg of hydrogen in a fuel cell bus, demonstrating that UK grid-based hydrogen is higher priced than diesel in 2023. Interestingly, recent hydrogen retail price in Los Angeles has risen from about \$13/kg to \$36/kg which suggests that Californian grid power is also far too expensive to make green hydrogen economically.

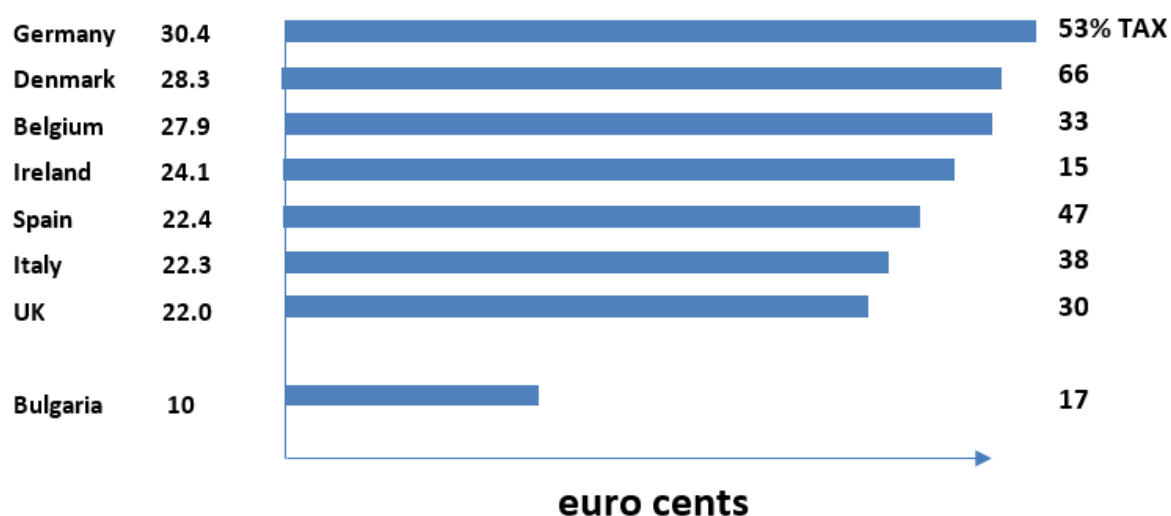


Figure 3. Electricity price comparison for the 29 countries of Europe.

3. Method: Ideal design of UK Green Hydrogen Refueling Station (UKGHRS)

Here we design the ideal UKGHRS on a private site, by considering all the factors mentioned above, allowing a timely estimate of the supply chain costs and the final profitable end-product pricing. The basic on-site design is shown in Figure 4, which starts with economic local renewable electricity, smart-powering an electrolyser which feeds green hydrogen at around 35 bar to a low-pressure (L pressure) storage tank to connect buildings. This is then compressed to between 350 bar and 700 bar filling the high-pressure (H pressure) store, which connects with dispensing to cars, buses and trailers that can ship hydrogen in and out.

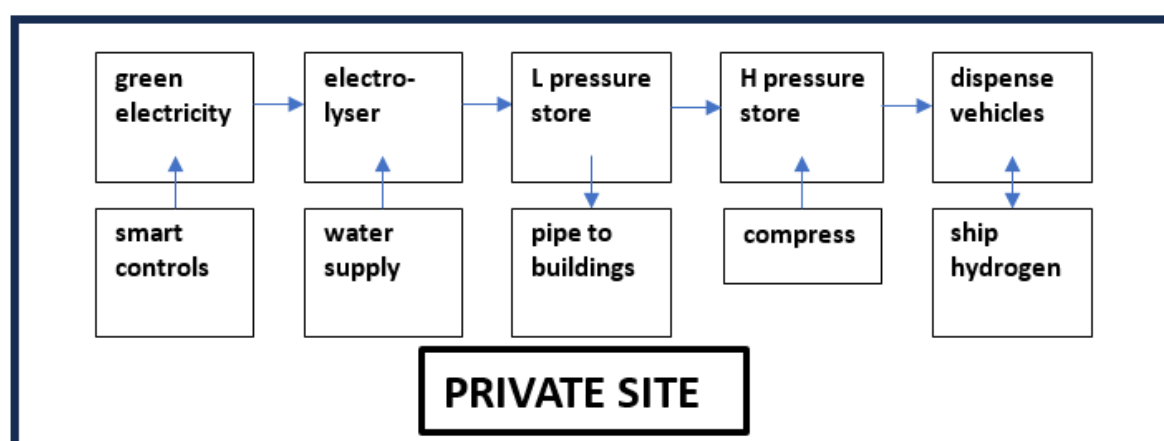


Figure 4. Scheme for ideal design of UKGHRS (UK Green Hydrogen Refueling Stations).

Scale is important to make profits. The first UK green hydrogen station in 2008 was only 10 kg/day, so was expensive. At £30/kg for green bio-hydrogen shipped-in, there was no chance of competing with fossil gas or diesel. The need now is upscaling to five hundred kilograms per day, using around 3 MW electrical power operating intermittently when economic renewable electricity supply is high, to bring costs down and satisfy an increasing number of hydrogen vehicles and community buildings. Future stations will grow bigger by 2050 and could reach 20 MW and more as millions of hydrogen vehicles together with thousands of hydrogen buildings spread around the UK by 2035.

A first model for such scale-up is the ITM station built in 2015 at the Rotherham headquarters of Motive Fuels Ltd, within the Advanced Manufacturing Park [12], shown in Figure 5b to contrast with the 2008 University of Birmingham plant utilising shipped bio-hydrogen (Figure 5a). The Rotherham site with a private wire grid was conveniently positioned next to the M1 motorway, but was small, having a 225 kW wind turbine and daily production to fill 220 kg of hydrogen storage at 350 bar with a compressor, upgraded to 700 bar in 2021. The green hydrogen output was only sufficient to fill about 20 vehicles per day. Expanding this by a factor of 15 to create the Tyseley station (Figure 5c) was completed in 2021 but unfortunately grid power was substituted for green electricity, thus reverting to expensive non-green fossil electricity. Motive Fuels has not revealed information on the different costs of hydrogen per kg comparing Rotherham and Tyseley, but there is little doubt

that changing to grid power has at least doubled the costs, since it is widely recognized that the main factor in green hydrogen manufacture is the price of the green electricity used.

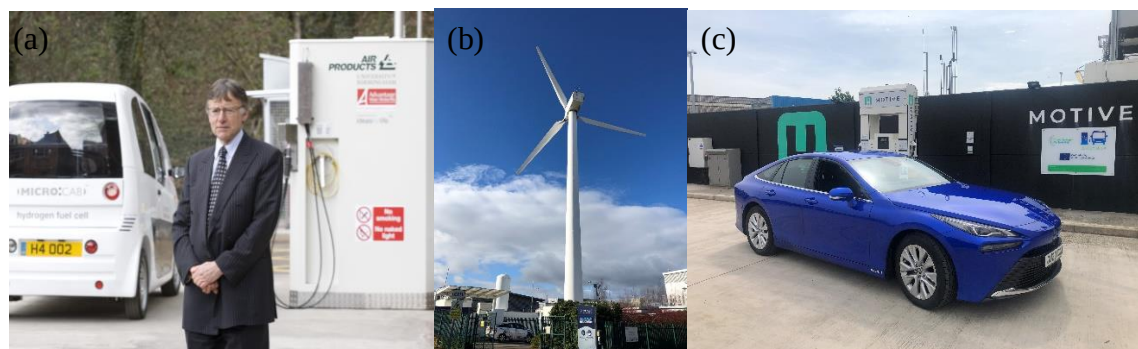


Figure 5. (a) The first UK green hydrogen station at University of Birmingham 2008; (b) 2015 Rotherham hydrogen station powered by on-site wind turbine; (c) Tyseley station 2023 is bigger but not green.

The experimental ITM installation at Rotherham was a 2015 breakthrough in showing that a private industry site could produce economic green hydrogen to fill dozens of vehicles. But the problem with wind-power is that it is low in summer and should be coupled with solar cells to boost the renewable energy from March to September. Solar power itself is only dominant in the summer months because UK is too far North to receive much solar input during November to February. The purpose of experiments on a small private site in the Midlands was to show that the combination of wind and solar electricity production, including battery storage to smooth the renewable power fluctuations, was sufficient to produce economic green hydrogen for refueling vehicles and powering buildings throughout the year. Although this production was small, around 50 kg/day, calculations could be scaled up to around half a ton per day and further to 2 ton/day to suggest that profitable operation of the supply chain would be possible. This would be sufficient to refuel a thousand heavy vehicles, such as buses, although produced only at peak renewable electricity generation, where the price of the renewable electricity is very low compared to that purchased from the grid.

4. Results: Keele University as a first UK example of economic green hydrogen

The critical approach is to match supply and demand on a private site in a fully connected green-electricity-hydrogen supply chain starting with renewable energy and ending with green-hydrogen vehicles fueled with a 3 MW electrolyser together with hydrogen powered buildings. At Keele University, it was possible to study this concept because of its unique Smart Energy Network Demonstrator (SEND [13]) project started at Keele in 2014 with EU regional funding, becoming operational in 2019. SEND was the largest such programme in Europe, allowing several important questions about sustainable energy to be answered by enabling the campus system operators to control how the generation from the renewable energy sources was self-consumed in the Keele distribution network, to sell excess generation to the grid at times of surplus and to optimize the energy use on campus by measuring the

grid carbon intensity [14]. Then in 2022, the HyDEX project [15] was started at Keele to push forward the hydrogen applications on campus, to be completed in 2024. This Keele energy park is 25 times bigger in green-energy scale than the Rotherham Advanced Manufacturing Park which installed a 0.225 MW wind turbine in 2009 to initiate a minigrid hydrogen system running in 2015 (Figure 5b). Such increase in scale should now allow the possibility of profitable green hydrogen to compete with diesel fuel and natural gas at today's prices.



Figure 6. The starting point for green hydrogen at Keele University: two wind turbines (1 MW each) a solar farm (4.4 MW) and battery (1 MWh) that can provide renewable power to manufacture green hydrogen economically.

Figure 6 shows the wind/solar green electricity equipment now at Keele [13,14]. In total, this is 6.4 MW, which is intermittent, so realistically delivers 3 MW on average. Buffering such fluctuations requires energy storage, supplied at Keele from a 1MWh battery that can bridge small fluctuations in green electricity production. In future, the energy storage needs to be much higher than 1 MWh when 6.4 MW is being generated at peak renewable input. One ton of hydrogen on site could store a day's renewable energy and could produce 40 MWh from fuel cell generators placed near buildings, ten times cheaper than a battery per kWh, and six times less weight when stored in composite cylinders. The missing links in the present supply chain are scaled-up green hydrogen storage and delivery. Now that Keele is installing and testing storage/delivery, it is possible to demonstrate and prove a fully-integrated-economic-green-hydrogen-supply-chain.

Our new approach encompasses several innovative ideas:

- A) Green energy must be generated by wind/solar with private wire to the hydrogen production.

- B) The National Grid is neither economic nor green and is relegated to a back-up role.
- C) Green Hydrogen should be stored near the production facility, with compressors nearby.
- D) Because the main high-pressure store is a tube trailer, excess green hydrogen may be shipped to partners, or shipped in during high demand periods.
- E) Local site demand for hydrogen vehicles and buildings is vital to match the green hydrogen production.
- F) Dedicated hydrogen pipes are needed to deliver pure hydrogen produced to both vehicles and buildings.

The postulates above allow the green hydrogen supply chain to be fully established on the private Keele site, ensuring that there is a profit margin at each step to allow sustainable rapid extension to other private UK communities.

5. Keele is now half green due to renewable wind/solar generation

The Keele renewable energy system was opened in 2022, costing £8.1M to provide up to 50% of the campus electricity demand which is near 7 MW on average. Thus, Keele is now a half-green site and could soon be upgraded towards 100% by doubling the wind/solar plant. It started with the SEND (Smart Energy Network Demonstration) project [14] with Equans installing the solar/wind farm and Siemens building the smart control system. Equans now runs the energy system on behalf of Keele University.

Figure 7 shows smoothed power results through a single day in September 2021 where the site electrical power demand was between 1 and 2 MW over the 24 hours, rising to a maximum about 2pm. The solar power fluctuated significantly between 9 am and 6 pm and peaked around 2pm, providing a total of 18 MWh, somewhat less than half the 40 MWh site daily demand. The problem was that the battery storage of 1 MWh was insufficient to shift the peak green electrical power to use later in the day. The surplus peak power was fed back into the grid at a low price, and should better be used to produce economic green hydrogen, as described below.

- From Figure 8, it is clear that the green power fluctuations are far too large to be handled by an electrolyser making hydrogen. The small 1MWh battery might smooth small fluctuations but the Grid is essential at present to fill the power gaps that occur naturally and frequently.
- The objective of this paper is to show that the surplus 4 MWh (equivalent to 80 kg/day of hydrogen) of renewable energy sold at a low price to the grid can be used in the HyDEX project [15] to produce economic green hydrogen for buildings and vehicles on site. Hydrogen production at Keele was first tested in the HyDEPLOY project [16] from 2021. The project experimentally produced 200kW of hydrogen (100 kg/day) by membrane electrolysis and blended 20 mol% of pure electrolytic hydrogen with natural gas to feed into the Keele gas grid, which worked satisfactorily. The cost of this hydrogen was not reported but a simple calculation indicates below

that it can be economic. Now the HyDEX project is continuing to make electrolytic green hydrogen with results emerging this year.

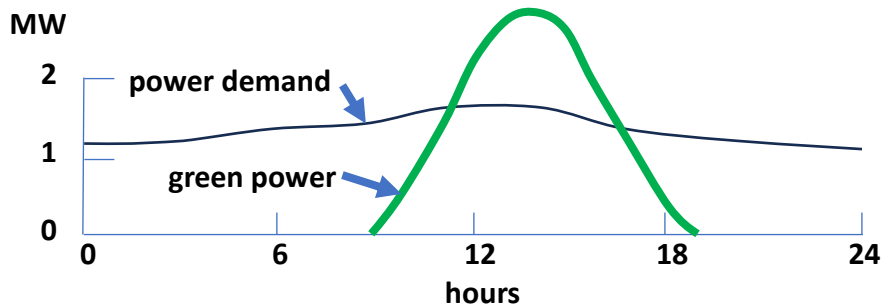


Figure 7. On-site power diagram showing the smoothed Keele demand between 1 and 2 MW on 27 September 2021 to compare with the smoothed green power from solar/wind.

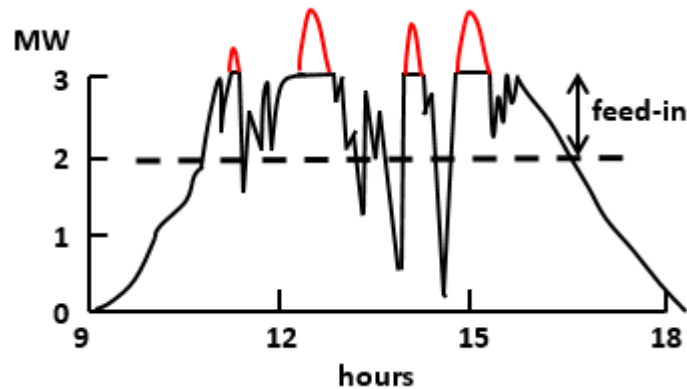


Figure 8. Green power produced on-site from 9am to 6pm on 27 September [14], with that above the dashed line fed back to the grid. The fluctuations were large and required the grid to supply power to fill the demand gaps. Above 1MW feed-in, grid acceptance was curtailed, shown in red.

6. Calculating the cost of present and future Keele electrolytic green hydrogen

The main financial benefit, gained by the Keele installation of 6.4 MW wind/solar renewable power, arises from the drop in Grid/utility company charges. A typical annual grid charge for 6 MW average at £100/MWh is £5.2M. Halving this by utilizing wind/solar renewable electricity saves £2.6M per year which pays back the £8.1M installation cost in 3 years approximately. Other costs, for example the Equans maintenance contract, also need to be accounted for.

The main difficulty to overcome is the fluctuating nature of the renewable power that displays large peaks and troughs (Figure 8), too big to be buffered by the relatively small 1 MWh battery installed on the site. This is where the green hydrogen production is beneficial because it can be operated intermittently for 6 hours per day to obtain green hydrogen from the peak power that is currently injected back into the grid at a low buy-back price of

£50/MWh on average. The financial benefit to the community of generating on-site green hydrogen could be estimated from Figure 8.

Figure 8 shows that a typical day gives 5 MWh feed-in which gains around £250 from the Grid buy-back. This gain is much lower than the value of 100 kg of green hydrogen made by electrolysis from the excess renewable electricity on site, then fed to company cars retailing at £10/kg paying £1000/day. Over a full year, the community could gain more than £300,000 by making green hydrogen for vehicles, instead of selling green electricity back to the National Grid monopoly. A further benefit would be manufacture of green hydrogen from curtailed renewable electricity at the peaks. At present, this is wasted green electricity which could also be used beneficially for hydrogen vehicles at zero cost. The main conclusion is that the grid is the most effective present system for balancing the electrical input to the electrolyser, a necessary stabilization because the renewable power is unsteady. Bigger batteries are unlikely to be cost effective in this role. However, the Grid does not pay a fair price for the excess renewable power unused on campus.

It is well-known that the cost of green hydrogen depends mainly on the price of green electricity. The Grid buy-back price of £50/MWh is the only measure we have for that value at present. From Figure 8 showing 9 hours of cheap solar power in September, renewable electricity should be available for 6 hours in winter to 12 hours in summer. Since the average peak renewable power remaining after satisfying the Keele demand is about 3 MW, an electrolyser of this power is needed. This is costed in Table 1 in the left-hand column. It will only operate for 8 hours average per day so should last for 45 years.

A low-pressure compressor and storage cylinder are needed to feed a new hydrogen pipeline leading to buildings on the Keele site.

To refuel vehicles, a high-pressure compressor and an 800 kg hydrogen tube trailer at 500 bar are required. This includes a dispenser for buses/trucks at 350 bar and for cars at 500 bar. Tube trailers should be available for 700 bar green hydrogen storage in the near future. Maintenance costs are included, but finance costs are not.

The right-hand column in Table 1 looks further ahead to the time when Keele goes 100% green. In this scenario, the main function of the grid is to balance the large fluctuations that stem from wind/solar generation, not easily solved by installing large batteries. This will require 14 MW of renewable energy onsite to reduce grid electricity towards zero, using more wind generation eg 8MW to spread the time range for 10 MW electrolyser operation. Scaling up reduces the cost of green hydrogen somewhat, but the main conclusion is that the green electricity price is still £50/MWh, allowing 2000 kg/day of green hydrogen to be produced at £5/kg, which competes with natural gas for buildings and gasoline/diesel for vehicles. However, such large quantities of hydrogen stored on site will require more safety regulation.

- The problem with green hydrogen costs and prices is that rapid changes are happening now. In addition, the units used to describe the amount of hydrogen are confusing. Both MWh or kg of hydrogen are used where \$1/kg is equivalent to \$30.25/MWh [17]. Here we use £ costs/prices per kg of green hydrogen because hydrogen is dispensed to vehicles in kg, with a target end price of £10/kg.

- The distribution cost of shipping and dispensing is also usually included but this is not significant at Keele because the vehicles and buildings are all on the Keele site. Hence, the approximate cost of hydrogen produced on campus at scaled-up quantities of 360 kg/day from grid electricity is £13/kg which cannot work because the end selling price must be lower than £10/kg to compete with fossil fuels like diesel. The figures in Table 1 show that scaled-up Keele green hydrogen made from wind/solar surplus power [18] is competitive with diesel pump prices and with natural gas. Hydrogen should be encouraged to fuel all vehicles and buildings on campus. It beats grid power by being almost 100% green depending on the carbon content of hardware, but also achieving a hydrogen cost near £5/kg, a factor 2.2 below national-grid-based-hydrogen, thus enabling supply chain companies to make profits [19].
- Interesting comparisons can be drawn from a recent analysis of offshore wind economics [20] that suggests £3/kg of green hydrogen is possible at large scale. More experimental results are needed to justify this low prediction. The important direction forward is described in a recent patent [21] that shows how existing large scale hydrogen production plants can be improved by existing green power technology insertion.

Table 1. Hydrogen costs from two green hydrogen plants, the 3 MW plant designed for the present 6.4 MW peak renewable site, compared to the 10 MW plant for the 100% renewable proposition in future. Finance costs are not included.

Costs	3 MW system		10 MW system	
	COST £	cost £/kgH	COST £	cost £/kgH
Electricity Keele surplus Grid Buy-price	1 MWh= £50	£2	1 MWh= £50	£2
Electrolyser (inc water)	£3M	£1.2	£8M	£1
Low pressure compressor	£0.1M	£0.04	£0.2M	£0.04
Low-pressure store	£0.3M	£0.12	£0.3M	£0.12
Compressor	£0.5M	£1.4	£1.2M	£1.2
High pressure store	£1M	£0.4	£2.5M	£0.3
Dispenser	included		included	
Operation/Maintenance	10%	£0.4	£0.3	£0.4
Total	£5.6/kg		£5/kg	

The two largest fossil CO₂ problems in the UK are caused by using fossil fuels to refuel vehicles and to power buildings. Therefore, the idea here is to test the green hydrogen generated on campus to feed into buildings at low pressure to produce fuel-cell combined heat and power replacing natural gas and grid electricity, while simultaneously refueling hydrogen vehicles at a campus high-pressure hydrogen station.

7. Conclusion

UK green hydrogen is attracting much interest but has not previously competed effectively with fossil fuels such as natural gas and diesel. In Birmingham, where the largest UK hydrogen refueling station was installed in 2021, several mistakes were made which produced hydrogen product that was neither competitive economically nor green.

But in 2023, Keele University has shown that profit can now be made by installing on campus 2 MW wind turbines, 4.4 MW solar panels and a 1 MWh battery, electrolysing water with a membrane device, and storing it in a low pressure store for feeding to buildings or to vehicle refueling plant comprising compressor/storage/dispensers at 500 bar. The Grid was vital in buffering the fluctuating green electricity generated from wind and solar, allowing the electrolyser to operate at steady voltage, but the Grid buying price was low, allowing excess wind/solar electricity to generate hydrogen production which was economic compared to grid powered electrolysis.

The scale of green hydrogen production is important to fit both the green-electricity production and the downstream demand for buildings and vehicles. Experimental testing was carried out at 0.2 MW scale that allowed calculations to predict a 3 MW hydrogen installation for a 50% green Keele, and ultimately a 10 MW electrolyser that could buffer the fluctuating wind/solar power with stored hydrogen for a 100% green campus. It should be noted that the UK government target for green hydrogen production by 2030 is 10 GW, supported by £1bn of funding, yet no profitable pathway has yet been suggested [19].

The main conclusion from this project is that the UK green hydrogen supply chain is now theoretically defined but requires further experimental proof, with profits to be made at each stage, as long as renewable electricity, priced at the Grid buying value, is used at peak production times on a large private wire community site, rather than being fed back into the Grid.

Acknowledgments

Thanks to Sharon George of Keele University for detailed discussions.

Conflicts of interests

The author declares no conflict of interest.

References

- [1] Number of hydrogen fueling stations for road vehicles worldwide as of 2022, by country. Available: <https://www.statista.com/statistics/1026719/number-of-hydrogen-fuel-stations-by-country> (accessed on 1 August 2023).
- [2] Ministry of Science and Technology (MOST). Accelerating the Development and Commercialization of Fuel Cell Vehicles in China; Ministry of Science and Technology (MOST): Beijing, China, 31 August 2016.
- [3] Kendall K, Pollet BG, Dhir A, Staffell I, Millington B, *et al.* Hydrogen fuel cell hybrid vehicles for Birmingham campus. *J. Power Sources* 2011, 196:325–330.
- [4] Collins, L. Two of London's three hydrogen filling stations will close this month due to insufficient demand. Available: <https://www.hydrogeninsight.com/transport/two-of->

- londons-three-hydrogen-filling-stations-will-close-this-month-due-to-insufficient-demand/2-1-1445060 (accessed on 1 August 2023). Wüst K. Security of blockchain technologies. Master's Thesis, ETH Zürich, 2016.
- [5] Fraser Nash Consultancy. Hydrogen transportation and storage infrastructure; Assessment of requirements up to 2035. Report for BEIS, London, December 2022. Available: <https://www.fnc.co.uk/discover-frazer-nash/news/frazer-nash-consultancy-provides-recommendations-for-hydrogen-transport-and-storage-infrastructure-to-assist-beis/> (accessed on 1 August 2023).
- [6] Armitt, J. Infrastructure Progress Review 2023. National Infrastructure Commission. Available: <https://nic.org.uk/studies-reports/infrastructure-progress-review-2023/> (accessed on 1 August 2023).
- [7] Tyseley Energy Park is committed to delivering low and zero carbon power, transport, heat, waste and recycling solutions for a greener, cleaner, healthier Birmingham. Available: <https://www.Tyseleyenergy.co.uk> (accessed on 1 August 2023).
- [8] Joint Initiative for hydrogen Vehicles across Europe. Available: <https://cordis.europa.eu/project/id/735582> (accessed on 1 August 2023).
- [9] Our H2 stations. Available: <https://h2-mobility.de> (accessed on 1 August 2023).
- [10] Strom Report: Infographics, charts, analyses. Electricity Prices Europe 2020. Available: www.strom-report.com (accessed on 1 August 2023).
- [11] ITM Motive. ITM Motive becomes a separate company group. Available: <https://motivefuels.com/news/itm-motive-becomes-a-separate-company-group> (accessed on 1 August 2023).
- [12] BBC News. England/ First hydrogen station opens. Available: http://news.bbc.co.uk/2/hi/uk_news/england/7353527.stm (accessed on 1 August 2023).
- [13] SEND. Keele University. Smart Energy Network Demonstrator. Available: <https://www.keele.ac.uk/society/keeledeals/newkeeledeal/priorities/smartenergynetworkdemonstratorsend/> (accessed on 1 August 2023).
- [14] Fan Z, Cao J, Jamal T, Fogwill C, Samende C, *et al.* The role of ‘living laboratories’ in accelerating the energy system decarbonization. *Energy Rep.* 2022, 8:11858–11864.
- [15] Keele leading programme to put the midlands at the forefront of hydrogen innovation. Available: <https://www.keele.ac.uk/about/news/2022/january/hydrogen-economy/hydex-midlands-industry.php> (accessed on 1 August 2023).
- [16] Hydeploy2 Project Report. Keele University, 2023. Available: https://hydeploy.co.uk/app/uploads/2023/03/22178_CADENT_HYDEPLOY_REPORT_JAN23_SPREADS-V3.pdf (accessed on 1 August 2023).
- [17] Martin P. World’s first green hydrogen price index launched—despite there being no trade in renewable H2. Available: <https://www.hydrogeninsight.com/production/world-s-first-green-hydrogen-price-index-launched-despite-there-being-no-trade-in-renewable-h2/2-1-1456231> (accessed on 1 August 2023).
- [18] Vartiainen E, Breyer C, Moser D, Román Medina E, Busto C, *et al.* True cost of solar hydrogen. *Solar RRL* 2022, 6(5):2100487.
- [19] Thomson P. UK Government Publishes Hydrogen Investment Roadmap. Available: <https://www.bakermckenzie.com/en/insight/publications/2022/04/uk-hydrogen-investment-roadmap> (accessed on 1 August 2023).
- [20] Bamisile O, Hatton L, Jansen M, Staffell I. Enabling the UK to become the Saudi Arabia of wind? Energy Futures Lab, Imperial College, London, 2023. Available: <https://www.imperial.ac.uk/energy-futures-lab/reports/briefing-papers/paper-12/> (accessed on 21 September 2023).
- [21] K. Kendall. Green Hydrogen Production, HydrogenUnited.org. Patent Application Number 2312934.9, 2023.