Fall 2019

Assessing the Implications of a Tidal Barrage Power Plant in Hvalfjörður, Iceland

Olive M. Colangelo
SIT Study Abroad

Recommended Citation

Colangelo, Olive M., "Assessing the Implications of a Tidal Barrage Power Plant in Hvalfjörður, Iceland" (2019). *Independent Study Project (ISP) Collection*. 3277.
https://digitalcollections.sit.edu/isp_collection/3277

Assessing the Implications of a Tidal Barrage Power Plant in Hvalfjörður, Iceland

Olive M. Colangelo

School for International Training

ABSTRACT

As climate change continues to threaten the future state of our world, we are searching for measures to take for mitigation. Among these measures, the most talked about method is the development of renewable energies. Great amounts of attention is paid to solar and wind power, but relatively little effort is given to researching the possibilities of ocean energy, particularly tidal barrage energy. This study assesses the possibility of a tidal barrage plant in Hvalfjörður, Iceland. This hypothetical power plant in Hvalfjörður would have an installed capacity of 840MWh and could produce 613GWh per year. This is less than 0.01% of Iceland's annual energy usage. A number of environmental issues have been taken with tidal barrage plants such as sedimentation changes, impacts to the benthic habitat, noise pollution, reduced area of intertidal habitats, a rise in water level, and negative effects to water quality. If we assume that this plant would cost a similar amount to the two largest tidal barrage plants in the world, La Rance and Lake Sihwa, such a barrage plant might cost around 600 million USD. A tidal barrage plant built in Iceland is not advised. The risk to the wildlife of the fjord seems to be too great and the energy output is too low. Furthermore, an overwhelming majority of electricity generated in Iceland is renewable, so there is not enough coal or oil to displace. More feasibility studies in other parts of the world are necessary to examine the true potential for tidal power and other forms of ocean energy.

1. INTRODUCTION

Models estimate that a "business as usual" scenario—known as RCP 8.5—for anthropogenic carbon dioxide emissions will result in planetary warming of about 4.5°C by the end of this century (IPCC, 2014). This warming spells out a dangerous state for our world in 80 years. Global climate change is predicted to cause devastation and displacement among low-elevation coastal settlements, a nearly worldwide decrease in crop yield, an increase in air pollutants, and a loss of ecosystem biodiversity (McGranahan, Balk, & Anderson 2007; Riahi *et al.*, 2011, Wheeler & von Braun, 2013; Craine *et al.*, 2011). Since most anthropogenic greenhouse gas emissions are from the burning of fossil fuels, renewable energy development and use is vital for mitigation (IPCC, 2014; Pawnar, Kaushik, & Kothari, 2011). Of the many methods of renewable energy generation, much attention has been given to solar, wind, and hydroelectric methods. This is for good reason. Photovoltaic cells offer energy that boasts a long equipment lifetime, a cheap maintenance cost, and reliability (Singh, 2013). Wind energy is widely applicable and offers reliable, cost-effective energy in many regions (Herbert *et al.*, 2005). A relatively small amount of attention is given to the several schemes of harvesting energy from the ocean. Forms of ocean energy include ocean thermal (OTEC), wave, current, tidal range, tidal current, and salinity gradient energy.

Harvesting a small fraction of the ocean's energy would actually be able to—theoretically—supply the world's energy needs, but, of these schemes, humanity has had the most history with tidal energy (Caillé *et al.*, 2007). Indeed, many primitive tidal mills have existed in England and Wales since the 12th century that take advantage of this predictable water flow (Charlier, 1982). Even so, it seems that little effort has been made to build and operate modern, large-scale tidal power plants despite the ever-growing need for energy (IPCC, 2014). There are only two examples of large-scale implementation of tidal energy: La Rance Tidal Barrage in France and the Sihwa Tidal Power Plant in Korea. Both take advantage of a large tidal range in their areas, known as a barrage plant. Since proving their effectiveness, a fair amount of research and modeling has been done to test the feasibility in different parts of the globe, though many of these studies focus on the British Isles (Burrows *et al.*, 2009; Hooper & Austen, 2013; Giorgi & Ringwood, 2013; Bricker *et al.*, 2017; Sangiuliano, 2017). However, no studies have been done on the prospect of a tidal barrage plant in Iceland. This study aims to assess that possibility.

2. METHODS

2.1 Site Description and Tidal Measurement

The location in which the feasibility of a tidal barrage plant will be assessed is in Hvalfjörður (64.323731, -21.858899), a fjord in Western Iceland. The mouth of the fjord is about 10km east from the town Akranes. Akranes is an industrial town of 7,500 people. A cement plant and an aluminum smelting plant are nearby, but fisheries remain a vital industry for Akranes. Hvalfjörður also boasts to have the few remaining active whaling stations in Iceland, though no whales are present in the fjord. Akranes has, historically, the largest tidal range in Iceland. The maximum tidal range is 5.84m (“Tide-Forecast Akranes,” n.d.).

Figure 1. Photo of Hvalfjörður (“Nordic Visitor Hvalfjörður,” n.d.).

Figure 2. Map of West Iceland. Star denotes proposed location of dam (GoogleMaps, 2019).

Currently, there is a tide monitoring station in Akranes. Since the station is fairly close to the fjord, these tidal measurements will be used to estimate the power generation of a power plant in Hvalfjörður. The tidal range from the last month will be collected and averaged from tide-forecast.com, a website that compiles tidal information from stations around the world. This average will be applied to calculations.

A dam in Hvalfjörður would have to span 3.5km long and be able to accomodate, at most, a 31m depth. A reasonable width for a two-way (or ebb and flow) generation tidal barrage is about 39m (de Laleu, 2009).

2.2 Overview of Tidal Physics

Tidal events are the apparent lowering and rising of the sea level due to a combination of the gravitational pull of the moon and the sun. Tractive forces result and create bulges on either side of the Earth (Simanek, 2003). This is illustrated in Figure 3. A tidal event occurs about every 12 hours and 25 minutes (Clark, 2007). One tidal event is when the tide moves from low to high, and then back to low again. This means that the time between low and high tides is about every six hours. The difference in sea level between high and low tide events is known as tidal range, or tidal amplitude.

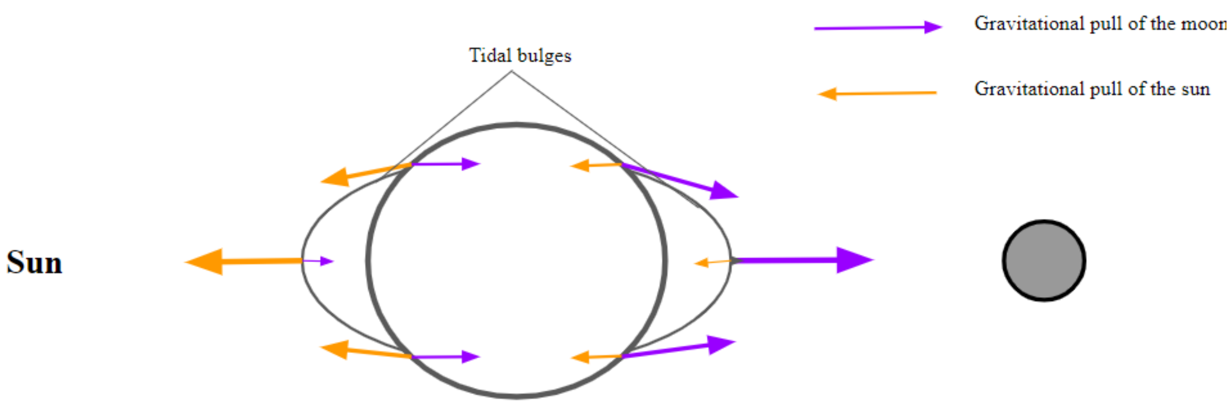

Figure 3. Forces acting upon the tides during a spring tide. Thickness of arrow denotes relative strength of the force. Gravitational force is inversely proportional to the distance squared. The forces of the sun and the moon work together to make the tidal bulges. Inertia is the same everywhere on the Earth.

There are two types of tides: neap and spring; they occur biweekly in alternating weeks. Spring tides are characterized by higher tidal ranges while neap tides by lower tidal ranges. The gravitational force exerted on the Earth by the moon is always the same, but Figure 3 demonstrates that the moon will "pull harder" on the side of the Earth to which it is closest. When the moon, sun, and Earth are aligned, or in syzygy, these bulges are relatively larger due to the Sun's gravitational influence. This is a spring tide. When the moon is not aligned with the sun and the Earth, during a first or third quarter, the gravitational influence of the sun and the moon "fight" in a way. The moon's ends up barely winning. This makes a smaller bulge, known as a neap tide.

2.3 Overview of Tidal Barrage Technology

Tidal barrage power plants operate by taking advantage of the difference in tidal range. Most designs involve building a dam across a bay or estuary. When the tide comes in, or floods, the dam is shut and creates a difference in water level between the inside of the bay and the outside. Once the water level on opposite sides of the dam is different enough, the water is fed through a turbine in a similar way to hydroelectric plants (Charlier, 1982). The same could happen when the tide recedes, or ebbs. For the most part, tidal barrage plants are constructed in areas that have a large tidal range, usually over 5m (Thorpe, 1999). This is the primary factor in considering how effective a tidal barrage plant will be in producing sufficient electricity (Prandle, 1984).

There are two main categories of tidal barrage plants: one-way generation and two-way generation. One-way generation only generates energy during the ebb or the flood of the tides. The Sihwa Tidal Power Plant in South Korea is an example of a one-way scheme. Two-way generation generates energy during both flood and ebb. La Rance Tidal Barrage Plant in France is an example of a two-way scheme. Since a two-way scheme has the potential to produce more electricity, we will assess the feasibility for a two-way generation tidal barrage plant in Hvalfjörður (Prandle, 1984).

2.4 Calculation of Power Capacity

The maximum power that can be generated by a tidal barrage plant has been deduced in previous studies. Prandle created an equation that shows the theoretical amount of energy that exists in a given tidal system (1984):

$$E_{max} = 4pgAh_a^2$$

Where g is acceleration due to gravity, p is the density of water, A is the impounded basin area, and h_a is the tidal amplitude.

Prandle claims that the theoretical proportion of actual extractable energy per tidal cycle is 0.27 for one-way generation and 0.37 for two-way generation. This is a rudimentary calculation for preliminary estimations, but it will be sufficient for our purposes.

2.5 Environmental and Economic Assessment Reviews

The environmental assessment will be a combination of a literature review and a case study of other tidal barrage plants, namely the ones in La Rance and Lake Sihwa.

An economic assessment will also be performed via literature review and case studies.

3. ETHICS

The data collected and the literature referenced has been faithfully recounted. No harm was done to the ecosystem of the fjord, nor was any disturbance made to the community of Akranes.

4. RESULTS

4.1 Power Capacity of Hvalfjörður Tides

The average range of 56 discrete tidal events off of Akranes (measured from 2019-10-19 to 2019-11-19) is 1.97m. This is a substantially lower range than the historical maximum of over 5m, but that is because this is also taking into account the neap tides. Of these 56 tidal events, the minimum range was 0.2m and the maximum was 4.39m.

We will suppose that a 3.5km dam is built at 64.371194, -21.687527. A dam at this location would impound a body of water with an area of approximately 54km-squared.

With all values known, we can now apply them to Prandle's equation to find the maximum potential energy in the system, neglecting all losses:

$$E_{max} = 4pgAh_a^2$$

$$E_{max} = 4(1000)(9.807)(54)(1.97)_a^2$$

$$E_{max} = 8220957\text{MJ}$$

$$= 2.28\text{GWh}$$

With his estimated proportion of 0.37 for a two-way generation scheme, the maximum capacity for this plant would become 0.84GWh, or 840MWh, or 3,041,532MJ. This is a fairly large amount of energy, considering it is over three times the installed capacity of both La Rance and Lake Sihwa (EDF, 2019; Korean Water Resource Corporation, 2019). The installed capacity in the context of a tidal barrage plant is the ideal amount of energy that a plant could produce each tidal event. Since there are, for the most part, two tidal events each day, this leaves the annual energy production at about 619 GWh, or 1.09PJ. The installed capacity is comparable to a handful of small fossil fuel power plants in Iceland and the annual energy production would provide Iceland with 0.0042% of its consumed energy for 2018 in petajoules (Orkustofnun, 2019). Since this hypothetical dam is planned to be 3km long, there would be ample space for all of the turbines necessary to utilize this power.

When Prandle applied this formula to tidal plants, he found that the installed capacity of a two-way generation system was half of the theoretical amount. He attributed this to inefficient sluicing, variability of tidal range, and power loss during turbining (1984). Thus, the installed capacity of this tidal barrage plant could be as low as 420MWh, or 1,520,766MJ.

4.2 Environmental Assessment

4.2.1 A New Energy Source

The most obvious environmental benefit to this tidal barrage plant is the use of renewable energy. Using an energy calculator provided by Norwegian Petroleum, the annual electricity generation that this plant could produce, 613GWh, would be the equivalent of 374,000 barrels of oil (2019). At an estimated 0.43 tonnes of carbon dioxide emissions per combusted barrel, this would prevent about 160,820 tonnes of carbon dioxide from entering the atmosphere (EPA, 2018). Mitigation of carbon emissions through a transition to renewable energy is critical to lessening the impacts of global climate change (Pawnar, Kaushik, & Kothari, 2011).

As far as the environmental benefits of this plant, renewable energy generation is where they stop. A number of concerns have been voiced regarding the ecological dangers of tidal barrage plants.

4.2.2 Sedimentation

The construction and the operation of a tidal barrage plant would directly alter the habitat of the fjord. Since the process of using a dam for energy purposes is very similar to a hydroelectric plant, their environmental concerns are very similar as well. Sedimentation is a specific example. In the first few years after installation of the dam in La Rance, widespread sedimentation modifications on the basin floor were observed (Retiere & Richard, 1980). Altered sedimentation is likely due to changed spatial flow patterns resulting from turbines and sluicing (Frid *et al.*, 2012). This change in sedimentation disrupted the benthic community of the basin, as it took about ten years to recreate a stable community balance (Retiere, 1994). Even so, species that recolonize the disrupted area—the area of construction—will not likely be exactly the same as the previous community (Hooper & Austen, 2013). The change in producer and herbivore benthic populations will, of course, be detrimental for higher trophic levels as well. However, it is unclear whether or not this is a given. Kirby & Retiere state that, while the sedimentations patterns have changed, the basin also has a higher carrying capacity and a more biodiverse benthic community than it had pre-construction (2009). Today, it appears that the sedimentation rate in La Rance is not abnormally accelerated compared to other nearby estuaries (de Laleu, 2009). More research must be conducted to be more sure about this subject.

In addition to sedimentation changes, operation of the plant may also affect the turbidity of the water. Areas near the dam, through which the water flow must be constrained and powerful to spin the turbines, mixing is encouraged (Frid *et al.*, 2012). The mixing will suspend the sediments in the water, causing a turbid condition. This turbidity can create a lower phytoplankton activity, possibly leading to a trophic cascade.

4.2.3 Noise Pollution

A tidal barrage plant is a feat of engineering and construction. Building such a plant will cause a substantial amount of noise that could possibly lead to the disturbance of marine life. It has been found that the use of heavy machinery during construction of offshore wind turbines, particularly pile drivers, causes displacement of porpoise populations and negatively impacts their echolocation ability (Henriksen *et al.*, 2004). According to Carstensen, these effects generally returned to normal after the construction was finished (2006). Noise pollution harm could also be done to marine life other than cetaceans as well, though research on the subject is incomplete and uncertain. As far as we are aware, noise pollution past the acceptable threshold can cause sensory loss and mortality among fish and aquatic invertebrates (US Department of Energy, 2009). Furthermore, the noise produced from both construction and operation can inhibit the taxis of pelagic invertebrate larvae, as they use subtle sounds as cues for orientation and settlement (Montgomery *et al*., 2006).

However, the noise produced during operation is less frequently studied. There is not much information on the amount of noise a tidal barrage plant produces while operating. It will depend on the amount and size of the machinery running. This plant would likely use 40 to 80 10MW turbines. The operating noise from this large amount of equipment may exceed the noise threshold of protecting fish and marine life; it can result in masked echolocation signals and an area of avoidance for fish (Frid, *et al*., 2012).

4.2.4 Change in Water Level

The act of impounding tidal water will actually raise water levels. Imagine that the sluice gates are shut during high tide. Once the tidal bulge “recedes” from the shore enough to create a sufficient water head, the gates are opened and the water levels become equal. Changing the tidal dynamic in this way stops the low tide from reaching the same point as it had before the dam was installed, but the high tide level does not change (Hooper & Austen, 2013). This phenomenon has been observed in La Rance basin. Due to the increase in water level, the tidal range of La Rance has decreased by 40% and the volume of water exchanged decreased by 30% (Kirby & Retiere, 2009). Predicting the rise in water level due to a tidal barrage dam is difficult, but models generally estimate a 50% decreased range (Burrows, Walkington, Yates, Hedges, & Wolf, 2009).

As noted before, a large tidal range is one of the most, if not the most, critical factor when determining the generation capacity of a tidal barrage plant (Prandle, 1984). Naturally, a reduction in range could be devastating to the plans and feasibility of the plant. In our case, the average tidal range in Hvalfjörður, if cut in half, would produce only a quarter of our previously estimated potential energy availability in megajoules.

A lower tidal range will also decrease the area of intertidal habitats. This can have varying impacts on the wildlife of the area depending on what lives in the basin, but microphytobenthos (MPB) will almost certainly be affected. MPB is mostly made of diatoms in the littoral zone, or the shallow water near the shore. Because of this, intertidal zones are where they flourish. As water level increases, their abundance decreases because light penetrates less the deeper the water. Underwood projected a loss of 76% of the intertidal habitat and a 77% loss of MPB production in the event of a Cardiff-Weston barrage being implemented in the United Kingdom (2010). A reduction of MPB biomass this drastic can ruin sediment stabilization and inhibit some biogeochemical cycles (Hooper & Austen, 2013).

4.2.5 Water Quality

Tidal flushing is a phenomenon in which the water of a bay or estuary is gradually replaced through successive tidal events. A tidal barrage dam will most likely inhibit this process. A reduction of tidal flushing would mean freshening of the basin water, a buildup of physical and chemical pollutants, and possible eutrophication due to the lack of vertical mixing and turbidity in areas away from the barrage (Wolf, Walkington, Holt, & Burrows, 2009).

4.3 Economic Assessment

4.3.1 Construction

The first and most substantial costs incurred from any renewable energy scheme is, of course, the construction. Since there are no tidal barrage plants of a comparable size to this hypothetical one in Hvalfjörður, case studies will not bring us as far. For example, the plant in La Rance Basin cost nearly 660 million USD, but is only 700m (de Laleu, 2009). This is only a fifth of our specifications. On the other hand, the Lake Sihwa barrage plant cost only 560 million USD, but measured 7km (Kim, 2016). The dam in Korea was ten times longer, but cost $100 million less. This suggests that there is a large fluctuation in cost of construction, but this fluctuation is likely exaggerated due to the long time-gap between these two projects. The Lake Sihwa Tidal Power Plant was constructed 45 years after La Rance Tidal Barrage Plant, so costs may decline as knowledge grows. For simplicity, we will assume a tidal barrage plant in Hvalfjörður will cost comparably to the one in Lake Sihwa.

4.3.2 Electricity Generation

As stated above, the maximum annual energy generation for this tidal barrage plant would be about 613GWh. The price for this electricity is highly variable based on the location of the site, but still relatively inexpensive. Electricity production costs for Lake Sihwa and La Rance are 0.02 USD/KWh and 0.05 USD/KWh respectively, but, again, these costs are site specific (IRENA, 2014). Compared to conventional carbon combustion plants, Lake Sihwa is producing electricity at half the cost while La Rance’s cost around the same (EIA, 2019).

Unfortunately, it is not possible to calculate the projected cost of energy at this time without arbitrarily assuming too many unknown variables. Should those variables be known, Levelized Cost of Energy (or LCOE) can be calculated with the following equation (IRENA 2012):

$$LCOE = \frac{\sum_{t=1}^{n}\left((I_t+M_t+F_t)/(1+r)^t\right)}{\sum_{t=1}^{n}\left((E_t)/(1+r)^t\right)}$$

Where LCOE is average lifetime levelized cost of electricity generation, I_t is the investment expenditures in the year *t*, M_t is the operations and maintenance expenditures in the year *t*, F_t is the fuel expenditures in the year *t*, E_t is the electricity generation in the year *t*, *r* is the discount rate, and *n* is the economic life of the system.

4.3.3 Other Economic Impacts: Tourism and Employment

Akranes is a short 45 minute drive from Reykjavik city center, a city which already experiences a large influx of tourists throughout the year. A renewable energy plant which uses a method that is currently rarely employed in the world is yet another tourist attraction to which the many ecotourists of Iceland can flock. HS Orka, a geothermal power company in Iceland, is already doing this with a geothermal plant near Reykjavik by offering tours. Likewise, France is taking advantage of this fortunate position. La Rance Tidal Barrage Plant welcomes 70,000 visitors every year (de Laleu, 2009). As tourism in Iceland grows, this plant would be another interesting site to see.

This plant would also create jobs for the Icelandic people surrounding Akranes and Reykjavik. An exact amount of jobs created is difficult to estimate with such little concrete information available, but jobs would of course be made from both construction and operation of the plant.

5. DISCUSSION

5.1 Possible Solutions

As seen above, a tidal barrage can have dangerous implications for the surrounding environment. Some research has been done to this end, but not much. Employing environmental mitigation strategies to prevent as much damage as possible could raise the cost of the produced electricity by 0.01 to 0.05 USD/KWh (Brinckerhoff, 2008). At that point, tidal barrage power at this scale in Hvalfjörður seems pointless to pursue, and perhaps that is true.

Tidal barrage power is not the only form of tidal power. Tidal current and tidal stream power are two other methods of harvesting electricity from the tides that are known to be less costly to the environment (Sangiuliano, 2017; Charlier, 2003). For regions where the tidal range is not quite large enough to justify the negative environmental impacts—such as Hvalfjörður—one of these schemes could be employed to extract tidal power instead.

5.2 New Energy in Iceland

Shifting to a renewable-energy focused economy is a path that must be taken if the nations who ratified the Paris Climate Accord intend to keep their promises. But is Iceland not already dozens of steps ahead of other states? Does Iceland need new forms of renewable electricity production? Iceland is in the fortunate position of having several geothermal areas active enough to generate electricity. In addition, they also have made great use of the many rivers and streams that run through the island with hydroelectric power. After all, the electricity production in Iceland is 99.99% renewable (Orkustofnun, 2019). The argument could be made that energy demands are always increasing, and that would be correct. However, most of the existing renewable energy power plants in Iceland are not using their full installed capacity and are quite capable of producing more electricity. Furthermore, Iceland has already been attempting to implement more wind farms as yet another source of renewable electricity generation (Orkustofnun, 2019). At least in Iceland, it appears that tidal power is not necessary. There are simply not enough fossil fuels to displace.

5.3 The Future of "Blue Green Energy"

Tidal power is not the only form of renewable energy that can be harvested from the ocean. Simply dismissing ocean energy as a whole because tidal barrage power is not feasible in Iceland would be unwise. This "blue green energy," to coin a phrase, has the potential to greatly add to our world's energy supply through a number of schemes that can, and should, be used together. Some methods, such as ocean thermal energy conversion or tidal power, are not compatible for many places in the world. In the end, it is all site-specific. What would be risky in Hvalfjörður could be endlessly beneficial in the Severn Estuary.

The disastrous effects of climate change still loom, and it is up to governments around the world to begin implementing mitigation strategies (IPCC, 2014). The Paris Climate Accord was a feat of diplomacy and supranational coordination, but promises alone will not save us; serious measures must be taken to prevent the worst impacts of climate change. Renewable energy development and research must be among these measures, and the ocean remains a relatively untapped source of vast energy potential (Charlier, 1982). In order to pursue this, more feasibility studies of *all* forms of ocean energy are required in many parts of the world. That would be the first step in transitioning away from a fossil fuel driven economy.

6. CONCLUSION

Despite its potential in some parts of the world, tidal barrage power is ill-advised in Iceland. It would be a superfluous expense that is much too costly to both the environment and the treasury. The small amount of electricity produced would be negligible when compared to the electricity that the geothermal and hydroelectric plants in the country could potentially produce.

ACKNOWLEDGEMENTS

I would like to thank Benjamin Farrer for his assistance in structuring this feasibility study.

References

Bricker, J.D., Esteban, M., Takagi, H., & Roeber, V. (2017). Economic feasibility of tidal stream power in post-Fukushima Japan. *Renewable Energy, 114*, 32-45.

Brinckerhoff, P. (2008). ANALYSIS OF OPTIONS FOR TIDAL POWER DEVELOPMENT IN THE SEVERN ESTUARY. *Interim Options Analysis Report for DECC, 1*.

Burrows, R., Walkington, I.A., Yates, N.C., Hedges, T.S., Wolf J., & Holt, J. (2009). The tidal range energy potential of the West Coast of the United Kingdom. *Applied Ocean Research, 31,* 229-238.

Burrows, R., Walkington, I.A., Yates, N.C., Hedges, T.S., Li, M., Zhou, J.G., … Proctor, R. (2009). Tidal energy potential in UK waters. *Maritime Engineering, 162,* 155-164.

Caillé, A., Al-Moneef, M., de Castro, F.B., Bundgaard-Jensen, A., Fall, A., de Medeiros, N.F., … Doucet, G. (2007). Survey of energy resources. *World Energy Council*

Carstensen, J., Henriksen, O.D., & Teilmann, J. (2006). Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). *Marine Ecology Progress Series, 321,* 295-308.

Charlier, R. H. (1982). *Tidal Energy*. New York: Van Nostrand Reinhold Company Incorporated.

Charlier, R.H. (2003). A “sleeper” awakes: tidal current power. *Renewable and Sustainable Energy Reviews, 7,* 515-529.

Clark, R.H. (2007). *Elements of Tidal-Electrical Engineering.* New Jersey: John Wiley and Sons.

Craine, J.M., Nippert, J.B., Towne, E.G., Tucker, S., Kembel, S.W., Skibbe, A., & McLauchlan, K.K. (2011). Functional consequences of climate change-induced plant species loss in tallgrass prairie. *Oceanlogia, 165,* 1109-1117.

De Laleu, V. (2009, October). La Rance Tidal Power Plant 40-year operation feedback—Lessons learnt. *British Hydropower Association Annual Conference.* Presentation from the 2009 BHA Annual Conference, Liverpool, U.K

Électricité de France. (2019). La Rance Tidal Barrage. Retrieved from https://tethys.pnnl.gov/annex-iv-sites/la-rance-tidal-barrage.

Frid, C., Andonegi, E., Depestele, J., Judd, A., Rihan, D., Rogers, S.I., & Kenchington, E. (2012). The environmental interactions of tidal and wave energy generation devices. *Environmental Impact Assessment Review, 32,* 133-139.

Giorgi, S. & Ringwood, J. (2013). Can Tidal Current Energy Provide a Base Load? *Energies, 6,* 2840-2858.

GoogleMaps. (2019). [Satellite map of South-West Iceland]. *Google Maps.* Retrieved from www.google.com/maps.

Henriksen, O.D., Carstensen, J., Tougaard, J., & Teilmann, J. (2004). Effects of the Nysted Offshore Wind Farm construction on harbour porpoises. *Annual status report for the acoustic T-POD monitoring programme during 2003, 33.*

Herbert, J.G.M., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. *Renewable and Sustainable Energy Reviews, 11,* 1117-1145.

Hooper, T. & Austen, M. (2013). Tidal barrages in the UK: Ecological and social impacts, potential mitigation, and tools to support barrage planning. *Renewable and Sustainable Energy Reviews, 23,* 289-298.

International Panel on Climate Change. (2014). AR5 Synthesis Report. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf.

International Renewable Energy Agency. (2012). Hydropower. *Renewable Energy Technologies: Cost Analysis Series, 1,* issue 3.

International Renewable Energy Agency. (2014). Tidal Energy Technology Brief. *IRENA Ocean Energy Technology Brief, 3.*

Kim, Y. (2016). Technology case study: Sihwa Lake tidal power station. Retrieved from https://www.hydropower.org/blog/technology-case-study-sihwa-lake-tidal-power-station.

Kirby, R. & Retiere, C. (2009). Comparing environmental effects of Rance and Severn barrages. *Maritime Engineering, 162,* 11-26.

Korean Water Resource Corporation. (2019). Sihwa Tidal Power Plant. Retrieved from https://tethys.pnnl.gov/annex-iv-sites/sihwa-tidal-power-plant.

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *International Institute for Environment and Development, 19(1),* 17-37.

Montgomery, J.C., Jeffs, A., Simpson, S.D., Meekan, M., & Tindle, C. (2006). Sound as an Orientation Cue for the Pelagic Larvae of Reef Fishes and Decapod Crustaceans. *Advances in Marine Biology, 51,* 144-188.

Nordic Visitor Hvalfjörður. (n.d). Retrieved from https://iceland.nordicvisitor.com/travel-guide/attractions/west-iceland/hvalfjordur/.

Norwegian Petroleum. (2019). Energy Calculator. Retrieved from https://www.norskpetroleum.no/en/calculator/about-energy-calculator/.

Orkustofnun. (2019). Energy Data Repository. Retrieved from https://nea.is/the-national-energy-authority/energy-data/data-repository/.

Panwar, N.L., Kaushik, S.C., & Kothari, S. (2011). Roles of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews, 15,* 1513-1524.

Prandle, D. (1984). Simple theory for designing tidal power schemes. *Advanced Water Resources, 7,* 21-27.

Retiere, C. & Richard, O. (1980). Conséquences écologiques de 10 années de fonctionnement de l’usine marémotrice de La Rance. *Rapport Electricité de France et Laboratoire Maritime de Dinard.*

Retiere, C. (1994). Tidal power and the aquatic environment of La Rance. *Biological Journal of the Linnean Society, 51,* 25-36.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., … Rafaj, P. (2011). RCP 8.5—A Scenario of comparatively high greenhouse gas emissions. *Climatic Change, 109*, 33-57.

Sanguiliano, S.J. (2017). Turning of the tides: Assessing the international implementation of tidal current turbines. *Renewable and Sustainable Energy Reviews, 80*, 971-989.

Simanek, D.E. (2003). Misconceptions about the tides. Retrieved from https://www.lockhaven.edu/~dsimanek/scenario/tides.htm.

Singh, G.K. (2013). Solar power generation by PV (photovoltaic) technology: A review. *Energy, 53*, 1-13.

Thorpe, T.W. (1999). An overview of wave energy technologies: Status, Performance, and Costs. *Wave Power: Moving toward Commercial Viability.*

Tide-Forecast Akranes. (n.d.). Retrieved from https://www.tide-forecast.com/locations/Akranes/tides/latest.

Underwood, G.J.C. (2010). Microphytobenthos and phytoplankton in the Severn estuary, UK: Present situation and possible consequences of a tidal energy barrage. *Marine Pollution Bulletin, 61,* 83-91.

United States Department of Energy. (2009). *Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies* (prepared for ESIA of 2007, Section 633(B)). Washington, D.C.

United States Environmental Information Agency. (2019). *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019.*

United States Environmental Protection Agency. (2018). Greenhouse Gases Equivalencies Calculator - Calculations and References. Retrieved from https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

Wheeler, T. & von Braun, J. (2013). Climate Change Impacts on Global Food Security. *Science, 341,* 508-513

Wolf, J., Walkington, I.A., Holt, J., & Burrows, R. (2009). Environmental impacts of tidal power schemes. *Maritime Engineering, 162,* 165-177.