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Energy storage

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Aim: The aim of this paper is to explore Energy Storage requirements and options to suit the needs of systems and transport fed from renewables. The variability of wind and solar sources in particular and the demand for transport energy are seen as key issues.

Design / Research methods: The paper outlines the need for energy storage and compares the energy density and power density of a selection of storage options.

Conclusions / findings: The results illustrate the difficulties of finding storage mechanisms to rival fossil fuels in both energy density and power density. Moreover finding the natural resources to provide sufficient storage will be a serious challenge even though the economic costs of storage systems are falling..
Originality / value of the article: The article demonstrates the importance of energy storage to the successful development of renewable energy systems, and of the economic and physical characteristics that such energy storage schemes should have.

Implications of the research: Energy storage as a topic should be given a high priority for research and development.

Limitations of the research: This article is not comprehensive and a review of best practice internationally would be a valuable extension to this work.

Key words: *: Renewable energy, Energy Storage, Climate Change.*

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1. Introduction

The transition from fossil fuels to renewables will require considerable investment in energy storage to deal with the intermittent nature of many of the renewable energy sources, and to ensure energy security. In this paper the importance of storage and the range of storage options is explored. Although the cost of storage is falling, limitations in storage solutions are shown to be extremely important, making it urgent to find much more energy storage.

Fossil fuels (coal, oil and gas) were essential to the growth of economies from the dawn of the industrial revolution to the end of the 20th century. Their high energy density, typically 10 000 Wh/kg (see Figure 2 for the data, see also Houghton 2009) means that they can readily be transported across large distances without using too much of the energy that they contain. For example a heavy goods vehicle (lorry or truck) could transport 30 000 kg of oil with emissions of CO_2 from burning diesel. The same journey to transport wood chips would consume the same quantity of diesel and emit the same amount of CO_2 but would only deliver about half the energy. This is due to the lower energy content or energy density of wood compared to oil and helps to explain the vital part that fossil fuels have played in the development of economies.

A typical car running on diesel has a large range of 750 km because the energy density of the 50 kg of diesel in the fuel tank is 12 900 Wh/kg. (see Figure 2 for data on energy densities, the fuel economy is based on UK Government data, 2022). If we replace the fuel tank with lead acid batteries, of the type found in all conventional internal combustion cars, then we would require 16 tonnes of batteries. This is clearly impossible in a car which only has a mass of 2 tonnes. The range of such an electric car would be restricted by the amount of batteries and the energy storage density of those batteries (around 40 Wh/kg). Of course the present generation of electric vehicles use advanced Li-ion batteries with greater energy storage density of around 160 Wh/kg and we will return to this later.

The attraction of fossil fuels is their energy density and ease of transport and storage. The geographical locations where substantial fossil fuels are found have prospered or have been subjugated by large companies or colonial powers. The control of fossil fuel supplies is very much a geopolitical issue (see Yergin 1991, 2021; Marshal 2015). That control is in a few hands and, as the current Ukrainian invasion shows, the impact of restricting flow of resources can be immense. Russia controls a significant fraction (around 40%) of the gas supply to Europe which will create severe difficulties for many European states particularly as the 2022/3 winter approaches and gas for heating is limited and/or expensive. See for example Reuters Business (2022).

There are two technical problems that arise from our exploitation of fossil fuels. The first is that of global resource: The BP annual review (2021) reports the ratio of resource to production for oil and gas at around 50 years. Each year these ratios remain at about the same level because as consumption reduces the resource so exploration, in ever more inaccessible remote locations such as deep water oceans, identifies more resource. Geologists recognize that there will be an ultimate resource limit: i.e. that total amount which was produced in geological time. It is fair to say that fossil fuel resources can only last a few decades and certainly not sustain our grandchildren.

Geopolitical tensions over the world's fossil fuel resources are already in play and perhaps they always were (Yergin 1991, 2021). The Arctic is one area where Russia, US, Canada, Denmark, Iceland and Norway are claiming territory. China has interests all over the World, including Greenland where climate change is reducing ice cover and revealing precious mineral resources. There is an internationally agreed embargo on exploitation of the Antarctic, but the strength of the agreement is as yet untested.

The second technical problem with fossil fuels is that burning them enhances the greenhouse effect and leads to climate change. This has been understood for some years and had drawn commitments from many countries at many conferences to restrict greenhouse gas emissions (principally from burning fossil fuels). Unfortunately none of these commitments has ever been fully met, and we are now in a climate emergency: probably posing the greatest ever risk to humanity. The November 2022 meeting of COP27 in Egypt must promote rapid progress needed to reach "zero carbon" to avoid transiting the tipping point of a global temperature rise of 1.5 or 2 ºC above pre-industrial levels.

2. Renewables and their storage

2.1. Solar energy

To replace fossil fuels, renewable energy in various forms has been investigated and a number of these have been taken through to deployment. Renewables are so called because they are “renewed” usually daily from the Sun. Solar energy can be converted to thermal energy, or to electricity or through photosynthesis to biomass. Tunisia, for example is deploying large areas of photovoltaic (PV) collectors (IRENA 2022). A proposed scheme to deploy vast arrays of PV collectors across North Africa to feed electricity into Europe was thwarted by the Arab Spring of 2010 which created nervousness in investors.

Solar panels produce direct current (dc) electricity which can be stored in batteries to meet demand on cloudy days or through the night. Integrating PV into a grid entails passing the dc electricity through an inverter to produce alternating current (ac) electricity. This ac electricity cannot be stored and so the PV owner must export surplus/import deficit from the grid.

Solar thermal collectors produce hot water which can easily be stored in a large drum at a domestic level as is common in Mediterranean countries. Hot water can be stored for a day or two, however storing enough energy during the summer to give winter space heating would require a much larger capacity container capable of storing heat efficiently over several months. The likely winter demand is almost certain to be several months behind the solar peak.

Some recent reports (Polar Night Heating 2022) of using sand rather than water as the storage medium are encouraging. Sand has a higher thermal capacity than water when heated to over 500 ºC, whereas water can only be heated to around 80 ºC .

2.2. Wind energy

Wind is created by weather patterns on the Earth, and is thus a result of solar insolation. Modern wind turbines produce electricity at competitive rates, and in many cases at lower cost than all other forms of energy (Lazard 2022). Many countries already have large wind farms feeding into their grids, and together with hydro and PV, renewables contributed 13% of total power generation (BP 2022; the report does not show resource to production rations, see previous years report), with China making up 36% and 40% respectively of world PV and wind. Oersted is developing the world's largest wind project, Hornsea Two in the North Sea with a capacity of 1.3 GW, from the deployment of 165 8 MW turbines. The next phase, Hornsea Three, will be rated at 2.8 GW.

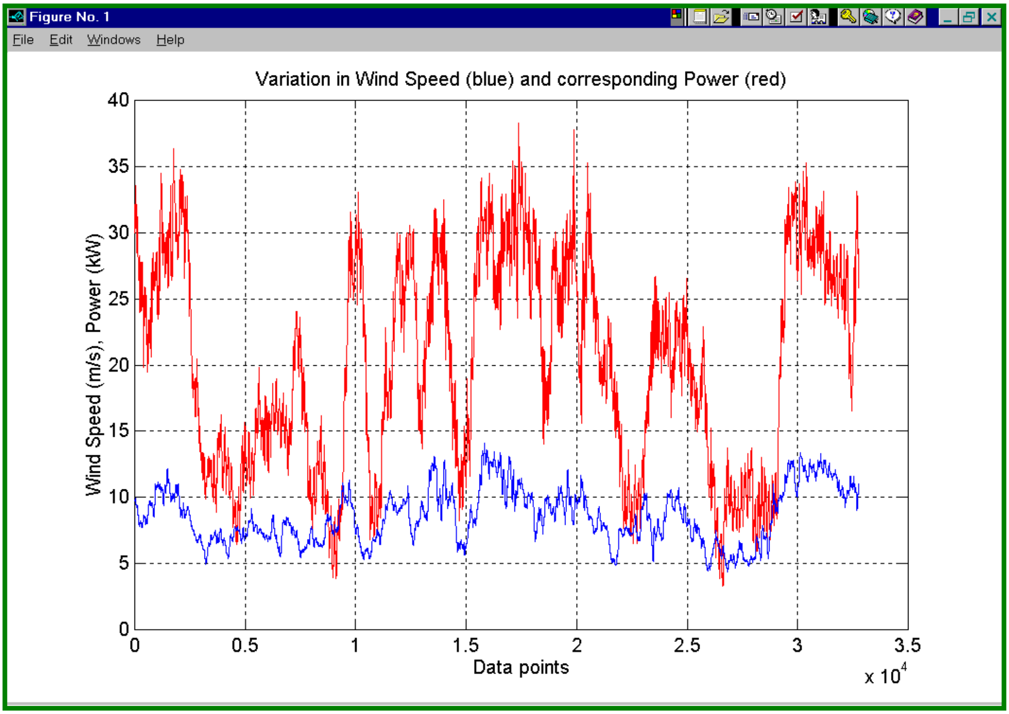
The intermittent nature of wind means that energy storage or an alternative source such as gas will be needed to meet demand during calm periods. This may mean storing energy for a day or two. The cost of energy storage is falling quickly (see Lazard 2022). Employing an additional source like a standby diesel generator also places economic strain on the scheme as there are addition investment costs as well as fuel costs. A shorter-term storage problem for wind turbines arises from the unsteady nature of the wind resource. Instead of blowing with a constant velocity, wind is prone to blow in gusts. Figure 1 shows the variation in wind velocity (V) over a few minutes as the lower trace. The electrical output from a wind turbine, which is loosely related to V^3, is the upper trace. This output must be smoothed before delivery to a consumer. In the case of large arrays there will be statistical smoothing, but small numbers of turbines will require energy storage over a few minutes to accomplish a steady output. Thus a single turbine or a collection of a few turbines might require battery storage.

2.3. Hydroelectricity

Hydroelectricity comes from solar induced weather. Most countries have constructed dams for flood control, water supply or power generation (or all of these). These dams schemes already contribute about 4500 TWh or 16% to world electrical supplies (BP 2022), but suffer from periods of low rainfall. This situation is increasingly concerning as more frequent episodes of extreme weather conditions are predicted as a consequence of climate change.

In terms of energy storage, though, dam schemes are ideal. The water held in the reservoir behind the dam is effectively "stored energy" which can be released to meet demand. The Itaipu dam shared by Brazil and Paraguay (completed in 1984) is the second largest in the world and serves Brazil and Paraguay with 14 GW of electrical power (Itaipu Binacional 2022).

Figure 1. Variation in wind velocity (lower trace) and associated power (upper trace) over a few minutes



Source: author's elaboration.

The Foyers hydro-electrical scheme built on the side of Loch Ness in Scotland has a much smaller capacity but does have an additional feature: it is a pump storage scheme (Foyers Hydro Scheme 2022). During times of surplus electricity on the grid its two Francis turbines are run as pumps and together pump 320 m^3/s of water up to Loch Mhor which is 179 m vertically above Loch Ness. When demand on the grid rises this water is released through the turbines back to Loch Ness. Loch Ness is linked to the sea and so is not vulnerable in times of low rainfall. The turbines each generate 150 MW into the grid. This scheme is quite small, and together with three other schemes have a combined storage capacity of around 2% of the average daily electricity supplied by the UK grid, the stored energy helps to smooth the supply/demand curve on the UK grid but is too small to offer energy security.

A second type of hydro-electric scheme is "run of river", which generally have no water storage. They are based on historical water mills, which were common throughout Europe 2000 years ago, and sometimes included a mill pond to collect water over a few days until there was sufficient water to drive the wheel and grind corn or other mechanical tasks. An example of a modern run of river scheme is Niagara Falls shared by US and Canada. In fact this is an unusual run of river scheme in that the falls that tourists experience during the day means that the energy is lost as water crashing over the falls. At night the falls become quiet as the authorities divert the water to a reservoir where it is stored overnight to provide electrical generation the next day. Most run of river schemes do not store water as potential energy.

2.4. Biomass

Biomass is produced through photosynthesis by captured solar energy. In terms of energy storage most forms of biomass mimic fossil fuels as they can readily be stored, transported and burned, although they are generally less energy dense.

2.5. Wave energy

Ocean waves result from the transmission of wind energy into water. Strong winds blowing across long fetches of ocean for many hours will generate large waves with associated high power densities. We can regard waves as a concentrated form of wind (and therefore solar energy). The west coast of Europe is subjected some of the most energetic wave climates in the World, and concepts to harness this resource have been envisaged for 200 years. Developments over recent decades are leading towards first generation schemes. The variation of height and period of waves makes them appear random and unpredictable and so exploiting this potential resource will demand suitable storage to be able to match supply to demand.

2.6. Tidal energy

Tidal ranges can reach 10 m or more in some locations of the World. Since the tides are produced by gravitational attraction and spinning of the Earth-Moon and Earth-Sun systems they are highly predictable, but occur on a 12h 25 m cycle so that the time of the peak tide is changing each day. Exploiting these large tides can be done by means of a barrage, such as the one at La Rance in France, which has been operational since 1969, or by the use of tidal stream technology. La Rance, and a similar scale (of around 250 MW) barrage scheme at Sihwa in South Korea, have some inherent storage. The La Rance tidal scheme output provides 0.12% of France's electrical generation. The water flow can be controlled to some extent as it enters and/or leaves the barrage and so it is possible to match supply to demand to some degree, and offers a modest storage, with a small amount of pumped storage also being available by running the 24 Kaplan turbines as pumps at high tide to increase the height of water inside the barrage. The tidal stream technology on the other hand only operates in real time in tidal flow and so storage of energy must be done externally. A good example of this is at Bluemull on the Scottish island of Shetland. Here Nova have installed four 100 MW underwater turbines to generate electricity from the flow of the tide. To ensure a 24-hour supply of electricity to the community a Tesla battery bank stores energy during the generation phase and delivers energy during the dwell phase of the tide (RenewableUK 2022).

3. Transport

Sustainable transport is a problem because of the need to carry a store of energy in the vehicle, and as pointed out earlier most renewables do not have the energy density of fossil fuels. Future developments must improve the energy density of renewables for use in transport. This section discusses some issues of storage of renewables for transport purposes.

Road: Lead acid batteries have poor energy storage density which renders them too heavy for modern electrical vehicles: in that the range is severely restricted. Alternative batteries such as Li-ion have superior storage density at 160 Wh/kg and so are already installed in electric cars. Electric lorries and buses are being developed. See Volvo (2022) for example.

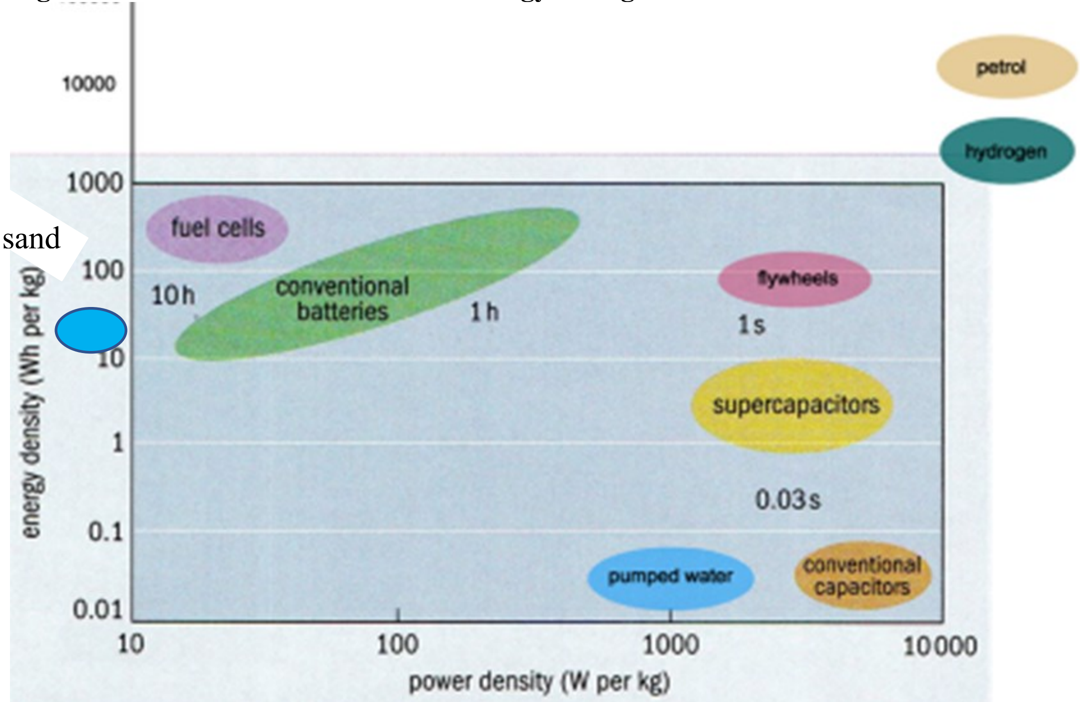
Aviation: Aviation is a difficult problem because minimising aircraft mass limits the number of batteries on board and hence the range of the aircraft. Several airlines are experimenting with biofuels and expect to reach similar properties to fossil fuelled aircraft (CAPA 2021).

Sea: Following COP21 in Paris, world shipping is not required to make any progress towards zero carbon. The International Maritime Organization (IMO) negotiated this on behalf of its members, but it is not clear why COP26 or other meetings accepted this stance since international shipping is responsible for 3% of global carbon emissions. Meanwhile IMO (2021) has set out aspiration measures for its members. Maersk is planning to gradually convert its fleet to run on green methanol manufactured using renewables (Shippingwatch 2022).

4. Choice of storage

Figure 2 shows the technical characteristics of a select group of energy storage options. Selection of the best option depends on a number of factors such as mass, energy density and rate of energy delivery – that is the power density, which is plotted along the x axis. Note that pumped water is more power dense than batteries but is much less power dense than flywheels and capacitors and substantially less then hydrogen and petrol. In terms of energy density (how much energy can be stored) pumped water is very poor, meaning that pumped storage is not a particularly good option even for static storage. Again, petrol and hydrogen are the best, which reinforces the point made in the introduction that fossil fuels are very energy dense and flexible to use. Flywheels are interesting as a means to put braking energy into a store and then recover that energy later on. Formula 1 cars can obtain a short burst of additional power from this mechanism (Mercedes 2019). A sand energy store is undergoing trials in Finland, where 100 s of tonnes of sand are heated to 600 to 1000 ºC. This heat is retained efficiently (99% is claimed by Polar Night Heating [2022]) for several months and has potential to permit summer heat to be stored and used over the winter. Nominal output of 100 MW and capacity of 20 GWh would mean 200 hours of output at full power, 2000 hours at 10% power. They estimate the capital cost at less than €10/kWh. Plotting sand storage onto Figure 2 on the basis of data from the pilot project (100 tonnes of sand heated to 500 ºC, delivering 100 kW with a capacity of 8 MWh) suggests a good energy density, but a low power density. In the context of space heating delivered over a long period at low power density this may be acceptable.

Figure 2. Characteristics of selected energy storage schemes



Source: Ragone diagram adapted from Houghton (2009) to included sand, hydrogen and petrol.

The energy density reflects the total energy stored in a kg of a scheme. How quickly that energy can be released is indicated by the "time" numbers which range from 0.03 s (and hence a high power density), to 10 h (a low power density).

Lead acid batteries contain about 30–40 Wh/kg whereas Li-ion batteries might hold 160 Wh/kg.

5. Cost of storage

Lazard (2022) give an annual review of Levelized Costs of Energy (LCOE) for all forms of energy, which includes energy storage. The costs for renewable energy have been falling for some years, due to improved performance and mass production, as have the costs for energy storage. In some aspects the renewables are extremely cost competitive, and investments in energy storage are bringing costs down. This all bodes well for the future, although BP review indicate that World fossil fuel gas consumption actually increased last year despite the obvious imperative to employ zero carbon technologies. Some of the explanation is the low capacity factor (that is low availability of renewable technologies, and the lack of sufficient storage to guarantee firm supply, or in the case of vehicles the apprehension (whether justified or not) about range. Investment in storage facilities will overcome these issues. Cost is unlikely to be a major impediment to providing firm power.

6. Limitations on energy storage

If cost and technical issues are overcome what are the concerns around the supply and storage of energy? One question is the ability to store enough energy to meet the needs of everyone. It is clear following the Russian invasion of Ukraine that most countries rely on real time supply of energy. At the moment sanctions against Russia and Russian gas from Siberia mean that Europe faces a shortage of gas. Some countries have attempted to store natural gas in depleted oil fields, and so provide a safety net of some months supply. The UK has some gas storage, but in March 2013 with heavy demand for gas heating found itself with only 6 hours supply left and the prospect of closing factories to ensure domestic heating could continue (Independent 2013). More recently, in July 2022, during adverse weather conditions, the UK had to purchase electricity from Belgium at a cost of €11500/GWh, whereas the normal price would be around €210/GWh (ITV 2022). A strategy of storing natural gas and electricity would clearly give more security of supply. As we move towards zero carbon such storage would have to be storage of electricity, heat and biofuels and that is limited by available heat biofuel, and pump storage sites on a large scale, and by battery technology for smaller scale and vehicles. Mineral resources for battery storage are already under pressure. The price of Lithium carbonate increased by 58% in 2021, and by 400% in the first five months of 2022 to €54,000/tonne (BP 2022). The World resource of Lithium carbonate is finite and unless Lithium batteries can be almost fully recycled there will not be sufficient Li to provide batteries for all future electric vehicles.

7. Conclusion

Zero carbon energy is the only energy path to a sustainable future, but much of the renewable energy which could meet our needs will require an associated storage mechanism. Storage methods available to us are becoming more affordable, but they are often less energy dense and less power dense than the fossil fuels that they replace. Apart from these drawbacks there is often limited availability of sites for storage, or of resources to build them. A crude estimate suggests that we have only 1% of the energy storage capacity that we will ultimately require. An urgent programme of energy storage development and deployment is recommended, in parallel with stringent energy efficiency and conservation measures. Such measures will reduce the demand for energy and hence for energy storage. Last, but perhaps most importantly we should adopt SMART technology, SMART grids and SMART human behaviour.

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