UNIVERSITY of STRATHCLYDE
CENTRE FOR ENERGY POLICY

Policy Briefing

What is the role of pumped hydro energy storage in generating value and reducing energy system cost in a net zero economy?

Karen Turner, Oluwafisayo Alabi and Constantin Brod

Summary

Pumped hydro energy storage is an **enabling/balancing technology** that allows low carbon electricity to be generated in one area at a given point in time and stored for later use when needed in that area or others. Thus, **it exploits very specific geographical resources that are plentiful in particular regional areas within the UK** (for example, the Scottish Highlands) and uses them to **deliver valuable outcomes for the UK electricity grid and the UK economy as a whole.**

In the first instance, electricity industry developments can have important employment impacts during their construction phase. For example, Hinkley Point is reported to have generated 6,500 direct construction jobs on site. According to UK Government 'employment multipliers', this could lead to an additional 5,785 indirect supply chain jobs. Similarly, just one large pumped hydro station could have important employment impacts across local, regional and national economies. For example, **development of the Coire Glas station in Scotland is estimated to require 3,500 direct construction industry jobs. This could generate an additional 3,115 supply chain jobs.**

At operational stage, pumped hydro is an **example of region- and/or location-specific capacity** that plays a key role in delivering a **national and increasingly electric powered energy system** that is at the same time **reliable, flexible, secure and where any market failure issues can be resolved, economically efficient.** The strategic importance of drawing on regional resources and has been highlighted by the **Committee on Climate Change (CCC)** in the context of the net zero carbon economy advice accepted by Government where Scotland has a more ambitious 2045 target for this reason. There is a **strategic case for deploying further pumped storage capacity** to service the UK energy system and economy, alongside other solutions such as increased interconnector capacity. This is particularly so if the UK takes a **path of increased electrification involving potentially quadrupling our reliance on renewable generation** coupled with **reduced reliance of both the gas grid** to provide flexibility in delivering heat, and reducing the **role of fossil fuels** by enabling bulk energy storage.

On the other hand the current market environment in which pumped hydro capacity decisions are made gives rise to a **very fundamental market failure.** This arises because the **individual station owners** who need to invest in new pumped hydro stations currently **cannot value the benefits that accrue to the wider UK electricity system, economy and society** in their investment decisions. Our provisional analysis suggests that **potential social benefits generated per unit of pumped hydro capacity will grow the more capacity is added to the system,** but this will not be reflected in the private revenues realised by station operators.

Policy intervention could address this market failure to allow the wider social costs and benefits of pumped hydro investments to be effectively taken into account in the decision making of the owners of pumped hydro capacity. This could **either be at the stage of investing in capacity and/or influencing the revenues that investment costs must be set against.** For example, where pumped hydro can play a similar role to interconnectors in moving electricity about the country when it is most needed, the type of 'cap and floor' mechanism may play a role in preventing distortive price fluctuations.

Introduction: a new 'net zero carbon' policy environment and the role of existing technologies

In June 2019, the UK Government formally accepted the advice of the Committee on Climate Change (CCC)[1] regarding delivery of a net zero carbon economy by 2050. Just a few weeks earlier, the Scottish Government accepted the CCC advice on a more ambitious target of net zero by 2045. The more ambitious Scottish target is set in the context of the particular resources and capacity available at Scottish level to both produce low carbon energy and to capture and sequester carbon emissions. For Wales a less ambitious target of a 95% reduction in carbon emissions is required by 2050.

While acceptance of the CCC advice has been viewed as a major development in the UK's energy and political economy environment, the CCC noted at the time of publication that the net-zero carbon target is basically a means of delivering on the commitment that the UK made by signing the Paris Agreement in 2015. Moreover, they note that meeting the targets is achievable with known technologies, and to do so in a way that is both cost-effective and can deliver net benefits for the people of the UK. The transition pathways under which emissions reductions can be achieved while sustaining and growing economic value and well-being are increasingly the focus of policy attention. Indeed, this – and the Just Transition element of the Paris Agreement may be a key focus of COP26 in Glasgow, Scotland which has established a Just Transition Commission[2].

One such known technology, deployed in the UK since the 1960s is pumped hydro energy storage. The focus of this paper is to consider the continued and growing role that pumped hydro could play in achieving our new net zero carbon economy targets. We do so in the context of there being some real challenges in terms of how the regions of the UK, and different actors in the economic and energy systems, interact in the delivery and use of energy services. For example, in how we heat our homes. Pumped hydro is widely recognised as having a role in balancing supply and demand for electricity across time and space, which becomes increasingly important as the need to electrify our energy system grows.

The purpose of this paper is to consider what type of valuable outcomes for a net zero 2050 economy may be delivered through increased pumped hydro storage capacity in the energy system, and just what type of market failures may hinder progress. We conclude that increasing pumped hydro capacity could indeed deliver greater societal benefits through reduced energy system costs and enabling more extensive renewable energy deployment. The problem is that such benefits do not all accrue to individual private sector station owners and, thus, will not be reflected in their decision-making processes. This is indicates a very basic market failure that requires policy intervention.

The challenge of decarbonising the economy in a way that sustains and creates economic value for society

In previous works, we have considered the role of a range of technological options and pathways in delivering outcomes that are valued in a broader political economy context[3,4,5]. To get to where we need to be in a net zero carbon future, the potential contribution of a full range of technologically feasible solutions will have to be considered. Solutions such as energy efficiency, the roll-out of electric vehicles, carbon capture and storage and, here, pumped hydro energy storage, do involve incurring significant costs at least in the near term. But arguably too much attention has been focussed on technology and upfront 'resource' costs. We are currently facing a range of investment decisions in our evolving low and ultimately net zero carbon economy. In this context, any cost must be set in the context of expected returns over time. Returns to low carbon investment extend beyond mitigating climate change to the creation of jobs, GDP and ways of making energy services more affordable.

However, market failures are in terms of how and by whom different returns are valued. This in turn, is set against who must deliver and, crucially, pay for the investment, deployment and operation of solutions. On the one hand, mitigating climate change is essentially a globally valued outcome that must be delivered at local, regional and national levels. On the other hand, the delivery of a cost effective net zero carbon energy system requires to underpin the transition to a net zero carbon economy can be done in a way that enables jobs and GDP to grow. These are outcomes valued at global or national societal rather than individual industry actor level. At whatever level returns are realised, the issue of 'who pays' is a complex one, ultimately determined by how the costs of delivering different solutions are determined and passed on. Where markets cannot deliver the desired outcome, there is a market failure and policy decision makers have a crucial role to play in considering the role of different solutions, and combinations of solutions, in exploiting opportunities to deliver valued outcomes. So how do we consider what policy interventions may be required in any particular context? As a first step, in considering the role of pumped hydro energy storage, we need to identify the outcomes valued by society that it can help deliver.

The role of a strong domestic industry in delivering a secure and reliable electricity supply for the UK economy

The UK electricity sector will play a key role in delivering net zero carbon emissions targets by 2050. Electricity generation, supply and distribution is an important industry to the UK economy. The reliable and secure supply of electricity enables activity in every sector of the economy. But the generation, transmission and distribution of electricity in the UK is also an industry that is heavily integrated within, and has extensive supply chain linkages across the UK economy. It purchases a large share of its own inputs from other UK sectors, which generates strong output, value-added and employment 'multiplier' effects. The UK electricity industry directly employs around 180,000 people.[6] Employment multiplier data suggest that for every direct full-time equivalent (FTE) industry job a further five (FTE) supply chain jobs are created across a wide range of sectors, including high value public and private service sectors.[7] The UK electricity industry also has important interconnection[8] and supply chain linkages with the rest of Europe.

All of this is crucially important in terms of ensuring the reliability of our energy supply and the confidence that the economy must have in a crucial utility industry of growing importance as our economy transitions to a net zero future. For example, the Committee on Climate Change (CCC) recommends that a range of emission reduction options, including quadrupling low carbon electricity generation, are necessary to meet the 2050 targets.[9]

Balancing the supply and demand for electricity as dependence on renewables increases

It is in a forward-looking renewables-dependent context that pumped hydro energy storage becomes increasingly important. This is because of the services that pumped hydro can and does provide in balancing supply and demand on the grid on a day-to-day basis, as well as in helping the system to restart and power up in the event of large scale system failure ('black start').[10]

In considering the transition required, it is important to recognise that our dependence on fossil fuels has not only allowed us to power our economy, it has also allowed us to store large quantities of fuels that have provided buffers of energy that could be called upon when needed to transform into electricity.[11] Shifting to harvesting primary electricity with wind and solar means that we are transitioning to a situation where this 'pre-transformation' storage will no longer be as available. This means that ways of storing energy once it has initially become electricity will become more and more important as we move through the net zero carbon transition.

In short, there is a central need to reconsider just how we ensure that the supply of electricity is reliable to all households, businesses and public sector activities across the UK. The role of low carbon but variable renewable generation is growing and the demand profiles for the use of electricity is changing. This means we need to find ways to ensure that supply is able to meet demand in a way that is both affordable and secure, and which allows us to store and optimise the use and value of generation from renewables. Moreover, if the transition is to achieve outcomes consistent with the need for a 'just transition' as set out in the Paris Agreement (and Scotland already has its own Just Transition Commission[12]), solutions are required that allow the electricity industry to continue to strongly support jobs and income across the economy.[13]

Replacing large-scale fossil fuel based system with large-scale electrical energy storage

To most people, batteries are the most familiar way of storing electrical energy. Batteries can be deployed at some scale and play an important role in providing grid balancing and energy management services. In the UK, some examples of sizable battery projects are the Broxburn project[14] in West Lothian (Scotland), Cleator and Glassenbury projects[15] (northwest and southeast England). Battery solutions such as these are important in terms of providing first response balancing input to the National Grid for short periods of about half an hour.[16] Technologies like batteries are particularly relevant due to their very fast response times. But where a longer duration of input from storage capacity (hours to days at a time) is required, then there is a need for a much larger scale, supplementary and sufficiently rapid response way of storing and releasing electrical energy. In this regard, pumped hydro energy storage has been the dominant approach around the world.[17]

Hydroelectricity may be more familiar to the wider public than pumped hydro energy storage, though the two are closely related. Most people will understand that electricity can be generated by using the force of water to power turbines, and that this – hydroelectricity – has long been part of our generation mix in the UK (in Scotland in particular). What may be less well understood is that the process of using water to generate electricity also allows us to store energy at a large scale, and, depending on the size of the turbines, to release it quickly, when it is needed most so that demand for electricity matches supply at all times. This is pumped hydro energy storage.

Between the 1960s and 1980s, there were significant levels of government investment in pumped hydro capacity in the UK, at that time to help balance our needs as our reliance on nuclear power grew. More than thirty years later, our need for this type of energy storage is growing again, but in a different way, as we become more reliant on renewable generation methods. The particular characteristics of pumped hydro energy storage means that it will play an increasing role in providing services to balance supply and demand within and across geographical regions, and helping to manage the transmission constraints between regions. In the latter regard, it can play a role not unlike that of interconnectors, but doing so wholly within UK boundaries and control.

Moreover, because of how it operates as a large scale quick release storage solution, pumped hydro can also play an important role in the process of restarting the national grid through different areas of the UK should we face a 'black out' situation. Thus, more generally, pumped hydro becomes important in terms of facilitating, and reducing the costs, of what needs to be done within the UK to secure a reliable and flexible electricity supply, particularly where other large scale low carbon solutions (such as CCS in combination with thermal generators and nuclear) prove to be very costly ways of delivering this outcome.

Supporting both local energy systems and high quality jobs in often remote regional economies

New pumped hydro capacity is being introduced in other countries, and both energy system and wider economic benefits are being argued. For example, the expansion with an extra 2 GW of installed capacity to the Snowy Mountain Hydro scheme. This complex site consists of eight hydroelectric plants and two pumped hydro plants, and enables the delivery of 175 hours of storage capable of powering 500,000 homes during peak periods. [18,19] The project is also being **associated with a wider set of benefits for the local and regional economy**, at both construction and operational stages.[20]

In a UK context, a project such as the proposed Coire Glas pumped hydro station in Scotland could provide balancing input to the UK grid that could compensate for the equivalent of about 20 hours of outage at one of the two units of the planned new nuclear power station at Hinkley Point. But Coire Glas is just one of a number of actively developed pumped hydro sites with approximately 4.1 GW total capacity, and further potential sites could be developed, too. What kind of value could such new capacity add?

In terms of economic 'multiplier' benefits from pumped hydro stations themselves, these will be significantly greater at the construction stage than at the subsequent operational stage. Nonetheless, these project-specific economic benefits are still important. Pumped hydro construction projects can take 5-6 years and generate important high quality civil engineering and supply chain jobs, often in quite remote regional economies. In the case of the Scottish Highlands, where depopulation is an ongoing public policy concern, new pumped hydro capacity may be regarded as an important economic development.[21,22] Where this is the case, the extent and nature of any local (and wider national) employment impacts associated with new pumped hydro capacity merit further study.

At this stage, in assessing the wider economic impacts of developing new pumped hydro stations, straightforward comparisons of other electricity industry asset developments can be made. For example, EDF have reported that 6,500 job opportunities have been created so far in the development of the Hinkley Point nuclear power station.[23] While caution must be applied in applying UK employment multipliers (which are reported in terms of full-time equivalent jobs), it can be estimated that an additional 5,785 indirect supply chain jobs are generated by construction activity on the Hinkley project.[24]

Similarly, just one large pumped hydro station could have important employment impacts across local, regional and national economies. For example, the development of the Coire Glas station in Scotland is estimated to require 3,500 direct construction industry jobs. Application of the same UK construction industry employment multiplier as above (1.89 wider economy jobs per direct job), suggests that this could generate an additional 3,115 supply chain jobs during the construction stage.

Using strategic regional capacity to ensure efficiency, reliability and value generation across the national energy system and economy

On the other hand, the regional context that discussions around pumped hydro naturally fall into can be problematic and misleading. Consideration of local jobs may be regarded as a potential offset to the geographical limitations of where pumped hydro stations can be located. The process involved in pumping water from a lower to a higher reservoir of water, and, when energy is required, releasing it with sufficient force to power a turbine, requires the type of 'hilly' location that tends, certainly in the UK, to be found in more remote regional locations (such as the Scottish Highlands). But this is an overly simplistic way of thinking about the case for pumped hydro. There is a note that national policy makers, and people/ communities who do not live in the type of regional locations suitable for locating pumped hydro stations, considering pumped hydro as a somewhat remote and region-specific solution.

If we take our lead from the Committee on Climate Change, the key to the UK economy delivering on its net zero carbon commitments lies in exploiting the strengths of its regional capacity and characteristics. That is why Scotland's net zero target is set five years earlier than that of the wider UK. The lesson to be learned is how resources and capability located in one region can help deliver outcomes for the wider national economy. The role of pumped hydro in generating value and reducing energy system costs in the net zero carbon UK economy needs to be considered in this context.

We have noted that pumped hydro is essentially an enabling/ balancing technology that allows low carbon electricity to be generated and stored to enable use in different areas and at different points in time. So the question is whether it can play this role in the context of different areas and regions of the UK in a manner that is economically efficient at *system* level. Based on the role it has played to date in the UK, the answer would seem to be that it can. For example, rather than curtailing excess wind generation in Scotland, pumped hydro can enable 'trade' in electricity without losing value from the UK's renewables. In terms of the role of pumped hydro located in Scotland, Wales, or some other regional location for the wider UK energy system, it is this enhanced bulk energy storage role that is crucial as the UK shifts away from gas in supplying heat. While shifting away from gas will aid the net zero carbon transition it reduces flexibility provided by the gas grid. Pumped hydro, particularly given the maturity of the required (and relatively highly domestically focussed) supply chains (established in the wake of past investment in capacity), can play a role in enabling increased flexibility of the electricity system, and reducing the system costs of doing so.

In short, bringing increased pumped hydro capacity on-line will deliver important value outcomes through the impact on the economic efficiency and reliability of the wider UK energy system. That is, the value case should not be considered solely in the context of the individual pumped stations themselves. But this is where the real challenge arises in measuring and communicating the value case for pumped hydro, and it is one of a very basic market failure. Investment decisions to bring pumped hydro capacity on line must be made at individual station level. However, unless the owners of those stations have reason to value the system outcomes, pumped hydro projects may not cross the 'net present value' investment hurdle.

Regulatory, market organisation and market failure problems associated with pumped hydro

The nature of the market failure that needs to be addressed if pumped hydro is to play the role(s) set out above is a complex one in the UK. One central problem is that the electricity market framework in the UK considers pumped hydro in the context of the hydroelectricity method of *generating* electricity. There are two issues here. First, as argued above, pumped hydro does more than just add to generation capacity, or even providing pure storage at large/bulk scale. Its relatively long-term and large-scale storage properties enable it to play a crucial role in providing balancing and flexibility services required by the national electricity grid, many of which cannot be imported and, thus, need to be provided from within the UK. However, these service needs are not known or procured far in advance and therefore may not be appropriately valued. Second, the system operators, who value the outcome of delivering an efficient and reliable electricity *system* are not the owners of generation capacity. While there are good regulatory reasons for the market being structured in this way, it does have the side effect of locking in the basic market failure argument set out above. That is, those actors who need to invest in pumped hydro are not the same ones as will value the benefits to the wider system.

In short, a very fundamental market failure occurs in the context of pumped hydro. It is one that is made worse by the fact that pumped hydro has very high up front capital costs in construction which increase risk. Moreover, it is exacerbated by the fact that long lead times between the development and operation of pumped hydro plants create significant financial risk for private firms, which further limits investment.[25]

How can this problem be overcome? How has it been overcome in other countries? Is it an issue of market organisation? The global market for pumped hydro is growing but just how, and how well, it works in different countries depends on a range of things. For example, potentially having a mix of public and private ownership on the basis that public owners will value the costs of reducing system costs and wider economic benefits accruing to local, regional and national economies. Whatever the ownership model, one core approach maybe around reducing the cost of capital, either through government investing or taking action to reduce risk. There may also be a role for market correcting instruments, such as 'cap and floor' instruments. These are used to overcome problems associated with market price movements potentially deterring the flow of electricity through interconnectors.

Questions in these broad areas will be common to a number of areas of low carbon development (such as carbon capture and storage). But just how they may be analysed in a system or society level assessment of cost and benefits will differ from case to case. How might this be done in the case of pumped hydro?

Valuing the societal and political economy role of pumped hydro energy storage

Where any project or activity has a wider set of system of societal costs and benefits than those that accrue to private investors, this provides a fundamental need for some form of public support and/or change in market arrangements. The justification for intervention strictly needs to be considered when using a social cost-benefit analysis (SCBA) framework. Ofgem already do this in the context of the regulator's responsibility for energy system outcomes.[26] But this will not take into account a full range of wider societal costs and benefits. The approach to more extensive and full *social* cost-benefit analysis is set out in HM Treasury's Green

Book.[27] Crucially, it involves considering social opportunity costs, reflected through measurement of 'shadow prices', rather than purely monetary costs and benefits. For example, if a project involves creating jobs in an area of high unemployment, the market costs of using labour are offset by the reduced need to pay unemployment benefits and/or the benefits of retaining populations in particularly rural regions of the country. This is a shadow price measurement of a social cost.

Similarly, in considering pumped hydro energy storage, we need to offset the purely (private and public) monetary costs of building and running pumped hydro stations against those associated with inflexibility and variability in the electricity system. This would allow us to consider the social cost of additional capacity. Another approach may be to consider the social benefits of increasing flexibility and reliability. For example, if exporting excess electricity generated from windfarms using renewables yields less value per unit than it costs to import electricity on days where there is no wind, the role of pumped hydro in better utilising the output of windfarms needs to be valued. This is a similar role to that already played by interconnectors, where 'cap and floor' mechanisms are employed to ensure that the value realised through trade in electricity cannot fall too low.

A potential approach to meeting the social benefit, or 'shadow price', of pumped hydro energy storage

How might the fuller societal benefit enabled by additional pumped hydro capacity in contexts such as the windfarm example above be measured? One possibility would be to consider the revenues that would accrue to all pumped hydro and/or other generation capacity if that additional capacity came on line. Consideration of such an accumulated return may permit projects to pass a social net present value where this cannot be achieved based on individual station revenues. On this basis, a study for the US took the average 'shadow price' of pumped hydro capacity to be measured by the annual revenue per megawatt hour of energy storage capacity extension enabled by pumped hydro. [28] A key finding there was that this measure of social benefit rose rapidly as pumped hydro capacity in a country or region rises under a range of climate scenarios.

Might a similar picture emerge in a UK context? Considering, this will involve tracking total industry revenues linked directly to extending pumped hydro capacity, and how this deviates from the incentive provided by revenue gains to individual operaters. However, prior to attempting to more fully articulate and to answer this question, it is crucial to clarify that the fundamental policy challenge, is one of closing the gap between the total social benefit and that recognised by individual station operators. Addressing this, may involve intervention on the revenue/benefit side (e.g. through a 'cap and floor' system affecting the price of electricity delivered) or by affecting the costs incurred by those operators (e.g. through sharing in capital costs or reducing them through management of risk) and against which revenue requirements are set.

Conclusion

The Committee on Climate Change, in the 2018 advice now accepted by the UK national and devolved governments, makes clear the importance of exploiting regional capacity and resources to achieve a net zero carbon economy by 2050. Pumped hydro energy storage is a good example of region- and/or location-specific capacity that can play an important role in delivering the outcome of a national increasingly electricity powered energy system that is at the same time reliable, flexible, secure and economically efficient. There is a challenge, however, in that continued development of pumped hydro capacity is hindered by a very fundamental market failure. This is in terms of individual station owners being currently unable to account for the value the wider energy system and societal benefits that their investments enable. The main positive message emerging is that this type of market failure is a fairly straightforward and fundamental one, rooted in the ownership of capacity and valuation of returns. Thus, it could be addressed through changes in regulation that may involve changing how pumped hydro is treated in the market framework (e.g. addressing the 'generation' designation). It may also help to enable permitting the implementation of existing instruments in the case of pumped hydro (e.g. the use of cap and floor mechanisms for the interconnectors that play a similar role). Alternatively, those actors who value the wider system and societal outcomes enabled by pumped hydro could intervene by sharing the ownership of capacity or contributing to the capital costs that make the cost-benefit trade-off so difficult to balance in developing and bringing new capacity on-line.

About the project

This project is funded by the University of Strathclyde, TIC-LCPE programme (Hydro 05 project). We acknowledge the input of SSE Renewables in providing information. We are also grateful to the participants of the Roundtable Discussion Event held on 14th June 2019 and other stakeholders who engaged with the project at various stages.

About the authors

Karen Turner is Director of the Centre for Energy Policy (CEP), University of Strathclyde and an expert on modelling and analysis on the economy-wide impacts of decarbonisation and low carbon solutions and energy policies. She is currently serving on the Scottish Just Transition Commission.

Oluwafisayo Alabi is a Research Associate at the Centre for Energy Policy, University of Strathclyde. She specialises in economy-wide modelling and analysis to understand the potential implications and impacts of different low carbon solutions and addressing the crucial question of 'Who Pays?' for the transition to a low carbon future.

Constantin Brod is a Graduate Research Assistant with a research interest in policy barriers to large-scale electricity storage and Social-Cost-Benefit frameworks to demonstrate the net benefits of the outcomes delivered by storage.

ENDNOTES

[1] Committee on Climate Change (2019). Net Zero The UK's contribution to stopping climate change (see pp. 14,15)

[2] Information on the Scottish Just Transition Commission can be found at https://www.gov.scot/groups/just-transition-commission/

[3] Figus, G., Turner, K., McGregor, P., & Katris, A. (2017). Making the case for supporting broad energy efficiency programmes: Impacts on household incomes and other economic benefits. *Energy policy*, *111*, 157-165

[4] Turner, K., Katris, A., Figus, G. & Low, R. (2018). Potential Wider Economic Impacts of the Energy Efficient Scotland Programme

[5] Turner, K., Race, J. & Sweeney, G. (2019). The economic opportunity for a large-scale CO_2 management industry in Scotland. Report published by Scottish Enterprise.

[6] Direct employment data for the UK electricity industry are given in https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/728374/UK_Energy_in_Brief_2018.pdf

[7] Employment multiplier data for the UK, generated by ONS, are available via archive

[8] Hawker, G., Bell, K., & Gill, S. (2017). Electricity security in the European Union — The conflict between national Capacity Mechanisms and the Single Market. *Energy Research & Social Science, 24*, 51-58

[9] See p.11 of the Committee on Climate Change technical report

[10] Akhil, A. A., Huff, G., Currier, A. B., Kaun, B. C., Rastler, D. M., Chen, S., Bingqing, Cotter, A. L., Bradshaw, D. T. & Gauntlett, W. D. (2015). DOE/EPRI

Electricity Storage Handbook in Collaboration with NRECA. Report published by Sandia National Laboratories.

[11] Wilson, I. A. G., McGregor, P. G., & Hall, P. J. (2010). Energy storage in the UK electrical network: Estimation of the scale and review of technology options. *Energy Policy*, *38*(8), 4099-4106.

[12] Information on the Scottish Just Transition Commission can be found at https://www.gov.scot/groups/just-transition-commission/

[13] See p.2 of the Paris Agreement

[14] Renewable Energy Systems (2017). Broxburn Energy Storage Project.

[15] VLC Energy UK's largest energy storage plants at http://vlcenergy.com/projects/

[16] The formal role of this type of battery project input is 'Enhanced Frequency Response (EFR)' to the National Grid.

[17] Barbour, E., Wilson, I. G., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. *Renewable and Sustainable Energy Reviews*, *61*, 421-432.

[18] SnowyHydro (2019). Why we need Snowy 2.0 and large-scale energy storage.

[19] Laschon, E. (2019). Snowy 2.0 project given funds and approval for early work phase by Federal Government. Available: https://www.abc.net.au/news/2019-02-26/snowy-2.0-project-approved-for-early-works-stage/10848412

[20] ARENA (2019). Pumped Hydro Storage at https://arena.gov.au/news/technology/pumped-hydro-energy-storage/

[21] See for information on unemployment in the Scottish Highlands http://www.hie.co.uk/common/handlers/download-document.ashx?id=539419df-0a1b-409e-81e9-e037e341f96b

[22] See for information on the concern of the depopulation of the Scottish Highlands https://www.pressandjournal.co.uk/fp/news/inverness/1690463/worry-over-declining-population-figures-in-rural-highland-areas/

[23] EDF Energy (2018) Hinkley Point C: Realising the Socio-economic Benefits

[24] Office of National Statistics (2013) Employment Multiplier Data. Note that Construction industry multiplier is 1.89. Therefore, the total direct and indirect multiplier is calculated by multiplying 6500 jobs by the multiplier value,1.89

[25] See the analysis of Foley et al. (2015) on this point in A long-term analysis of pumped hydro storage to firm wind power, *Applied Energy*, 137, 638-648.

[26] Ofgem (2016). Impact Assessment Guidance at https://www.ofgem.gov.uk/system/files/docs/2016/10/impact_assessment_guidance_0.pdf

[27] HM Treasury (2018). The Green Book. Central Government Guidance on Appraisal and Evaluation

[28] Madani, K. & Lund, J.R. (2010). Estimated impacts of climate warning on California's high-elevation hydropower. *Climate Change, 102* (3-4), 521-538