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Potential Site Energy Reduction for Artificial White Water Courses

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Abstract

Artificial white water courses are becoming popular venues for international competition, recreational sport, rafting and safety services training. Increasingly, these courses are using water pumps to provide a flow of water to the course. While these pumps only operate for relatively short periods of time, almost exclusively throughout the day and evening, they consume large amounts of energy. This thesis aims to identify if renewable generation technologies could be installed on site to reduce the site energy consumption. Electrical storage was also investigated as a way to reduce reliance on the grid and further utilise electricity generated on-site. A study in to course designs that would remove the energy consumption completely was then undertaken. Finally, two case studies were used to study how the solutions from the general investigation could be applied to existing courses.

The results of the investigation found that becoming a net zero energy site could be relatively straightforward depending on the climate of the site. The size of the water pumps and the price received for exported energy would have a large impact on the cost effectiveness of the solutions.

Electrical storage proved problematic due to the high power draw from the pumps. A large number of batteries would be required which had a large impact on the cost. Generally, electrical storage was found to not be feasible for this application.

Non-generation design concepts showed that there may be scope to build and artificial white water course without using pumps yet retaining all the benefits that water pumps bring. Locations for courses using these designs would be greatly limited with regards to suitable sites.

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1. Introduction

Artificial white water courses (AWWCs) are venues that are used for a variety of activities including; recreational and competitive water sports, commercial rafting and emergency services training (Figure 1).

There are currently 7 AWWCs in use around the UK and many more all over the world. Of the courses in the UK, three divert water from a river to provide flow to a channel, and five have pumps installed to move water from a basin to the top of the channel.

Pumped white water courses have many benefits compared to sites that use flow diversion. The ability to instantly turn the course on and off and control the flow rate make pumped white water courses much more attractive to those seeking to build an AWWC. While this type of solution does bring benefits, it is an inherently energy intensive solution.

Figure 1 Left: Lee Valley White Water Centre in use at the London 2012 Olympics. Right: Pinkston Watersports being used for emergency services training.

1.1. Common AWWC Layouts

There are three main types of layouts used for AWWCs all across the world; flow diversion, pumped and dam release. Any AWWC should mimic the characteristics of a natural river commonly used for canoe slalom or other white water sports. Therefore there must be a sufficient gradient, volume of flow, a variety of features and consistency of water flow.

Flow Diversion Courses

Flow diversion AWWCs operate in a similar way to run-of-river hydropower. With regards to run-of-river hydro schemes, the International Energy Agency (2012) note that:

> *“In the absence of such upstream reservoir HPP generation depends on precipitation and runoff, and normally has substantial daily, monthly, seasonal and yearly variations.”p.12*

The statement is true of flow diversion AWWCs as well. Often they can be built in a way that minimises the impact that a change in river level would have on their operation but this cannot be completely negated. The National Water Sports Centre in Nottingham is a good example of careful placement to avoid any negative effects from river level variations. The inlet to the course is placed above a weir on the river Trent, ensuring that the river level at the course inlet stays relatively stable. This configuration is shown in Figure 2.

Figure 2 National Water Sports Centre, Holme Pierrepont: Nottingham (Google, 2016)

While the solution at Nottingham control the river levels at the inlet to the course, the outlet of the course can also affect the site. Figure 3 shows the white water course with the inlet closed. Due to the river level at the outlet the course becomes “backed up” and is unable to operate.

Figure 3 Nottingham "backed up". Image courtesy of Matthew Footitt.

Figure 4 shows the same section of the course as displayed in Figure 3 (from below) in normal flows. Note the lower river level and defined rapids.

Figure 4 Nottingham in normal flow. Image courtesy of Matthew Footitt

Pumped Courses

Pumped AWWCs vary from flow diversion in that they are generally closed loop systems. Water that is pumped down the course returns to a basin where it can be used again. Lee Valley White Water Centre (Figure 5) is an example of this type of course.

Figure 5 Lee Valley White Water Centre (Google, 2016)

Pumped courses don't rely on having sufficient flow from a natural river to operate. This means that the flow rate can be altered and quickly turned on or off if need be. This allows pumped courses to be designed in a way which allows the white water rapids to be quickly changed to suit different purposes if need be (Figure 6). There is no real requirement for this type of course to be placed on a body of water or river to operate.

Figure 6 Modular blocks can be used to modify the flow of water down the course

Since the water is used multiple times, filtration systems can become attractive additions to this type of course, ensuring that the water is of a high quality. Pinkston Watersports in Glasgow makes use of a UV filtration system that is capable of filtering 20,000 litres of water per hour.

Dam Release

White water courses that make use of planned dam releases sit somewhere between an AWWC and a natural river. The Welsh National White Water Centre on the river Tryweryn and the River Washburn (Figure 7) are two examples of this kind of site in the UK.

Figure 7 River Washburn below Thruscross Reservoir Dam

Both of these sites use a heavily modified river bed to create rapids that can be used when a planned dam release occurs. These types of white water courses often have no control with regards to the release of water from the dam. They rely on a schedule to be agreed between the river user and dam operator, making sites like this hard to control.

1.2. Pumped AWWCs in the UK

As noted in the opening paragraph of this thesis, there are a number of pumped AWWCs currently operating in the UK. This section will briefly describe each site that has pumps installed.

Nene Whitewater Centre

Nene Whitewater Centre was the first artificial pumped white water course to be constructed in the UK and is located on the outskirts of Northampton. It was completed in 1999. It is 300m long and has 3 pumps installed to provide a flow of water to the course. In addition, it has facilities that use the natural flow of water to provide a small volume of flow to part of the course. This is shown in Figure 8.

Map data ©2016 Google, Imagery ©2016 DigitalGlobe, Getmapping plc, Infoterra Ltd & Bluesky

Figure 8 Nene Whitewater Centre

Cardiff International White Water Centre

Cardiff International White Water Centre was completed in 2010 (Cardiff Council, 2010). It is located in Cardiff Bay and is a 258m long course fed by 3 pumps. The flow rate can vary from 4 to 16 m/s (Hydrostadium, ND).

Lee Valley White Water Centre

Lee Valley was built for use in the 2012 London Olympic Games and is located in Lee Valley Regional Park just north of Greater London. It was completed in 2011 (EPD, ND). The course is 300m long and has 5 installed pumps, of which 4 are used when operating (Lee Valley, ND; Steve Gibbon, 2016). The pumps operate at approximately 270kW each (Steve Gibbon, 2016). A test reports of one of the pumps installed at Lee Valley can be found in Appendix 1.

The venue has a second, smaller channel which can be use independently or at the same time as the Olympic channel.

Pinkston Watersports

Pinkston Watersports was completed in 2014 (Scottish Canals, ND) and is located approximately one mile from Glasgow city centre. The course has a maximum flow rate of 7.5 m3/s which is provided by three 90 kW pumps.

Pinkston has both a long and short channel. It is only possible to operate one of the channels at a time since the same pumps are used for each.

Tees Barrage

Tees Barrage White Water course is primarily a flow diversion site, but in 2011 four Archimedes screws were installed (UK Water Projects Online, 2011) (Figure 9). The main function of these screws is not to provide flow to the top of the course channel, but to lower the level of the bottom basin at high tide.

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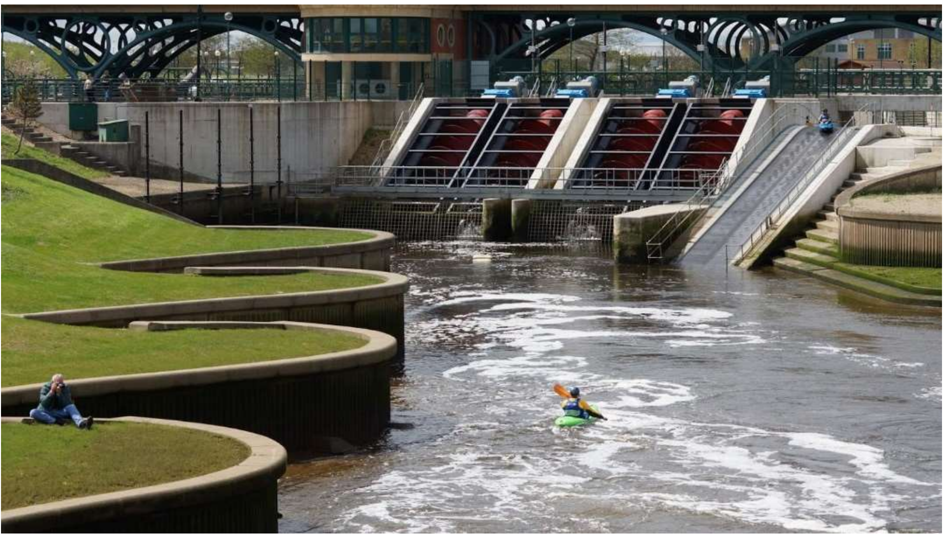
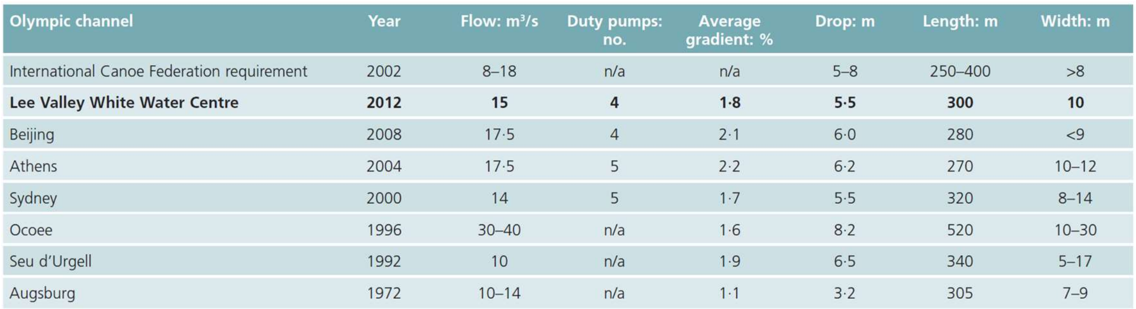


Figure 9 Archimedes screws installed at Tees Barrage

The course is constructed at a point on the river Tees which is affected by the tide. As the tide comes in, the river level increases and the water in the bottom basin cannot naturally flow back to the river Tees. This causes the level of the lower basin to rise so that the white water course backs up and causes the lower rapids to disappear. This is similar to the effect shown in Figure 3.

1.3. Examples of AWWCs Around the World

There a number of artificial white water courses constructed around the world. Most have similar characteristics to those within the UK. Nash *et al.* (2012) compiled the specification of AWWCs that have been used as part of the Olympic Games (Figure10):



Olympic channel	Year	Flow: m^3/s	Duty pumps: no.	Average gradient: %	Drop: m	Length: m	Width: m
International Canoe Federation requirement	2002	8–18	n/a	n/a	5–8	250–400	>8
Lee Valley White Water Centre	**2012**	**15**	**4**	**1·8**	**5·5**	**300**	**10**
Beijing	2008	17·5	4	2·1	6·0	280	<9
Athens	2004	17·5	5	2·2	6·2	270	10–12
Sydney	2000	14	5	1·7	5·5	320	8–14
Ocoee	1996	30–40	n/a	1·6	8·2	520	10–30
Seu d'Urgell	1992	10	n/a	1·9	6·5	340	5–17
Augsburg	1972	10–14	n/a	1·1	3·2	305	7–9

Figure 10 Technical specification of Olympic courses (Nash et al., 2012)

1.4. Pumps Used at AWWCs

Both Pinkston Watersports and Lee Valley White Water Centre provided technical specification that were used throughout the project. Pinkston Watersports is one of the smallest AWWCs operating in the UK, and Lee Valley is the largest. This allowed for a robust investigation with regards to the varying sizes of white water courses.

Pinkston uses three 90 kW water pumps that are connected directly to the low voltage grid network. The pumps are rated at 400V and 210A. When the course is operating they run at maximum output. Figure 11 shows the pumps when not operating.

Figure 11 Pinkston Watersports pumps

In comparison, Lee Valley has five installed pumps, of which four are used to provide a flow of water to the course. These pumps are rated at approximately 270kW each and operate at approximately 400V and 426.9-495.4A (Steve Gibbon, 2016).

1.5. Energy Use

The site energy consumption of a pumped AWWC is heavily dependent on its use throughout the year.

Between September 2015 and July 2016, Pinkston Watersports operated the pumps for 1301.5 hours in total. The average monthly use was 108 hours with the lowest use of any month being December, 45 hours. The busiest month was March, when the course operated for a total of 169 hours. If the assumption is made that all three pumps were running when the course was operating (a typical scenario), the energy use for the year would be 351,450 kWh.

A yearly schedule of use was not available for Lee Valley. Therefore, if the assumption is made that Lee Valley is used approximately as much as Pinkston Watersports, then the energy use for that venue would be 1,041,333 kWh. This estimated energy use is solely for the "Olympic" channel and does not include the shorter course. If the shorter course is considered and usage is estimated at approximately half of the main channel, the three pumps would consume approximately 390,450 kWh. This means that the total energy use for Lee Valley White Water Centre, not including changing rooms and other additional facilities, would be greater than 1,431,783 kWh.

As a comparison, the Aviva Stadium in Dublin consumed 6,425,000 kWh of electricity in 2013 (Byrne *et al.,* 2014). Of the total electricity consumption, the "grow lights" used to aid the growth of the grass on the pitch consumed 1,200 kWh of electricity. The grow lights share some similarities to the water pumps used on AWWCs in that they offer little scope for a reduction in energy use without replacing them with a more efficient system.

A more appropriate venue to compare AWWCs to might be an indoor ski slope, typically called a snowdome. Snowdomes, like AWWCs, attempt to create a venue which allows for a sport typically affected by natural conditions to be undertaken all year round under controlled circumstances. The annual energy consumption for a medium sized facility can be upwards of 1,500,000 kWh (Salome *et al.*, 2012). The temperature inside a snowdome must be kept at a consistent level. This leads to a lower but more constant energy consumption throughout the year. This contrasts a pumped AWWC which has many periods of non-operation. While daily snowmaking may create a spike in energy demands, over a year, the daily demand profile will be much flatter than that of a pumped AWWC.

1.6. Driving Factors

There are a number of reasons for investigating possible energy reducing solutions for artificial white water courses, including cost, energy reduction and carbon emissions.

Cost

Observing the design choices at recently constructed AWWCs in the UK and across the world, the current trend appears to favour pumped courses. The operation of these sites is inherently expensive due to the high power draw of the pumps. This is caused by the volume of flow required by the courses and the head that the water has to be moved by the pumps. Depending on the size of the course, the cost of electricity used to operate the pumps can range from approximately £40-120 per hour. In addition, there are other operating costs for the business which increases the cost of use for the end user ranging from £70-270 per hour. The total operating cost of the pumps over a year can range from approximately £50,000-200,000. Therefore cost can be a significant factor for those who would ideally want to use the course regularly. Full time athletes based at a pumped AWWCs can be required to train twice a day but this may be unachievable due to the cost involved. Any reduction in energy use would have a positive effect on the costs associated with operating a pumped AWWC not only for the operator but potentially also the end user.

Carbon Emissions

In addition to the significant cost of operation, there are other factors to consider such as the carbon footprint of the site. The Intergovernmental Panel on Climate Change (IPCC, 2014) state that:

> *"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have widespread impacts on human and natural systems" (p.2)*

They go on to say:

> *"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and oceans have warmed, the amounts of snow and ice have diminished, and sea level has risen" (p.2)*

There has been a worldwide driver to try to reduce both consumption and greenhouse gas emissions. In 2008 the UK government introduced the Climate Change Act which states that:

> *"It is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline" (s.1 (1)).*

Because of this there has been a shift towards low carbon generation technologies and a higher proportion of distributed renewable generation, this increase is shown in Figure 12.

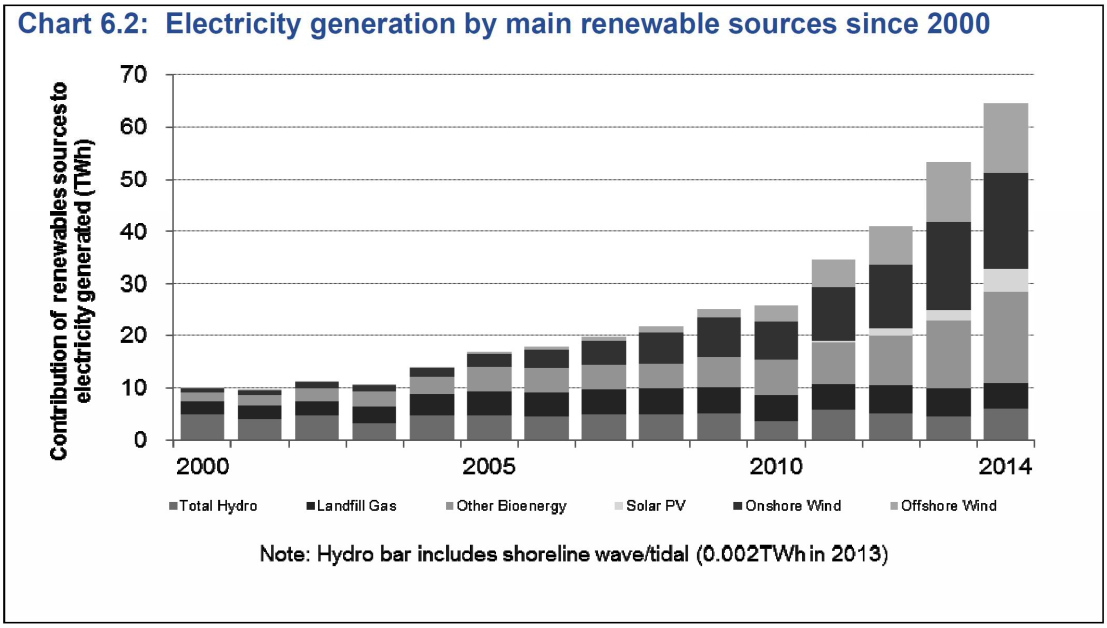


Chart 6.2: Electricity generation by main renewable sources since 2000

Note: Hydro bar includes shoreline wave/tidal (0.002TWh in 2013)

Figure 12 Electricity generation by main renewable sources since 200 (DUKES, 2015:p164)

While there is now an increase of renewable energy supplied to the UK grid, this does not guarantee that energy consumed from the grid has been generated from renewable sources. For this reason, the Department of Energy & Climate Change and the Department for Environment, Food and Rural Affairs have provided emission values per kWh of grid electricity consumed (DECC and DEFRA, 2016). Using this value it is possible to estimate the carbon emissions for a consumer. As an example, the carbon emissions for Pinkston Watersports over the course of a year are approximately 162,415 kg of $CO2_{e.}$

Both cost and carbon emissions can be directly affected by energy consumption. For this reason it would be beneficial to investigate ways to reduce the energy consumption of AWWCs.

1.7. Aims

As discussed previously, nearly all white water courses constructed recently in the UK use pumps. This preference in course design is also evident across the world, with newly constructed courses in the United Arab Emirates, Brazil, United States of America and New Zealand using pumps to provide a flow of water.

Due to the nature of pumped white water courses, they are inherently energy intensive. Moving a large volume of water, even with a head of only a few metres, results in a high power draw. Regardless of this limitation, the current trend for new AWWCs in the UK appears to be using pumps to provide a flow of water. Due to both cost and environmental concerns, it would be beneficial to attempt to reduce the energy consumption of AWWCs.

Because of this, the focus of this thesis will be to identify solutions that will reduce the overall energy consumption of an artificial white water course. The baseline throughout the investigation will be to become a net zero energy site. The aim will be to achieve this through the use of either renewable generation or the design of the course. Any solution should retain all the advantages provided by modern pumped artificial white water courses.

Nearly all AWWCs have on-site changing facilities and offices. They often also have meeting rooms and cafes. These were not considered throughout the project as investigations with the focus of reducing the energy consumption of buildings is an area with extensive coverage.

Solutions for both retrofit and new courses were considered throughout the project. While any energy consumption reductions achieved through the design of the course would be hard to implement at an existing AWWC, any solution involving renewable generation would be suited to both retrofits and new courses.

1.8. Project Outline

In order to achieve the aim of the project a number of steps were undertaken. First there was a review of current renewable generation and electrical storage technologies. This was used to identify technologies which could be suitable for inclusion in a system that would reduce the energy consumption of an AWWC.

Using this information, modelling was undertaken to study, in depth, the quantitative effect that the inclusion of specific generation and storage technologies would have on the energy consumption of an AWWC.

An investigation into different design options that have currently not been implemented at AWWCs was then undertaken. This investigation focused on completely removing the energy consumption of an AWWC while still retaining the benefits of a pumped AWWC.

Finally, case studies of Pinkston Watersports and Lee Valley White Water Course were undertaken to identify how the energy consumption of existing AWWCs could be reduced.

2. Renewable Generation and Site Operation

An obvious solution that would reduce the amount of grid energy used by pumped AWWCs would be the installation of on-site renewable generation. Demand could then be either fully or partially met by the renewable generation.

Renewable generation can have the potential to generate large amounts of energy, yet has some significant drawbacks that must be overcome if it is to be utilised well. The stochastic nature of many renewable sources means that power generation may not meet the demand (Figure 13).

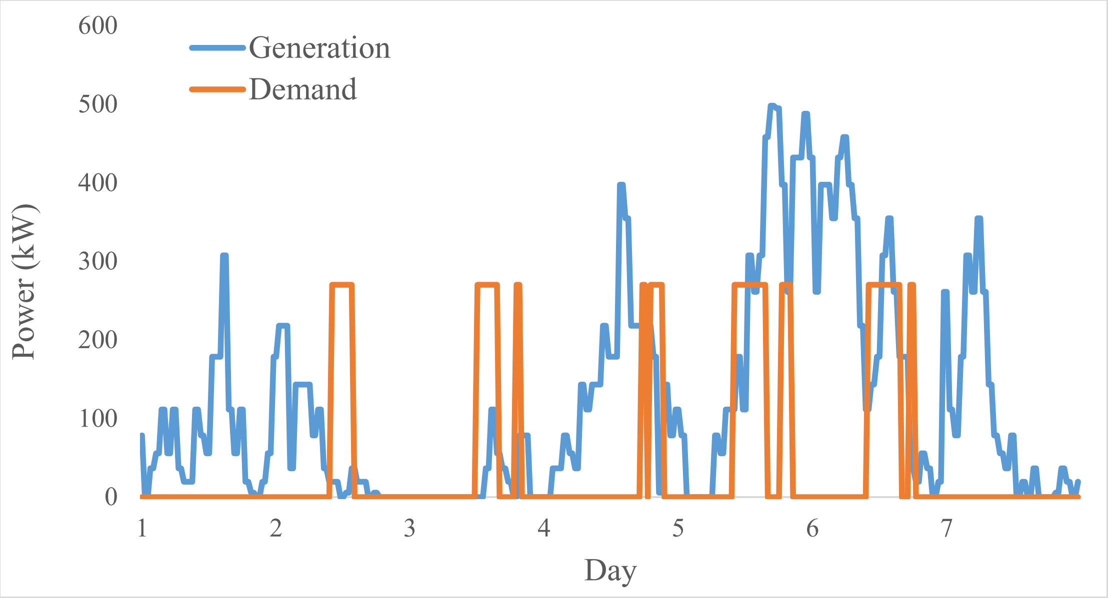


Figure 13 An example of mismatched energy generation and demand.

To overcome this limitation, despatchable generation could be used alongside stochastic generation. The output of despatchable generation can be controlled to ensure that the desired output is achieved. Another solution would be the use of electrical energy storage.

Since the location and surroundings of AWWCs can range from urban to rural settings, the suitability of different renewable generation technologies may vary significantly. For example, the installation of a large wind turbine may not be possible in an urban setting such as Pinkston Watersports or Cardiff Bay, but may be more feasible in the more rural setting of Lee Valley Regional Park. Because of this, a wide range of renewable generators must be considered. A number of different operating scenarios and renewable technologies are therefore explained in this section.

2.1. Site Energy Definitions

In order to better understand what impact the installation of renewable energy might have, it is important to define a number of different ways a site could operate. While these definitions are more commonly used for buildings, it is possible to apply them elsewhere.

Net Zero Site Energy

A net zero site energy site will generate as least as much energy as it consumes over a year (Hootman, 2013). The on-site renewable generation will not necessarily match the demand instantaneously. Generated electricity that is not used on-site is exported to the grid.

Net Zero Source Energy

A net zero source energy site is similar to that of a net zero site energy but also has to take in to account losses during transmission of energy from off site (Torcellini *et al.*, 2006). Therefore the total on-site renewable generation must be higher than the total consumption of the site.

Autonomous

An autonomous site is able to supply all of its demand using conventional or renewable on-site energy generation. This means that no energy is imported from the grid. If a grid connection is available, any excess energy can be sold to the grid.

2.2. Site Operation

For the purpose of this investigation, any solution that involved more than one technology, be it generation or storage, will be considered to act as a micro grid. Utsun *et al.* (2011) define a microgrid as:

> *"a small-scale power system with a cluster of loads and distributed generators operating together with energy management, control, protection devices and associated software" (p.4031)*

By operating the technologies together in this way it allows for the system to make decisions regarding whether generated electricity should directly power the pumps, charge the batteries or be sold to the grid.

For a site to operate autonomously, the system would also require a way to connect and disconnect from the grid. Doing this is beneficial as any excess electricity can be sold to the grid and any deficit can be imported from the grid. Some renewable technologies are able to directly connect to the grid, removing this obstacle. Technologies that are not able to do this must have a way to match frequency and voltages the instant that the microgrid is connected or disconnected. The Consortium for Electric Reliability Technology Solutions have developed a static switch which is able to do this (Lasseter *et al*., 2011).

2.3. Generation Technologies

There are a number of renewable technologies that have become popular for smaller scale distributed generation. Of the available technologies, few are capable of generating enough electricity to satisfy the high power demands of an AWWC. Because the aim of the investigation was to identify feasible renewable generation technologies, immature technologies such as hydrogen were considered to be out of scope.

Wind

Wind turbines harness the energy of the wind across the surface of the earth to generate electricity. Wind energy can be extremely abundant depending on the area, making it a popular choice with regards to distributed generation. Average wind speeds in the UK are generally higher than much of Europe (Figure 14), making wind energy a popular choice for distributed generation.

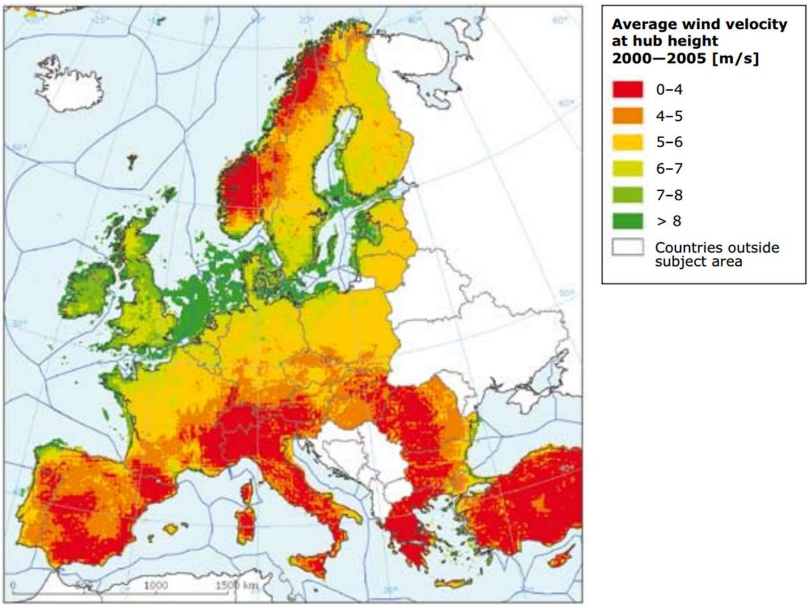


Figure 14 Average wind velocity across Europe (EEA, 2009)

Wind turbines can vary greatly in size and design. There are both vertical and horizontal axis design, yet the most popular design is a three bladed horizontal axis turbine (Burton *et al.*, 2011). The variation in design allows for wind turbines to be appropriately sized for their planned use, making them a very versatile form of generation. Turbines are able to operate either independently or connected to the grid.

While there can be variation in wind turbine design, the power output can also vary. This is defined by the expression:

$$P = \frac{1}{2} C_p \rho A U^3$$

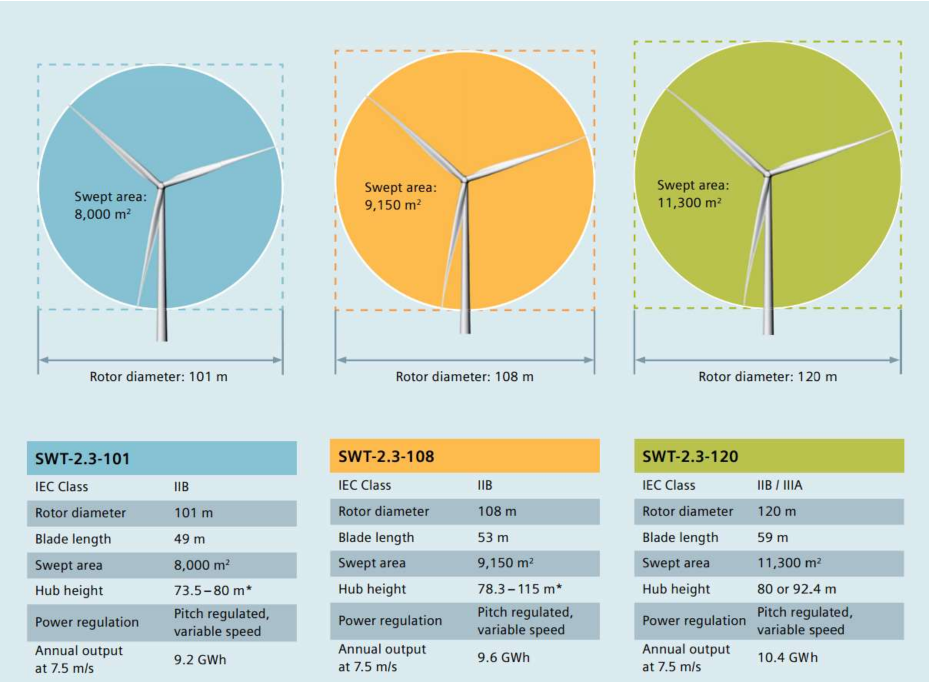
$\rho = density\ of\ air$

$A = the\ rotor\ swept\ area$

$C_p = the\ power\ coefficient$

$U = the\ wind\ speed$

Because the density of air and wind speed are affected by the climate, there are only two variables that can be controlled in order to influence the power output of a turbine. The power coefficient is the ratio of power generated to wind passing through the turbine blades. A number of factors can effect this ratio such as the efficiency of the generator, blade design, and rotation speed. The larger the rotor swept area, the more air is flowing past the turbine, increasing the potential for energy generation. Figure 15 shows how different swept areas and turbine sizes can affect the output.



SWT-2.3-101	
IEC Class	IIB
Rotor diameter	101 m
Blade length	49 m
Swept area	8,000 m²
Hub height	73.5 – 80 m*
Power regulation	Pitch regulated, variable speed
Annual output at 7.5 m/s	9.2 GWh

SWT-2.3-108	
IEC Class	IIB
Rotor diameter	108 m
Blade length	53 m
Swept area	9,150 m²
Hub height	78.3 – 115 m*
Power regulation	Pitch regulated, variable speed
Annual output at 7.5 m/s	9.6 GWh

SWT-2.3-120	
IEC Class	IIB / IIIA
Rotor diameter	120 m
Blade length	59 m
Swept area	11,300 m²
Hub height	80 or 92.4 m
Power regulation	Pitch regulated, variable speed
Annual output at 7.5 m/s	10.4 GWh

Figure 15 An example of wind turbine specifications (Siemens, 2015: p.7)

While the output of a wind turbine varies with wind speed, this technology is not able to operate at very low or very high speeds. Turbines have cut-in, cut-out and rated wind speeds. Below the cut-in wind speed, a wind turbine will not generate any electricity as the velocity of the wind is not high enough to rotate the blades. Above the cut-out wind speed, a turbine will stop generating electricity. This is to avoid any damage to the turbine caused by high wind speeds. At the rated wind speed and above, the turbine output will be at its maximum. These constraints make it important to size wind turbines according to the wind profile of the site. Figure 16 illustrates an example power curve for a turbine.

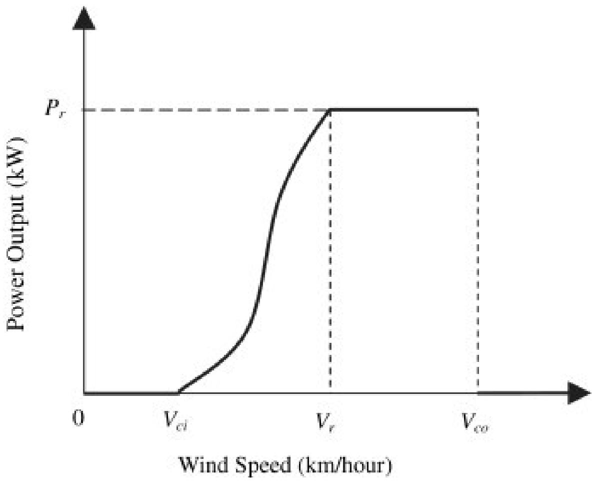


Figure 16 (Xie and Billinton, 2011)

Hydro

According to the International Energy Agency (IEA) (2012), hydroelectricity is one of the most reliable and proven renewable generation sources. It also has the capability to be used as a form of energy storage. The IEA also note that between 2005 and 2012, the increase in generation capacity for hydropower was larger than all other renewables sources combined.

Hydro generation harnesses the potential energy of water at a height. The force of the water falling is used to rotate a turbine connected to a generator. Breeze (2005) notes that there are two main ways to design hydro power schemes: dams and run-of-river. Dams are able to operate as energy storage if configured as a pumped hydropower scheme (Figure 17). Construction of hydropower facilities is generally expensive, especially with regards to large scale facilities. Operational costs are relatively low, so profits can be made over a long period of time.

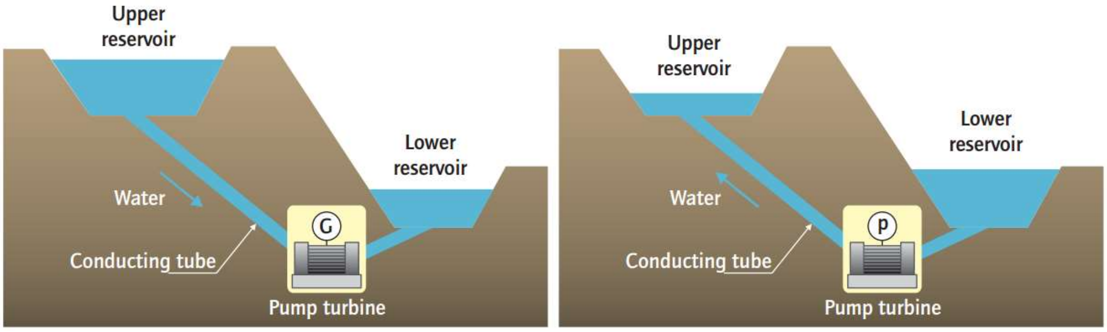


Figure 17 Pumped Hydro Scheme design (Inage, 2009)

Run-of-river hydropower schemes differ from those using an upper reservoir in that there is a much smaller head, although there may still be a small barrage to increase this (Figure 18). Though this type of site is normally smaller in scale, it brings a number of advantages. The number of potential sites is increased and the costs are much lower than larger schemes.

Figure 18 Low-head run-of-river hydropower scheme (Anderson et al., 2014)

Despite hydropower being the largest source of renewable electricity worldwide, it was not considered to be a suitable technology for this project. Bearing in mind the operation of AWWCs, it would make little sense to use electricity generated from a small-scale hydro scheme. Instead the water could be used to provide flow directly to a course, thus removing energy losses that would occur during both the generation of electricity and consumption in the water pumps.

Solar

Solar energy is the most abundant renewable energy source on earth. The amount of solar energy that the earth receives from the sun is approximately $17\text{x}10^{16}$ Watts (Cherne, 1975). Of that, approximately 40% is reflected back into space, and therefore only around $10.3\text{x}10^{16}$ Watts reach the surface (Cherne, 1975). The W/m^2 can significantly vary across the world due to the distance that light has to travel through the atmosphere. The longer it has to travel, the less energy reaches the surface. The highest concentration of solar energy is available at the equator, while the lowest is at the poles. At the equator, available solar energy is relatively constant throughout the year. Towards the poles of the earth, there is a seasonal variation as the Earth tilts on its axis through the year. Figure 19 demonstrates how more northerly countries have a lower potential for energy generation from photovoltaic than those closer to the equator.

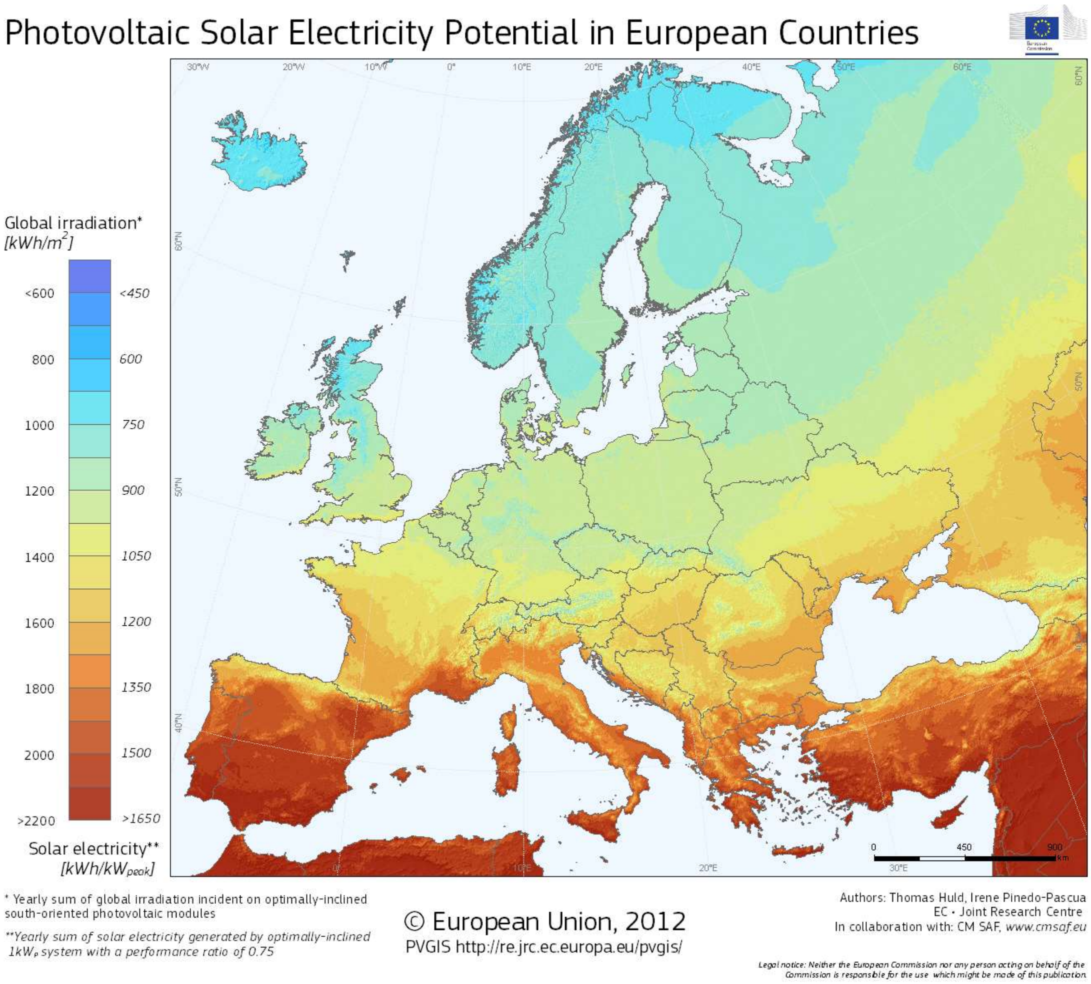


Figure 19 PV Electricity Generation Potential in Europe (European Union, 2012)

In addition to the lower solar irradiation that the UK receives, the climate is dominated by the Atlantic which can lead to a relatively low number of days of sunshine a year.

While the efficiency of photovoltaic panels changes only slightly throughout its working range, the output will be affected by reduced irradiance on the panel (Patel, 2006).

With regards to the process of generating electricity from solar energy, the conversion from solar to electrical energy is relatively inefficient, ranging from approximately 15-22% (Bunea *et al.*, 2006). This can lead panels requiring a large area to produce the required capacity. Using data from the Energy Saving Trust (2015) it is possible to estimate a general power rating of approximately 140W/m^2 for solar panels.

Biomass

Biomass is often touted as a cheap and carbon neutral way to generate both electricity and heat. Fuel is burnt in order to generate steam which can be used to rotate a turbine connected to a generator. Waste heat from the exhaust flue can be captured in a heat exchanger so it can be utilised. A Rankine cycle (Figure 20) can be used for energy generation, making this process very similar to more traditional generation. This means that biomass can be used as a despatchable generator, allowing it to be controlled to meet the demand instantaneously.

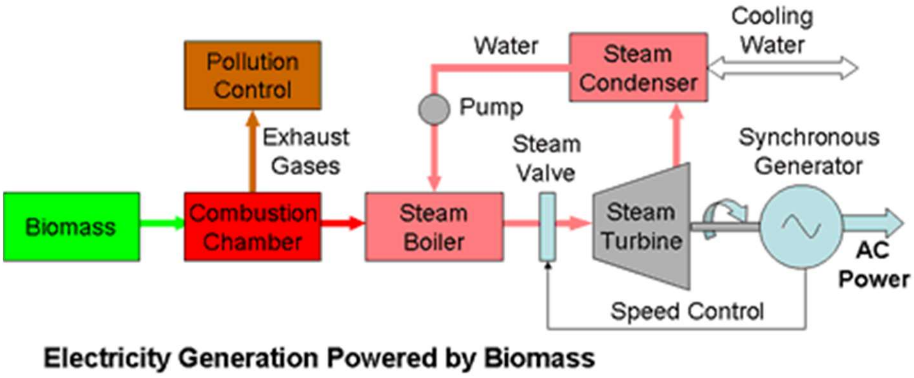


Figure 20 Energy Generation Biomass (Woodbank Communication Ltd, ND)

There has been a debate regarding whether biomass is carbon neutral and how sustainable the supply is. The Department for Energy and Climate Change (2014a) published a report that suggests that how the fuel is sourced, including the growing conditions and transportation, can have a large impact on the carbon content. Some of the important steps in this process are outline in (Figure 21). Due to the large scope of this area, the effect on the carbon footprint for different biomass sources were not considered for electrical generation. Best and worst case carbon content per weight of fuel will be used with this information taken from the DECC BEAC tool (DECC, 2014b).

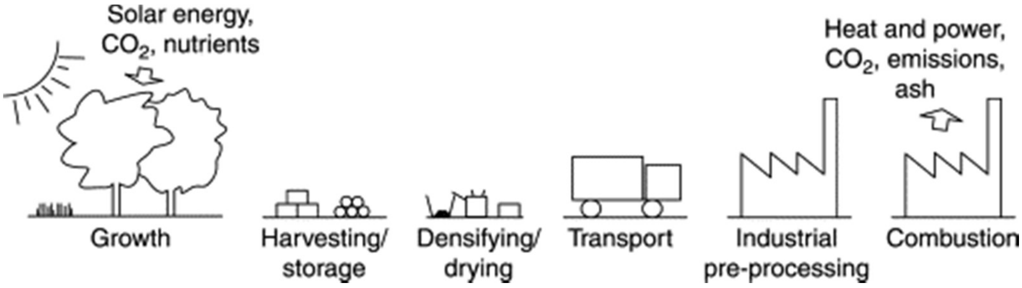


Figure 21 Life Cycle (Mandø, 2013 p.61)

Generally when biomass is used to generate electricity the excess heat is also utilised, which can in turn significantly increase the overall efficiency of the plant. While there is scope to utilise this heat within the office buildings and changing rooms, the thermal demands of these facilities would likely not match with the generation. Often the peak demand for office heating occurs early in the morning when the offices are being heated before occupants arrive. At this time, the white water course would not be operating. For this reason, heat was not considered as part of the biomass investigation.

3. Electrical Energy Storage

Electrical energy storage can be advantageous as part of a system with renewable energy generation. The ability to store generated energy and use it when needed makes a stochastic renewable supply much more versatile in its application. Nevertheless, there are some significant hurdles that need to be overcome if electrical energy storage is to become a larger part of our current energy infrastructure. Chief among these drawbacks is the high cost of electrical storage which becomes more apparent at large capacities. This can often make grid-scale storage unfeasible with the exception of a small number of technologies.

Evans *et al.* (2012) note that there are four classes of electrical energy storage systems: mechanical, electrical, thermal and chemical. The International Electrotechnical Commission split chemical energy storage into two categories: electrochemical and chemical (Figure 22).

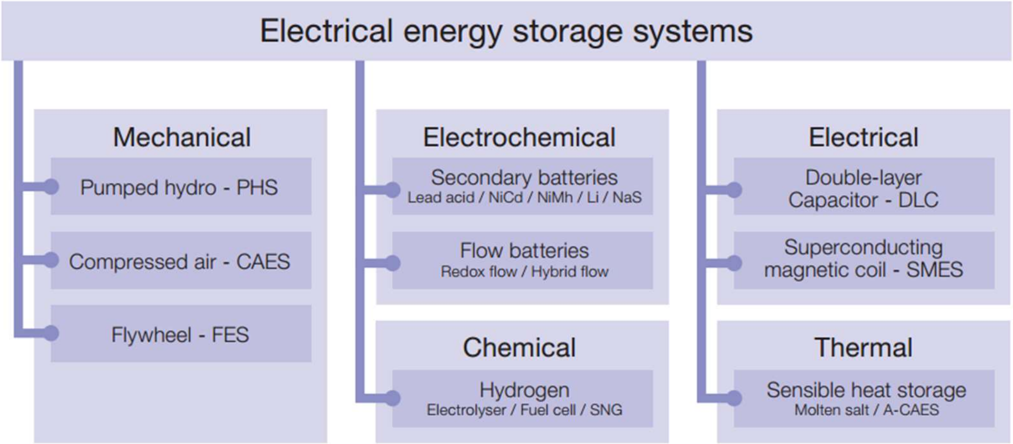


Figure 22 (International Electrotechnical Commission, 2011)

There are only four types of energy storage systems that have an installed capacity greater than 100MW: sodium-sulphur batteries, pumped hydro, compressed air and thermal storage (Evans *et al.*, 2012)

3.1. Mechanical

Mechanical energy storage systems convert electricity to kinetic or potential energy which can then be converted back to electrical energy when required. Some examples of these types of systems are compressed air, pumped hydro or fly wheels (Evans *et al.*, 2012). The efficiency of this type of storage is limited due to the conversion of energy from electrical-mechanical-electrical, although high efficiencies can still be achieved.

Compressed Air Energy Systems

Compressed air energy systems (CAES) typically make use of existing geological features such as salt caverns, aquifers and abandoned mines (Abbaspour *et al*., 2013). Excess electricity is used at times of low demand to compress air and store it in the reservoir. When demand is high, the compressed air can be used to generate electricity. A simplified schematic for this type of system is illustrated in Figure 23.

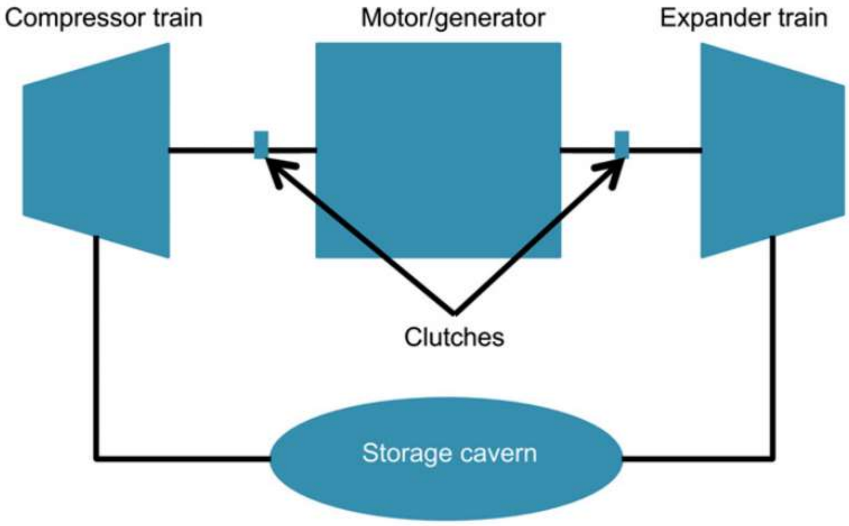


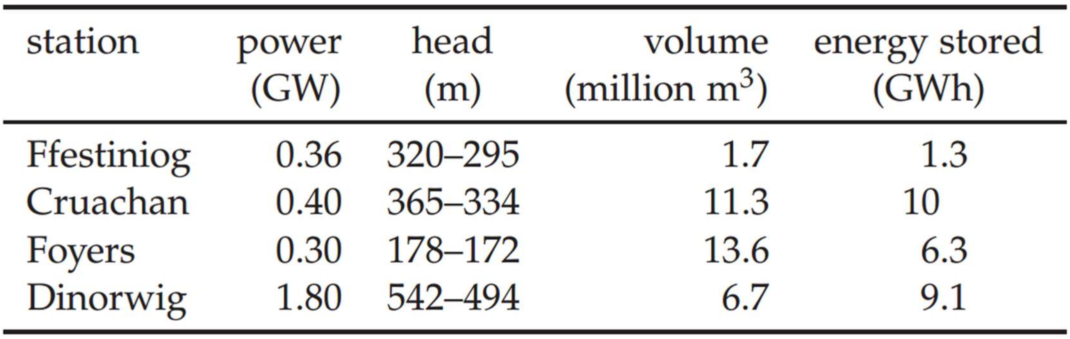
Figure 23 CAES Schematic (Fertig, E., Apt, J., 2011: p.2331)

There are currently two CAES plants operating worldwide: Huntof, Germany and Alabama, USA (Raju and Khaitan, 2012). Both of these plants operate at a relatively large scale, 290 MW and 110 MW respectively. The focus of this type of storage appears to be at a utility scale and the geological requirements severely limit suitable locations (Fertig and Apt, 2011). Therefore it was not considered as a feasible technology for integration with AWWCs.

Pumped Hydro

As discussed in Section 2.3, hydropower can also be used as a storage medium. Pumped hydro storage uses excess electricity to pump water to a reservoir. The water can then be used to turn a turbine to generate electricity when there is demand. (Figure 17).

Pumped storage has the advantage of being able to store significant quantities of energy but is a net consumer since more is used pumping the water than is generated. Figure 24 lists the specifications of pumped hydro storage currently operating in the UK.



station	power (GW)	head (m)	volume (million m^3)	energy stored (GWh)
Ffestiniog	0.36	320–295	1.7	1.3
Cruachan	0.40	365–334	11.3	10
Foyers	0.30	178–172	13.6	6.3
Dinorwig	1.80	542–494	6.7	9.1

Figure 24 Pumped storage schemes operating in the UK (MacKay, 2009. p.191)

With regards to artificial white water courses, it makes little sense to store water for energy generation when instead the water could be used directly in the course. Therefore pumped hydro was not considered a suitable form of electrical energy storage.

Flywheels

Flywheels can be used to convert electrical energy to kinetic energy for later use when there is demand. The energy is stored in the angular momentum of a spinning disk. The electric motor that is used to spin the wheel is also used to generate electricity (Figure 25).

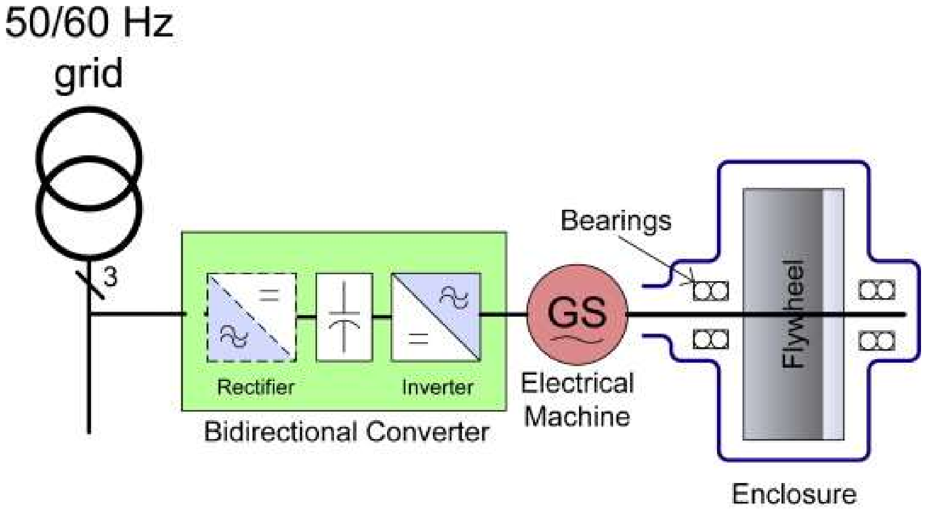


Figure 25 Flywheel Energy Storage System schematic (Sebastian and Alzola, 2012)

While flywheels can have a high efficiency, high power density, quick recharge and fast response times (Evans *et al*., 2012) they are only suitable for short storage times, which can be as low as 5-30s (Ramli *et al.*, 2015). In the case of a pumped AWWC where there may be days between use, this type of storage would be unsuitable.

3.2. Electrical

Electrical energy storage removes any need to convert the energy which can improve the peak efficiencies. Storage technologies that belong in this category include capacitors, super-capacitors and superconducting magnetic energy storage systems.

Capacitors

Capacitors store energy in an electric field between two electrodes that are separated by an insulating material (Wang, 2010). They have a relatively low capacity and energy density making them unsuitable for most large scale storage applications. Capacitors are generally not used for energy storage as they have been superseded by super-capacitors (Evans *et al*., 2012).

Supercapcitors

Some important features of supercapcitors are their long life, fast charging and discharging properties, and a high power density (Teymourfar *et al.*, 2012).

Supercapcitors suffer from a high rate of self-discharge making them unsuitable for any application where there may be a significant duration between uses (Chang, 2013). Both capacitors and supercapacitor are well suited to short term energy storage to control power quality. Due to their high self-discharge rate, supercapacitors were not considered to be a feasible technology with regards to this investigation.

Superconducting Magnetic Energy Storage Systems

Superconducting magnetic energy storage systems store electrical energy in the magnetic field of a large coil. These systems are still relative immature and the focus is on power quality and short term fluctuations (Weedy *et al*., 2012). Therefore this would not be suitable for the longer term electrical storage needs of an AWWC.

3.3. Chemical

Chemical energy storage consists of conventional batteries, flow batteries and fuel cells. While the technology used in chemical storage technologies is advancing relatively quickly due to the increasing popularity of consumer electronics like smartphone and laptops, it is less widely used on a larger scale.

A major limitation to all conventional chemical batteries is that as they go through charge and discharge cycles, they degrade, reducing both the capacity and performance. In order to reduce the degradation over their lifetime, the total depth that they are discharged can be limited. By doing this the number of cycles can be significantly increased.

With all forms of chemical energy storage comes concerns regarding the resources used in their construction. Many batteries use toxic chemicals which can pose problems with regards to disposal or recycling at the end of their life cycle.

Lead-Acid

Lead-acid batteries are one of the most mature battery technologies. Nevertheless they have short life cycles, low energy density and their capacity can be affected by low temperatures. Regardless, they are one of the most widely used electrical storage systems worldwide. Their versatility and relatively low cost compared to other battery technologies often make them the only feasible option for larger scale electrical storage. Microgrids often utilise lead-acid batteries as a form of electrical storage. The Isle of Eigg uses 96 lead acid batteries as electrical storage (Chmiel and Bhattacharyya, 2015) while Kodiak in Alaska have a 3 MW (2 MWh) lead acid battery installed as part of their microgrid (Bunker *et al.*, 2015).

Sodium Sulphur

Sodium sulphur batteries appear to be a more attractive option due to their high number of cycles before degradation and high energy density. While there are examples of Na-S batteries for large scale storage across the world, a major limitation appears to be the cost. Notrees Battery Storage System build by Duke Energy cost approximately £1000/kWh (Duke Energy, 2011), slightly less than twice the cost of Lead-acid batteries. Currently the technology appears to be more suited to large grid-scale installations, and was therefore not considered suitable as part of a system installed at an AWWC.

Flow Batteries

Flow batteries operate due to the reaction between two liquid electrolytes that contain ionized metals (Alotto *et al.*, 2013). Fuel cells are a relatively immature technology when compared to technologies like lead acid batteries which have been in use for over a hundred years. They are also an expensive technology making them an unattractive option when cost is a factor.

3.4. Thermal

Thermal energy storage involves the storage of heat in a material, either liquid or solid, which can then be used to generate steam to be used for energy generation.

This type of storage has been successfully implemented at concentrating solar power plants. Mirrors are used to concentrate the sunlight on to one point which heats a molten salt solution. This molten salt solution can then heat water which is used in a Rankine cycle (Figure 26). A plant like this is able to store the hot molten salt for a number of hours so that electricity can be generated over night or when there is enough demand.

There are a number of these types of plants operating around the world. In 2011 Spain had seven 50 MW plants online, each with the ability to generate for 7.5 hours without solar energy input (Dunn *et al.*, 2012).

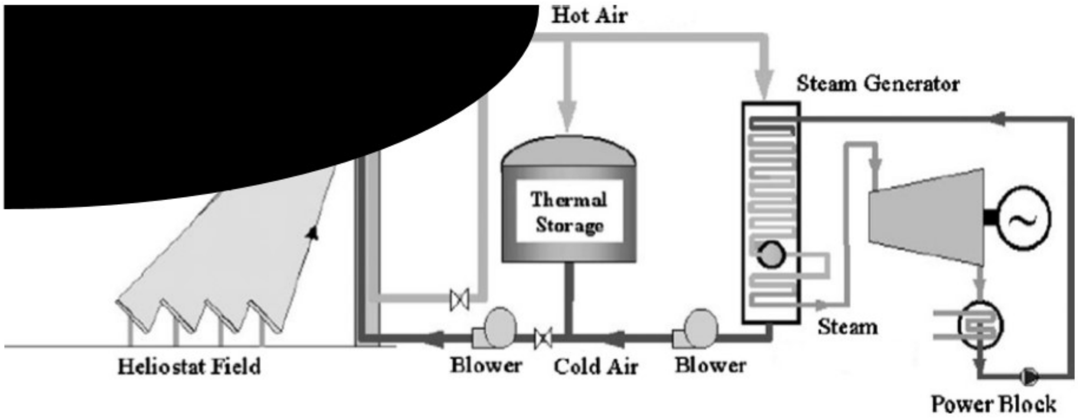


Figure 26 Solar Thermal Power Plant Schematic (Ávila-Marín, 2011)

While thermal energy storage has been demonstrated as viable way to generate and store energy, it is not considered a suitable technology with regards to AWWCs. The large capacities vastly outsize the demand of an AWWC, making them more suited for grid-scale energy generation rather than small-scale distributed generation. In addition, while the focus of the investigation is on AWWCs without consideration of their location, solar collecting plants require an area with a high availability of solar energy. This would significantly limit the number of suitable sites.

4. Modelling an Artificial White Water Course

In order to investigate what mix of generation and storage options would be suitable for supplying the pumps of an AWWC, a modelling investigation was undertaken.

Because the aim of this investigation was to identify if any renewable technologies would be able to have a positive impact on the overall energy consumption of a pumped AWWC, there were no limitation with regards to the installation of renewable technologies.

4.1. Software

MERIT, HOMER and Microsoft Excel were considered as possible options for the supply-demand investigation.

MERIT is an open source software packaged in development at the University of Strathclyde. The software package is a quantitative evaluation tool (ESRU, ND) which will inform the user of the level of match between the supply and demand. MERIT can handle multiple loads and generators.

HOMER is a software package that was originally developed by the National Renewable Energy Laboratory (HOMER Energy LLC, ND). It is now in development by HOMER Energy LLC, Colorado. The main purpose of HOMER is the optimisation of microgrids, specifically the ability to determine the best solutions for a system that may have multiple loads or generators. Essentially, HOMER is able to undertake supply-demand matching.

Microsoft Excel can be used to manually create a tool for supply-demand matching. While this gives the user full control, it makes creating problems more time consuming.

While all of the available software options would have been suitable for the investigation, HOMER was chosen as the software package to be used. This choice was made due to HOMERS ease of use and in-depth simulation outputs. In addition the

HOMER software package offered increased reliability and stability over the other options. This was a major consideration when choosing a package.

4.2. Constructing the Models

First, a number of models were created in HOMER. Demand profiles, loads, generators, resources (wind and solar gains) and convertors (invertors and rectifiers) had to be input to HOMER.

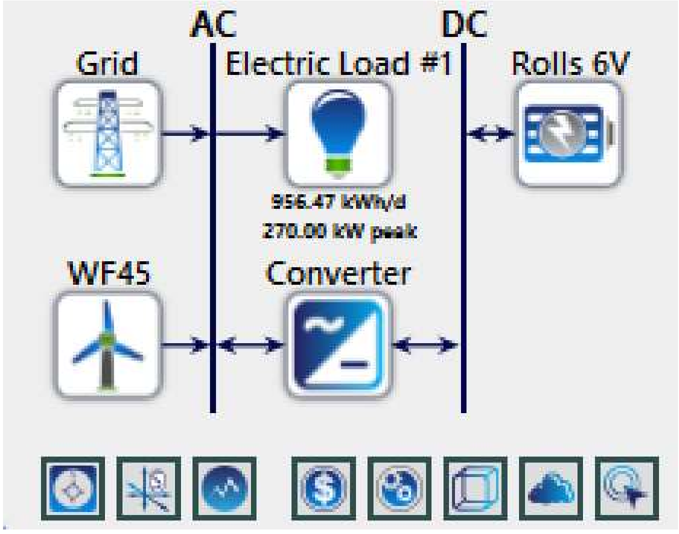


Figure 27 HOMER model schematic

Four models were created using different generation technologies and demand. A summary of these models is shown in Table 1:

Table 1 Model outlines

Model	Pump Size (kW)	Number of Pumps	Type of Generation
1	90	3	Wind
2	90	3	PV
3	270	4	Wind
4	270	4	PV

Electric Load

Using a calendar of bookings for Pinkston Watersports from September 2015-August 2016, a typical demand profile for an AWWC was created. This could then be imported to HOMER to use as a load throughout all scenarios, albeit with modification for model 3 and 4.

A time step of 30 minutes was used for the demand profile, this corresponds with the half hourly slots that Pinkston Watersports operate under. It was known that one day a week only two pumps would operate for a booking and this was reflected in the demand profile. For the rest of the bookings the calendar did not specify how many pumps were being used. Therefore a worst case scenario of all three pumps operating at full power was assumed to be the case.

Grid Connection

In all scenarios constructed in HOMER, a grid connection was included, regardless of if the solution would create an autonomous facility. Any solution likely to be implemented at an AWWC would need to include a grid connection as a backup in case of failure of any generation technologies. In addition, installed generators would likely need to have maintenance undertaken throughout the year, if no grid connection was present, the pumps would not be able to operate during those periods.

A grid connection would also allow for excess electricity generated from a renewable source to be sold to the grid if the scenario did not include electrical storage.

Electrical Storage

Lead-acid batteries were chosen as the electrical storage technology in HOMER. This choice was due to their high capacity and relatively low cost. In addition, there are few examples of electrical storage systems of this scale that do not use lead-acid batteries.

The battery specification of the Rolls 6CS27P (Rolls, 2014), was input to HOMER. The specification sheet can be found in Appendix 2. HOMER allowed for the voltage, capacity and hour rate at varying currents to be input.

This battery is a 6V deep cycle battery designed for use with renewable generation. They are similar to the batteries installed on the Isle of Eigg microgrid (Chmiel and Bhattacharyya, 2015).

The Rolls 6CS24P allows for a maximum current draw of 304A, making it a suitable choice for supplying the water pumps which would be installed on site. One major drawback of lead-acid batteries in scenarios similar to this is their low voltage. The low voltage means that in order to meet demand requirements, the minimum number of batteries in a string must be 67. One string is required per pump. Because of this, as the number of pumps increase, the minimum cost of electrical storage for an AWWC rises.

In order to extend the lifetime of the battery a minimum charge value was set to 30%.

Converters

Depending on the type of renewable generation, the electricity generated may be AC or DC. The pumps operate using AC and the batteries, DC. For this reason an inverter would be needed to utilise electrical storage. A rectifier would also be needed if renewable generation producing electricity in AC and electrical storage was part of the simulation.

HOMER allows for a single converter which can act as both an inverter and a rectifier. This was included in the model with a large capacity to ensure that the converter would not become a bottleneck.

Renewable Generation

The renewable technologies included in the investigation were wind turbines and photovoltaic panels since these were identified as potentially being able to meet the needs of an AWWC. The wind turbine specification used in the simulations were from the HOMER database.

The Windflow 45-500 is a two-bladed design with a rated capacity of 500kW. This turbine uses a synchronous generator allowing it to be directly connected to the grid (Windflow, NDa). Windflow UK are a subsidy of Windflow Technology Group based in New Zealand. They specialise in mid-size turbines that they claim are lighter and more compact than conventional three-bladed turbine, allowing easy transportation and on-site installation (WindFlow UK, NDb). The specifications and characteristics of this turbine made it a suitable choice for use in the model. The cost per turbine used in the investigation is estimated from values provided in Ohunakin *et al.* (2012) and Rohani & Nour (2013).

Generic photovoltaic panels included in the HOMER database were used in the model. Each panel is 1kW, non-tracking and produces DC current. The generic panels were used as there would be little variation between different models of solar panels. Any small differences could be estimated using the results from the model.

A short biomass investigation was carried out independent of HOMER. The aim of this short investigation was to calculate the tonnes of fuel needed per year in order to generate enough electricity to satisfy the demand. The reason that HOMER was not used in this study is that if a biomass plant was to be used for generation, it would likely be the only form of onsite energy generation making an investigation in to the total fuel required relatively simple.

Resources

In order to generate realistic output for the renewable generation resource data was input to HOMER. Historical data was acquired from the MERIT/ESP-r database. Glasgow was used as a basis for the simulations. Wind speed, temperature, and solar radiation (both direct and diffuse) data was input to HOMER.

Costs

Throughout all scenarios undertaken in HOMER, technology, fuel and maintenance costs were set to zero. HOMER attempts to satisfy the demand of a load but also takes in to account maintenance and deterioration costs. This can lead to technologies not being utilised due to costs associated with deterioration of a technology, most evident in batteries. The purpose of the investigation was to try and find feasible technologies therefore this feature was not considered necessary.

An analysis of equipment costs was undertaken out with HOMER using example costs from a number of sources. Maintenance costs were not considered in the study. Table 2 shows the costs used in the study.

Table 2 Costs used in the investigation

Item	Cost	Source
Grid Electricity	15p/kWh	Pinkston Watersports
Windflow 45-500	£550,000	Ohunakin et al, 2012; Rohani and Nour, 2013
PV Panels (per kW of capacity)	£3,300	HOMER
Inverter/Rectifier	£55,000	Solaris, ND

The cost of electricity used in the investigations was £0.15 per unit (per kWh). This value was provided as a typical example of what Pinkston Watersports currently pay for their energy. The price received per unit of exported electricity was set at £0.05. This value was projected using Feed-in-Tariff (FIT) estimations produced by the Energy Savings Trust (ND). The price per unit was reduced as Feed-in-Tariff rates would not apply to electricity sold on such a large scale. The FIT scheme only applicable to installations with a capacity of less than 50 kW.

When calculating the payback period of reach scenario, the profit produced from the export of generated electricity after paying for imported electricity was used.

Carbon Impacts

The carbon impacts for each scenario were also investigated. This was undertaken using values for UK grid electricity from DECC and DEFRA (2016). Since it is impossible to know where the energy that is being consumed was generated, this value takes in to account the UK generation mix to give an average value. This value is 0.46219 kg CO_2e per kWh.

Any renewable energy that was exported to the gird was not considered to off-set the carbon impacts of energy that was being imported. For this reason, the total carbon footprint of each scenario considered only imported electricity.

Scenarios

A number of models were created to represent different scales of AWWCs that have been constructed around the world.

The first model was constructed used the load data described above, this was to represent a small AWWC. This model was then simulated using both wind turbines and photovoltaic panels as a means of electrical generation.

The demand data was then scaled to be representative of the largest pumped AWWC that has been built. While Beijing is not commercially operated (Ganyet & Smedt, 2014) it was chosen as a point of reference since it is one of the largest examples of a pumped AWWC in the world. By comparing the flow rate and head of Beijing to Lee Valley White Water Centre, it was possible to make an estimation of the pump sizes (Table 3).

Table 3 Estimating the pumps power of the Beijing Olympic course.

Course	**Flow (m^3/s)**	**Head (m)**	**Pump Power (kW)**	**No. of Pumps**	**Total Power Draw (kW)**
Pinkston	7.5	2	90	3	270
Lee Valley	15	5.5	270	4	1,080
Beijing	17.5	6	313 (estimated)	4	1,252

The demand data could then be scaled to reflect the higher power consumption. Using this demand data, investigations were undertaken, again with both wind turbines and photovoltaic panels as the generation technologies.

4.3. Modelling Results

Renewable fraction is used throughout the results to give an indication of how the scenario is utilising the generated renewable energy. The renewable fraction is the percentage of energy consumed by the pumps that was generated from renewable sources. In each scenario this would be exclusively on-site renewable generation. A renewable fraction of 100% indicates that the site would be able to operate autonomously. A renewable fraction of 50% would suggest that the site is a net zero energy site.

The scenarios for each model increase the number of turbines or photovoltaic panels installed on site. A varying number of installed batteries on site was also simulated. The number ranged from the minimum batteries required to deliver power to the pumps, to the maximum number of batteries before no more gains with respect to renewable fraction are achieved.

Model 1: Small AWWC Using Wind Turbines

The model results for a small AWWC model using wind turbines as generators are listed in Table 4:

Table 4 Small AWWC using wind turbines as generators

	No. of Turbines	No. of Batteries	Renewable Fraction (%)	Energy Imported (kWh)	Energy Exported (kWh)	CO2e Emissions (kg CO2e)
1	1	0	67	265,368	464,124	122,650
2	1	201	72	194,112	347,693	89,716
3	1	5,494	89	50,937	113,819	23,543
4	2	0	83	231,410	978,032	106,955
5	2	201	89	158,487	858,876	73,251
6	2	5,494	99	8,161	613,243	3,772
7	3	0	89	212,002	1,506,486	97,985
8	3	201	92	140,316	1,389,355	64,853
9	3	5,494	100	0	1,160,076	0

In order to achieve full autonomy, a small AWWC would need 3 WF45-500 wind turbines and 5,494 Rolls 6CS24P lead acid batteries. The site would be 100% autonomous, with no electricity being imported from the grid.

Table 5 includes the costs involved with each of 9 scenarios:

Table 5 Costs and payback period of each scenario

	Cost of imported energy (£)	**Value of exported energy (£)**	**Yearly Profit (£)**	**Equipment Cost (£)**	**Payback period (years)**
1	39,805	23,206	-16,599	550,000	n/a
2	29,116	17,385	-11,732	827,634	n/a
3	7,641	5,520	-2,120	5,241,996	n/a
4	34,712	48,902	14,190	1,100,000	78
5	23,773	42,9439	19,171	1,377,634	72
6	1,224	29,742	28,518	5,791,996	203
7	31,800	75,342	43,542	1,650,000	38
8	21,047	69,468	48,420	1,927,634	40
9	0	56,264	56,264	6,341,996	113

The state of charge of the electrical storage throughout each scenario are illustrated in the figures below:

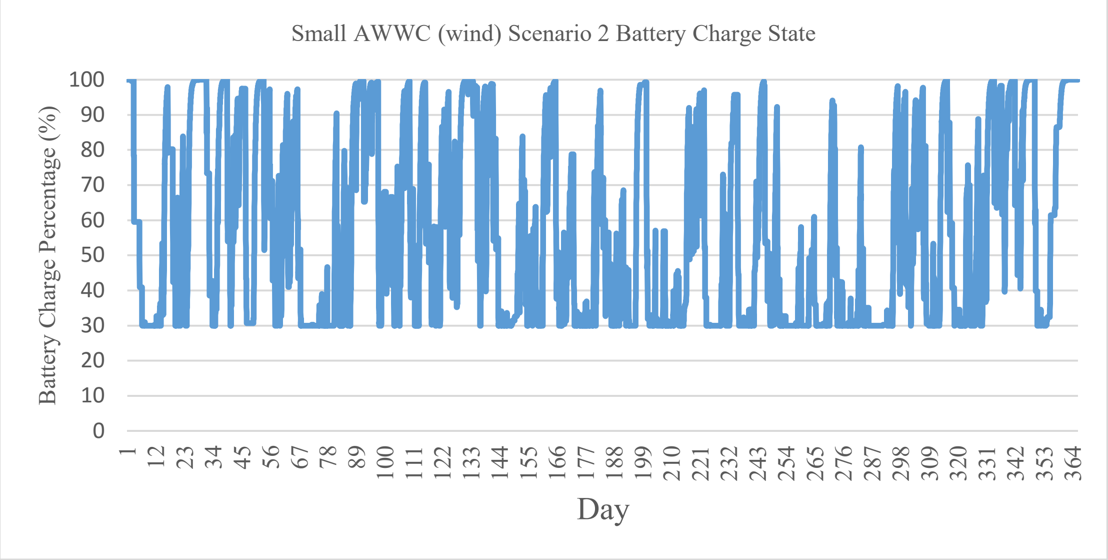


Figure 28 Battery charge state: small AWWC using wind turbines. Scenario 2.

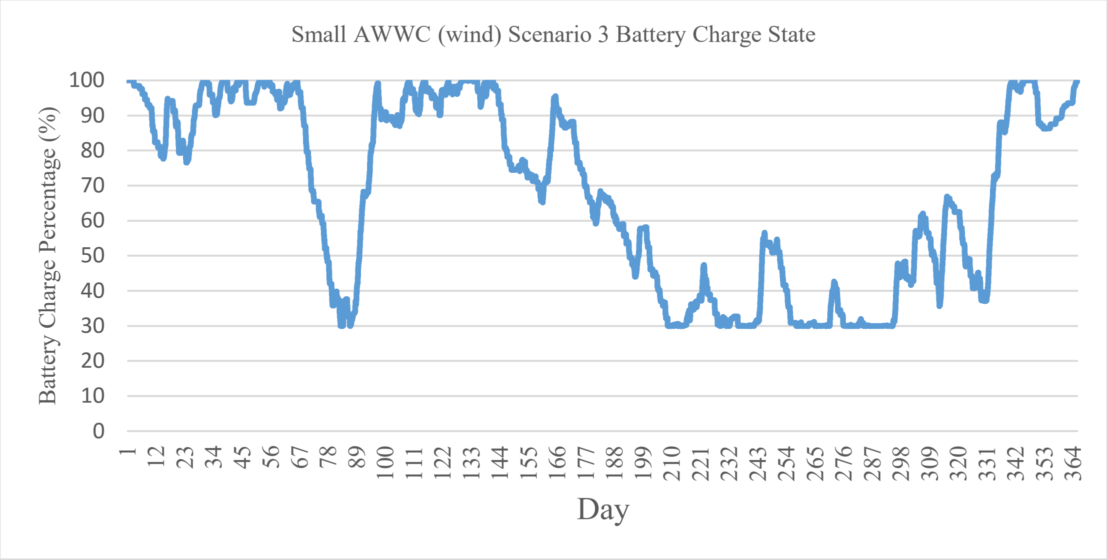


Figure 29 Battery charge state: small AWWC using wind turbines. Scenario 3.

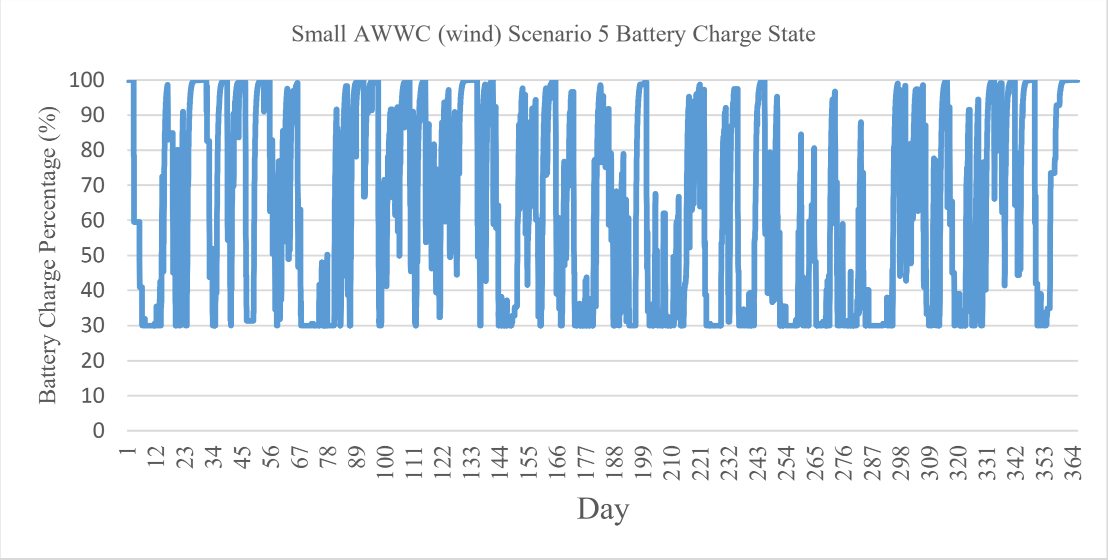


Figure 30 Battery charge state: small AWWC using wind turbines. Scenario 5.

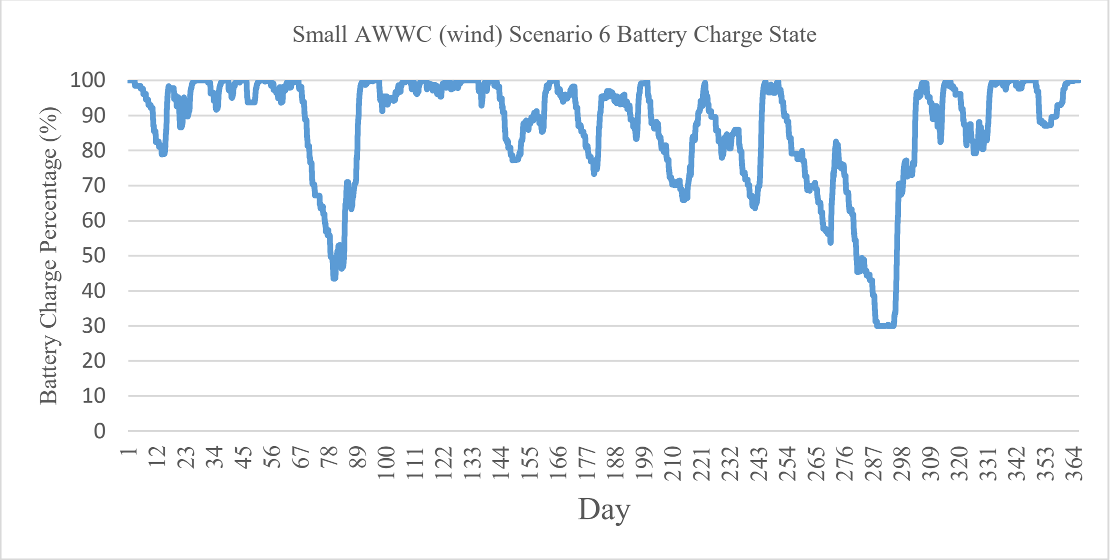


Figure 31 Battery charge state: small AWWC using wind turbines. Scenario 6.

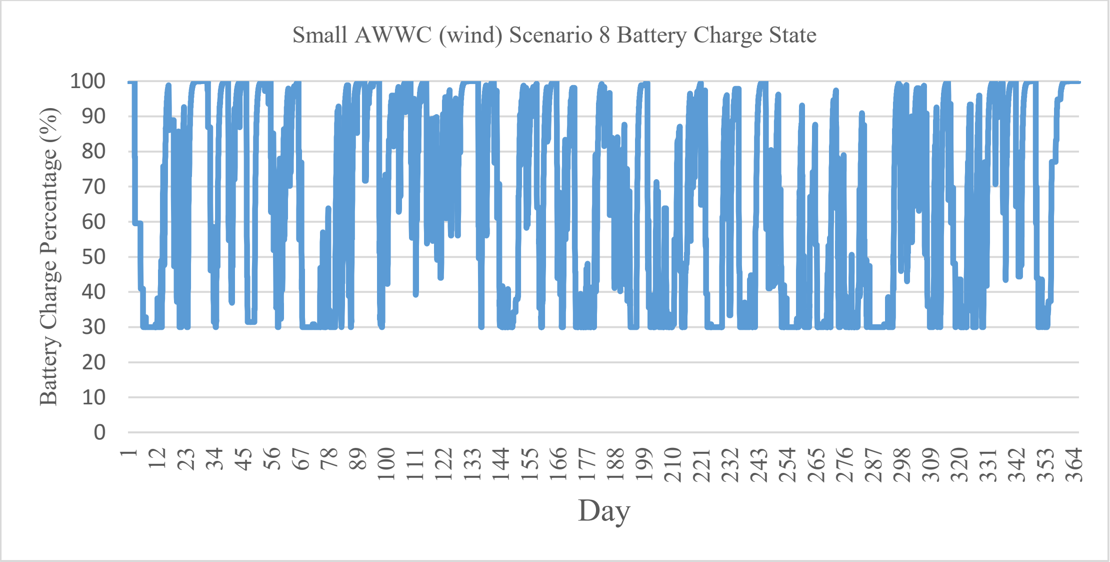


Figure 32 Battery charge state: small AWWC using wind turbines. Scenario 8.

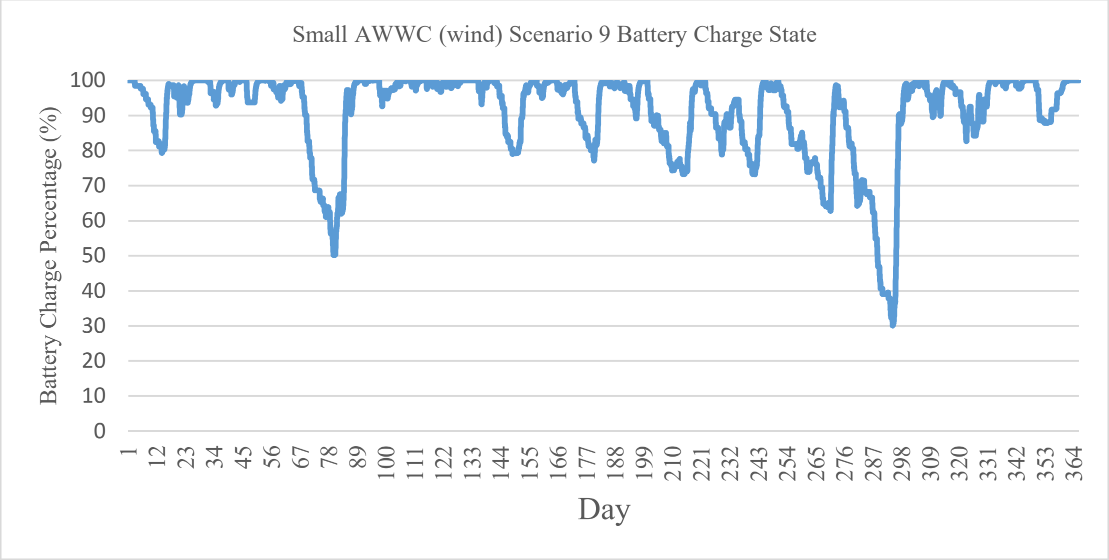


Figure 33 Battery charge state: small AWWC using wind turbines. Scenario 9.

Model 2: Small AWWC Using PV

The results for a small AWWC using photovoltaic panels for generation are listed in Table 6:

Table 6 PV generation scenarios for a small AWWC

	No. of PV Panels	**No. of Batteries**	**Renewable Fraction (%)**	**Energy Imported (kWh)**	**Energy Exported (kWh)**	**Carbon Emissions (kg CO2e)**
1	1,420	0	67	226,910	346,147	104,876
2	1,420	201	79	116,672	208,349	53,925
3	1,420	10,385	100	0	116,246	0
4	2,130	5,494	100	5	332,991	2

Table 7 includes the costs involved with each of the 4 scenarios:

Table 7 Costs for small AWWC using PV generation

	Cost of imported energy (£)	**Value of exported energy (£)**	**Yearly Profit (£)**	**Cost (£)**	**Payback period (years)**
1	34,037	16,788.13	-17,248.37	4,741,000	n/a
2	17,501	10,104.93	-7,395.87	4,908,634	n/a
3	0	5,637.93	5,637.93	13,402,090	2,377
4	0.75	16,150.06	16,149	11,665,996	922

The state of charge of the electrical storage in each scenario is illustrated in the figures below:

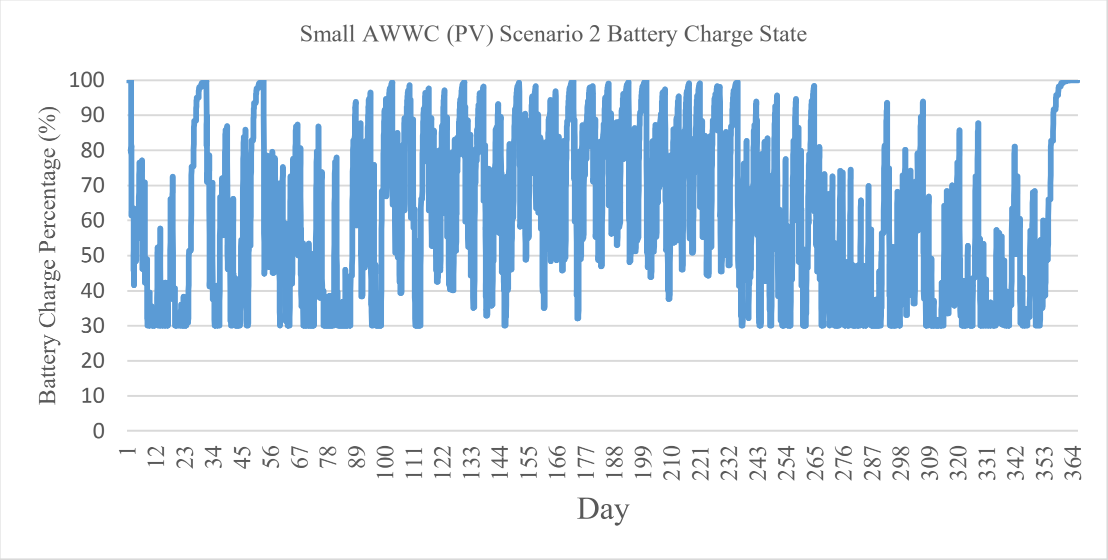


Figure 34 Battery charge state: small AWWC using PV panels. Scenario 2.

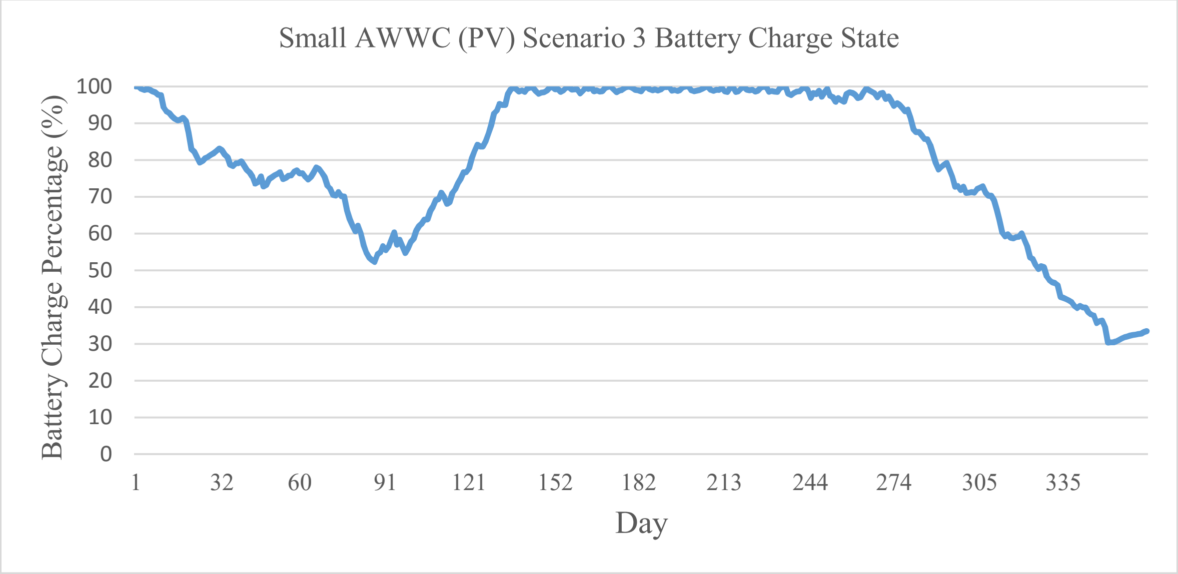


Figure 35 Battery charge state: small AWWC using PV panels. Scenario 3.

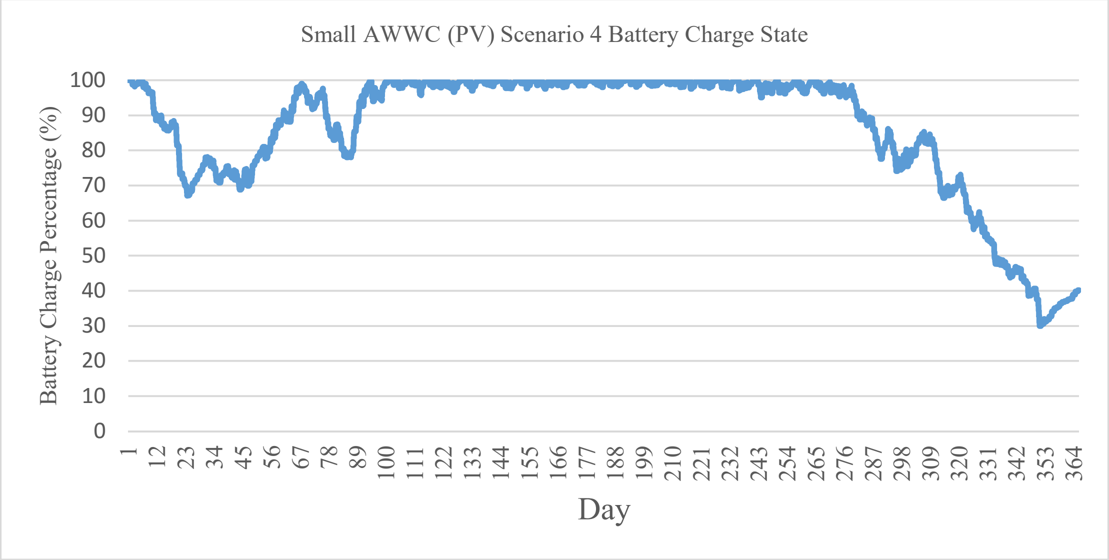


Figure 36 Battery charge state: small AWWC using PV panels. Scenario 4.

Model 3: Large AWWC Using Wind Turbines:

The results for each scenario in the large AWWC model using wind turbines for generation are listed in Table 8:

Table 8 Results for a large AWWC using wind turbines for generation

	No. of Turbines	No. of Batteries	Renewable Fraction (%)	Energy Imported (kWh)	Energy Exported (kWh)
1	1	0	26	1,523,587	447,204
2	1	268	25	1,408,406	258,998
3	2	0	44	1,423,136	894,619
4	2	268	44	1,286,458	671,286
5	3	0	55	1,333,170	1,352,515
6	3	268	57	1,195,492	1,127,551
7	3	5,360	63	727,315	363,667
8	3	10,720	65	643,503	226,724
9	4	0	63	1,269,026	1,836,240
10	15	0	89	968,890	7,562,616

Table 9 includes the costs involved with each of 9 scenarios:

Table 9 Costs for a large AWWC using wind turbines for generation

	Cost of imported energy (£)	Value of exported energy (£)	Yearly Profit (£)	Cost (£)	Payback period (years)	CO2e Emissions (kg CO2e)
1	228,538	21,689	-206,849	550,000	n/a	704,187
2	211,261	12,561	-198,700	883,512	n/a	650,951
3	213,470	43,389	-170,081	1,100,000	n/a	657,759
4	192,969	32,557	-160,411	1,433,512	n/a	594,588
5	199,976	65,597	-134,379	1,650,000	n/a	616,178
6	179,324	54,684	-124,639	1,983,512	n/a	552,544
7	109,097	17,638	-91,459	6,230,240	n/a	336,158
8	96,525	10,996	-85,529	10,700,480	n/a	297,421
9	190,354	89,058	-101,296	2,200,000	n/a	586,531
10	145,334	366,787	221,453	8,250,000	37	447,811

The state of charge of the batteries in each of the scenarios is illustrated in the figures below:

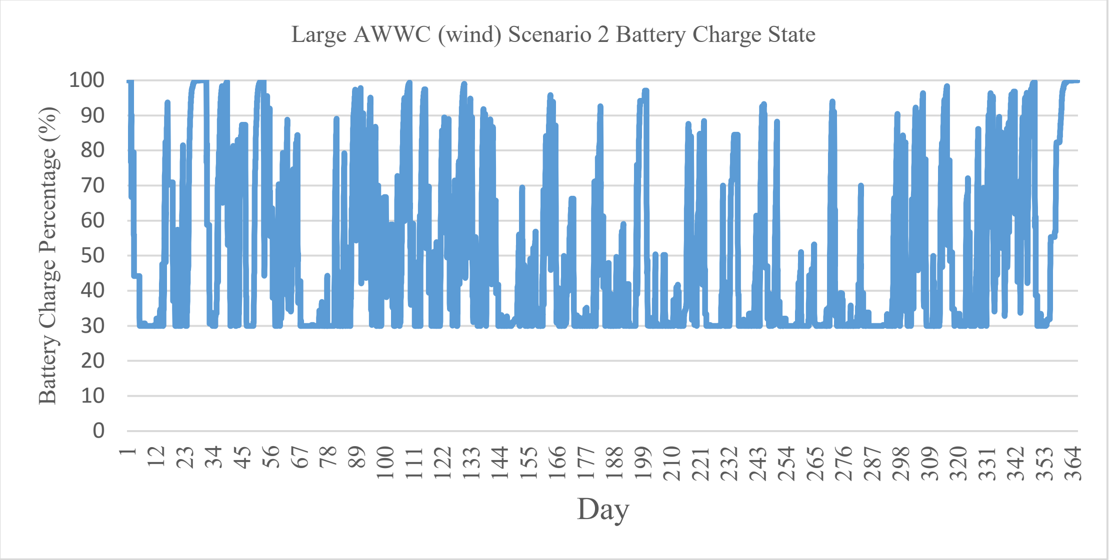


Figure 37 Battery charge state: large AWWC using wind turbines. Scenario 2.

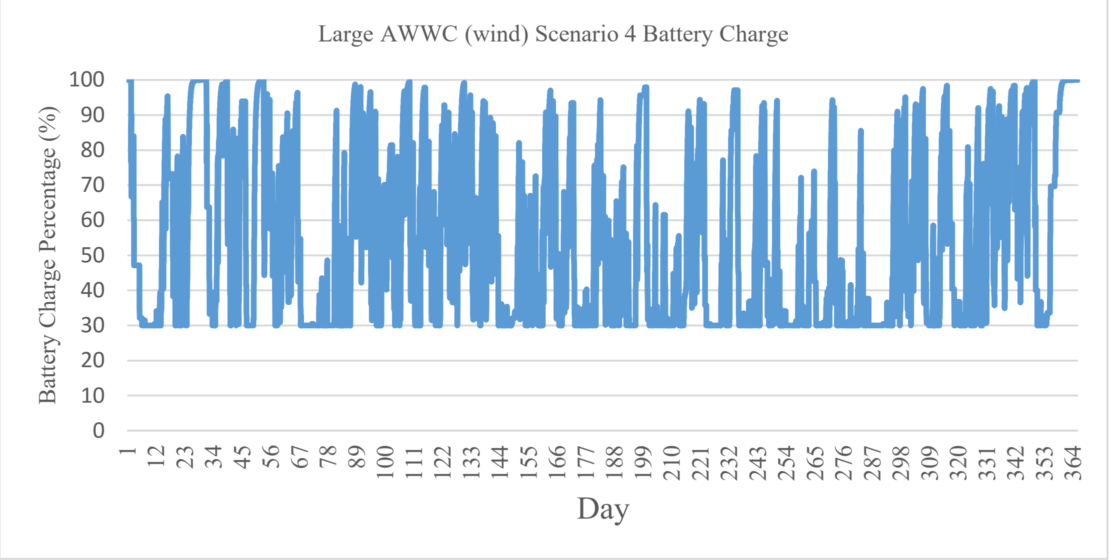


Figure 38 Battery charge state: large AWWC using wind turbines. Scenario 4.

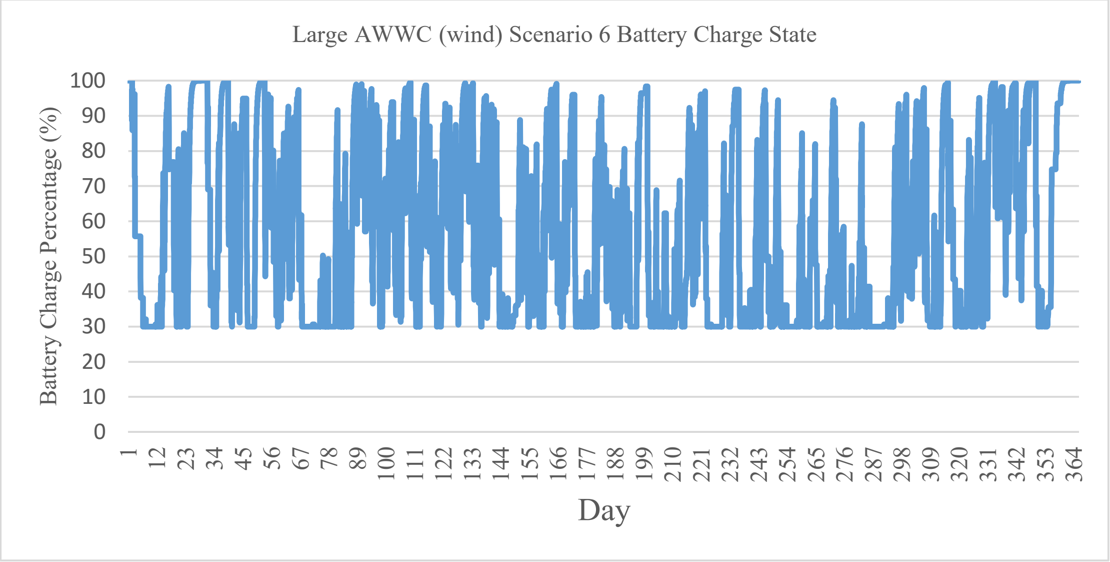


Figure 39 Battery charge state: large AWWC using wind turbines. Scenario 6.

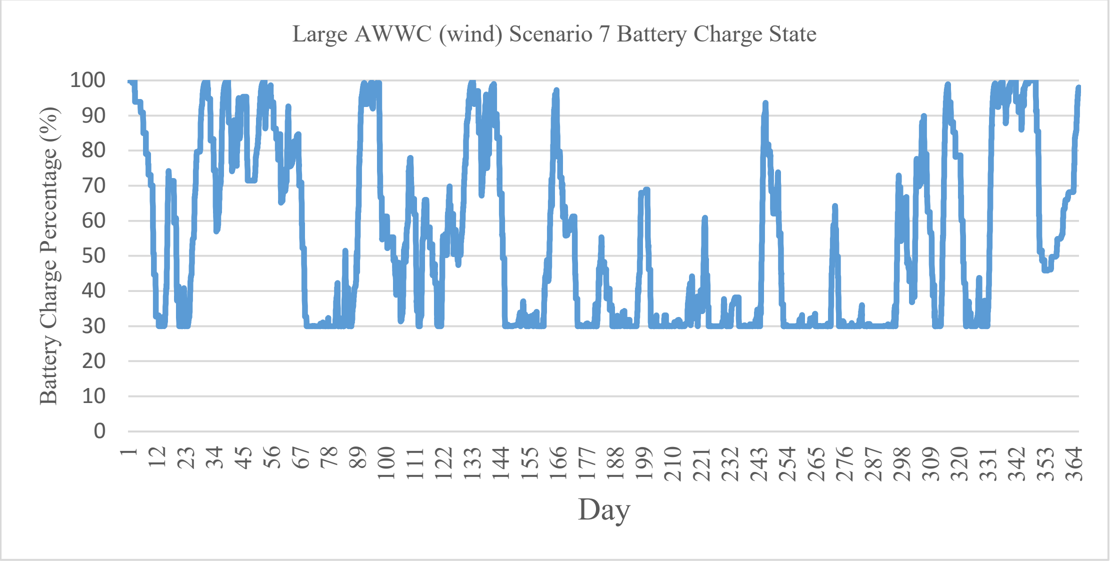


Figure 40 Battery charge state: large AWWC using wind turbines. Scenario 7

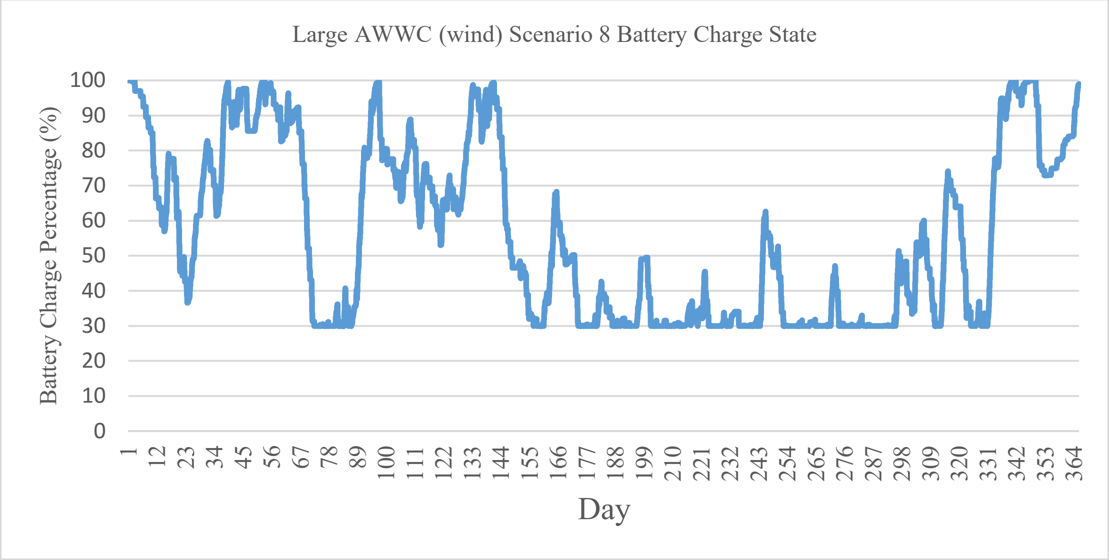


Figure 41 Battery charge state: large AWWC using wind turbines. Scenario 8.

Model 4: Large AWWC Using PV

The results for each scenario in the large AWWC model with PV panels are listed in Table 10:

Table 10 Results for a large AWWC using PV panels for generation

	No. of PV Panels	**No. of Batteries**	**Renewable Fraction (%)**	**Energy Imported (kWh)**	**Energy Exported (kWh)**
1	1,350	0	23	1,505,781	326,790
2	1,350	268	23	1,348,135	129,733
3	2,000	0	31	1,448,740	484,133
4	2,000	268	33	1,274,240	266,007
5	7,500	0	69	1,030,272	1,656,303

The costs involved with each scenario are listed in Table 11:

Table 11 Costs involved with using PV panels and storage at a large AWWC

	Cost of imported energy (£)	**Value of exported energy (£)**	**Yearly Profit (£)**	**Cost (£)**	**Payback period (years)**	**CO2e Emissions (kg CO2e)**
1	255,867	15,849	-210,018	4,510,000	n/a	695,957
2	202,220	6,292	-195,928	4,733,512	n/a	623,095
3	217,311	23,480	-193,831	6,655,000	n/a	669,593
4	191,136	12,901	-178,235	6,878,512	n/a	588,941
5	154,540	80,330	-75,210	24,805,000	n/a	476,181

The state of charge of the electrical storage in each of the scenarios are illustrated below:

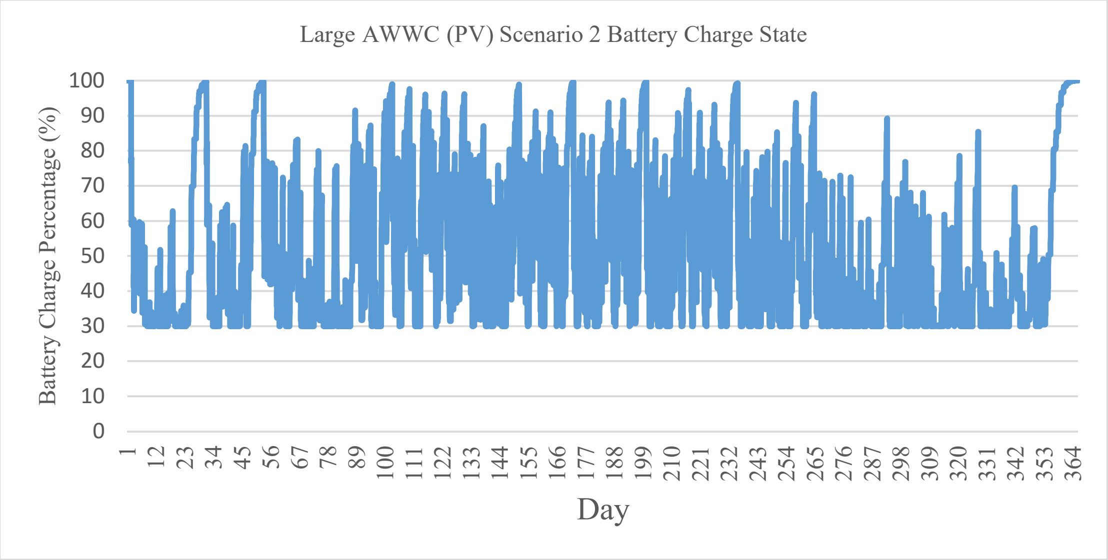


Figure 42 Battery charge state: large AWWC using PV panels. Scenario 2.

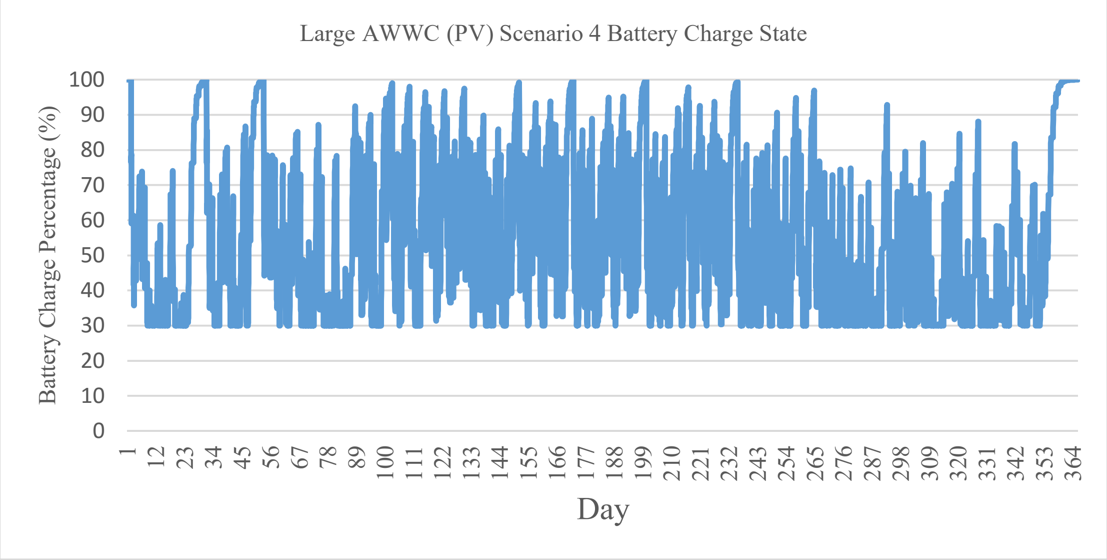


Figure 43 Battery charge state: large AWWC using PV panels. Scenario 4.

4.4. Biomass Investigation

In order to estimate the amount of biomass needed to supply a small AWWC for a year, some simple calculations were undertaken.

Wood chips with a moisture content of 30% have an energy content of approximately 3,500 kWh per tonne (Biomass Energy Centre, ND). Therefore, a demand of 351,405 kWh would require 100.4 tonnes of biomass per year to be satisfied. However this total does not account for the efficiency of the plant. A more realistic value of 176 tonnes per year would be required if the efficiency of the plant was approximately 25%.

Using best and worst case values from the DECC BEAC tool, 0kg CO_2e/kWh and 0.935 kg CO_2e/kWh respectively, the yearly carbon emissions for this scenario could range from 0-328,563 kg CO_2e.

For a larger AWWC with a demand of 1,405,620 kWh over a year, 703 tonnes of biomass would be required. The yearly carbon emissions for this site, using the same value as above, would be between 0-1,314,255 kg CO_2e.

4.5. Discussion

These results from all models highlight that it is not cost effective for a site of this nature to become completely autonomous using any combination of the renewable technologies described in section 2.

From the investigation, it was clear that because of the high power draw of the pumps, a large generation capacity is required to ensure that the instantaneous demand is met as much as possible. While this high capacity ensures the large demand is met, it also means that there is a significant amount of excess energy produced throughout the year.

Model 1

While the total energy consumption by the pumps of a small AWWC is not excessively large (351,405 kWh), it is consumed in just 1,301 hours over the year. This equates to only 15% of the year that the pumps are operating. Because of this short demand window, a large generation capacity is required if the aim is to instantaneously cover the demand. This is true throughout all of the models.

With only one 500 kW wind turbine installed, a small AWWC could easily become a net zero energy site (Table 4, scenario 1). In this configuration, 1.7 times more energy is exported than is imported.

The addition of electrical storage throughout any of the scenarios only increases the renewable fraction by a small amount compared to the additional cost introduced. Scenario 2 (Table 4) introduces the minimum amount of batteries that could be installed on site. By doing this, the renewable fraction is increased by 5% and both the energy imported and exported is reduced, demonstrating that energy generated on-site is being utilised by the pumps. This comes at a cost approximately 1.5 times more than using a single wind turbine. In order to increase the renewable fraction from 67% to 89% using only one turbine, 5,494 batteries would be required. This solution is 9.5 times more expensive than installing a single wind turbine.

In order for the site to generate a profit from exported energy, two wind turbines would be required (Table 5, scenario 4). This solution increases the renewable fraction to a higher value than scenario 2 which makes use of electrical storage.

Scenario 6 is close to achieving full autonomy with only 2% of the demand being imported from the gird throughout the year. However, this comes at a significant cost of £5,791,996.

By installing 3 turbines with no electrical storage (Table 4, scenario 7), the renewable fraction is able to reach 89% and achieve a payback period of 38 years (Table 5, scenario 7), this is the lowest of any of the scenarios. Using 3 wind turbines with 5,494 batteries, the renewable fraction can be increased to 100% making the site fully autonomous. Doing this comes with a significant cost of £6,341,996.

Figures 28-33 illustrate the state of charge of the electrical storage throughout each of the scenarios where it is included. Scenarios 2 (Figure 28), 5 (Figure 30) and 8 (Figure 32) all include the minimum number of batteries that would be able to provide power to the pumps. In this configuration, the batteries are regularly discharged to their minimum charge state. Scenarios 3 (Figure 29), 6 (Figure 31) and 9 (Figure 33) all include larger battery banks and the result is the batteries undergoing a shallower discharge cycle. Figure 29 suggests that for busy periods throughout the year (day 210-298) the capacity of the generation was too small to charge the batteries sufficiently between pump operations. The increased generation capacity in scenario 6 and 9 (Figures 31 and 33) solved this issue. While the lowest state of charge is reached during the same period, the batteries are quickly charged back to a higher capacity.

Model 2

From the results in Table 6, it is clear that in order to achieve a similar renewable fraction and to become a zero net energy site, a larger installed capacity of solar panels is required compared to wind turbines. This largely stems from the climate data used in the model. The climate data was representative of Glasgow, where solar energy intensity is lower than potential wind energy available.

With regards to the addition of electrical storage in the scenarios, similar results to those achieved in model 1 were observed. While there is an increase in the renewable fraction and a decrease in energy imported and exported, the cost is high relative to the gains.

Due to the need for a larger installed capacity compared to wind generation, the equipment costs are also increased. Achieving 67% renewable fraction with wind turbines in model 1 would cost £550,000 (Table 4 and 5) whereas to achieve the same percentage with PV would cost £4,741,000 (Table 6 and 7). While it was possible to achieve zero imports using photovoltaic generation and electrical storage, the costs are substantial.

Figures 35 and 36 show the batteries state of charge throughout the year, it is unclear whether these scenarios would be sustainable. Both scenarios make use of a large number of batteries for electrical storage. At the beginning of the simulation, the state of charge of the batteries is 100%. It is unclear whether the batteries would recover to this high a charge state after the steep drop from around day 270. This period coincides with the start of winter, where the potential to generate electricity from sunlight is significantly reduced, and a particularly busy period of operation for the pumps. A longer simulation would be required to study if this combination of generation and storage would work long term. Regardless of these problems, the cost is significantly larger than achieving the same results using wind generation.

Model 3

While an increase in the size of the electrical demand of model 3 caused a noted drop in renewable fraction for scenarios similar to previous models, the results largely follow a similar patterns. In order to become a net zero energy site, 3 wind turbines would be required.

The number of turbines required to export enough electricity to offset the cost of imported electricity would be 15 (Table 8 and 9, scenario 10).

Figures 37-41 highlight how electrical storage struggles with a power draw of this size. In all scenarios, the storage is not able to supply demand for a number of periods throughout the year even when an extremely large number of batteries are installed in scenario 8 (Table 8). This problem could be solved by increasing the generation capacity.

Model 4

As with model 2, to achieve similar results to using wind generation but with solar power, a larger installed generation capacity is required.

Costs are also increased significantly. Achieving a 26% renewable fraction in model 3 would cost approximately £550,000 (Table 8 and 9) in contrast to the £4,510,000 to achieve a 26% renewable fraction in model 4 (Table 10 and 11).

Wind Power Solutions

Throughout all scenarios additional turbines increases the renewable fraction of energy used and increases the amount of energy that can be exported. While this could be beneficial, the amount of energy that could be exported would need to be considered. If there are any constraints on the export of generated electricity, there may be an effect on the yearly costs of running the pumps, making it more difficult to justify the installation of more renewable generation capacity.

Generally, scenarios that include wind turbines only and no electrical storage have the lowest pay back periods. The payback periods are out with the typical lifespan of the wind turbine, likely in the region of 25 years. In addition, they do not take in to account the maintenance costs - a factor that would slightly increase the payback period.

The payback period is heavily dependent on the price received for exported energy. If an export price of £0.065/kWh could be achieved, instead of the £0.05/kWh used in the investigation, the payback period for scenario 4 would be approximately 25 years. This brings the payback period in line with the life expectancy of a wind turbine. Ideally, a higher price per kWh would want to be received to make a system like this commercially viable and reduce the payback period as much as possible.

Photovoltaic Generation

In both model 2 and 4, larger generation capacities of solar panels are required to achieve similar results to model 1 and 3 where wind generation is used. A small AWWC would require an installed capacity of 1,420 kW of photovoltaic panels in contrast to a single 500 kW producing the same results. With this increase in installed capacity also comes a much greater cost and more land would need to be dedicated to PV generation than would be needed for a wind turbine. The total amount of electricity exported from the site is also smaller than a system that used wind turbines.

In order to achieve 100% renewable energy use by the site, either an extremely large number of batteries or PV panels are needed. The large generation capacity and electrical storage in a scenario like this mean that payback periods are extremely long.

Another constraint is the area required for the solar panels. The Energy Saving Trust (2015) estimate that a 1m^2 solar panel will have a capacity of approximately 137 Watts. Therefore to install a capacity of 1420 kW, an area of 10,365 m^2 would be required. Figures 35, 36, 42 and 43 also raise question with regards to how the batteries would perform over a longer time period. At the start of the simulation the batteries are at full capacity, for the majority of the year they are near peak capacity with lows of 50% at the start of the year. At around day 280 in each figure there is a significant drop in the state of charge for each battery, it is unclear if there would be enough excess generation to re-charge the battery as well as provide power to the pumps. A longer term simulation would need to be run to investigate longer term behaviour of the electrical storage options.

Electrical Storage

From the results we can make the conclusion that batteries are generally not a cost effective way to cover the demand. This is most apparent when scenario 8 and 9 of model 1 are compared (Table 4). In order to increase the renewable fraction from 92-100% the cost is multiplied 3.3 times. This is reflected in all of the scenarios where electrical storage is included. While the electrical storage does improve the utilisation of energy generated on site, the gains are small compared to the cost involved. The low voltage and relatively low capacity of lead acid batteries mean that a large number are needed to make a significant increase to the renewable fraction of the site. This problem inherently stems from the high power draw of the pumps - no battery technologies can provide this power without using a large number of batteries.

One benefit that was apparent from the installation of a large number of lead-acid batteries is that the life cycle would be extended. The life cycle of lead-acid batteries is reduced the lower they are depleted each cycle. By using a large number of batteries, the amount that the batteries are depleted is limited, increasing their life span. Scenarios for each model that used the minimum number of batteries regularly underwent deep battery cycles where the lower limit was reached. Figure 44 illustrates how the depth of discharge negatively effects the life cycle of the Rolls 6CS27P.

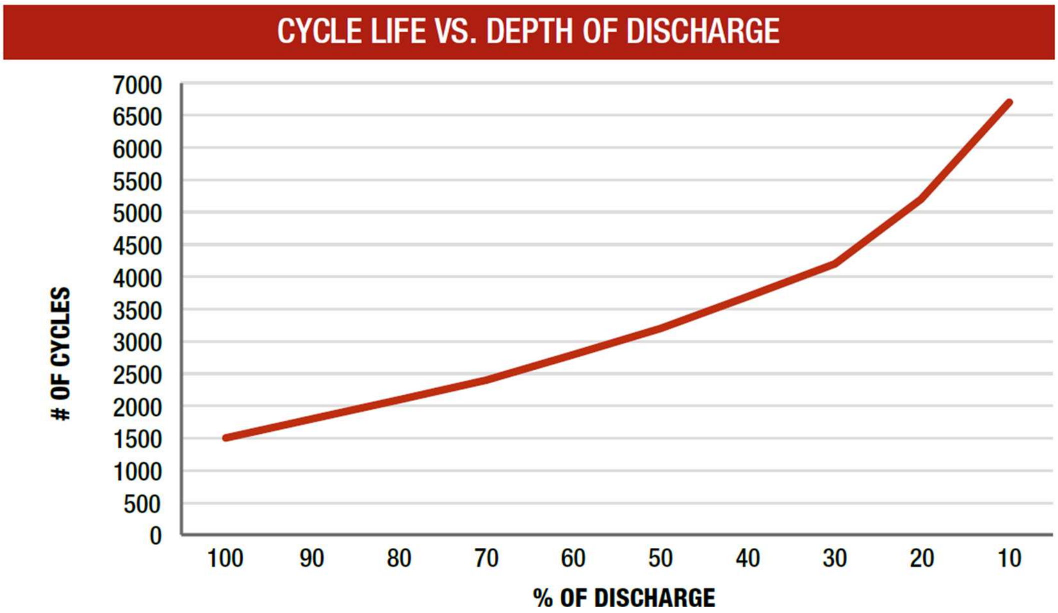


Figure 44 Rolls 6CS27P cycle life vs depth of discharge (Rolls, 2014)

Sodium-sulphur may be a more suitable solution with regard to the amount of energy they can store and their operating voltage. Unfortunately their high cost makes them impractical for many situations, regardless of their higher capacity and life cycle.

Biomass Generation

From the investigation undertaken to evaluate how much fuel would be required, it is clear that the source of the fuel would need to be carefully considered to ensure the carbon content of the fuel is kept low. This was outside the scope of this project.

The operation of an onsite biomass generator would also likely have some complexities. If the generator was using a Rankine cycle, there would be a period of time that no generation could take place while the operating temperature is being reached. This would increase fuel consumption and reduce the flexibility of the course with regards to turning it on and off over short timeframes.

An addition problem that would come with this type of generation is that air quality could be affected. This is an important factor when how the site is being used is considered. Giles and Koehle (2013) noted that athletes can be significantly affected by poor air quality since they have an increased intake of air while exercising. All of these factors make biomass an unattractive option for use on an AWWC.

5. Non-Generation Designs

While adding on site generation may increase the percentage of green energy used, it does not solve the root of the problem: pumped artificial white water courses are energy intensive due to the high power water pumps.

In order to remove or reduce the energy use, an investigation was undertaken with regards to course design. These designs would need to retain the benefits of a pumped AWWC. These include the ability to quickly turn the course on and off, modify features and if possible, be constructed in an area where another type of course, specifically a run-of-river, could not be constructed. While run-of-river courses are able to remove the energy demand of a white water course, there are a limited number of suitable sites to construct them. In addition, modifying the course of a river, or abstraction of water is strictly controlled under legislation (The Water Environment (Controlled Activities) (Scotland) Regulations, 2011: The Water Environment (Water Framework Directive) (England and Wales), 2003). In order for an AWWC to be commercially successful it must be located in relative proximity to a populated area. Town or cities situated near large rivers are generally build on a relatively flat sections of the river. This is not conducive to constructing an AWWC any larger than a course such as Pinkston Watersports.

The International Canoe Federation (ICF) have set out guidelines to be considered during the design and construction of a white water course (Ganyet and Smedt, 2014). These state that the flow of water should be between 8-14 m^3/s and a total drop of between 3.75m and 7m. While these guidelines are a good baseline for any design, it should be noted that the focus of the ICF is international standard canoe slalom competition. These guideline do not necessarily fall in line with the needs of other AWWC users. This is highlighted by the success of smaller AWWCs such as Pinkston Watersports and Nene Whitewater Centre. For this reason, the characteristics of Pinkston Watersports were used as a baseline for the investigations carried out.

5.1. Water Flow and Volume

In order to further develop concepts for an AWWC that do not use water pumps and do not significantly alter the flow or course of a river, it is important to understand the demand of the course. While in the previous investigations, the electrical demand was considered, here the water demand must be considered.

The characteristics of a small artificial white water course was used as the basis for this investigation. If the flow rate of a course is 7.5 m^3/s, the volume of water used over an hour would equate to 27,000 m^3.

5.2. River Charging

As discussed previously, locations suitable for building a run-of-river AWWC are limited. In order to sidestep this limitations, it may be possible to simply divert a small volume of flow away from the main river to a basin. This basin can then be used to store water until it is needed. This type of design would be similar to a dam release course but the main purpose of the site would be the AWWC rather than power generation. This would allow for the site to be much smaller in scale than a dam and also provide the benefit of control to the course operator rather than having to rely on the dam operator for water releases.

Reservoir Outflow

For a design like this to work, carful considerations of the outflow of the upper reservoir would have to be considered. If the design of the basin and outflow are considered as an idealised reservoir with the outflow through a nozzle, Bernoulli’s principle can be used to calculate the minimum head needed to provide a specific flow of water.

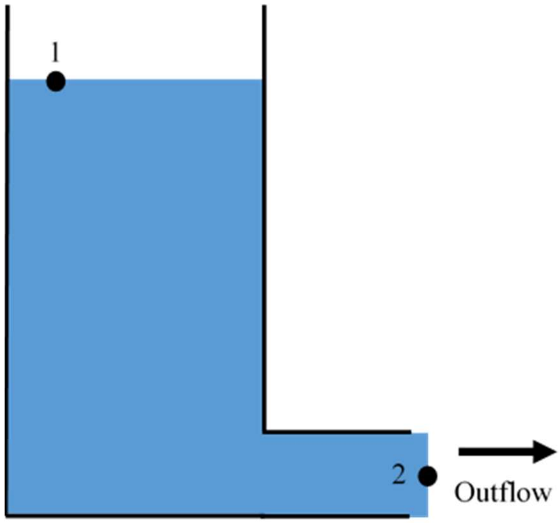


Figure 45 Reservoir and Outflow

Bernoulli's principle states that for a steady flow along a streamline, the total energy of the fluid must be constant (Douglas *et al.*, 2005). At point 1 in Figure 45, the assumption is made that the water is static, meaning its kinetic energy is zero. At point 2 it is assumed that the potential energy is zero. This is shown below:

$$pressure\ + kinetic\ energy + potential\ energy = constan$$

$$p_{atm} + \frac{1}{2}mv_1^2 + mgH_1 = p_{atm} + \frac{1}{2}mv_2^2 + mgH_2$$

$Where:$

$p_{atm} = pressure = 1$

$m = mas \quad 1$

$v = velocit$

$g = gravity \quad 9.81$

$h = height$

$$\therefore gH_1 = \frac{1}{2}V_2^2$$

This equation can then be rearranged to give the speed of water at point 2:

$$V_2 = \sqrt{2gH_1}$$

Using the speed at point 2 it is then possible to calculate the volumetric flow rate depending on the area of the outlet. This is found by:

$$q = C_d A V_2$$

$Where:$

$C_d = discharge\ coefficient$ A = area

C_d can vary depending on the outlet design. Hayward (ND) suggest 0.98 as a value for an outlet with rounded edges.

To achieve a minimum outflow of approximately 7.5 m^3/s there are a number of configuration that would be suitable. These are outlined in Table 12:

Table 12 Flow Rate

Height (H_1) (m)	Area of outlet (m^2)	Flow rate (m^3/s)
1	1.74	7.6
2	1.23	7.5
3	1.02	7.7
4	0.87	7.5
5	0.79	7.6

These results from the calculations show the height of the water above the outlet increases, the area of the opening can be reduced yet still produce the same flow rate.

If the flow is regulated at the outlet, then it is possible to keep a constant flow of water at any head above the minimum. If a course with an outlet of area 1.7 m2 is constructed, the lowest head the course could operate on would be 1m.

Water Storage

To store enough water to provide flow to the course for two hours, a water tank would need to be approximately 50 x 50 x 22m in size. The scale of this tank would lead to issues, not only with ensuring it was an adequate height above the white water course but also with cost. While large tanks upwards of 200,000 m^3 are used at oil refineries (Kinder Morgan Inc, 2013; Oil Review, 2015), it is likely that the cost of these tanks would be prohibitive with regards to AWWCs. Nevertheless it would be possible to store nearly 9 hours' worth of water if tanks of these size were used. Using a natural body of water or a man-made basin would be a more practical solution, yet would act as a significant barrier to the construction of an AWWC for a number of reasons. Finding a body of water this size, close to a population centre that is not already in use may severely limit potential sites. Additionally, there may be difficulties in being granted permission to use such a body of water due to legislation (The Water Environment (Controlled Activities) (Scotland) Regulations, 2011: The Water Environment (Water Framework Directive) (England and Wales), 2003).

Figure 46 shows the area of the basin at Pinkston Watersports. The depth of this basin is 1.8m therefore the basin holds a total of approximately 7,200 m^3 of water. To store enough water to provide flow for a small AWWC for only an hour, a basin of the same depth would need to have an area of 15,200 m^2.

Figure 46 Area of lower basin at Pinkston Watersports

Water Source

In order for a solution this to work, a water source would need to be available to fill the reservoir at times when the pumps are not operating. If the maximum number of hours an AWWC plans to operate over a day is 8 hours, then the total volume of water that would be required is 217,987 m^3. Ideally, the basin would be filled with this volume overnight. If the operating hours of the course are between 9am and 9pm, this would allow 12 hours to fill the reservoir. In this time frame a volume flow rate of 5.05 m^3/s would be needed to fill the reservoir.

An investigation into rivers that would be suitable for a constant 5.05 m^3/s extraction was undertaken. The rivers included in the investigation are all relatively close to population centres and the scope was limited to within Scotland. Data from the National River Flow Archive (ND) was used to obtain daily flow rates from a period between 2010 and 2015. The extraction percentages are the percentage of flow that is being removed from the river. Ideally the mean extraction percentage should be as low as possible to limit any effect on the river. The max extraction percentage should also be carefully considered, ideally this should also be a small as possible a value even if the value was only reached over short periods of the year.

Table 13 River extraction values

River	**Gauge**	**Min Flow (m^3/s)**	**Mean Flow (m^3/s)**	**Max Flow (m^3/s)**	**Min Extraction %**	**Mean Extraction %**	**Max Extraction %**
Clyde	Daldowie	7	54	592	0.9	20	73
Tay	Ballathie	33	204	1150	0.4	4	15
Forth	Craigforth	4	51	545	1	23	124
Dee	Park	6	41	463	1	14	90
Ness	Ness-side	17	98	665	0.8	8	30

The results in Table 13 indicate that for three out of the five rivers studied, the mean extraction would be over ten percent of the total flow. If a continuous 5.05 m^3/s was extracted from the Clyde, or Dee during low flow the majority of the flow would be used by the AWWC, significantly altering the flow of the river. At low flows the Forth has less than 5.05 m^3/s, so the operating hours of the course would be reduced. Only the Tay and Ness appear large enough to sustain a constant 5.05 m^3/s extraction without drastically affecting the flow of the river. The maximum percentage of flow diverted from the Tay would be 15% and the Ness, 30%. Regardless, these percentages of total flow are still significant and would no doubt introduce complications with regards to gaining planning permission.

While this kind of design of AWWC does reduce the flow extracted from a river, there are some significant hurdles which would need to be overcome to make this design more appealing than a run-of-river course. An increase of only 2.5 m^3/s would allow for the construction of a run-of-river course which would likely have less draw backs compared to a "charging" course.

5.3. Pump Charging

If a water source is not available for an AWWC, a similar system to that described in the last section could be used, except pumps would be used to move water from a lower body of water to a higher reservoir. This design would have the benefit of being able to make use of cheap electricity by pumping water overnight, but could also be used on demand if the upper reservoir is depleted.

This type of design would most likely require a large amount of space as both the upper and lower reservoir would have to be of similar size. The lower reservoir would likely need to be slightly larger to allow a suitable minimum water level to be maintained.

Using typical energy prices provided by Pinkston Watersports, it is possible to calculate the approximate costs and potential savings for a course operating in this way. Currently Pinkston Watersports operate on a tariff with a static price of electricity. This is more cost effective as the site often operates at peak times. Since a significant amount of operation occurs during peak times, a variable tariff would provide little scope for cost saving. Costs used in the calculations are listed in Table 14:

Table 14 Example electricity costs for a AWWC

Tariff	**Price per unit of electricity (£)**
Peak	0.20
Off-Peak	0.10
Static price	0.15

To pump enough water overnight to allow operation of the course for 8 hours the cost of electricity would be £216 using the off-peak price. At current prices the cost is £324 creating a price differential of £108.

If a pumped AWWC operates for 1,300 hours over the course of a year, the total savings by using off-peak electricity compared to a static tariff would amount to £17,563. Operating in this way could lead to a 33% reduction in operating costs.

Whereas filling a reservoir to provide flow to an AWWC is limited in scale by the size of the river and how much water can be extracted, the only limitation to a course like this would be the size of both the upper and lower reservoir and the volume of water that the pumps are able to move to the upper reservoir.

Overnight there may be an excess of renewable generation and a need for the grid to be balanced. Due to this, electricity can become available at reduced rate. If electricity was available at half the cost of the standard tariff, the cost saving could be even greater. An example of the savings using further reduced off-peak rates is listed in Table 15:

Table 15 Savings for reduced energy costs

Cost of Energy per kWh (£)	**Savings (£)**
0.05	35,127
0.03	42,152
0.01	49,177

Pumping the water at a reduced rate would make very little difference to the cost of operation. The pump, and by extension, courses are designed so that the pumps are operating at their peak efficiency when providing water to the course. For this reason, it would make little sense to operate at a reduced rate.

5.4. Tidal

Tidal lagoons and tidal barrages both operate in a similar way, using a manmade structure to trap water at high tide and create a head when the tide retreats. The water in the lagoon can then be used to generate electricity. Swansea Bay tidal lagoon is currently undergoing planning and design but once completed hopes to be able to produce enough electricity to supply approximately 155,000 houses (Waters and Aggidis, 2015).

This principle could be applied to AWWCs, albeit on a smaller scale. The total volume of water that Swansea Bay will hold is estimated to be approximately 100,000,000 m^3 and the maximum discharge rate will be approximately 10,000 m^3/s (Tidal Lagoon (Swansea Bay) plc, 2014). Enough water to provide a 7.5 m^3/s flow to a course for 37 hours. The scale required for an AWWC would be significantly smaller than this.

There are some significant drawbacks for a site operating using this design. Because there are two high and two low tides a day, the operating window for the AWWC would be restricted to a time when there is a suitable head to allow water to flow back to the sea. The operating window will also be dictated by the changing time of high and low tides throughout the lunar cycle. This would further reduce the flexibility of the AWWC, making any solution utilising tides a much less attractive option than using pumps. For these reasons, his type of design was ruled out as a feasible alternative for AWWCs.

5.5. Discussion

Of the designs that were evaluated in this investigation, each had significant drawbacks that would need to be overcome.

The river charging and pump charging designs both require a large volume of water to be stored in order to provide a flow to the course. This requirement would significantly limit suitable sites and would not allow a course like this to be constructed in an urban environment. If this problem could be overcome, possibly utilising an existing body of water, there could be some potential benefits to using one of these designs over a pumped course.

While the river charging design is able to allow an AWWC to operate using a river which would not be able to support a run-of-river course, there are still some significant limitations. A large volume river is required to limit the effects from the extraction of water, in addition, there would need to be sufficient gradient in the river so that an upper reservoir and the course could be constructed. Careful consideration would also need to be taken with regards to how the water flow back to its source. Without sufficient gradient on the site, the course could “back up”, something that is also an issue with run-of-river courses (Figure 3).

If the AWWC was able to use an existing body of water, it could make pump charging a very attractive option. Using pricing examples provided by Pinkston Watersports, a third of the energy costs of a pumped artificial white water course could be removed by ensuring that all energy was consumed during off peak times. There is potential to further reduce this cost if an agreement between the utility company and the course operator could be established with regards to the price of energy consumed overnight. This arrangement would prove to be beneficial for both the utility company and course operator since it would provide a small load that could be used to help balance the grid over night when demand is low.

It was clear after a short investigation that a course exploiting the difference in head between high and low tides would not be feasible. While the scale required for a white water course is much smaller than what is required for an energy generating tidal barrage or tidal lagoon, the limiting factor is the operational window. This type of design would require the course to be operated only at specific times, which is contrary to what the project aimed to achieve, namely find a solution that would provide all the benefits of a pumped AWWC.

6. Case Study

Two case studies of UK sites were undertaken. The aim of the study was to investigate solutions that would be best applicable to the specific sites.

The sites selected represent two very different artificial white water courses. Both use pumps to provide a flow of water two the course, yet the size and location of each course is very different.

6.1. Pinkston Watersports

Pinkston Watersports is located in Port Dundas industrial estate, only 1 mile north of Glasgow City Centre. The location is highlighted in Figure 47.

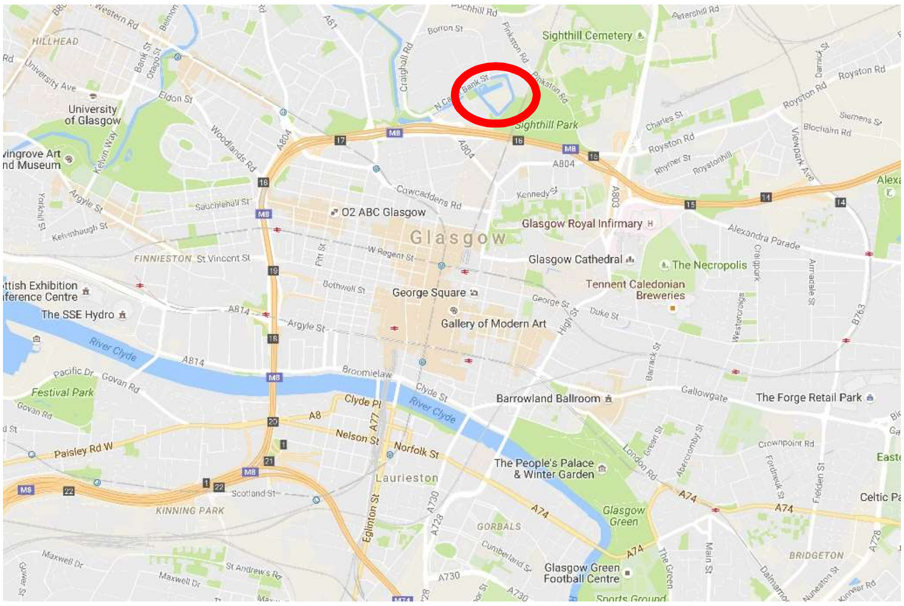


Figure 47 Location of Pinkston Watersports

From the investigation undertaken in section 4, it is clear that the best solution for reducing the renewable energy used by a pumped AWWC is the installation of on-site wind turbines. However, for a number of reasons installation on this site may be problematic. While there is land available adjacent to the white water course, the urban environment may prove problematic for energy generation from wind. Booker *et al.* (2010) note that wind turbines in the urban environment have had variable success and are generally smaller scale than installation in more rural environments. Booker *et al.*

(2010) also state that technologies implemented in large scale wind turbine installations may not be applicable in urban environments.

Instead of on-site generation Pinkston Watersports could benefit from investment into a turbine located off-site. This could act in a similar way to existing community projects where cooperatives, charities, development trusts or other community-based organisations own shares in a wind farm development (Okkonen and Lehtonen, 2016). While this type of project is generally more suited for smaller isolated communities, there may be an opportunity for a similar project within the Port Dundas and Sighthill area of Glasgow where Pinkston Watersports is located. Both Sighthill and Port Dundas are areas which are undergoing regeneration (The Scottish Government, Scottish Canals and Glasgow City Council, 2014; Glasgow City Council, ND), therefore there may be potential for a community group to invest in an off-site wind turbine. This kind of solution would not directly supply the site and would therefore be a way to off-set energy consumption.

The non-generation solutions investigated throughout the project would also be difficult to implement at Pinkston Watersports. Since the site is located so close to the city centre of Glasgow, there is little available space that could be used for the storage of water.

6.2. Lee Valley White Water Centre

Lee Valley White Water Centre has good potential for the installation of on-site renewable generation because of its location in Lee Valley Regional Park.

An investigation with regards to the possibility of becoming a net zero energy site using renewable generation was undertaken in HOMER. The demand data used in the general investigation were scaled to represent the pumps installed on the course, this is listed in Table 3. This demand data only considered the “Olympic” channel since pump data was not available for the smaller channel. The smaller channel could be considered a similar size to Pinkston Watersports and therefore the general results would be applicable. Climate data from Kew was imported from the MERIT/ESP-r database to better reflect the climate at Lee Valley White Water Centre. Kew is located just 30km from Lee Valley White Water Centre. This change was made to better represent the weather conditions in the south of England. The climate in the south of England varies from that used in the original model, being notably milder than the climate in Glasgow.

A number of model were created, as outlined in Table 16:

Table 16 Model used in the Lee Valley case study

Model	Type of Generation	Turbine Size
1	Wind	500 kW
2	Wind	1500 kW
3	PV	-

Throughout all of the models the electrical storage technologies were kept consistent with the general investigation. In model 1 the wind turbine specification was also kept consistent using the Windpower 45-500. Model 2 used a generic 1500 kW turbine from the HOMER database. This larger wind turbine was used because of the power draw of the pumps at Lee Valley. Since the total power draw of the pumps is 1,080 kW, a larger turbine may be more suitable and therefore this was investigated. Model 3 used photovoltaic panels for generation, similar to model 2 and 3 in the general investigation.

The state of charge of the batteries was not considered during the case study since it was clear from the general investigation that electrical storage would likely not be a feasible solution.

Using 500kw Turbines

The results from the first model simulation are in the table below:

Table 17 Lee Valley case study model 1

	No. of Turbines	No. of Batteries	Renewable Fraction (%)	Energy Imported (kWh)	Energy Exported (kWh)	CO2e Emissions (kg CO2e)
1	1	0	17	1,334,917	211,300	616,985
2	1	268	15	1,253,478	78,229	579,345
3	4	0	48	1,168,913	863,910	540,260
4	4	268	49	1,036,630	647,761	479,120
5	5	0	55	1,129,804	1,097,673	522,184
6	5	268	56	994,411	876,443	459,607
7	6	0	60	1,094,708	1,335,448	505,963
8	6	268	62	957,578	1,111,380	442,583

The costs associated with the scenarios are listed in Table 18.

Table 18 Lee Valley scenario costs

	Cost of imported energy (£)	Value of exported energy (£)	Yearly Profit (£)	Equipment Cost (£)	Payback period (years)
1	200,238	10,248	-189,990	550,000	n/a
2	188,022	4,231	-183,791	883,512	n/a
3	175,337	41,900	-133,437	2,200,000	n/a
4	155,495	31,416	-124,078	2,533,512	n/a
5	169,471	53,237	-116,233	2,750,000	n/a
6	149,162	42,507	-106,654	3,083,512	n/a
7	164,206	64,769	-99,436	3,300,000	n/a
8	143,637	53,902	-89,735	3,633,512	n/a

1.5 MW turbine

The results for model 2 are listed in Table 19:

Table 19 Lee Valley Model 2 scenario results

	No. of Turbines	No. of Batteries	Renewable Fraction (%)	Energy Imported (kWh)	Energy Exported (kWh)	CO2e Emissions (kg CO2e)
1	1	0	56	1,107,462	1,115,680	511,858
2	1	268	58	936,326	836,047	432,761
3	2	0	75	912,702	2,325,628	421,842
4	2	268	78	743,546	2,049,229	343,660

The costs associated with the model 2 scenarios are in Table 20:

Table 20 Lee Valley model 2 costs

	Cost of imported energy (£)	Value of exported energy (£)	Yearly Profit (£)	Equipment Cost (£)	Payback period (years)
1	166,119	54,110	-112,009	3,000,000	n/a
2	140,449	40,548	-99,901	3,333,512	n/a
3	136,905	112,793	-24,112	6,000,000	n/a
4	111,532	99,388	-12,144	6,333,512	n/a

PV Panels

The results of model 3, using photovoltaic panels for generation are in Table 21:

Table 21 Lee Valley Model 3 results

	No. of PV Panels	No. of Batteries	Renewable Fraction (%)	Energy Imported (kWh)	Energy Exported (kWh)	Carbon Emissions (kg CO2e)
1	800	0	58	1,011,994	1,023,284	467,734
2	800	268	62	820,082	793,393	379,034

The costs for the scenarios using solar panels are in Table 22:

Table 22 Lee Valley model 3 costs

	Cost of imported energy (£)	**Value of exported energy (£)**	**Yearly Profit (£)**	**Equipment Cost (£)**	**Payback period (years)**
1	151,799	49,629	-102,170	2,640,000	n/a
2	123,012	38,480	-84,533	2,973,512	n/a

Discussion

While the previous HOMER investigation proved wind to be much more effective in the Glasgow climate, this was not reflected at Lee Valley White Water Centre. The lower average wind speed and higher solar radiation made photovoltaic panels much more effective for on-site generation. An installed capacity of 2,500 kW (Table 17, scenario 5) using wind turbines would produce approximately the same results as 800 kW installed capacity of solar panels (Table 21, scenario 1). The cost of installing photovoltaic panels would also be less than the cost of using wind turbines, £2,640,000 (Table 21, scenario 1) and £2,750,000 (Table 18, scenario 5) respectively. This is also favourable when compared to using larger turbines. A single 1,500 kW turbine would produce similar results to the scenarios described above, allowing the site to become a net zero energy site. However the cost of this would likely be in the region of £3,000,000. No scenarios throughout the case study were able to offset the cost of electricity imported from the gird by selling excess electricity. Approximately 5,840 m^2 would be required to install this capacity of photovoltaic panels. Given the surroundings of Lee Valley White Water Course, there the potential for the installation of this number of solar panels. Figure 48 shows the approximate area required:

Figure 48 Area required to create a net zero energy site using solar panels

With regards to retrofitting Lee Valley to incorporate one of the non-generation design, there appears to be little scope for the river-charging design to be used. Although there is no river flow data for the river Lee in close proximity to the white water course, gauges further upstream and from surrounding tributaries suggest that the flow rate is too low to support any extraction. In addition, the river Lee is used as part of a large flood relief system, the River Lee Flood Relief Channel (Environment Agency, 2013), meaning the waterways are heavily managed.

There would also be some significant hurdles to overcome if a pump-charging design was to be used. While the area is a flood plain with a number of large natural bodies of water, creating a sufficient head that would allow volume flow to the course and away from the course would be difficult. For this reason, a man-made body of water would need to be created.

7. Conclusion

It is clear from the work undertaken during this project that reducing the site energy consumption of a pumped artificial white water course presents significant challenges. These difficulties stem from the high volume flow rate of water that is required even at the smallest of artificial white water courses. While small-scale courses can often require a flow less than half of what a large course requires, this still amounts to a significant volume per second. In order to pump this large volume of water to instantaneously provide flow to a course, high power pumps are required.

Renewable generation could significantly reduce the net energy consumption of an AWWC, and in the process reduce the carbon footprint. There are a number of major challenges that would need to be overcome to make this feasible. The high power consumption of the pumps means that a large capacity needs to be installed if this demand is to be instantaneously met. The large installed capacity could potentially be used to export a significant amount of energy to the grid since there are long periods when the pumps are not operating. The price received for exported energy has a large impact on the cost effectiveness of many solutions. If this exported energy was instead utilised on site, by storing it for later in batteries, it would be possible for the site to become autonomous and not require a grid connection. This solution is expensive and in the investigation the payback periods were always lengthy and expected to be significantly longer than the lifespan of the equipment. All of this makes it impractical to remove the grid connection and utilise only renewable generation and electrical storage.

The high cost and relatively low capacity of electrical storage are currently the technology's biggest drawbacks. Because of these characteristics, electrical storage can be unsuitable for high power applications if cost is a major consideration. The significance of the cost of electrical storage is further highlighted when the total cost for construction of Pinkston Watersports is considered. The project cost approximately £3,000,000 to build, and the cheapest scenario in any of the models that included electrical storage was £5,241,996. Of this, £4,691,996 was attributed to batteries and conversion technologies, significantly more than the cost of constructing the course alone.

While the general modelling investigations undertaken in HOMER suggested that wind generation was much more suited to supplying the high power requirements than solar, the Lee Valley case study suggested the opposite. This is down to the difference in climate between the models. The models throughout the general investigation used climate data from Glasgow. There is greater potential to generate electricity from wind than from solar in this area. The Lee Valley case study used climate data from Kew, located 30 km from Lee Valley. There is a much greater potential for electrical generation from solar energy than from wind in this region of the UK, hence the results of the case study. The climate of a site would need to be carefully considered when deciding on a renewable technology to implement.

Solutions that would remove the energy consumption of the pumps show promise, but would likely encounter severe limitations due to very specific site requirements. All of the design concepts make use of an upper reservoir to store water. In order to retain the benefits of a pumped course, these reservoirs need to be able to hold large volumes of water. In addition, there is a requirement for either an additional reservoir below the course or the ability for the water from the course to flow away freely. Because of this, there are not only limitations with regards to storing the water, but also with creating sufficient head to allow water to flow from the reservoir and away from the white water course.

If a pump or river charging design were to be constructed, identifying bodies of water that would be suitable to use as a reservoir could present significant challenges. Data regarding the volume of lakes or reservoirs is not readily available. Because of this, a separate study would have to be carried out to identify appropriate sites. Geographical information systems (GIS) could be used to estimate volumes before more detailed land surveys are carried out.

Instead of using an existing body of water, a reservoir could be created with the specific purpose of providing water to an AWWC. This solution would again come with some significant constraints, notably site location. There are also a number of legislations that would need to be complied with depending on the area. The Reservoirs Act (1975) is applicable in England and Wales, the Reservoirs (Scotland) Act (2011) would have to be considered for sites in Scotland, with the Flood and Water Management Act (2010) requiring compliance across the whole of the United Kingdom. These acts currently apply to bodies of water over 25,000 m^3, yet reservoirs larger than 10,000 m^3 will soon be included. The acts control the management of reservoirs with one of the main focuses being safety. The biggest challenge faced by all of the designs using a reservoir for storage is not only finding an appropriate site but also finding an appropriate site that is close to a suitably large population centre.

Large tanks, similar to those used in the oil industry, appear to be a promising way to store large volumes of water. 200,000 m^3 tanks would be able to store enough water for approximately 7.4 hours of flow at 7.5 m^3/s. There were difficulties finding the costs associated with tanks of this size, yet it is likely that costs would be significant enough to make a traditional pumped design more attractive.

Extracting water from a natural river to store in an upper reservoir appears to be feasible using medium to large volume rivers. The larger the river, the less impact the extraction would have. This is especially important in summer flows, when the river could be at a low level for a long period. As with the other non-generation solutions, geography would play an important role with regards to a suitable site. A sufficient head is not only required over the white water course, but also between the river and reservoir and also at the outflow of the course. By operating an AWWC using this type of design, filtering the water would not be an attractive proposition. Water filtering can be achieved in closed cycle systems since it can be used a number of times. It would not be economical for a river-charging design to filter all of the water that flows down the course. The omissions of this type of system would likely not be considered a limiting factor as current run-of-river AWWCs do not filter water.

While exploiting the head created by the tide is an attractive way to generate electricity, this appeal does not transfer to AWWCs. The operational constraints that would be imposed on the course due to the time of the high and low tides are significant enough to make this concept extremely unattractive.

The case studies highlighted how implementing on-site renewable generation is limited by the location of the course. There is little scope for on-site generation at Pinkston

Watersports, yet at Lee Valley White Water Course there could be an opportunity to install either wind turbines or solar panels. Solar panels would be the preferred technologies due to the climate of the area. Non-generation design concepts would not be feasible at either site. Specific sites that could accommodate these types of designs would be required as opposed to retrofitting an existing site.

8. Future Work

At present there is little scope for other renewable generation technologies to be further investigated. The technologies that were studied in this investigation are some of the cheaper forms of renewable generation, and integration in to an AWWC was problematic. As other renewable generation technologies develop, they may become suitable for this kind of application but until then, the scope is limited. The findings from this study could be applied to other sports venues with high power draws. Snowdomes and stadiums which have been discussed previously could prove to be interesting areas to study.

Because the focus of the investigation was to identify renewable generation and electrical storage technologies that would be suitable to power a pumped AWWC, maintenance costs were not considered. This could be included in a future study.

Unless there is either a significant drop in price or a marked improvement in battery technology, there is little scope for further investigation in this field.

As discussed previously, there is scope for an investigation to find a suitable site for a river of pump charging design. This would likely be a lengthy study due to the method required.

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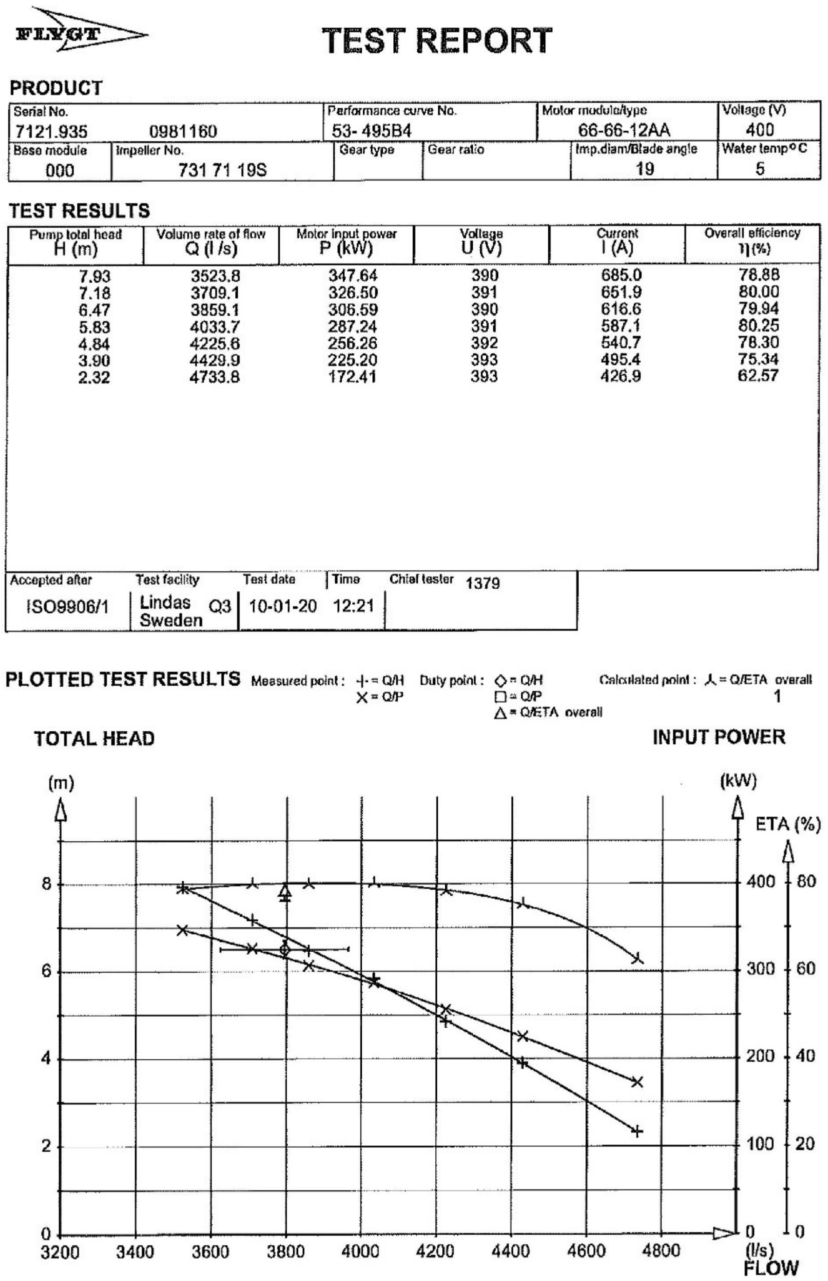
Appendix 1



FLYGT

TEST REPORT

PRODUCT

Serial No. 7121.935 0981160	Performance curve No. 53- 495B4		Motor module/type 66-66-12AA	Voltage (V) 400
Base module 000	Impeller No. 731 71 19S	Gear type	Gear ratio	Imp.diam/Blade angle 19	Water temp °C 5

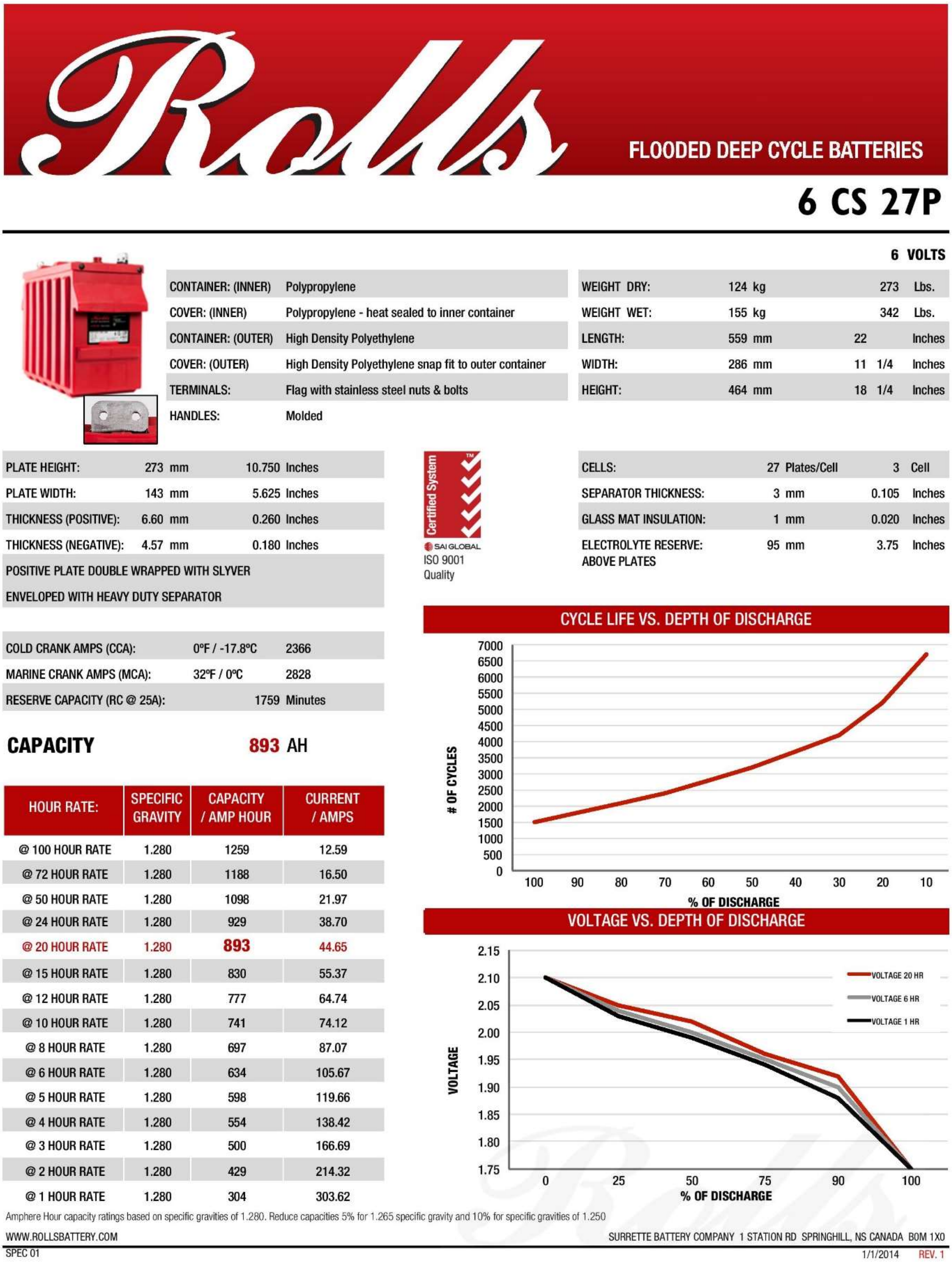
TEST RESULTS

Pump total head H (m)	Volume rate of flow Q (l /s)	Motor input power P (kW)	Voltage U (V)	Current I (A)	Overall efficiency η (%)
7.93	3523.8	347.64	390	685.0	78.88
7.18	3709.1	326.50	391	651.9	80.00
6.47	3859.1	306.59	390	616.6	79.94
5.83	4033.7	287.24	391	587.1	80.25
4.84	4225.6	256.26	392	540.7	78.30
3.90	4429.9	225.20	393	495.4	75.34
2.32	4733.8	172.41	393	426.9	62.57

Accepted after	Test facility	Test date	Time	Chief tester
ISO9906/1	Lindas Q3 Sweden	10-01-20	12:21	1379

PLOTTED TEST RESULTS Measured point : ┼ = Q/H Duty point : ◇ = Q/H Calculated point : 人 = Q/ETA overall
× = Q/P □ = Q/P 1
△ = Q/ETA overall

Appendix 2



FLOODED DEEP CYCLE BATTERIES

6 CS 27P

6 VOLTS

CONTAINER: (INNER)	Polypropylene
COVER: (INNER)	Polypropylene - heat sealed to inner container
CONTAINER: (OUTER)	High Density Polyethylene
COVER: (OUTER)	High Density Polyethylene snap fit to outer container
TERMINALS:	Flag with stainless steel nuts & bolts
HANDLES:	Molded

WEIGHT DRY:	124	kg	273		Lbs.
WEIGHT WET:	155	kg	342		Lbs.
LENGTH:	559	mm	22		Inches
WIDTH:	286	mm	11	1/4	Inches
HEIGHT:	464	mm	18	1/4	Inches

PLATE HEIGHT:	273	mm	10.750	Inches
PLATE WIDTH:	143	mm	5.625	Inches
THICKNESS (POSITIVE):	6.60	mm	0.260	Inches
THICKNESS (NEGATIVE):	4.57	mm	0.180	Inches

POSITIVE PLATE DOUBLE WRAPPED WITH SLYVER

ENVELOPED WITH HEAVY DUTY SEPARATOR

Certified System TM

SAI GLOBAL

ISO 9001
Quality

CELLS:	27	Plates/Cell	3	Cell
SEPARATOR THICKNESS:	3	mm	0.105	Inches
GLASS MAT INSULATION:	1	mm	0.020	Inches
ELECTROLYTE RESERVE: ABOVE PLATES	95	mm	3.75	Inches

COLD CRANK AMPS (CCA):	0ºF / -17.8ºC	2366
MARINE CRANK AMPS (MCA):	32ºF / 0ºC	2828
RESERVE CAPACITY (RC @ 25A):		1759 Minutes

CAPACITY **893** AH

HOUR RATE:	SPECIFIC GRAVITY	CAPACITY / AMP HOUR	CURRENT / AMPS
@ 100 HOUR RATE	1.280	1259	12.59
@ 72 HOUR RATE	1.280	1188	16.50
@ 50 HOUR RATE	1.280	1098	21.97
@ 24 HOUR RATE	1.280	929	38.70
@ 20 HOUR RATE	1.280	**893**	44.65
@ 15 HOUR RATE	1.280	830	55.37
@ 12 HOUR RATE	1.280	777	64.74
@ 10 HOUR RATE	1.280	741	74.12
@ 8 HOUR RATE	1.280	697	87.07
@ 6 HOUR RATE	1.280	634	105.67
@ 5 HOUR RATE	1.280	598	119.66
@ 4 HOUR RATE	1.280	554	138.42
@ 3 HOUR RATE	1.280	500	166.69
@ 2 HOUR RATE	1.280	429	214.32
@ 1 HOUR RATE	1.280	304	303.62

Amphere Hour capacity ratings based on specific gravities of 1.280. Reduce capacities 5% for 1.265 specific gravity and 10% for specific gravities of 1.250

CYCLE LIFE VS. DEPTH OF DISCHARGE

VOLTAGE VS. DEPTH OF DISCHARGE

WWW.ROLLSBATTERY.COM

SURRETTE BATTERY COMPANY 1 STATION RD SPRINGHILL, NS CANADA B0M 1X0

SPEC 01

1/1/2014 REV. 1