ES4E0 Assignment: Hydropower Report

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Abstract

This report evaluates the use of hydropower as a renewable energy source. The underlying technological principles are explored, with consideration to turbine design and plant architecture. Strong geographical dependence was identified as the greatest barrier to further adoption; 75% of hydro potential in the EU is already exploited yet with a corresponding power share of only 14%. Regardless, hydro can prove extremely cost competitive, with levelised costs of electricity (LCOE) as low as 1.9p/kWh. Many social, political and environmental concerns were identified, including population displacement, fauna habitat loss, embodied CO_2 emissions and methane from biomass degradation. Potential improvements were identified in the form of novel applications of hydro technology and the further availability of smaller schemes. Overall it was determined that hydropower presents unique capabilities and at certain scales, a very efficient and resilient energy source. However, its strong geographical dependence and significant environmental caveats reduce it to a minority fraction of global energy production.

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Introduction

Hydro power relates to the process of energy capture, in which the kinetic and/or gravitational potential energy of a flow of water is utilised for mechanical work or electricity. Unlike many conventional means of electricity generation, hydro generation is characterised by consistently high conversion efficiency (typically > 85%) and is practised at scales from a few hundred watts up to the current maximum of 22.5 GW for the Three Gorges dam, the current largest hydro scheme and electrical power plant in the world.

Several power categories exist for hydro plants, ranging from pico and micro hydro (100 W - 10 kW) to small (0.1 to 10 MW), medium (10 to 100 MW) and large (> 100 MW). Plants can be run-of-the-river, where no significant storage is kept and little disruption made to a river's natural course and flow conditions. Alternatively, impoundment plants (typically larger) may possess structures such as reservoirs and dams, with the ability to control discharge and account for natural variations in flow. Such control may be utilised for grid flexibility as well as flood control and irrigation.

Hydropower constitutes ~ 16% of the world's electricity generation (Fichtner, 2015). This report will attempt to further highlight the context of hydro use and provide an insight into its key strengths and limitations. It consists of four main sections; an investigation into the underlying principles and technology, an evaluation of its economic characteristics, exploration of the outstanding limitations and lastly, consideration of how and whether hydro power can be developed in the future.

1 Hydropower technology

1.1 Operating principles

There are two main river parameters that underpin the operation of any hydro power plant. These are the hydro-static head and the volumetric flow rate - indicative of the gravitational potential or the kinetic energy associated with the section of flow, respectively. The relative proportions of these parameters, exhibited by a hydro site, determines what type of turbine will prove the most efficient and practicable proposition.

Reaction and impulse turbines are these two main types, with contrasting ideal operating conditions. Reaction turbines are best suited to sites with relatively high flow rates and low head, whereas impulse turbines favour high head, low flow conditions. Coincidentally, these types correspond to the typical characteristics of the upper and middle courses of the graded long profile of a river. The upper course occurs at high elevations with sharper gradients yet a reduced drainage basin, corresponding to the conditions for impulse generation. As these higher elevations tend to be home to smaller populations, such schemes tend to be smaller in scale and power output (pico, microhydro).

Reaction turbines, in contrast, make better use of the middle course of a river - where a larger accumulated drainage basin results in larger flow rates, still coupled with some gravitational potential. These sites make up the largest proportion of hydropower production, as they offer the greatest power capacity for a given site area (Bostan et al, 2013).

In terms of arrangement and design, impulse turbines rotate in air, under the effect of a high speed jet of water. One, or more, of these would strike the turbine; a wheel with radial spoons which deflect the water. As a jet strikes each spoon, a process of impulse-momentum transfer occurs, leading the wheel to spin at approximately half the speed of the jet. To reach a speed suitable to spin the turbine for electricity generation, the water requires a considerable head, as the jet speed is a function of the accumulated pressure. In most schemes, a penstock (pressurised pipeline) is used to divert the water over a gradient drop where this can be achieved.

Reaction turbines differ in that they operate whilst immersed in water. Furthermore, all the blades of a reaction turbine interact with the flow of water, simultaneously. This is quite unlike an impulse turbine where only one or two spoons interacts with the jet of water, at a time. A combination of pressure, swirl and flow rate, drives the turbine by the lift generation typically associated with propellers, wings and wind turbines. Reaction turbines are usually positioned for the intake of axial flow, though cross-flow turbines also exist.

Beyond head and flow rate, there are further factors to consider in effective turbine selection. Rivers can vary hugely in their flow rates and for run-of-the-river schemes, it is important that turbines retain reasonable efficiencies regardless of flow variation. In this area, impulse turbines triumph, as some designs are capable of maintaining >80% efficiency at down to 10% of the design flow for the plant. For reaction turbines, a limit of 20 - 40% of design flow is more typical (Fichtner, 2015).

1.2 Geographical dependence and intermittency of hydro sites

Hydropower, by definition, necessitates the local presence of rivers with considerable volumes and gradients. Utilisation of hydro potential varies globally, to a regional maximum of 75% for the EU and country maximum of 52% for the USA. In contrast, utilisation throughout sub-Saharan Africa is thought to average just under 8% (IEA, 2017). A rough indication of the area density of hydropower can be given by the fact that the 75% EU utilisation results in only 14% of total power capacity. Clearly there is still significant potential for hydro development, but what is less clear is whether it is always better to pursue this, given the trade-off of area to cost to the potential for energy capture.

Intermittency, though not typically associated with hydropower, presents some challenges towards smaller schemes without storage capacity. Rivers are subject to immense variation in flow conditions as a result of the many complex contributing factors to the hydrological cycle, both natural and anthropogenic. In a survey of over 400 rivers in Europe, it was found that variations of between 17% and 134% were possible in their mean annual flow rates (EEA, 2016). For small schemes to not disrupt river flows at low percentiles, appropriate control mechanisms are required, leading to increased cost and complexity.

2 Economic considerations

2.1 Scales of use, capital investment, operation and maintenance costs

The required capital is often deemed to be one of many barriers to hydro installation. Typical investment costs for large plants can range from £800 - £6000/kW or £900 to £6150 for smaller plants (IRENA, 2017). The upward shift for small hydro plants relates to poor economies of scale for turbines, alternators and power electronics (Bostan et al, 2013). The capital investment costs of hydro compare unfavourably to all sources but Nuclear at around £6000 to £7400/kW (IEA, 2018). The variation of these costs results from the regional differences in labour and material costs required for the civil works typical in the construction of utility-scale power stations.

The operation and maintenance (O&M) costs of hydropower plants are relatively low, typically constituting 3% or 4%, yearly, of the required capital (IPCC, 2014). These costs predominantly relate to the rewinding of generators and minor replacements for races and piping. The design lives of the majority of installed equipment typically exceeds plant life (Fichtner, 2015). As hydropower is so often seen to be a developed technology, there is little known scope for cost reductions in the future. This is further complicated by the fact that civil work costs and project cost control is often hard to distinguish from other installation costs, given the scale of plant constructions (IRENA, 2017).

Despite this, there are many further scales of hydropower generation that are still deemed worthwhile. Micro and picohydro plants often prove a reliable power source for off-grid communities. In developing countries, there is further potential for the use of microhydro to provide mechanical power for agricultural machinery, as is common to remote Himalayan villages across Nepal and India. Furthermore, microhydro plants are sometimes taken on by enthusiasts with engineering expertise, often at disproportionately higher costs, simply for the enjoyment of achieving some form of energy self-sufficiency.

2.2 Levelised Costs of Electricity

The levelised cost of electricity (LCOE) is a measure for cost comparison of different energy sources. In short, it is the required price of electricity at which a plant can break even. It attempts to account for the installation, maintenance and operational costs over the lifetime of a plant, in one figure. It is a convenient, indicative benchmark albeit with several caveats. Approximations are nearly always taken for the required factors of: investment capital, operation and maintenance (O&M) and plant lifetime. These often vary considerably with plant scale, even of the same source, and vastly by location (local costs of materials, labour etc.). The former is significant as hydro spans a large range of power outputs whilst the latter can differ similarly between developed and emerging economies.

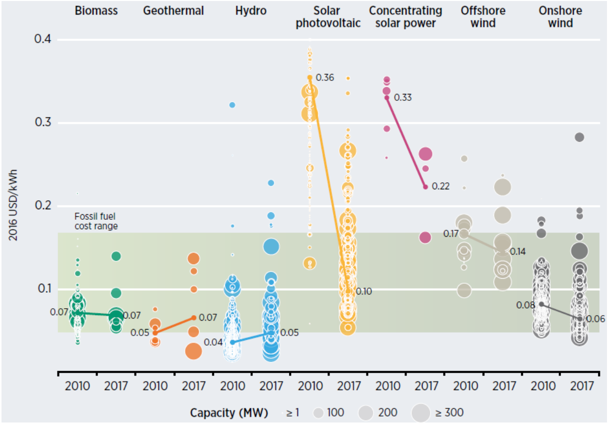

Figure 1: LCOE comparison for main energy sources (IRENA, 2017)

Figure 1 shows the average LCOE for hydropower to come to 0.05 USD /kWh or 3.8p/kWh in 2017. This is representative of the majority of medium - large impoundment plants (IRENA, 2017). Note that there is a considerable spread up to over 0.2 USD /kWh (15p/kWh), this being typical of grid connected microhydro schemes which suffer from poor economies of scale with regards to the electrical and mechanical (E&M)equipment required (Fichtner, 2015). Clearly in 2017, hydropower was amongst the most cost-effective energy sources. Geothermal was comparable, but only available at a small fraction of the already limited area utilised for hydro. In the seven year span, the price of geothermal and hydro increased on average, whilst fossil fuels remained similar. However, it would be very shortsighted to assume this will remain to be the case.

In stark contrast, the trend in cost reduction of solar and wind looks to overturn this state imminently. Through linear extrapolation, Solar PV was due to undercut hydro by early 2018, whilst onshore wind is set to do the same by mid 2021. it was assumed that the cost of hydro remained at 0.05 USD/kWh, so if this increases as the trend suggests, then hydro would lose its price competitiveness even sooner. Given that one of the key drivers of any technology is value-for-money, it looks unlikely that large hydro can maintain its leading position. For future relevance, hydro might have to rely on unique technologies such as pumped hydro storage, this is discussed further in the penultimate chapter.

3 Context of use: environmental and political landscapes

3.1 Environmental considerations

Hydropower proves a complex subject of environmental assessment. As a renewable source, it has the long-term benefits of large scale, low carbon generation yet with significant drawbacks. The embodied $C0_2$ in the cement required of reservoirs in larger plants, detracts significantly from this carbon reduction. A study conducted by Phil Purnell for the Institute of Civil Engineers (ICE) found that for the Roller Compacted Concrete (RCC) commonly used in dams, embodied CO_2 typically came to $\sim$ 300 kg per m^3 of concrete, equivalent to 13% of the mass of RCC produced.

Furthermore, schemes that demand the flooding of vegetated areas can continually produce emissions as a result of biomass degradation, and the subsequent escape of methane to the atmosphere. Methane has an intermediate warming impact of up to 34x that of CO_2, albeit with a reduced impact duration (EPA, 2016). A harsh implication of this phenomenon is that it presents further barriers to developing countries; tropical Asia and sub-Saharan Africa present large opportunities for hydro growth, however if hydro plants in these warmer climates possess a sufficiently large reservoir area and vegetation is not cleared before inundation - the resulting emissions may be comparable to fossil fuels (Pandey, 2017). In confirmation of all the above, the IPCC ranks hydropower as the leading cause of indirect emissions and overall environmental damage, of any renewable source.

The end result is that for certain plant sizes and without due care to embodied carbon, hydropower can inflict considerable damage to the environment. A solution to these issues is readily available in the form of run-of-the-river plants, where no river damming takes place - though at a loss of river storage and control. A compromise is therefore required between the advantages offered by reservoirs (irrigation & flood control, pumped storage) and those of ultra-low carbon generation.

Hydro schemes often have further disruptive consequences to local ecosystems and river environments. Large impoundment structures and even smaller run-of-the-river schemes present significant disruption to the passage of aquatic life. These effects can range from a reduction in migratory species like Salmon to total extinction of some species such as the Yangtze river dolphin. The social and political opposition that results from such consequences are detailed in the next chapter.

3.2 Social, political and legal implications

There are considerable direct and indirect sociopolitical implications of hydro use, most significantly in the compromise between the mitigation of climate change vs. the immediate local environmental effects, explored previously. A significant social concern of large hydro installation is that of the cost of relocating riverside populations. Construction of the Three Gorges Dam led to the displacement of nearly 1.2 million people, costing the Chinese government $ 3.5 billion, roughly 6% of the total plant cost of $ 59 billion (Reuters, 2012).

The joint effects of environmental, social and political opposition can lead to widespread disapproval or even outright rejection of hydropower. Over the course of 2016, a proposed 600 MW plant on the Susitna River in Alaska was mothballed, despite its potential to provide two thirds of the state's power supply (AEA, 2016). A local campaign lobbied for the protection of pristine wildernesses and cited a reliance on wild salmon runs and hunting for the local economy. The campaign went to appeal to audiences of outdoor enthusiasts worldwide, through film screenings that showcased the biodiversity of the Susitna River basin. The associated Susitna River Coalition was later recognised as a key influence on the eventual decision of the governor, to veto the dam's construction (EPA, 2016).

In some instances, hydro installations can cause international political tension. Impounded hydro plants afford their owners significant control of a river's flow, which can affect the livelihoods of large populations of people. Many rivers transcend regional and national borders and so, exertion of this control can lead to conflict. Ethiopia's proposed 6.5 GW dam on the Blue Nile is indicative of this, having led to serious deterioration in relations with Egypt. Though recent co-operation between Ethiopia and Egypt has improved, in June 2013 - the Egyptian president Mohammed Morsi expressed that he would not rule out the threat of war, if Egypt's water security was in any way compromised (BBC, 2013).

For hydropower to remain a viable renewable option, it is clear that much attention must be paid to the social, political and legal landscapes of its use. In this sense, hydropower is much more than just an engineering issue.

4 Future developments and challenges

Hydro power is generally considered to be at a mature phase in its technological development (Fichtner, 2015). However, as for anything, there is always room for improvement. With larger schemes, reductions in embodied carbon or the use of alternate materials will be necessary to justify the environmental cost of hydro installation. In developing countries, further refinement of component manufacturing processes and material procurement could reduce costs further and therefore lessen the motive for fossil fuels. Though pumped hydro is a currently used technology, its importance will certainly increase, as the intermittency of other renewables becomes more prominent - even if accounted for by high averages of baseline wind and solar production.

4.1 Pumped hydro storage

Though even further limited by specific geographical conditions, pumped hydro remains to be one of the most effective means of providing high-power frequency response in matching peak grid demand. As of 2016, only two commercial technologies were capable of providing discharge powers of greater than 100 MW for more than two hours; pumped hydro and compressed air energy storage (CAES). The latter is simple and quick but operates at efficiencies of little more than 50% and is still in its infancy. Pumped hydro, however, is the world's most established large-scale form of energy storage (IRENA, 2018) and boasts rapid response times along with unrivalled energy and power discharge capacity.

The Dinorwig plant in Llanberis, North Wales, is the biggest such scheme in the UK - storing up to 9.1 GWh, with the ability to reach a peak discharge rate of 1.32 GW in 12 seconds from start-up. To put this into context, this peak discharge rate can provide ~4% of the average instantaneous power demand of the UK, for nearly 7 hours. It is estimated that there is the potential for a 10x increase in pumped hydro capacity if further adoption was to occur globally, along with some retrofitting of existing plants (Fichtner, 2015).

There is an undeniable trend towards increased renewables in the UK, with the expectation for their grid proportion to more than double by 2035 (Gov, 2017). Pumped hydro is likely to play an important part in tackling their associated intermittency. Though it is possible that the minimum average production of renewables may largely deal with this issue, the ongoing lack of investment into UK nuclear will mean that a strong reliance on gas and pumped hydro will be needed for continued flexibility and consistency (Arup, 2016).

4.2 Novel applications

One of the ways in which hydropower can prove useful, beyond its geographical limitations, is through novel applications outside of natural watercourses. An example of this lies in the innovative use of pico-hydro turbines to reclaim energy from the water mains of tall buildings in Hong Kong. Being a densely populated city, high-rise buildings are dominant and these demand very high mains pressure for usable flow rates at high building levels (up to 8 bar, where 3-4 is typical in the U.K). A collaboration between Arup and HK Polytechnical University designed a vertical axis turbine that generated up to 876 kWh a year when installed in the water mains of commercial buildings (Arup, 2016). This proved sufficient to continuously light up a lift lobby which, though tiny in a grid context, is a useful work output that would otherwise have been completely lost to ambient mains pressure.

5 Conclusion

This report has found hydropower to be a valuable source of renewable energy, yet one with complex and significant drawbacks. Large scale hydro installations offer some of the most competitive rates of electricity generation of any energy source in the world. However, this is at the cost of limited geographical siting and a diverse array of damaging environmental effects. In the instance of the latter, the resulting social and political repercussions can even mothball projects like the Susitna dam in Alaska. Furthermore, the rate of commercialisation of solar PV and onshore wind is already beginning to surpass the cost benefits of hydropower. Overall, the future of hydro is more likely to lie in the realms of pumped storage or decentralised micro schemes, with their lesser environmental disruptions and more adaptable approaches to demand matching and control.

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