Mechanical Engineering Advances 2024, 2(1), 282.
https://doi.org/10.59400/mea.v2i1.282

Article

Low carbon integrated vehicles and buildings

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CITATION

Kendall K. Low carbon integrated vehicles and buildings. Mechanical Engineering Advances. 2024; 2(1): 282. doi: 10.59400/mea.v2i1.282

ARTICLE INFO

Received: 31 October 2023
Accepted: 3 January 2024
Available online: 30 January 2024

Abstract: This paper defines vehicles and buildings as main sources of United Kingdom (UK) carbon dioxide (CO_2) and seeks to cut such emissions using green hydrogen made from combined wind and solar energy. Combustion vehicles powered by fossil petroleum emit near half of UK climate-warming CO_2 while buildings heated by natural gas provide a third. First, current UK grid problems are defined: Electricity, gas and petroleum grids. Refueling green vehicles has been a particular problem. Then experiments on the private wire community of Keele University show how green hydrogen could integrate both green vehicles and buildings. Next, the model supply chain is planned and tested. Finally, experiments and calculations are outlined, analyzing the optimum system design criteria proposed. We conclude that economic green hydrogen can displace petroleum in vehicles, while powering buildings instead of natural gas. Also, the prospect in 2024 is that profits can be made all along the green hydrogen supply chain, such that new businesses involved in local private clean communities can cost less than the National Grid monopoly and other dominant fossil energy companies.

Keywords: wind turbines; solar energy; green hydrogen; green vehicles; green buildings

1. Introduction

The two largest problems for UK global warming are vehicles that combust petroleum-based fuels, and buildings that rely on natural gas for heating [1]. Together, these two sources of fossil CO_2 add up to three-quarters of UK climate change emissions. This paper explains how both problems could be solved by combining local wind power, solar electricity and hydrogen for energy storage [2].

Vehicle emission has been the worst issue because fossil CO_2 from transport has continued to rise whilst other polluters like industry and the electrical power network have cut fossil CO_2 over the last 30 years. Vehicle emissions rose as UK cars increased to 40.7 M vehicles in 2023, while doubling in weight that demanded twice the fuel since 1980. Buildings come second because there has been progress in new buildings, where energy standards have risen, with an EU prospect of mandatory solar panel installation from 2027 [3].

The advance [4] of solar renewable energy in UK homes reached almost 1.2 million in 2023 out of 26 million houses, giving around 4% penetration. Battery electric car penetration was near 2%, but only half green because the grid delivering the battery-charging is still dependent on natural gas until 2035 when off-shore wind should replace many gas and coal fired power stations.

The first part of this paper discusses difficulties for our grids trying to eliminate fossil-fuelled vehicles and buildings, then moves on to define several problems of green fuelling. Second: the combination of wind, solar and hydrogen energy in vehicles and buildings is invoked, using Keele University as the experimental area, the largest campus in Britain with 12,000 population needing about 7 MW of power on average throughout the year, mainly for buildings but also for recharging electric vehicles. Then, experiments making green hydrogen on-site are described, followed by estimates of scale-up costs and benefits as the present gas and electricity grids are transformed by local wind + solar [5]. Finally, the conclusion is that combining wind, solar and hydrogen can play a profitable part in cutting the Keele fossil CO_2 intensity as the campus moves from 40% now to 100% green in the future.

2. Grid energy issues

Three main grids supply energy around Britain: Electricity, natural gas and petroleum. Since privatisation of gas in 1986 and electricity in 1990, government policy has been to define several major energy sources where electricity is generated or fuels are imported, with regional distribution run by around 6 large gas/electric companies and 5 big liquid fuel companies [6]. Transport fuels and natural gas dominate but the National Grid company running UK electricity infrastructure supplies 21% of UK energy (**Table 1**) through cables and this has been viewed as the future technology that should overtake the others, but it is only the number 7 in the league table of UK energy companies at present. National Grid is monopolistic in owning the English high-voltage wires which other companies must use, so prices are among the highest in Europe. A key problem is that the present electricity grid has little storage so balancing supply and demand is a minute-by-minute process that differs from storing diesel liquid in tanks or natural gas in caverns. The diesel grid could consist of pipes, but it is easier and cheaper to ship liquid fuels by road tankers.

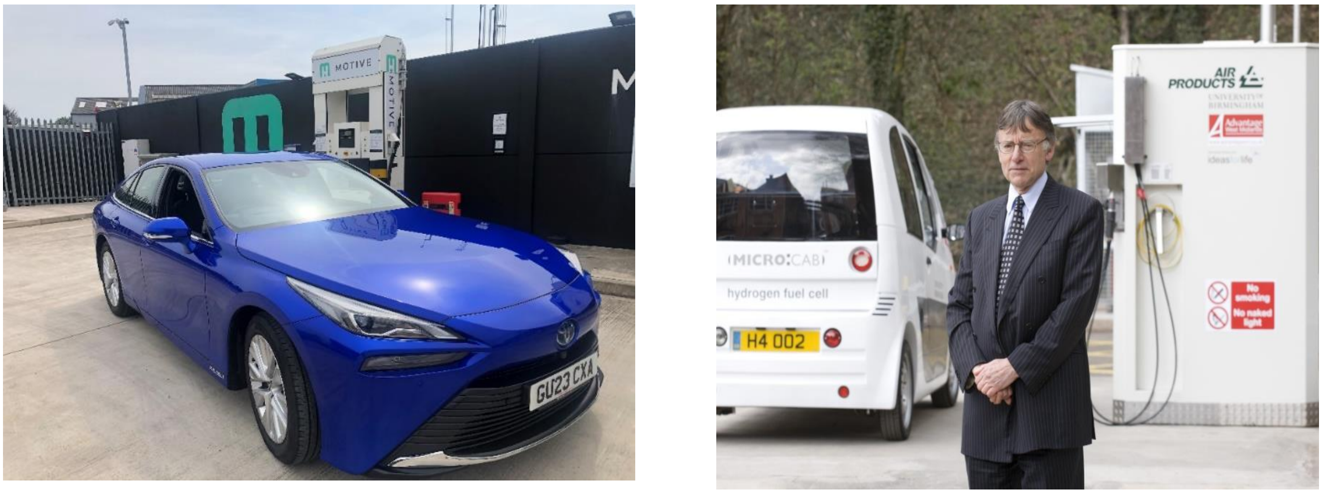
Table 1. UK energy split in 2021 [6].

Energy supplied	**TWh**	**Percentage**
Electricity grid	308	21%
Gas grid	485	34%
Petroleum	638	45%
Total	1431	100%

As things stand in 2023, there is little chance that National Grid can increase its energy deliveries by a factor of 5 to replace gas and petroleum with green electricity. In the first place, it has swopped the feed-in tariff to a ‘smart export guarantee’ in 2019, reducing payments to green electricity generators. The original Grid feed-in-tariff was more generous and made solar panels popular since 2010, based on the Millennium German law, requiring energy companies to accept power from homes with solar generators. Second, the National Grid has not provided sufficient electricity to charge electric vehicles effectively. Third, hundreds of green energy projects are stalled waiting for Grid permissions to connect. Finally, National Grid supplies most of its energy from 181 large power stations and has not embraced distributed energy, which includes both wind and solar power, today established as our cheapest energy sources [5].

Cadent is now modifying the gas grid to carry green hydrogen in its pipes, but it is still not clear what the quality will be, mainly because odorants must be added to detect leaks by smell. Several projects have put hydrogen into houses [7], but problems of gas leaks and flame speed remain. In thermodynamic terms, combusting hydrogen is both toxic and inefficient, and should be replaced by electrochemical Combined Heat and Power (CHP) based on hydrogen fuel cells. 100GW of green hydrogen production will be needed to replace petrol/natural gas throughout the UK and this will take decades to achieve.

Petroleum companies are finding it easier to address the green transition because they have been adding biofuels to their fossil liquids since 2010 and are now experimenting on hydrogen as a zero-emission fuel in buses and trucks. This was tested by shipping hydrogen tube trailers to petrol stations, changing the dispenser to suit the hydrogen vehicles. The cost of this shipping process is well understood throughout the UK's 8000 petroleum refuelling station infrastructure because various alternative fuels (e.g., diesel, LPG, biofuel, LNG) have been tried over the last 50 years. £500,000 is sufficient to get results on a green hydrogen refueler, whereas a permanent hydrogen station like the 2021 Tyseley (**Figure 1**) installation cost near £5M because it includes an electrolyser, large storage vessels and compressors to deliver both 700 bar and 350 bar pressurised gas. Moving to battery charging of electric vehicles across the refuelling station network is another major difficulty because high powered rapid chargers are needed, up to 100 kW DC, which require new electric power supplies, while the 80% charging time of 30 min for batteries is six times slower than hydrogen filling, meaning that many more electric charging units are required than hydrogen dispensers.



(a) **(b)**

Figure 1. (a) Tyseley hydrogen station refuelling a Toyota Mirai; **(b)** First UK green hydrogen refueler opened in 2008 in the University of Birmingham by the author.

The conclusion is that the existing grids cannot easily change, so it is now vital to consider distributed energy across the UK in the form of thousands of private wires combined with solar/wind electrical communities with big hydrogen storage for use in vehicles and buildings. Changing vehicles from combustion to hydrogen fuel cell battery electric vehicles (HFCBEVs) is the simplest first move because vehicle fuels are shipped and can be flexible, so hydrogen merely adds to petrol, diesel, biofuel, propane, LNG, etc on 8000 existing UK sites that can gradually go green, avoiding the present electric vehicle refuelling problems.

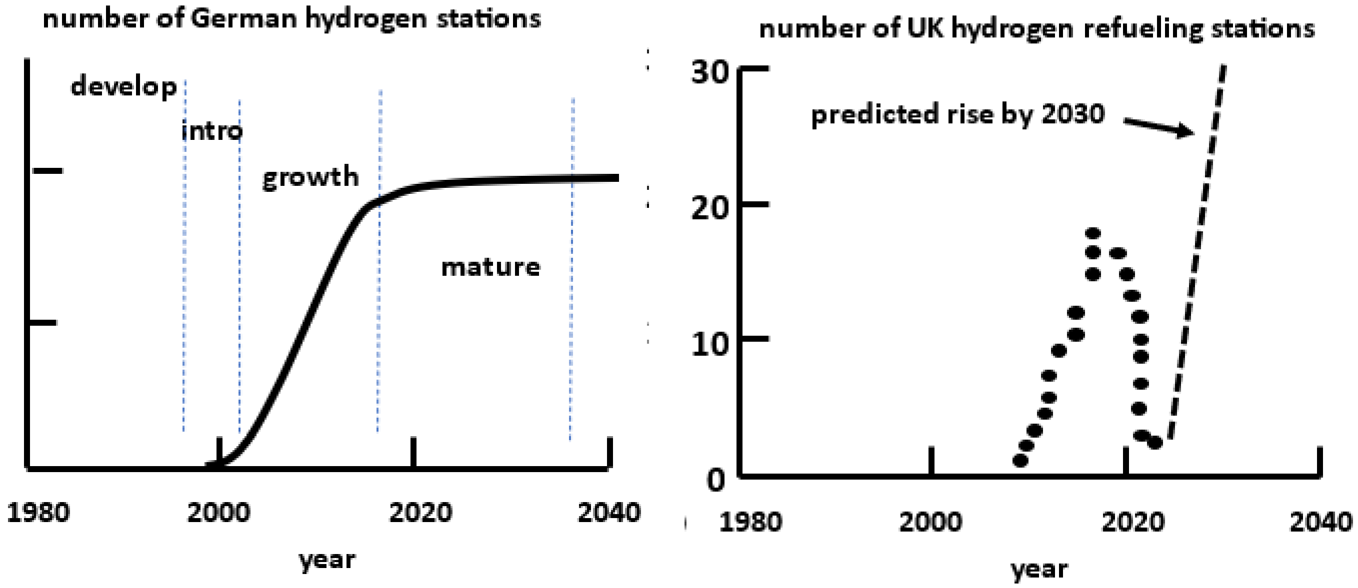
3. Problems of green refuelling

The standard product lifetime description [8] of development, introduction, growth, and maturity is illustrated in **Figure 2(a)** which shows how the number of German hydrogen refuelling stations increased from the first in 1999 to 92 in 2023. The first phase is the development, followed by introduction, then growth, stabilising at maturity which probably is premature because many more stations are planned in the future. Other regions like China, Japan, and Los Angeles have followed this trend, with installations proceeding steadily over time. In 2005, Los Angeles started its project on hydrogen cars and refuellers along with Japan which was manufacturing hydrogen cars at an increasing rate. China introduced its first two stations in 2008, but it took a decade before the growth phase started, rising steadily to 250 units in 2022, with hydrogen bus, truck and car manufacture beginning seriously in 2017.

In **Figure 2(a)**, the first phases of German growth and introduction were long, with experimentation from 1995 but seriously starting in 1999 at the opening of the first hydrogen station at Munich airport. The third phase, growth, started in Germany with the European Union projects on hydrogen buses in 2003, where the largest cities installed hydrogen stations, but not green. Then the third mature phase began around 2020 when there was an infrastructure across the country but insufficient demand from buses, trucks and cars which had to be introduced incrementally to make the whole hydrogen transport system economic. Subsidies were used to support the losses during this time, but eventually it is expected that the stations will grow naturally as profits become apparent.

Figure 2(b) shows that the UK experience was different. The first UK green hydrogen refuelling station was installed by the author at University of Birmingham in 2008 (**Figure 1**) and the enthusiasm for more stations around Britain then started, with Loughborough University following in 2009 and further plants built during the next decade as shown in **Figure 2(b)**. Then in 2018, the installation of UK hydrogen stations stopped, falling to four in 2023 as refuellers were closed, shown by results of **Figure 2(b)**, which compares the German results (**Figure 2(a)**) with the UK picture. Shell/ITM closed three of their hydrogen stations in 2022–2023.

Britain was behind but showed rapid growth (**Figure 2(b)**) until 2015 when the Aberdeen station opened and 2018 when Shell and ITM completed three hydrogen refuellers at motorway services near Gatwick, Cobham and Beaconsfield. Although the Government and UK industry had predicted 65 by 2020, small loss-making stations started to close, for example the Coventry and Birmingham University units which were too small and had low demand. The final blow came in 2022 when Shell closed their stations in England, leaving just Aberdeen, Rotherham, Birmingham and Heathrow operating. The strange shape of this curve may be explained by a product sales dip when early consumers realise that snags arise over the first years, followed by correction and optimisation that produce steady growth later.



(a) **(b)**

Figure 2. (a): Diagram showing how the German introduction of hydrogen stations followed the standard model for product sales [8]; **(b)**: Results in the UK showed a different picture where the early stations closed because of economic losses through failure to match supply and demand, followed by a predicted surge as profit is demonstrated in 2023.

The interesting differentiation of UK from Germany and China is that large hydrogen subsidies were not deployed in Britain so the premature acceleration to hundreds of refuelling stations seen overseas was killed by £M financial losses of companies like Motive Fuels and Shell. A similar closing of hydrogen stations happened at Everfuel in Denmark because losses were high due to low demand from hydrogen vehicles. However, in 2023 it was demonstrated in UK [9] that profits could be made along the green hydrogen supply chain, allowing capitalist forces to grow the market further as predicted by the dashed line predicting rapid growth of UK hydrogen stations after 2025 in **Figure 2(b)**.

Problems that caused the financial issues were readily identified [9]. First was the lack of demand for hydrogen vehicles, whose UK numbers rose very slowly at first because all hydrogen vehicles were imported and consumers did not buy them. Second, battery electric vehicles were strongly supported by the government with substantial subsidies, distracting hydrogen vehicle enthusiasts, who received no incentives. The third and most important issue was that the largest hydrogen refuelling installations were powered by grid electricity, which was neither green nor economic, costing twice the desired price-point of £10/kg that could compete with petroleum fuels.

The main loss-making decision was to manufacture hydrogen by electrolysis of water using grid electricity. Whereas the first station in Birmingham (**Figure 1(b)**) had used green biohydrogen and the 2015 ITM station in Rotherham had used wind-power green electricity, other units depended on the Grid which is not green and generally too expensive with prices ranging from £100/MWh to above £160/MWh which leads to a retail price in Birmingham of £23/kg, far too high to compete with diesel at current prices. The fact is that electricity price for powering electrolysis is the main factor raising green hydrogen costs. £10/kWh is required at the retail point, so the price at the hydrogen manufacturer must be much less, around £5/kg or lower [9]. £10/kg is near the German retail price, which is subsidised [10]. California also appears to have a grid problem since 2023 retail hydrogen price rocketed to $36/kg from the original $13/kg. This makes grid sourced hydrogen non-competitive with fossil fuelled transport.

4. Combining wind and solar with hydrogen in vehicles and buildings

The profitable supply chain model described here was evaluated first in 2022 [9], using Keele University community of 12,000 people as an example of a private wire integrated renewable energy system using green hydrogen as energy storage material. At present, the system is running according to the model supply chain illustrated in **Figure 3** [11].

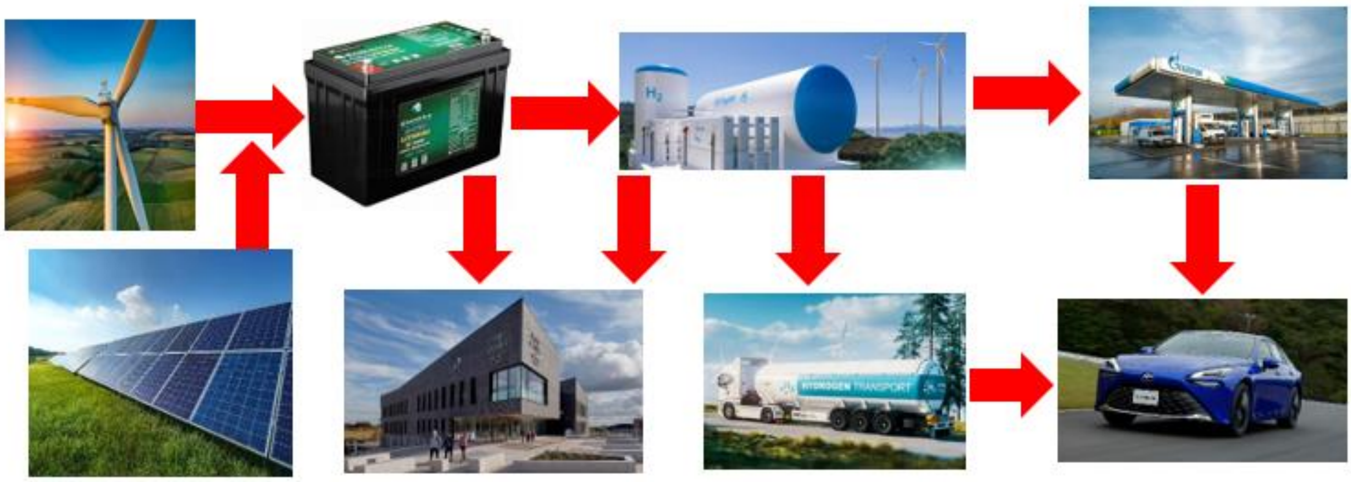


Figure 3. Diagram of the supply chain for a green private wire community starting on left with solar/wind charging a battery that feeds buildings and powers an electrolyser /hydrogen store leading to hydrogen for shipping plus vehicle refuelling and buildings energy.

The wind is combined with solar electricity on the left of **Figure 3** to feed a battery that can bridge short-term fluctuations (minutes) while feeding buildings to replace the usual grid power. Surplus electricity is produced at peak wind/solar operation, feeding a water electrolyser with low pressure storage that powers buildings with CHP (combined heat and power by fuel cell) when renewable electricity is low. The hydrogen is compressed to 500 bar to feed tube trailer storage on the right of Fig3 which can bridge a day of low renewables, and which can also ship and dispense hydrogen. 500 bar hydrogen runs the hydrogen refueller for trucks and buses, while 700 bar compression is needed for cars and vans.

Keele may be viewed as a village community of 12,000 souls requiring 7 MW on average, whereas a larger private site may rise to 30,000 people, a town requiring about 20 MW for homes. In 2022, the Keele Smart Energy Network Demonstration (SEND project) was opened to cut grid electricity input to Keele by half, saving approximately £2 M per annum, at a capital investment of £8.1 M for design/build by Siemens and run by Equans [12]. Experimental quantities around 0.2 MW of green hydrogen were also produced but insufficient to make Keele campus fully green, which would require 5 MW of electrolyser capacity to absorb peak renewable electricity production, producing 2 tons per day of hydrogen to be stored for bridging a day of low wind/solar generation.

Early results shown smoothed in **Figure 4** reveal that a typical low-power autumn Keele day provides excess power from solar around noon for several hours, with 2 MWh of energy fed back into the National Grid. This was a day where wind was near zero, so solar input dominated. The National Grid buying price was low, about £50/MWh which is normal in the UK because the Grid is a monopoly that commands low prices for spare electricity. To avoid this, the excess Keele green power could be fed experimentally to the water electrolyser manufacturing green hydrogen for storage as shown in **Figure 3**, electrolysing water to make green hydrogen for application in buildings and vehicle refueling. To go fully green, the renewable energy input would need to be 12 MW_{peak} such that 40 MWh of hydrogen could be stored to avoid using the Grid as a reservoir. Better yet would be a heat storage tank underground to make use of renewable electricity generation not accepted by the electrolyser. Because green hydrogen should retail at £10/kg when refueling cars, it was estimated that the average surplus 10 MWh/day grid-fed at £50/MWh (i.e., £500) would generate £700,000/a from retail hydrogen at £10/kg, four times more than Grid receipts for feed-in of spare Keele electricity generated.

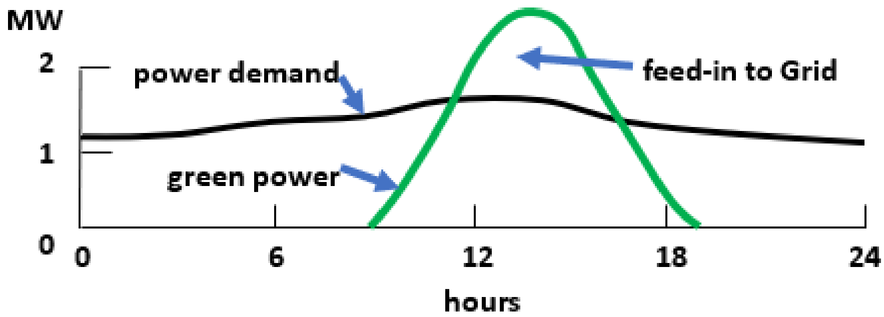


Figure 4. Smoothed Keele results [9] for 24 h on 27 September 2022 showing surplus green electricity fed-in to Grid when it could alternatively produce green hydrogen.

5. Moving to 100% green using hydrogen storage

Right now, Keele private wire community of 12,000 people is half-green and is paying back the original £8.1 M investment in about 4 years, owing to the approximate £2 M/a saved from utility bills. The prediction is that another £2 M/a will be saved by installing 6 more MW of renewable electricity, with a predicted similar payback time. However, investment cost must rise because more green hydrogen needs to be produced by electrolysis to give energy storage supplying days of stored energy which can drive campus buildings through CHP driven by fuel cells when wind and solar inputs are low. Going from the 3 MW electrolyser needed now to 10 MW in 2025 will utilise most of the excess renewable electricity, more than absorbed by buildings and vehicles, producing stored hydrogen gas in bigger low-pressure containers. Typically, the electrolyser can then be run for about 12 h per day when sun and wind are good, manufacturing 2000 kg/day of green hydrogen worth £20000/day at retail (£3.6 M/a). The extra equipment requiring investment includes the electrolyser, storage, hydrogen pipes and fuel cells in buildings. Further excess electricity production can be stored in a hot water tank for heating buildings.

The key point about the Keele proposed plant is that it uses only renewable electricity that would have returned to the grid at £0.05/kWh and so can produce green hydrogen at a low electricity cost of £2/kg, contrasting with £8/kg for Grid electricity at Tyseley station (**Figure 1(a)**) [9]. This high Grid electricity price dominates hydrogen cost, with the other costs mainly for electrolyser, compressors and storage tanks. The conclusion is that green hydrogen can be produced at Keele community site at a cost near £5/kg whereas the existing Tyseley refueller (**Figure 1**) makes un-green hydrogen costing about £12/kg, leading to £23/kg price for consumers at retail.

6. Comparing green vehicle and buildings model with the UK government plan

If the Keele community project can be completed to approach 100% green, with hydrogen used as the major energy storage medium on-site, and an attractive pay-back time of about 4 years, then it is timely to consider the benefits of multiplying this technology across the UK.

Recent analyses of the existing Government plan to supply UK electricity from extensive offshore wind farms [13] suggest that the green energy for 2035 is planned to be transmitted along the National Grid to all citizens, or converted to hydrogen that can be piped across the country. This sounds fine but there are substantial difficulties that must be considered: First, the chemical industry already makes by-product hydrogen using grid electricity which needs to go green at low cost [14]; Second, there are only about 100 km of UK hydrogen pipelines at present, but it is believed that 2000 km of the natural gas pipes could be repurposed to convey hydrogen instead [15]; Third, the National Grid pylon network would need to expand by a factor 5 to carry all the electricity required to power transport, buildings and industries that currently use petroleum or gas. This erection of 80,000 unsightly new overhead cable structures could create a public backlash like that occurring in the 1940s when the original National Grid was established [16]. Both hydrogen pipes and electric cables are under consideration, but a key alternative is combined onshore wind turbines and solar farms banned by David Cameron in 2015 because he disliked their appearance. The dilemma this decade is choosing between pylons and turbines, which are discussed now.

7. Doubling onshore wind turbines or quadrupling pylons

The UK government effectively stopped wind turbines onshore in 2015. If a single person complained about a wind turbine, the installation could be halted, and planning consent deleted. Yet, the government now plans to double the number of National Grid pylons soon and is going ahead in 2023 [17]. There will probably be a negative reaction to this from the public, many of whom are concerned about living near transmission lines [18]. Keele University installed its 2 MW of wind turbines by reducing their height, hiding them behind trees and responding to answer all complainants. They also installed the solar farm shown in **Figure 5** without serious questions from the public.

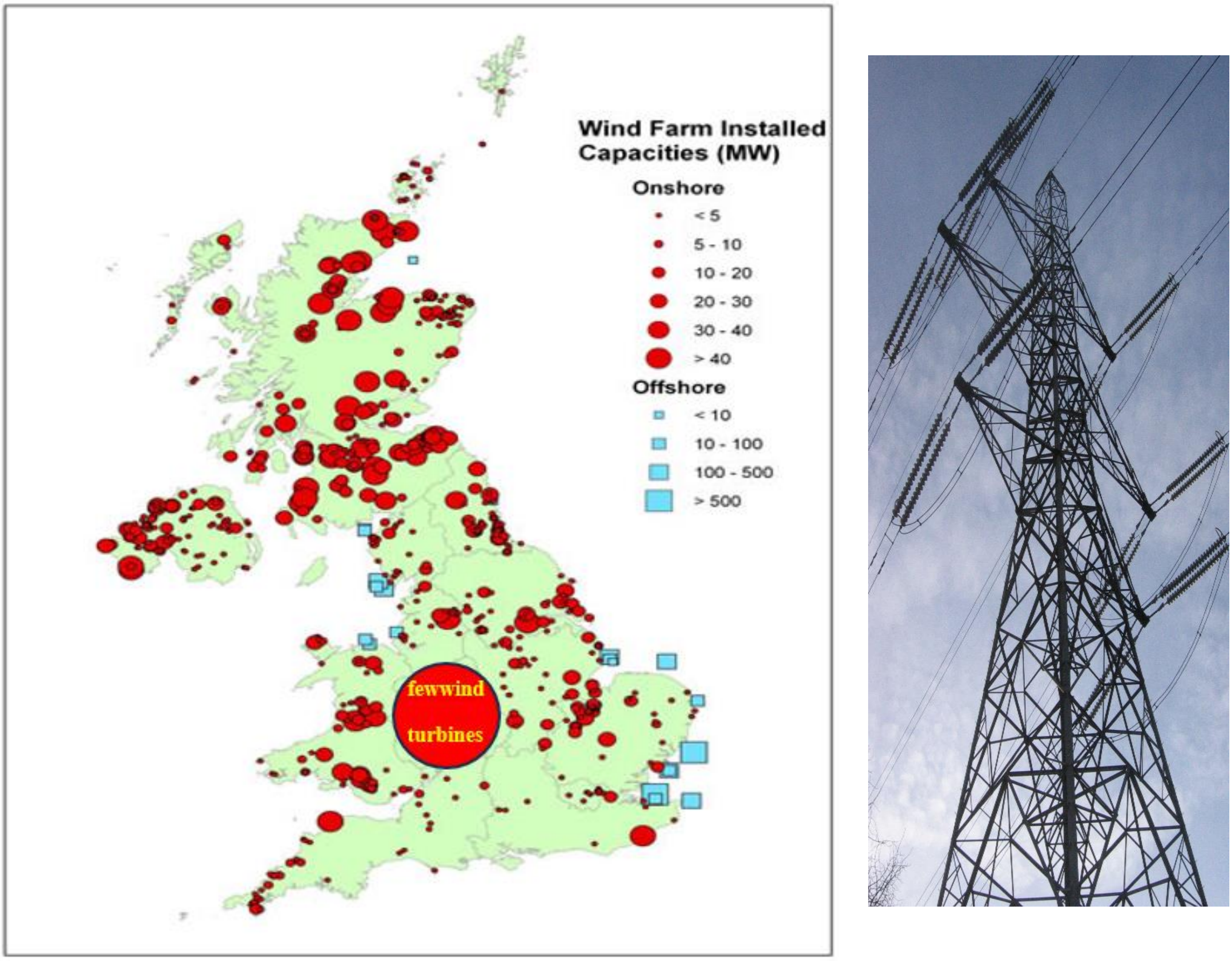
Figure 5. The Keele renewable generator equipment shows the two small wind turbines generating 2 MW, plus the solar panel array contributing 4.4 MW.

Pylons in the UK number around 22,000, far more than the 10,000 onshore wind turbines approved before the 2015 ban. Yet, the British government has produced a model of the UK running completely on grid electricity and therefore is beginning to erect between 2 and 5 times more pylons because the grid must replace both natural gas and petroleum to achieve net zero by 2050. The plausible outcome of this policy is that 80,000 pylons might be required, to be detested by many citizens (**Figure 6)**

Instead of considering a logical scheme for distributed power based on local energy sources like solar and wind within every community, the utility companies are planning to continue the 20th-century concept of hundreds of remote power plants feeding the national wire grid, rather than millions of renewable generators on all buildings, University sites, industry parks, retail areas, etc. [19].

In this paper, we suggest that hydrogen vehicles will be distributed across the UK, leading to a requirement for thousands of distributed green hydrogen refueling stations on private wire sites, each containing a 5 MW wind turbine and 5 MW of solar panels, modelled on the Keele experiment. 10,000 such filling stations would produce green hydrogen for communities, buildings and vehicles, totalling 100 GW_{peak} of new clean peak power to replace fossil gas and petroleum. For large quantities of locally stored hydrogen, above 1 ton, regulations will need to be applied [20], depending on the analysis of future green hydrogen demand [21].

The map of **Figure 6** shows the UK Midlands problem, that almost no wind turbines exist in the Birmingham region, whereas Scotland and coastal areas have close access to green wind generated hydrogen, which should accelerate green-hydrogen-transportation in those areas. The final tally of onshore wind turbines required to solve the UK green transport problem should reach 20,000 by 2035, still less than the existing 22,000 pylons, and far neater than the 80,000 new pylons predicted by the government eventually. Several solutions have been proposed to overcome this grid problem for charging millions of electric vehicles, but none have yet been demonstrated [22]. However, the future possibilities for green hydrogen have been discussed widely [10,11,21,23].



(a) **(b)**

Figure 6. (a) Map of onshore and offshore wind turbines across the UK showing the lack of wind power in the West Midlands [19]; **(b)** a typical Grid pylon in UK.

8. Conclusions

The existing UK electrical and hydrogen pipeline grids cannot develop fast enough to replace fossil energy by 2030. Therefore, it is essential now to consider distributed renewable electricity storing energy in hydrogen gas, because wind and solar are naturally spread thin on energy content while being the lowest cost generator installations. In such a distributed energy system, green hydrogen is the ideal storage molecule that allows fluctuating renewables, wind, and solar, to be stored successfully and economically, powering vehicles and buildings, our main fossil carbon problem sectors.

The Keele private wire local community model has demonstrated that combined wind and solar energy can power the campus, potentially using green hydrogen as the main storage medium, producing a new standard for energy prices, replacing the current UK grid support, which has prices among the highest in Europe, too high to manufacture competitive green hydrogen. Such local new private grids, wind-solar-electric combined with hydrogen storage, could power all UK vehicles and buildings without major increases in the grid pylon numbers.

If this Energy Community at Keele turns out to be an optimum dimension near 10 MW of wind/solar capacity, driving catalytic water electrolysers on peak renewable power, then it could be reproduced across the UK 10,000 times to power distributed vehicles and buildings giving 100 GW_{peak} of new UK power generation, with an estimated cost of £100 bn and payback time of around 4 years.

Funding: This research was funded by HydrogenUnited.org, a UK charity based in Birmingham, England.

Acknowledgments: Thanks are due to Dr Sharon George at Keele University for discussing this project with the author and explaining the Keele model.

Conflict of interest: The author declares no conflict of interest.

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