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An Evaluation of Seawater Pumped Hydro Storage for Regulating the Export of Wind Energy to the National Grid

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AN EVALUATION OF SEAWATER PUMPED HYDRO STORAGE FOR REGULATING THE EXPORT OF WIND ENERGY TO THE NATIONAL GRID

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Declaration

I hereby certify that the material, which is submitted in this dissertation, is entirely my own work and has not been submitted for any academic assessment other than as part fulfilment of the assessment procedures for the program Bachelor of Science in Electrical Services and Energy Management (BSc (Hons)) (DT 018).

Signature of student:

Date: 08/05/2013

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I would like to thank the staff and students of Lycée Livet Nantes, France, who during their visit here in 2012 gave me the foundation of the idea for this research. Their interest in and enthusiasm for their visit to Turlough Hill, which was kindly facilitated by Mr. Paul Marah sparked an interest for me in Pumped Hydro Storage.

Lastly I would like to thank my wife and children for their unending support of the monster behind the laptop for the last number of months.

Abstract

Hydroelectric power generation has been in use for a very long time. From the earliest watermills to the current large scale Hydro power plants, this is a technology that is proven to be reliable and commercially viable. The use of wind energy to provide mechanical power for the purpose of turning a rotor is also not a new concept.

Four years ago TCD Professor of Applied Physics Igor Shvets conceived the idea of solving Ireland's energy crisis by taking these two proven renewable technologies and combining them. (McGreevey, 2012) The spirit of Ireland initiative seeks to resolve the biggest issues facing those involved in wind generated electricity, namely what to do when the wind is not blowing.

There has not been a new Pumped Hydro Electric storage Power Plant built in Ireland since Turlough Hill in 1973 and one of the reasons for this may be the high capital costs associated with this type of project.

The premise of using the sea as the lower reservoir in a low head, high volume system is at the centre of The Spirit of Ireland Proposal. This type of system should offer a lower capital cost, but is it low enough and could it provide a viable source of energy for today's modern grid.

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Glossary of Terms

PHES	Pumped Hydro Electric Storage
WE	Wind Energy
DCENR	Department of Communications Energy and Natural Resources
NREAP	National Renewable Energy Action Plan
ESB	Electricity Supply Board
GHG	Green House Gases
EU	European Union
TSO	Transmission Supply Authority
SNSP	Synchronous Non Synchronous Penetration
ROCOF	Rate of Change of Frequency Relay
HVDC	High Voltage Direct Current
OR	Operating Reserve
DSO	Distribution Supply Authority
MW	Mega Watt
kw	Kilo Watt
MWh	Mega Watt Hour
kWh	Kilo Watt Hour
TWh	Terra Watt Hour
IWEA	International Wind Energy Association
US	United States
EWEA	European Wind Energy Association
m	Metres
O & M	Operation and Maintenance
REFIT	Renewable Energy Feed in Tariff

1 Introduction

Since 2009 the idea of using Pumped Hydro storage (PHES) as a method of storing the electricity produced from wind has been constantly raised in discussion. The spirit of Ireland group had started looking for capital investment in early 2012. However at the time of writing there appears to have been little progress in this area or in any other area relating to the proposal in general and there website does not appear to have been updated recently. That being said, until such time as this proposal can be completely written off, it must surely be worth investigating further, especially as energy prices continue to rise and the threat of peak oil remains present.

1.1 Dissertation Structure

1.1.1 Dissertation Aim

The aim of this dissertation is to establish the viability or otherwise of using PHES as a means to improving the use of wind energy (WE) in Ireland. Energy use is not constant, the wind is not constant and the chances of these 2 variables overlapping in any useful way is slim, so with that in mind this dissertation hopes to highlight any potential benefit that may be derived from this area.

1.2 Dissertation Objectives

In order to meet the overall aim of this dissertation, there are a number of specific areas that must be discussed. This dissertation is based on said factors and the objectives are as follows:

1. Demand for PHES

   The first requirement for the author was to establish if there was a need for an increase in PHES capacity in Ireland. Then if there is a need, then what are the key drivers in this area?

2. Available Resource to Meet Demand

Having established a demand for an increase in PHES, the next objective was to assess the available resource available to meet this demand. This involved an appraisal of Ireland's intention to increase the penetration of renewable energy, specifically wind on to the national grid and an investigation of proposed PHES sites and Gate 3 connection agreements.

3. Pumped Hydro System Evaluation

To properly assess any potential site it was felt that an understanding of the history and operation of PHES was required

4. Dundrum Inner Bay Site Assessment

An assessment of a potential site was deemed essential in determining the viability of this kind of project. The assessment was carried out from a technical and financial perspective.

1.3 Dissertation Layout

Each chapter contains its own introduction and conclusion. Literature reviewed for each chapter is referenced throughout.

Chapter 1 introduces the project, its objectives and aim. It outlines the rationale behind the selection of the research topic and the scope of the project.

Chapter 2 presents an assessment of the current demand for PHES. It examines the key drivers in this area; policy both National and European, increased integration of intermittent, asynchronous power on to the national grid and the requirement of EIRGRID for the provision of ancillary services such as operating reserve, reactive power and blackstart.

Chapter 3 examines Ireland's wind potential and its current installed capacity. It also details some of the requirements for exporting this wind energy on to the grid in addition to reviewing some of the proposed PHES sites in Ireland.

Chapter 4 provides an overview of the history of PHES, how it works and the factors that determine its capacity. This chapter also includes a detailed study of Yanbaru seawater PHES in Okinawa, Japan. Consideration is given to the design features required to enable it to operate in seawater, the environmental concerns relating to bringing seawater inland and how these concerns were addressed and overcome.

Chapter 5 provides an analysis of one potential location for a PHES system using seawater in Ireland. A complete site analysis is provided, from assessing the capacity, required flow and duration of output to an appraisal of the technical and financial merits of this proposal.

Chapter 6 summarises the overall conclusions of the research and suggests areas where further research may be warranted.

1.4 Rationale Behind Research Topic

Energy independence is the premise behind the Spirit of Ireland project and an ideal situation for any country to find itself in. Ireland's import dependency in 2011 was a staggering 88% although this was down from 90% in 2006. (SEAI, 2012) This represents an annual spending of approximately €6 billion, which when you consider that Minister for Communications, Energy and Natural Resources, Pat Rabbitte, told a meeting of the British Irish Parliamentary Assembly that he envisaged the government spending approximately €1 billion in total on civil engineering projects over the next 2-3 years, is quite a significant amount of money that is not being spent in Ireland (Ryan, 2013)

In 2011 alone the savings brought about by renewables was a €300 million reduction in natural gas imports. This is money that is being spent on creating jobs within Ireland and developing Ireland's indigenous energy supply.

It is not just the pressing need to achieve some measure of energy independence that is driving the development of renewable energy resources. Ireland, along with other countries has made agreements to reduce the amount of CO^2 that it is producing. In the period 2008 – 2011 the average energy related CO^2 emissions were 40 Mt or 34% above 1990 levels. Irelands target is to reduce these emissions to 13% above 1990 levels for the period 2008 - 2012 (Department of the Environment, Heritage and Local Government, 2006)

Wind Energy is an abundant resource in Ireland and it currently contributes the majority of our electricity from renewable sources. It does however have a number of drawbacks. There are the widely publicised, public opposition to wind farms being located next to them, with regard to noise pollution and aesthetics as well as concerns over the effect on migrating birds. It is not these issues however that will be considered here but the potential effects on the current generation system, both technical and financial.

Wind is an intermittent resource and unlike conventional generation equipment, the output may not necessarily match customer demand. If it is assumed that WE is given priority dispatch, then the output required from other generation sources becomes more volatile. This can create difficulties in terms of start-ups and ramping duty as it increases associated costs and mechanical and thermal stresses on existing units (ESB National Grid, 2004)

With all these factors in mind it would seem prudent to investigate some method of regulating the export of wind power to the national grid without having a detrimental impact on the existing equipment. The method to be investigated in this dissertation is Pumped Hydro Electric Storage.

1.5 Scope of Dissertation

This dissertation will examine the technology that is currently available to provide large scale energy storage in Ireland. It will also assess the benefits of this storage both from an environmental perspective and as a valuable addition to a secure national grid. The author will use existing information and research to reach an informed opinion on the technical and financial merits of said proposal.

1.6 Limitation of Dissertation

This dissertation will not examine any other existing proposals as an alternative to PHES but will exclusively focus on the gathering and distillation of existing work in the PHES area to arrive at a definitive conclusion.

2 The Demand for Large Scale Energy Storage

2.1 Introduction

There are many reasons for introducing more PHES onto the national grid and this chapter looks at each of these areas in detail. What follows in this section is a review of the relevant and seminal works in this area, which have been used by the author to inform and support the various conclusions arrived at in this document. The selected works will include policy documents, both European and National, published and unpublished academic writings in the field of PHES. The information obtained and distilled from this section is referenced throughout this document.

2.2 Policy

Under the agreements set down in the Kyoto protocol, Ireland has committed to limiting its growth in carbon emissions to 13%. Between 2002 and 2008 Ireland's emissions were in the range of 122 – 125% of the 1990 level, well above the agreed 113% (CSO, 2012). This figure began to decline in 2009 and as of 2011 the figure is 110%, 3% below the Kyoto target. To help Ireland meet its target the Government developed the National Climate strategy in 2000 and this has been updated for the period 2012 – 2020. Under Directive 2009/28/EC Ireland is legally obliged to ensure that by 2020 at least 16% of energy consumed in the state is from natural resources (DCENR, 2012). Furthermore under section 4 of this article each member state was required to submit a National Renewable Energy Action Plan (NREAP). As part of this plan the Irish government has set a target of 40% of electricity consumption from renewable resources by 2020 (DCENR, 2010). With this target in mind the National Climate strategy has set out the following 5 strategic goals.

<u>Strategic Goal 1</u>

Progressively more renewable electricity from onshore and offshore wind power for the domestic and export markets.

Strategic Goal 2

A sustainable bioenergy sector supporting renewable heat, transport and power generation.

Strategic Goal 3

Green growth through research and development of renewable technologies including the preparation for market of ocean technologies.

Strategic Goal 4

Increase sustainable energy use in the Transport sector through biofuels and electrification.

Strategic Goal 5

An intelligent, robust and cost efficient energy networks system. (DCENR, 2012)

In 2008 The Department of Communication, Energy and Natural Resources carried out a study on the national grid, to assess the ability of the grid to handle increasing amounts of renewable energy and one of the key conclusions to come out of the study was that there must be market mechanisms to facilitate the installation of flexible, dispatchable plant, to maintain adequate levels of security (DCENR, 2008). The study also found feasible levels of renewable integration representing 37 – 46% of total generation capacity, and it would appear that the results of this study went some way towards encouraging the DCENR to introduce their target of 40% renewables that is set out in NREAP.

In March 2007 the European Council set out two legally binding targets that have fed directly into national policy development. These are

1) A reduction of at least 20% in greenhouse gases (GHG) by 2020 – rising to 30% if there is an international agreement committing other developed countries to "comparable emission reductions and economically more advanced developing countries to contributing adequately according to their responsibilities and respective capabilities".

2) A 20% share of renewable energies in EU energy consumption by 2020. (Commission of the European Communities, 2008)

It is clear that a reduction in greenhouse gases (GHG) achieved through the increase in renewable energy is a priority at national and European level.

2.3 Integrating Intermittent Power

The combined power systems of Ireland and Northern Ireland will have more wind farms installed, as a percentage of the overall energy requirement, than anywhere else in the world by 2020 (EIRGRID and SONI, 2011). It is estimated that by this time the island of Ireland will generate 37% of its electricity from wind power. As the current installed wind capacity can meet 15% of the electricity requirements, changes in the transmission and distribution structure that currently exists. In 2009 EIRGRID and SONI carried out a suite of Studies to examine the facilitation of renewables in Ireland. One of the findings from these studies was that “the integrity of the system following a frequency event is potentially comprised at high instantaneous penetrations of wind” (EIRGRID and SONI, 2011). The studies also noted that voltage disturbances may cause the temporary loss of output from wind farms, thereby endangering the system stability. The studies did however also determine that the TSO’s can securely manage the system so long as the System Non - Synchronous Penetration (SNSP[1]) remains below 50% in real time operations (EIRGRID and SONI, 2011). The studies also indicate that with the correct investment in transmission and distribution infrastructure, that SNSP levels of up to 75% could be achievable.

The introduction of asynchronous power on to the national grid, can lead to a reduction in the overall system inertia. Inertia is the automatic response of the synchronous generation equipment to changes in frequency. It is known that Rate of Change of Frequency (ROCOF) Relays will operate for frequency changes of greater than 0.5 Hz, potentially causing a loss of generation, leading to system instability (EIRGRID and SONI, 2010). There is a link between system inertia and primary operating reserve; the lower the system inertia, the quicker

[1] SNSP is a measure of the non-synchronous generation on the system in an instant. It is a ratio of the real-time MW generation from wind and HVDC imports to demand plus HVDC exports (EIRGRID and SONI, 2011)

the frequency will fall following loss of generation and therefor the faster the primary reserve needs to be. (EIRGRID and SONI, 2011). One of the recommendations to come out of this report to mitigate a reduction in system inertia is to improve the speed and magnitude of the reserve response. (Lalor, 2005) Suggests the use of ROCOF relays to trigger pumped storage generating units to compensate for frequency disturbances.

2.4 Ancillary Services

EIRGRID currently charge for a number of ancillary services that they provide, the 3 main ancillary services are:

1) Reserve
2) Reactive Power
3) Blackstart

2.4.1 Operating Reserve

As system operator EIRGRID must constantly try to maintain the balance between the demand for electricity and the generation of electricity. If they fail to maintain equilibrium the frequency of the system will drop. Correcting these low frequency events requires an increase in generation or a reduction in demand (SEAI, 2004). Operating Reserve (OR) may be required after a frequency incident for a period of 5 sec up to 24 hrs depending on the nature of the event. An increase in PHES plant in Ireland would provide more Operating Reserve, thereby increasing the reliability of the system.

2.4.2 Reactive Power

Voltage in electricity grids can only be controlled by the use of generation equipment capable of either absorbing or creating reactive power (Norton, 2012). As Distribution System Operator (DSO) networks and consumers are mainly passive in relation to reactive power, only large electricity generators contribute to reactive power. Reactive power cannot be transmitted over long distances and therefor Transmission System Operators (TSO) must carefully manage local reactive power capabilities to ensure system security. PHES units with variable speed drives can be used to control the amount of reactive power on the grid (Suul, 2009)

2.4.3 Black-start

Another important ancillary service that the TSO must provide is black-start capability. Black-start capability is the supply of electricity to restart generation equipment after a loss of power (Gonzalez, McKeogh and O Gallachoir, 2004). This is usually supplied by relatively expensive diesel engines but due to its quick discharge time and large power capacities, PHES can be used to fulfil this service (Connolly, 2010).

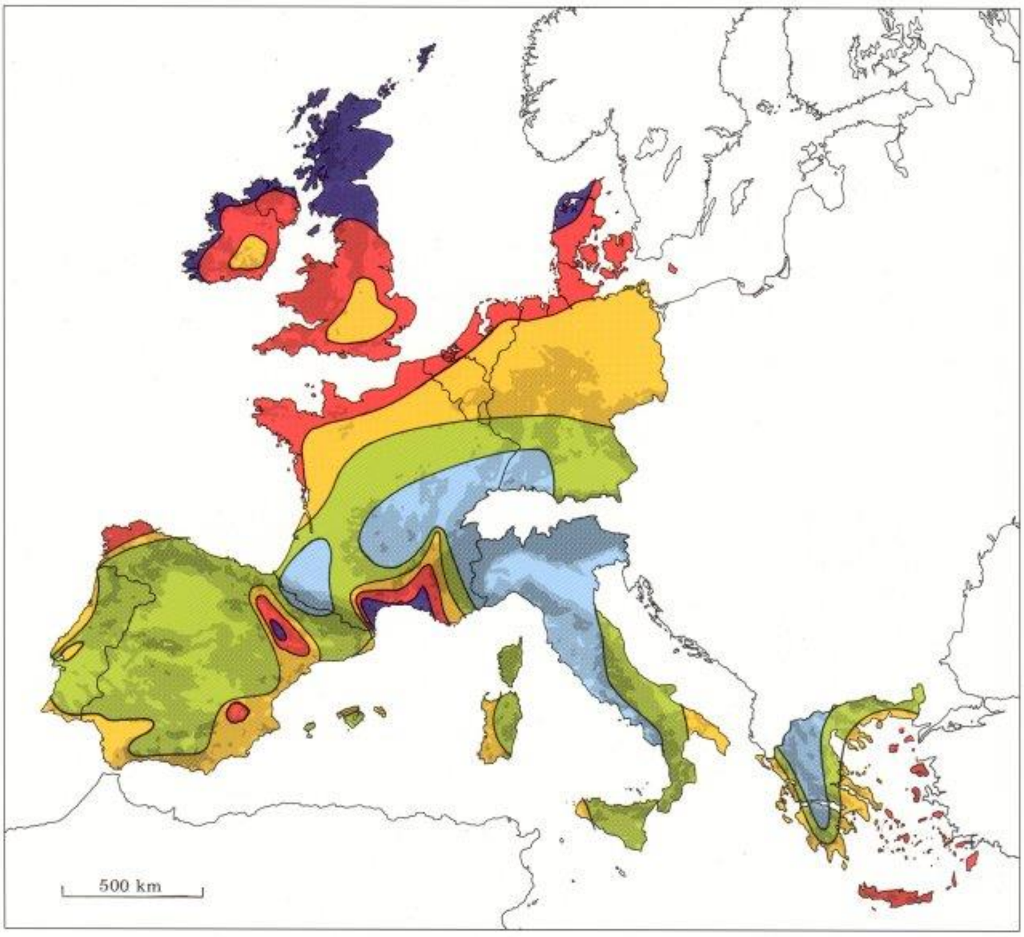
2.5 Conclusion

It can be seen from the reviewed writings in this area that policy, both National and European is driving Ireland towards a power system with significant penetration of asynchronous generation. This situation is clearly going to require changes in the national grid and its generation portfolio. In addition to compensating for intermittent power from Wind Farms, PHES can also supply many of the ancillary services that the TSO is currently providing from more conventional generating equipment. It seems clear that from a technical point of view, PHES is a viable option for Ireland’s modern grid. It is the opinion of this author, and many others that the main drawback to PHES is its financial viability.

3 Ireland's Greatest Resource

3.1 Introduction

Ireland has one of the greatest wind resources in Europe and this fact combined with the government's strategic plan to have 40% of electricity generated from renewable resources, means that Ireland is on its way to becoming a European if not world leader in wind energy. The figure below shows a wind map of Europe and it can be seen from the dark blue shading along the west coast, that Irelands wind resource is matched by very few other countries.



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 3-1: European Wind Map at 50M

(Riso National Laboratory, 2011)

The figure below shows the installed wind capacity in Ireland by county. It can be seen from this that the largest installed capacities are predominantly along coastal counties.

Figure 3-2: Current Installed Wind Capacity

(IWEA, 2013)

As of the most current information Irelands total capacity is 2195.41MW generated from 191 wind farms in 26 counties (IWEA, 2013), however the maximum wind output for 2013 was 1494 MW and the total maximum load for 2013 was 4537 MW. The maximum load occurred on Tuesday 22nd of January and the maximum wind output occurred on Thursday 17th January (EIRGRID, 2013). This represents 32.93% of instantaneous demand being met by wind output. A more realistic picture is given by the monthly demand to monthly renewables. These figures are 2.43TWh total electricity demand for January 2013 and 0.582 TWh renewable generation. This renewable figure includes large scale Hydro but it is mainly wind and it represents 23.95% of monthly demand (EIRGRID, 2013). From these figures it can safely be said that wind penetration is still below 20%. As the level of wind penetration increases to meet current targets, some provisions will need to be put in place to enable this amount of intermittent asynchronous power onto the current synchronous grid.

3.2 The Requirement for Regulating the Export of Wind Energy to the National Grid

ESB National Grid produced a paper entitled “Impact of Wind Power Generation in Ireland on the Operation of Conventional Plant and the Economic Considerations” (ESB National Grid, 2004). This paper highlights the potential increase in Start-up costs for existing Power Generation equipment as a result of thermal plant being used as reserve. It also examines the increase in wear and tear of existing plant as it ramps up and down. It also addresses issues associated with the reduction in capacity factor of the existing Generation equipment. A further study from the National Renewable Energy Laboratory in the US suggests that WE penetration of between 10 & 15% could be handled by current grid arrangements but beyond this, some action will be required to mitigate the negative impacts of such an intermittent resource (National Renewable Energy Laboratory, 2006)

In their paper “2050: Facilitating 50% Wind Energy” the European Wind Energy Association (EWEA) highlight Energy Storage as a key design consideration (European Wind Energy Association, 2010).

A joint paper produced by EIRGRID and SEAI found that while WE had reduced wholesale electricity prices in 2011 by €74 million, thereby covering any WE associated costs, in order to maintain a safe and secure power system, there are a minimum amount of conventional generators that must be kept running to provide reserve and voltage support and that sometimes a certain percentage of WE will go unused (SEAI & EIRGRID, 2011).

In his presentation for the EIRGRID Annual Customer Conference 2007, Dr. Eamon McKeogh states that an increase in PHES is required to meet the demands that an increasing amount of WE is placing on the grid (McKeogh, 2007)

Based on the opinions taken from the above literature, not only can it be seen that storage solutions are required to effectively introduce large scale (15-20%) WE penetration on to the grid, but also that the preferred option currently seems to be PHES.

3.3 Analysis of Potential Pumped Hydro Locations in Ireland

There is currently one PHES Power Station in Ireland, located at Turlough Hill in Co. Wicklow. This station can generate up to 292MW during Peak Demands. (ESB, 2013). There are currently very few proposals for new installations; however this section examines the current proposals that do exist.

Organic Power Ltd. Have proposed the building of a 1200MW seawater PHES at Glinsk Co. Mayo (Nolan, 2012). This proposed site is located within 30km of most of the areas wind and wave resources. The required civil works will involve the removal of 550000 m^3 of peat from the mountain top to create the upper reservoir.

Dr. David Connolly has during the course of his research identified numerous potential locations across Ireland using specially designed software that was able to look for locations that demonstrate a suitable geographical profile to support the upper and lower lakes. (Connolly, 2010). This was then cross referenced with a capacity and cost calculator to assess the financial suitability of the highlighted areas. After conducting an assessment in Co. Clare (Connolly, 2010) estimated that one site alone in County Clare could have a power capacity up to 570 MW and a storage capacity up 22.5 GWh, at a total investment cost of approximately €230-390 million.

Enerco Energy Ltd. Had applied to for connection to gate 2 for a 70 MW plant at Kippagh Lough, Co. Cork, however it appears that their application was not processed in time. They also applied for Gate 3 but their application was removed due to non-firm connection offer not being accepted. The application will remain in queue position for future gates (EIRGRID, 2010)

Coomacheo Pumped Storage facility in Co. Cork has been accepted for connection in Gate 3 as has the 70 MW facility at Knocknagreenan, Co. Cork (EIRGRID, 2010)

All of these locations are the typical PHES arrangement with an upper and lower reservoir. However there is another potential option that may reduce the capital costs required; the use of an inland saltwater bay as the upper reservoir and the sea as the lower reservoir, it is this option that will be explored in more detail in the final section of this document.

4 Pumped Hydro System Evaluation

4.1 Introduction

Hydropower was first used to generate electricity in 1887, in England, by William George Armstrong (Baxter, 2006). The first Hydroelectric Power Station was built in Wisconsin, in the US in 1882 with an output of 12.5 kW (EEM 08, 2008). Since then it has become a widely used and trusted source of electricity generation across the world.

These early designs used a separate turbine generator and pump impeller system. Since the 1950's a single reversible turbine design has become the common model. (Baxter, 2006). Pumped Hydro Storage did not really become popular until the 1960's, when many countries saw PHES as a solution to nuclear base load power plants.

Pumped hydro storage is the only widely adopted form of large scale electricity storage currently in existence. It has been used since the 1890's and currently Japan has the largest PHES capacity in the world with 25.2 GW (Yang, 2009)

There are essentially two main types of PHES systems. The more traditional type uses freshwater pumped up from a lower reservoir to a higher one and then released through turbines back to the lower reservoir. An example of one such system in Ireland is Turlough Hill, Co. Wicklow. Turlough Hill can produce 292 MW of power at times of peak demand and is essential in balancing current supply and demand in Ireland (ESB, 2013).

The decline in popularity of PHES plants may be attributed to many factors such as low fossil fuel prices as well as economic and environmental concerns but it is making a recent surge as countries are required to introduce RE generation in a bid to reduce their carbon footprint. RE from sources such as wind and solar is intermittent and unreliable and as such causes problems for grid operators. The fluctuations in RE generation do not reliably match the demand profile for electricity so it may produce too much at times of low demand and too little at peak times. It is for this reason that pumped hydro storage is being looked at to try and balance this anomaly.

4.2 How Pumped Hydro Works

Pumped Hydro Storage is one of the few tried and tested methods of storing electricity on a large scale (Connolly, 2010). Most PHES systems consist of an upper reservoir, waterways, a pump, a turbine, a motor, a generator and a lower reservoir. The majority of pumped Hydro schemes use a system of two reservoirs, where at times of low demand water is pumped up from a lower reservoir to a higher reservoir, then at times of high demand this process is reversed and the water flows back down to the lower reservoir, driving turbines as it goes. This can enable power companies to purchase cheaper electricity when capacity exceeds demand and sell more expensive electricity when the demand is highest. This is the system currently employed in Turlough Hill, in Co. Wicklow. (ESB, 2013).

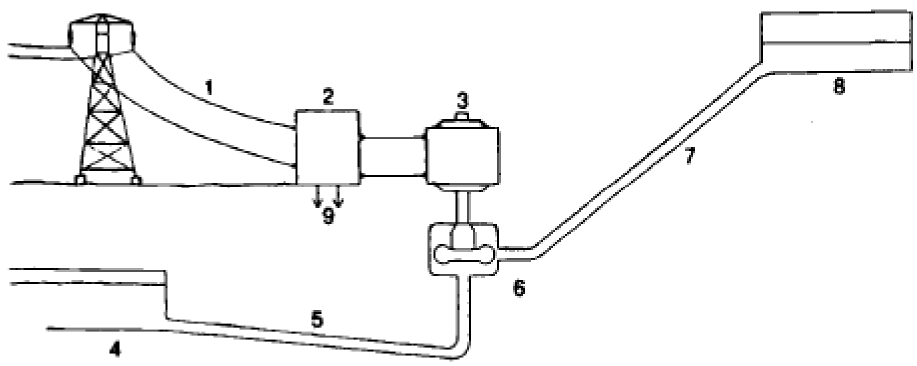


Figure 4-1: Typical PHES Layout

(Ter-Gazarian, 1994)

1 Transmission

2 Transformer

3 Motor – Generator

4 Lower Reservoir

5 Tail Race

6 Pump - Turbine

7 Penstock

8 Upper Reservoir

9 To Loads

Until recently all PHES throughout the world have used freshwater from rivers or lakes as their storage medium, but in 1999 a 31.5 MW test facility was built in Okinawa, Japan. The use of Seawater as the storage medium presented a number of difficulties such as the environmental impact of a saltwater leak and the corrosive effect on associated equipment (Fujihara, Imano and Oshima, 1998). This is the type of system envisaged by the Spirit of Ireland group as it reduces construction costs by using the sea as the lower reservoir. Critics continue to argue that the use of saltwater inland poses too great of an environmental hazard.

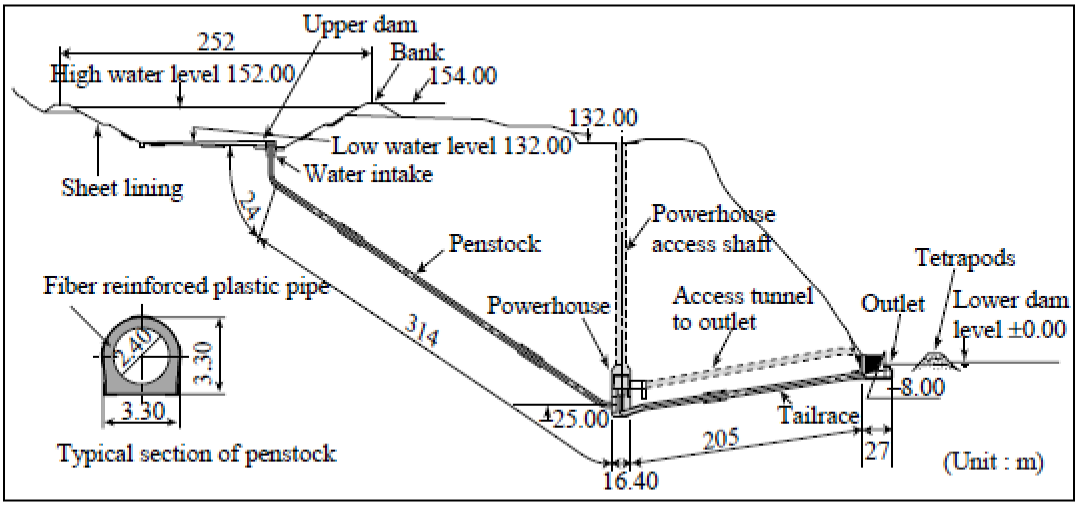


Figure 4-2: Sectional View of Okinawa Plant

(Fujihara, Imano and Oshima, 1998)

4.2.1 Operation and Capacity

A typical PHES has a hydraulic head of 300m. This is the vertical distance between the upper and lower reservoirs. The power capacity of the plant in kW is dependent on the flow rate and the hydraulic head and can be calculated using the following formula:

Equation 1: $P_c = pgQH\eta_p$

(Connolly, 2010)

Where:

P_C = Power Capacity in Watts

p = Mass density of water in kg/m^3

g = Acceleration due to gravity in m/s^2

Q = Discharge through the turbines in m^3/s

H = Effective head in metres

η_p = Pump Efficiency

The energy storage in kWh is dependent on the hydraulic head and the reservoir capacity and may be calculated using the following formula:

Equation 2: $$S_C = \frac{\rho g H V \eta_T}{3.6 \times 10^9}$$

(Connolly, 2010)

Where:

S_C = Storage capacity in MWh

V = Volume of water that is drained and filled each day in m^3

p = Mass density of water in kg/m^3

g = Acceleration due to gravity in m/s^2

H = Effective head in metres

ηT = Efficiency of the Turbine

It can be seen from these two formulae that the main factors in determining the available power and energy storage are the effective head, reservoir volume and the machine efficiency.

4.2.2 Machine Efficiency

The efficiency of modern PHES is in the region of 70 -85%. This level of efficiency is currently being improved by the use of variable speed machines (Anagnostopoulos and Papantonis, 2007). This is a significant development as the overall efficiency of the system is limited by the efficiency of the Pump and Turbine units used in the system (Gonzalez, McKeogh and O Gallachoir, 2004).

4.2.3 Hydraulic Head

It can be seen from the above formulae that the hydraulic head and the reservoir capacity have a significant bearing on the plant output. It is however generally preferable to construct a PHES plant with the greatest possible head rather than a large capacity reservoir as cost has a bearing on this aspect of the design. It is cheaper to build a system with a high hydraulic head and a small volume reservoir than it is to build a plant with a similar output that has a low head and a large volume reservoir (Connolly, 2010). The reasons for this are as follows:

- Less material needs to be removed to create the desired reservoir
- Smaller piping is required, which means smaller boreholes when drilling
- The turbine is physically smaller

It is generally accepted that the ideal ratio of the horizontal to vertical distance between the upper and lower reservoirs should be in the region of 4:1 but this can be lower in favourable situations for example at Turlough Hill, Co. Wicklow where it is 2.5:1 (Ter-Gazarian, 1994)

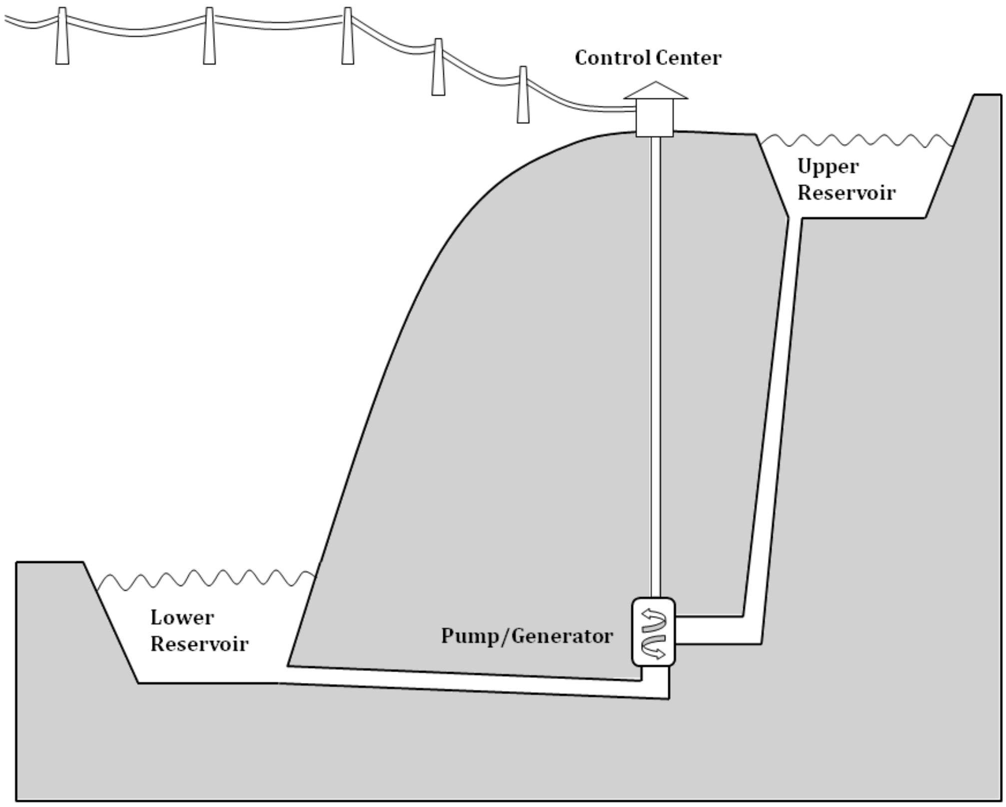


Figure 4-3: Typical Pumped Hydro Storage Layout
(Yang, 2009)

4.3 Reservoir

Reservoirs have been widely used to control the natural flow of water for hundreds of years. At the beginning of the century, all hydro-electric plants with reservoirs were equipped with a pumping mechanism to increase the natural flow of water to the upper reservoir; the driving motive for this was to create seasonal storage in a hydro-electric power system. (Ter-Gazarian, 1994). The next stage in the evolution of hydro plants was to create a reservoir that was to be filled only by artificial means or pumping and these PHES, which were predominantly used with thermal generators, were designed for daily or weekly storage.

The majority of PHES power plants use the standard upper and lower lake, filled with freshwater as seen below.

Figure 4-4: Turlough Hill
(ESB, 2013)

Another type of reservoir used to great effect in Dinorwig, Wales, is an underground reservoir. In excess of one million cubic meters of earth had to be excavated to create the underground reservoir, which is Europe's largest man made excavation (Mitsui & Co. LTD, 2013).The advantage of this type of reservoir is that the upper reservoir can be smaller than a standard system as the head can be created artificially. The expense of the excavation may be offset by placing the station close to a load centre, thereby reducing transmission costs (Ter-Gazarian, 1994). This type of system is limited by geological constraints as rock formations and characteristics need to be correctly assessed.

A new type of system currently being tested in Okinawa, Japan uses the sea as the lower reservoir. This reduces the build cost by removing the need to create an artificial reservoir but there are concerns over the potential environmental impact of a saltwater leak. This plant will now be looked at in greater detail due to its relevance to this thesis.

4.4 Case Study - Okinawa Hydro Plant

The construction process involved in a building a traditional pumped hydro power plant is restrictive in two ways. Firstly it is very expensive, the cost being in the region of €0.5m – €1.0m (Connolly, 2010). This would be a cost of €146m to €292m to construct a plant with a maximum output of 292 MW, equivalent to Turlough Hill. The second drawback is the required geology of the site requiring an upper and lower lake. The idea of using the sea as the lower lake in the Okinawa plant reduces build times and also construction costs. However to use seawater for PHES, one major difficulty need to be overcome and this was the corrosive effect of salt water on the pump turbines. Research began in 1981, construction began in 1991 and the plant was completed in 1998 at a cost of 32 million Yen (€250m) (Aravossis et al., 2006).

4.4.1 Introduction

The area in Okinawa were the Yanbaru plant is located, daily load fluctuations were being met by thermal and gas turbine plants and this led to the consideration of a pumped storage plant to provide a load balancing function. Fresh water is relatively scarce in this particular area and this is what led to a salt water plant being considered. It is the only plant of its type in the world.

4.4.2 The Turbines

In 1981 Electric Power Development Co. LTD. Began the survey and development program for a saltwater test facility called “Verification tests and Investigation for seawater pumped storage techniques” (Fujihara, Imano and Oshima, 1998). Systematic tests began in 1984 to assess the corrosive effects of saltwater on metallic objects and any measures that may be taken to mitigate these effects such as corrosion – preventative paint and cathodic protection. The pump turbine that was developed was designed so that the runner may be easily removed for inspection and maintenance and the water passage surface was simplified as much as possible to minimise crevice corrosion (Fujihara, Imano and Oshima, 1998). Table 4-1 shows the anti – corrosive measures that were applied to each individual part.

Part	Structural Measure Taken
Main Shaft Sealing Box	Ceramics applied to sealing element. Water drain pipes provided to prevent water leaking on to the head cover.
Wicket Gate Stem bearing Assembly	Stem packing doubled to prevent sea water entering the bearing housing.
Wicket Gate seal Packing	Rubber packing is jointed to a stainless steel base by a rubber moulding process.
Main shaft and runner	Connection joint between shaft and runner is completely sealed by rubber gaskets.

Table 4-1: Structural Measures taken to reduce corrosion

(Fujihara, Imano and Oshima, 1998)

In addition to the structural methods outlined in Table 4-1, several material types were specifically used and treated to avoid corrosion. These methods were chosen by considering both the corrosive prevention of the material and the economic viability. The materials were also divided in to two categories, high – flow velocity and low – flow velocity. Mild carbon steel coated with paint was used for the low – flow areas and stainless steel was used for high – flow areas. In addition to this, to prevent corrosion due to paint damage and crevice corrosion, cathodic protection was used (Fujihara, Imano and Oshima, 1998). Corrosion is an electro – chemical process that involves the flow of electrons from one part of the metal to another part of the same metal. This process produces free electrons which are consumed by the cathodic reaction. Corrosion only affects the materials cathode not the anode. Cathodic protection works by passing a dc current through the material to be protected to another metal. This other metal becomes the cathode thereby protecting the original metal. (Kean and Davies, 2003)

Due to the fact that corrosion is relative to the flow velocity, the cathodic protection was to be carried out by an external power source so that the dc current may be adjusted as required (Fujihara, Imano and Oshima, 1998). These measures taken are listed in Table 4-2.

Part	Materials & Corrosion Prevention Method
Spiral case and stay ring	Rolled steel for welded structures. Water passage surfaces coated with anti-corrosion paint
Head cover and discharge ring	Rolled steel for welded structures. Water passage surfaces are stainless steel
Wicket gate, runner and main shaft	Wicket gate, runner are stainless steel. Main shaft is fitted with a slip ring for cathodic protection and is made from stainless steel.
Draft Tube	Rolled steel for welded structures. Water passage surfaces coated with anti-corrosion paint
Main shaft sealing box	Seal is Ceramic. Other parts are stainless steel. Due to space, cathodic protection is provide by a sacrifice electrode.

Table 4-2: Materials & Corrosion Prevention Method

(Fujihara, Imano and Oshima, 1998)

4.4.3 Prevention of Marine Organisms

Barnacles are a typical type of marine organism that can adhere to surfaces were the flow is less than 5m/s and most easily when the flow is 1 or 2 m/s. These organisms can cause problems by clogging up pipes and reducing the plant efficiency. To avoid this happening in areas of low flow, the materials in these areas were treated with an anti – pollutant type paint (Fujihara, Imano and Oshima, 1998)

4.4.4 Plant Specifications

Item		Specification
River system		-
Catchment area		-
Power Plant	Name	Okinawa Yanbaru Power Plant
	Max. output	30 MW
	Max. discharge	26 m^3/s
	Effective head	136 m
Upper regulating pond	Type	Excavated type, Rubber
	Max. embankment	25 m
	Crest circumference	848 m
	Max. width	251.5 m
	Total storage capacity	$0.59 \times 10^6 m^3$
	Max. depth	22.8 m
Waterway	Penstock	Inside dia. 24 m Length 314 m
	Tailrace	Inside dia. 27 m Length 205 m

Table 4-3: Okinawa Plant Specifications

(New Energy Foundation, 2006)

4.4.5 Environmental Issues

The primary environmental concern surrounding this project was the damage that may be caused to plant and animals by saltwater spray due to the pumping process. This was tested using wind tunnels and numerical model analysis and the findings were that this would have no more impact than saltwater spray coming off the sea naturally (New Energy Foundation, 2006). Table 4-4 shows the environmental concerns that were addressed during this process.

Environmental impact assessment items		
Meteorology, Weather, Air quality, Water quality, Noise, Vibration, Offensive odor, Soil contamination, Ground settlement, Topography, Geology, Sea current, Marine phenomenon		
Salt spray, Seawater seepage		
Plant	Vegetation, Rare plant, Soil profile, etc.	
Animal	Terrestrial	Mammals, Birds, Reptiles, Amphibians, Insects, Soil
	Aquatic	Gully animals
	Marine organism	Coral, Fishes, Benthic organisms, Plankton, Eggs and fry, Tideland organisms, Seaweed, grasses

Table 4-4: Environmental Impact Assessment

(New Energy Foundation, 2006)

The environmental factors listed in Table 4-4 were considered and a list of counter measures was suggested to mitigate the associated risk. These proposals were discussed with locals and then approved. Table 4-5 shows the recommended measures that were taken.

Environmental impact factor		Countermeasure
a) Outflow of muddy water produced from the construction area into gullies and sea area near	Construction water	- Chemical treatment by turbid water plant
	Turbid water from red soil	- Chemical treatment by turbid water plant - Reduction of turbid water by separation into red water and clear water - Reduction of red water by spraying asphalt emulsion or seeds on bare ground - Install gabion weir at downstream area of
b) Reduction in habitat area due to changes in land	Reduction of area changed	- Layout of powerhouse and waterways underground - Omit access road and work add it to outlet and powerhouse - Reduce construction area by balancing cuts and embankments as much as possible
	Protection, restoration of vegetation	- Sculpt and green construction site without delay - Protect existing forest by planting low-
c) Noise, vibration from heavy equipment		- Prohibit night-time work in surface construction - Use low-noise type machinery - Travel at low speed inside construction area
d) Harm to small animals from construction vehicles and accidents due to falls down to structures		- Capture and remove animals and plants in construction area - Install facilities (intrusion prevention nets) to prevent entry of rare animals - PR activities using posters, lecture meetings, Pamphlets, etc. - Prevent accidents from falls of small

Table 4-5: Countermeasure by Environmental Factor

(New Energy Foundation, 2006)

These environmental measures were not without their cost and the breakdown of these costs can be seen in Table 4-6. The final figure of 1650 million Yen (€1.3million) for environmental costs was 5% of the total cost for the power plant (Aravossis et al., 2006).

Item	Costs (million yen)	Contents
Greening	220 (13%)	Greening of construction area Management
Water Quality	350 (21%)	Reservoir of turbid water Drainage facilities Protection film of sediment yield Measurement of water quality
Animals	290 (18%)	Monitoring Safeguard and movement
New Natural Space	790 (48%)	Arrangement of garden plant Development of ground Waterway, bridge, road etc.
Total	1650 (100%)	

Table 4-6: Environmental Costs Breakdown

(Aravossis et al., 2006)

4.5 Conclusion

As can be seen from this chapter, there are a number of types of system available for pumped hydro storage. The main difference in the systems that are currently being utilised across the globe is in the reservoir design. The type of reservoir to be used will have a major impact on the location and the cost of the chosen system.

5 Dundrum Inner Lake – Site Assessment

5.1 Introduction

Dundrum is a small village, located along the Mourne coastal Route in Co. Down. It is a small sheltered bay approximately 6km long and 1.4km at its widest point. With the exception of the entrance channel the entire inner bay is intertidal. Three main rivers flow into the bay, the Blackstaff, the Carrigs and the Moneycarragh (Aquafact, 2012).

The purpose of this chapter is to assess the technical and financial viability of using the bay as an upper reservoir to the seas lower reservoir for the purpose of PHES. There are a number of similar locations across the island of Ireland and with an expected increase in demand for energy storage capability, options like the one presented in this document are certain to be given consideration in the near future.

Figure 5-1: Dundrum Inner Bay

(By Eoin McLean,2013)

5.2 Site Assessment

The assessment of this site is based on information and the methodology from (DIE, 1982). The first step is to perform a rapid assessment of the power potential of the site. This low cost measure will help to determine whether or not to proceed with further investigations.

5.2.1 Area of Reservoir

Using a map of the bay, plotted on a grid with 13 mm squares as seen in Figure 7, each square representing 0.5 km^2, the total area of the reservoir was obtained by counting the full squares and parts of squares (DIE, 1982). The result was two full squares and 20 half squares, giving a total equivalent of 12 full squares, resulting in an area of $6km^2$.

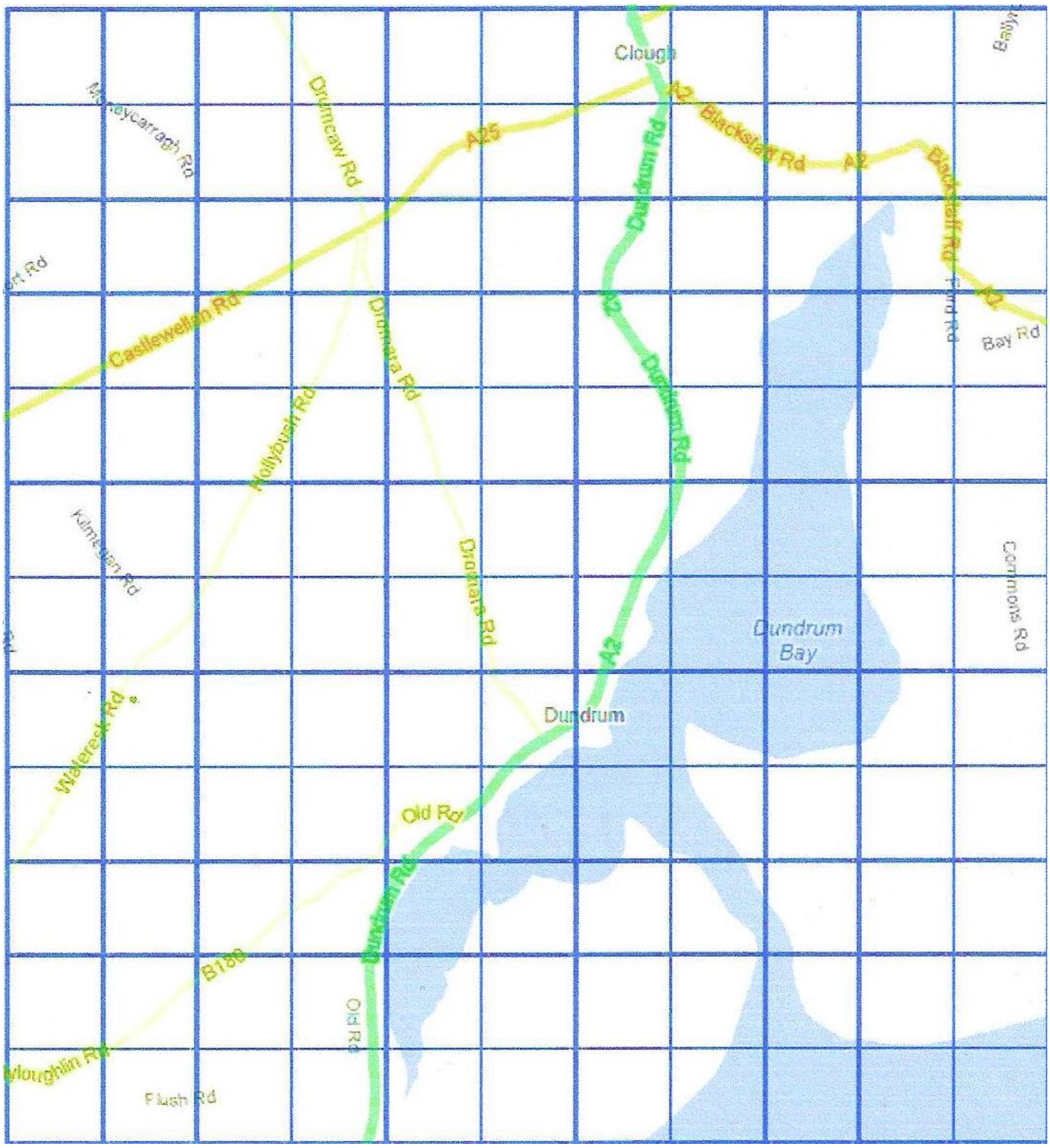


Figure 5-2: Scale Map of Dundrum Bay

(Google Maps, 2013)

5.2.2 Flow & Power Capacity

Flow is the volume of water passing through a turbine and is measured in cubic metres per second (m^3/s) (DIE, 1982). Power capacity is essentially the product of flow and head. If the head height doubles the flow could half in value and the power capacity would remain the same. Figure 5-3 shows the expected flow rates for different values of head heights.

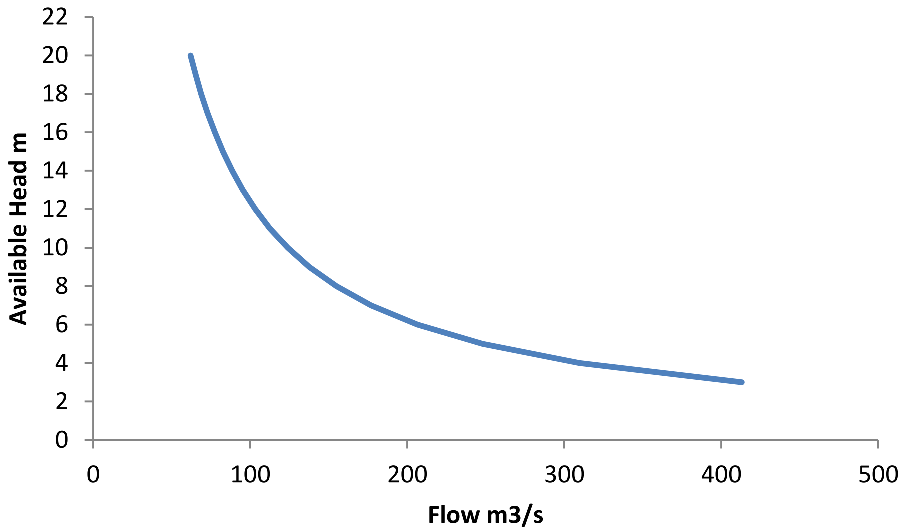


Figure 5-3: Comparison of Flow Rates and Head

The flow for this system was calculated using the following formula.

$$P_c = pgQH\eta_p$$ (Connolly, 2010)

Equation 3: $\therefore \varrho = \frac{P_C}{p \times g \times H \times \eta_p}$

Where:

P_C = Power Capacity in Watts

p = Mass density of water in kg/m^3

g = Acceleration due to gravity in m/s^2

Q = Discharge through the turbines in m^3/s

H = Effective head in metres

η_p = Pump Efficiency

5.2.3 Head

The head for this type of system will need to be created by building up the walls of the bay. For the proposed system the reservoir will be built with a depth of 4m and a minimum head of 6m. It should be noted that the head will change at high and low tides and this will need to be factored in to the final design.

5.2.4 Turbine

Turbines are chosen for their suitability based on available head and flow rates as shown in Figure 5-4.

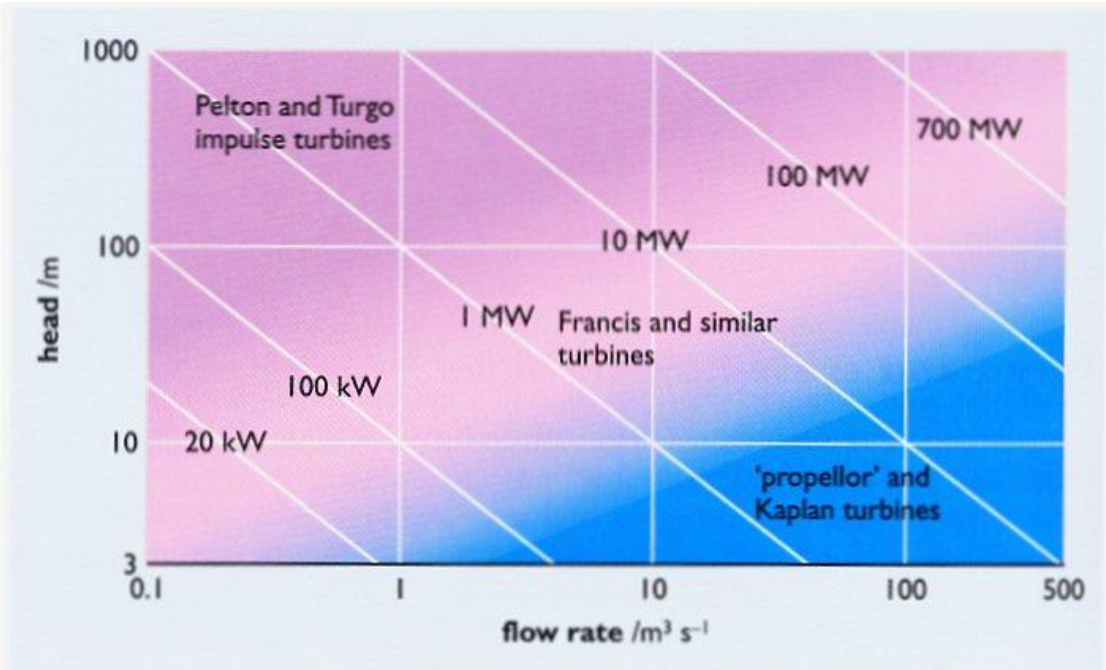


Figure 5.23 Ranges of application of different types of turbine. Note the overlap at the boundaries (see text)

Figure 5-4: Turbine Selection Chart

(Boyle, 2004)

The proposed turbine for this system is 10MW bulb turbine, used at La Rance Barrage in France (laleu, 2009).

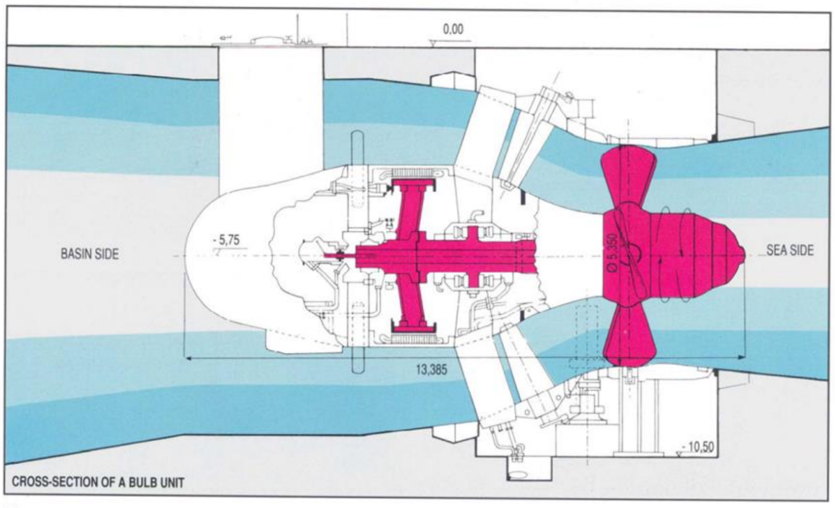


Figure 5-5: Cross Section of a Bulb Unit

(laleu, 2009)

The primary reasons for this are that the turbines in La Rance have lasted in excess of 40 years in saltwater, they can operate at low head and high flow rates, in addition using a number of 10MW turbines will allow the plant output to be easily controlled. The flow through each turbine is calculated as follows:

$$ϱ = \frac{P_C}{p \times g \ \times H \ \times \eta_p}$$

$$ϱ = \frac{10 \ \times 10^3}{1.028 \times 9.81 \ \times 6 \ \times 0.8} = 206.58m^3/s$$

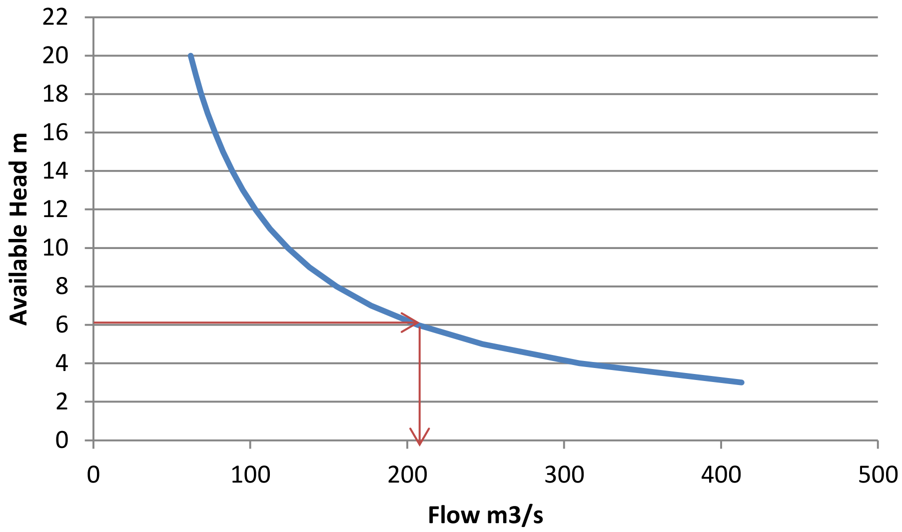


Figure 5-6: Mean Flow at Head of 6m

Taking a nominal head of six metres and a generator efficiency of 80%, the proposed system would have a mean flow of 206.58 m^3/s. Based on a preliminary design using 10 turbines; the system would have the following specification as shown in Table 5-1.

Item		**Specification**
Power Plant	Name	Dundrum Bay Power Plant
	Max Output	100 MW
	Max. Discharge	2066 m^3/s
	Effective Head	6 m
Upper Reservoir	Type	Rubber Sheet - Lined
	Max. Embankment Height	7 m
	Circumference	13.3 km
	Max Width	6 km
	Total Storage Capacity	24 X 10^6 m^3

Table 5-1: Proposed Plant Specifications

5.2.5 Plant Operating Time

Depending on the requirements of the grid at any particular time, the output of the plant can be easily controlled by switching turbines in or out. This flexibility will be useful as the plant will be capable of proving primary, secondary or tertiary reserve at different power ratings. Table 9 shows the different options available, with the proposed maximum output highlighted. The plant will be able to provide 10 MW output for up to 32 hours more than covering the tertiary and contingency requirements that currently exist (SEAI, 2004). At maximum output the plant could provide 100 MW for 3.2 hours. It can be seen from the information contained in Table 8 and Table 9 that the installation of this plant would significantly increase the current levels of hydro operating reserve

Type of Reserve	Available Power (MW)	Required Time
Primary	3	0 – 15 sec
Secondary	35	15 sec – 90 sec
Tertiary	55	90 sec – 24 hrs

Table 5-2: Current Hydro Operating Reserve

(SEAI, 2004) (Murphy, 2013)

Energy	Volume	Turbine Power	Number of Turbines	Power	Mean Flow	Total Flow	Duration
MWh	m^3	MW		MW	m^3/s	m^3/s	hours
323	24000000	10	1	10	207	207	32.3
323	24000000	10	2	20	207	413	16.1
323	24000000	10	3	30	207	620	10.8
323	24000000	10	4	40	207	826	8.1
323	24000000	10	5	50	207	1033	6.5
323	24000000	10	6	60	207	1240	5.4
323	24000000	10	7	70	207	1446	4.6
323	24000000	10	8	80	207	1653	4.0
323	24000000	10	9	90	207	1859	3.6
323	24000000	10	10	100	207	2066	3.2
323	24000000	10	11	110	207	2272	2.9
323	24000000	10	12	120	207	2479	2.7
323	24000000	10	13	130	207	2686	2.5
323	24000000	10	14	140	207	2892	2.3
323	24000000	10	15	150	207	3099	2.2

Table 5-3: Plant Output and Operating Times

5.2.6 Financial Appraisal

In July 2010 Turlough Hill was taken off-line to repair a hairline fracture in the generators rotors. In her dissertation (Petcova, 2012) estimates the cost of this outage for the year 2011 at €80.6 million. The maximum output of Turlough Hill is 292 MW, the proposed plant in Dundrum Bay would have a Maximum Output of 100 MW, so assuming a linear relationship between cost and MW, Figure 5-7 suggests a potential annual value of Dundrum Bay to the electricity market of €27.6 million

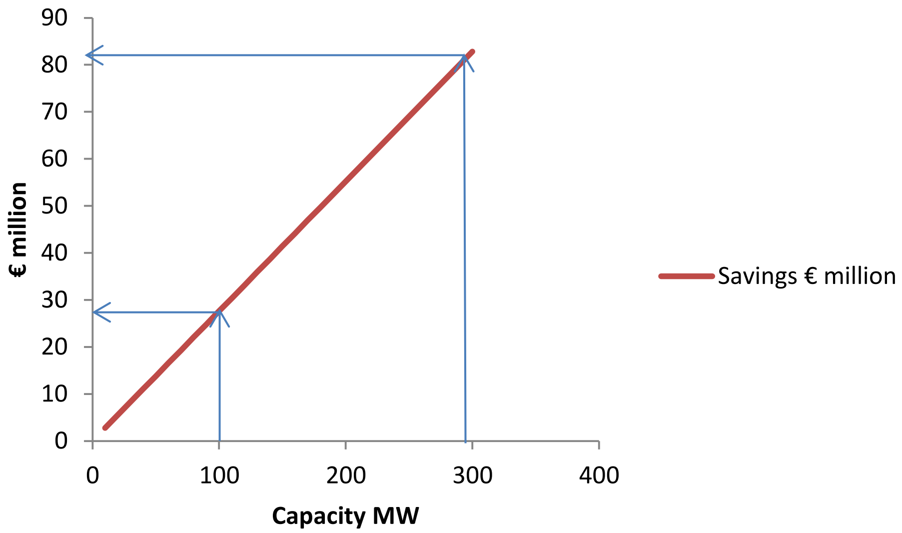


Figure 5-7: Potential Savings per MW

The majority of PHES proposed and completed projects across Europe between the years 2000 and 2020 have a cost per kW of €500 - €1500 (Zach, Aeur and Lettner, 2012). It is expected that the Dundrum Bay project would come in at the lower end of this scale due to the lower costs associated with a single reservoir construction. For the purpose of this study the midpoint of €1000 per kW is used. This would result in an initial capital cost of €1,000 million. (Connolly, 2010) Suggests that annual O&M costs would be in the region of 1-2% of the capital cost, again in this study the midpoint of 1.5% is used. A discount factor of 6% has been used to allow for loan repayments and a useful life of 40 years has been allowed for. The yearly income is based on estimates from (Petcova, 2012). Table 5-4 shows the project making a large loss over the project lifetime.

Year	Capital Cost €million	O&M cost €million	Income €million	Cash Flow	Loan Rate	Discount Factor	DCF	NPV €million
0	€1,000			-€1,000.0	6%	1.000	-€1,000.0	-€1,000.0
1		€15.0	€27.6	€12.6	6%	0.943	€11.9	-€988.1
2		€15.0	€27.6	€12.6	6%	0.890	€11.2	-€976.9
3		€15.0	€27.6	€12.6	6%	0.840	€10.6	-€966.3
4		€15.0	€27.6	€12.6	6%	0.792	€10.0	-€956.3
5		€15.0	€27.6	€12.6	6%	0.747	€9.4	-€946.9
6		€15.0	€27.6	€12.6	6%	0.705	€8.9	-€938.0
7		€15.0	€27.6	€12.6	6%	0.665	€8.4	-€929.7
8		€15.0	€27.6	€12.6	6%	0.627	€7.9	-€921.8
9		€15.0	€27.6	€12.6	6%	0.592	€7.5	-€914.3
10		€15.0	€27.6	€12.6	6%	0.558	€7.0	-€907.3
11		€15.0	€27.6	€12.6	6%	0.527	€6.6	-€900.6
12		€15.0	€27.6	€12.6	6%	0.497	€6.3	-€894.4
13		€15.0	€27.6	€12.6	6%	0.469	€5.9	-€888.5
14		€15.0	€27.6	€12.6	6%	0.442	€5.6	-€882.9
15		€15.0	€27.6	€12.6	6%	0.417	€5.3	-€877.6
16		€15.0	€27.6	€12.6	6%	0.394	€5.0	-€872.7
17		€15.0	€27.6	€12.6	6%	0.371	€4.7	-€868.0
18		€15.0	€27.6	€12.6	6%	0.350	€4.4	-€863.6
19		€15.0	€27.6	€12.6	6%	0.331	€4.2	-€859.4
20		€15.0	€27.6	€12.6	6%	0.312	€3.9	-€855.5
21		€15.0	€27.6	€12.6	6%	0.294	€3.7	-€851.8
22		€15.0	€27.6	€12.6	6%	0.278	€3.5	-€848.3
23		€15.0	€27.6	€12.6	6%	0.262	€3.3	-€845.0
24		€15.0	€27.6	€12.6	6%	0.247	€3.1	-€841.9
25		€15.0	€27.6	€12.6	6%	0.233	€2.9	-€838.9
26		€15.0	€27.6	€12.6	6%	0.220	€2.8	-€836.2
27		€15.0	€27.6	€12.6	6%	0.207	€2.6	-€833.5
28		€15.0	€27.6	€12.6	6%	0.196	€2.5	-€831.1
29		€15.0	€27.6	€12.6	6%	0.185	€2.3	-€828.8
30		€15.0	€27.6	€12.6	6%	0.174	€2.2	-€826.6
31		€15.0	€27.6	€12.6	6%	0.164	€2.1	-€824.5
32		€15.0	€27.6	€12.6	6%	0.155	€2.0	-€822.5
33		€15.0	€27.6	€12.6	6%	0.146	€1.8	-€820.7
34		€15.0	€27.6	€12.6	6%	0.138	€1.7	-€819.0
35		€15.0	€27.6	€12.6	6%	0.130	€1.6	-€817.3
36		€15.0	€27.6	€12.6	6%	0.123	€1.5	-€815.8
37		€15.0	€27.6	€12.6	6%	0.116	€1.5	-€814.3
38		€15.0	€27.6	€12.6	6%	0.109	€1.4	-€812.9
39		€15.0	€27.6	€12.6	6%	0.103	€1.3	-€811.6
40		€15.0	€27.6	€12.6	6%	0.097	€1.2	-€810.4

Table 5-4: Projected 40 Year Payback

Year	Capital Cost €million	O&M cost €million	Income €million	Cash Flow	Loan Rate	Discount Factor	DCF	NPV €million
0	€1,000			-€1,000.0	6%	1.000	-€1,000.0	-€1,000.0
1		€15.0	€81.5	€66.5	6%	0.943	€62.7	-€937.3
2		€15.0	€81.5	€66.5	6%	0.890	€59.2	-€878.1
3		€15.0	€81.5	€66.5	6%	0.840	€55.8	-€822.3
4		€15.0	€81.5	€66.5	6%	0.792	€52.6	-€769.7
5		€15.0	€81.5	€66.5	6%	0.747	€49.7	-€720.0
6		€15.0	€81.5	€66.5	6%	0.705	€46.9	-€673.2
7		€15.0	€81.5	€66.5	6%	0.665	€44.2	-€629.0
8		€15.0	€81.5	€66.5	6%	0.627	€41.7	-€587.3
9		€15.0	€81.5	€66.5	6%	0.592	€39.3	-€547.9
10		€15.0	€81.5	€66.5	6%	0.558	€37.1	-€510.8
11		€15.0	€81.5	€66.5	6%	0.527	€35.0	-€475.8
12		€15.0	€81.5	€66.5	6%	0.497	€33.0	-€442.8
13		€15.0	€81.5	€66.5	6%	0.469	€31.2	-€411.6
14		€15.0	€81.5	€66.5	6%	0.442	€29.4	-€382.2
15		€15.0	€81.5	€66.5	6%	0.417	€27.7	-€354.5
16		€15.0	€81.5	€66.5	6%	0.394	€26.2	-€328.3
17		€15.0	€81.5	€66.5	6%	0.371	€24.7	-€303.7
18		€15.0	€81.5	€66.5	6%	0.350	€23.3	-€280.4
19		€15.0	€81.5	€66.5	6%	0.331	€22.0	-€258.4
20		€15.0	€81.5	€66.5	6%	0.312	€20.7	-€237.7
21		€15.0	€81.5	€66.5	6%	0.294	€19.6	-€218.1
22		€15.0	€81.5	€66.5	6%	0.278	€18.4	-€199.7
23		€15.0	€81.5	€66.5	6%	0.262	€17.4	-€182.3
24		€15.0	€81.5	€66.5	6%	0.247	€16.4	-€165.9
25		€15.0	€81.5	€66.5	6%	0.233	€15.5	-€150.4
26		€15.0	€81.5	€66.5	6%	0.220	€14.6	-€135.8
27		€15.0	€81.5	€66.5	6%	0.207	€13.8	-€122.0
28		€15.0	€81.5	€66.5	6%	0.196	€13.0	-€109.0
29		€15.0	€81.5	€66.5	6%	0.185	€12.3	-€96.7
30		€15.0	€81.5	€66.5	6%	0.174	€11.6	-€85.2
31		€15.0	€81.5	€66.5	6%	0.164	€10.9	-€74.3
32		€15.0	€81.5	€66.5	6%	0.155	€10.3	-€64.0
33		€15.0	€81.5	€66.5	6%	0.146	€9.7	-€54.2
34		€15.0	€81.5	€66.5	6%	0.138	€9.2	-€45.1
35		€15.0	€81.5	€66.5	6%	0.130	€8.6	-€36.4
36		€15.0	€81.5	€66.5	6%	0.123	€8.2	-€28.3
37		€15.0	€81.5	€66.5	6%	0.116	€7.7	-€20.6
38		€15.0	€81.5	€66.5	6%	0.109	€7.3	-€13.3
39		€15.0	€81.5	€66.5	6%	0.103	€6.8	-€6.5
40		€15.0	€81.5	€66.5	6%	0.097	€6.5	€0.0

Table 5-5: Required Income to Break Even

Table 5-5 shows that an annual income of €81.5 million is required for the project, to break even over the 40 years. The next step is to try and estimate the potential earnings of the plant were it to be operated as a conventional generating plant. Under the current REFIT scheme Hydro generators are guaranteed 7.2 c/kWh for the next 15 years (SEAI, 2013). To achieve the required income to break even assuming the REFIT prices remain constant for 40 years, electricity would need to be purchased at 6.2 c/kWh. This situation is allowing for the plant to operate at maximum output of 100MW for 3.2 hours per day at an overall efficiency of 85%. Table 5-6 shows the projected payback for the project over 40 years. Following the analysis of these figures it is the author’s opinion that PHES is not going to be a financially viable option without some form of financial support/investment.

Year	Capital Cost €million	O&M cost €million	Income €million	€ per kWh Sold	€ per kWh Purchased	Generating Hours Per Day	Pumping Hours Per Day	Daily Energy kWh	Discount Factor	DCF	NPV €million
0	€1,000.0								1.000	-€1,000.0	-€1,000.0
1		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.943	€62.7	-€937.3
2		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.890	€59.2	-€878.1
3		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.840	€55.8	-€822.3
4		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.792	€52.6	-€769.7
5		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.747	€49.7	-€720.0
6		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.705	€46.9	-€673.2
7		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.665	€44.2	-€629.0
8		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.627	€41.7	-€587.3
9		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.592	€39.3	-€547.9
10		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.558	€37.1	-€510.8
11		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.527	€35.0	-€475.8
12		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.497	€33.0	-€442.8
13		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.469	€31.2	-€411.6
14		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.442	€29.4	-€382.2
15		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.417	€27.7	-€354.5
16		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.394	€26.2	-€328.3
17		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.371	€24.7	-€303.7
18		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.350	€23.3	-€280.4
19		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.331	€22.0	-€258.4
20		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.312	€20.7	-€237.7
21		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.294	€19.6	-€218.1
22		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.278	€18.4	-€199.7
23		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.262	€17.4	-€182.3
24		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.247	€16.4	-€165.9
25		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.233	€15.5	-€150.4
26		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.220	€14.6	-€135.8
27		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.207	€13.8	-€122.0
28		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.196	€13.0	-€109.0
29		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.185	€12.3	-€96.7
30		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.174	€11.6	-€85.2
31		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.164	€10.9	-€74.3
32		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.155	€10.3	-€64.0
33		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.146	€9.7	-€54.2
34		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.138	€9.2	-€45.1
35		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.130	€8.6	-€36.4
36		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.123	€8.2	-€28.3
37		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.116	€7.7	-€20.6
38		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.109	€7.3	-€13.3
39		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.103	€6.8	-€6.5
40		€15.0	€81.5	€0.072	€0.061	3.2	3.8	320,000	0.097	€6.5	€0.0

Table 5-6: Projected Full Load Operating Payback

5.3 Environmental Issues

5.3.1 Saltwater

One of the main concerns with this type of PHES is the effect on vegetation and animals caused by bringing saltwater inland. An environmental study carried out on the Yanbaru plant in Okinawa found that there was little to no increased saltwater penetration due to pumping than there was from the natural saltwater spray coming off the sea (Fujihara, Imano and Oshima, 1998). There are obvious issues involved with bringing saltwater inland, however the choice of location in Dundrum Bay ensures that these issues are not a concern due to the natural proximity of the bay to the sea.

5.3.2 Drainage and Spillage

The three main rivers flowing in to Dundrum Inner Bay will need to be rerouted around the reservoir to ensure adequate drainage of the catchment area around Dundrum bay. Figure 5-8 shows 14 rivers flowing in to the outer bay and three flowing in to the inner bay. The three rivers in question will be rerouted to join up with existing rivers or given a new route to the sea. This decision will be made on planning approval.

A spillage drain will also be provided around the reservoir to contain any possible spillage caused by overflow or flooding. This too will be routed to the sea.

Figure 5-8: Rivers Flowing into Dundrum Inner Bay

(Aquafact, 2012)

5.4 Conclusion

Having assessed the results obtained in this chapter, the author has drawn two conclusions:

1. Installation of this PHES in Dundrum bay is technically viable
2. The installation of this PHES in Dundrum Bay is probably not financially viable

There appears to be little doubt that the installation of this kind of PHES would be of benefit to the national grid, not just for the operating reserve that it could provide but also to facilitate the increased wind penetration that is planned for 2020. There is also little doubt that the capital costs associated with a PHES plant are currently prohibitive from an investment point of view and (Connolly,

2010) suggests that some form of financial assistance is required to make this an attractive proposition for would be investors.

6 Conclusions

The first section of this document set out a number of objectives that would lead the author to the overall aim of this dissertation. This final section provides the overall conclusions of this research, as follows:

1. Demand for PHES

   The demand for PHES is driven firstly by National and European policy. If the Irish government intend to hit their 2020 target of 40% of electricity generation from renewable sources, then some form of energy storage is required. By its very nature RE is intermittent and asynchronous and as such, some form of energy storage is going to be required to ensure a stable grid. Having PHES operating as spinning reserve will allow EIRGRID to import all the electricity produced by wind farms on to the grid without destabilising it. In addition it will enable to increase the capacity of their current ancillary services portfolio.

2. Available Resource to Meet Demand

   There is little doubt that Ireland possesses the .natural resources to hit the government's 2020 targets. Ireland is well on its way to becoming a world leader in Wind generation due in part to its plentiful wind resource. This high penetration of WE combined with a PHES portfolio would certainly improve Ireland's security of supply and its energy independence.

3. Pumped Hydro System Evaluation

   A number of different types of PHES systems were considered with the main difference between then being in their reservoir design. From the traditional upper and lower reservoir design, in evidence at Turlough Hill, underground reservoir in Dinorwig and the sea as the lower reservoir in Yanbaru, Okinawa. The advantages and disadvantages of these systems were considered and barring a favourable natural geology it is this area of system design that has a large bearing on the construction costs.

4. Dundrum Inner Bay Site Assessment

The assessment of the inner bay at Dundrum showed a definite technical viability but in the absence of exact costs it was difficult to produce an accurate financial assessment. A financial appraisal was carried out using the midpoint construction and O&M costs based on current and projected European spending on PHES projects. The projected income was based on savings currently attributed to the 2011 Turlough Hill outage and this assessment showed no viability whatsoever. A second appraisal was carried out to determine the yearly income required to break even at the end of a 40 year lifespan. A third and final assessment was carried out to determine the maximum purchase price of a unit of electricity if the plant was operating at maximum output for 365 days per year. The maximum price that could be paid per kWh was calculated as 6.2 c. This particular section require further work to get an accurate assessment of the financial viability but to date the author has found little to contradict the view of many others that it is the high capital cost of PHES that continues to be its main stumbling block.

6.1 Summary

The author has come to two firm conclusions during the course of this research and they are

1. Some form of large scale energy storage is required to enable the integration of large amounts of wind energy on to the existing grid.
2. PHES is technically viable when using a high volume, low head saltwater system

One question that has not been conclusively answered is whether or not PHES is financially viable from an investor’s point of view as things currently stand.

6.2 Recommendation for Further Research

The following questions and many others can be considered for further research:

- Is Pumped Hydro Electric Storage the best energy storage solution for Ireland?
- What is the cheapest type of Pumped Hydro system to construct?

- What is the best way to utilise new PHES were it to be built?
- What is the potential projected income from a new PHES Plant?
- What steps can be taken to improve system efficiency?
- What are the implications for using wind energy to directly feed a PHES plant and using the PHES plant to feed on to the grid?

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