Analysis of Reservoir-Based Hydroelectric versus Run-of-River Hydroelectric Energy Production

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LRES Capstone 12/09/2014

Introduction

Greenhouse gases are a product of combustion methods for energy production, and therefore there is a need to harness clean energy. Furthermore, since fossil fuel reserves are dwindling, the need for renewable energy is growing. Hydropower is cleaner than burning fossil fuels and is considered a renewable source of energy. Only water and gravity are being used to generate electricity, therefore easing the reliance on fossil fuels and eliminating new greenhouse gas emissions.

Current hydropower energy usage in the world and US is 3,516 and 286 terawatt-hours (TWh), respectively (Paish, 2002). Hydropower produces about one-fifth of the world's energy, and produces about ten times the amount of energy than all other renewable sources (Schiermeier et al., 2008). In developed countries, the potential for new hydropower has almost been reached, however, in underdeveloped countries there is further potential for more infrastructure and development of small hydropower projects. Thoughtful consideration of hydropower will allow for its advancement in the energy future of the world. Using a three pronged approach, consisting of economic, ecological, and social standards (Kumar and Katoch, 2014), this paper will attempt to prove that hydropower is the most viable renewable energy source compare to other renewable sources such as wind and solar.

This assessment will consider storage-based projects versus run of river (RoR) projects. Storage based projects use a dam that entirely blocks a stream channel to form a reservoir. When energy is needed, water from the reservoir is released and allowed to flow downstream through the dam and through a turbine (Margeta and Durin, 2014). When the turbine is rotated, the kinetic energy from the downstream flow of water is converted to electricity via a connected generator. Transmission lines then distribute the power to electricity users.

RoR projects are based on small diversions of a river channel, the diverted water then rotates a turbine and powers a generator. Exploited parameters for this method are the flow of the water and the elevation gradient between the diversion and the point where the water reaches the turbine (Kumar and Katoch, 2014). RoR systems lack significant dams and storage reservoirs.

Reservoir Based Economics

Storage based hydroelectric projects are economically lucrative due to their sustainable and multifunctional nature. As reservoir-based hydroelectric project utilizes but does not consume a continually flowing river, there is no net loss in the resource itself (the river). The damming of the river results in a large impoundment of water, the reservoir, which can be used as a source of water for irrigation and municipal needs (Tarlock 2012). During the spring, water flow from the dam is constricted to maintain high levels of reservoir water. The release of water can then be increased during the summer months to meet the needs of agriculture. The dam facility can also house a municipal water distribution and treatment plant to provide nearby cities with a reliable water source (Tarlock 2012).

Withholding the water protects downstream development from surges of water caused by flood events as the reservoir disperses the impact of the high flow. However, this also causes a buffering effect from the natural variations in flow rate over the course of a year. This affects biotic populations downstream that rely on the seasonal influx of sediment and water. This effect can be mitigated by releasing water at rates that mimic the natural flow rates of the season (USGS, 2010).

Dams can be used in low flow areas in conjunction with solar and wind power facilities by acting as a pumped energy storage unit. To store the energy, two reservoirs are built: one for upper level water storage, with a closable dam unit in between, and a lower level water storage area. Excess energy produced by the solar and wind power components is directed to a dam, which uses the energy to pump water from the lower to the upper reservoir, therefore creating an elevation gradient. When energy demand increases, the elevation gradient is harnessed and water is released from the upper level and passes through the power plant creating the energy needed (Figure 1; Margeta and Đurin, 2014).

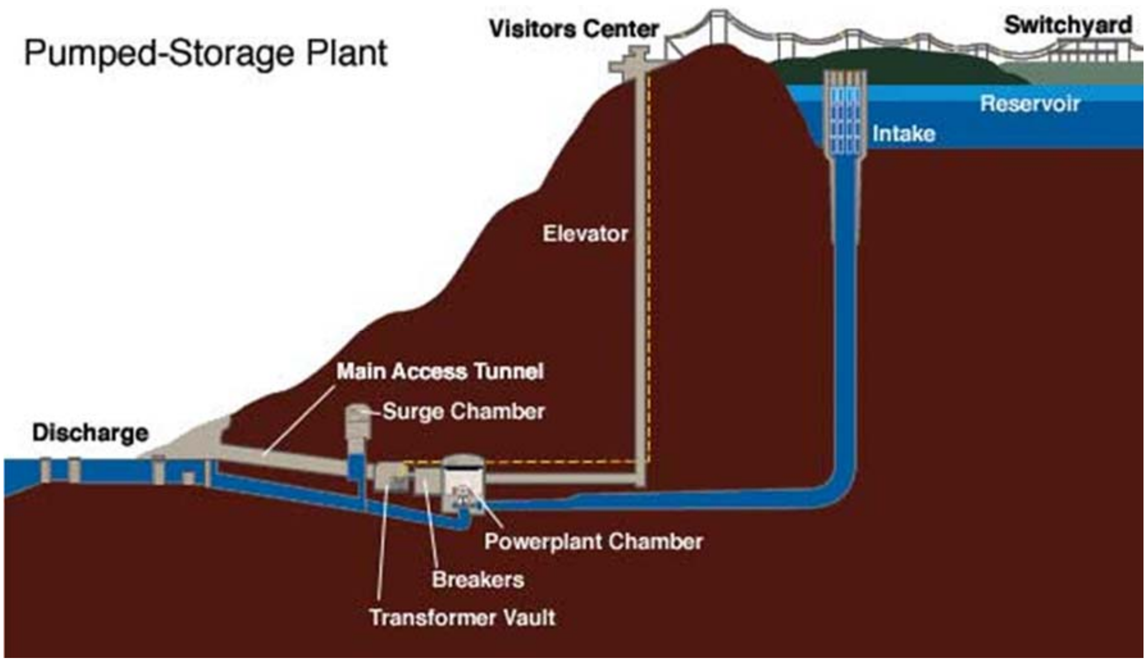

Figure 1: Diagram of pumped-storage hydroelectricity plant (Margeta and Đurin, 2014).

Reservoir Based Social Implications

The public is already accustomed to the idea of hydropower, as it has been around for decades and the technology is proven as well as improving (Hidalgo et al., 2014). The social advantages of the reservoir also benefits the area by increasing public interest and tourism. There are recreational perks to reservoirs as it creates large bodies of water for fishing and boating. Property value surrounding the reservoir also increases as lakes/reservoirs are favored as private vacation areas or public recreation areas. These recreation areas are a benefit to the region and can be used by many surrounding communities.

However, the original riparian habitat that was near the river before the dam will be modified as a result of the creation of the reservoir. This is not a benefit to the newly created habitat though as the increased anthropogenic activity in the area has large detrimental impacts on the aquatic and surrounding terrestrial habitat. Increased tourism can lead to a flux in traffic and pollutants within the area, potentially harming the surrounding ecosystem. Additionally, any houses that were previously along the edge of the river will be displaced. The positive public opinion on such a large and influential structure may decrease if the ecological impacts start to become so great that the general community can observe the damage.

Such is the case in China downstream of the Three Gorges Dam, which spans the Yangtze River. Sediment that had previously been allowed to flow downstream now settles out in the reservoir and as a result the downstream river is pulling sediment from the banks below the dam causing significant erosion and ecological issues (Yang et al., 2007). These issues not only impact the environment but also the housing and agricultural development around the downstream riparian zone (Yang et al., 2007). These impacts are visible to the public and thus affect the social value of the facility, which in turn affects the future development of hydropower in the area.

Reservoir Based Ecology

Dams alter the ecosystem of a river by artificially regulating the conditions and processes downstream. Abiotic effects include modification in discharge, flow regime, temperature regime, changes in the composition of suspended material, and nutrient fluxes in the river's system (Olden & Naiman, 2010). Biotic effects include disruption of life cycles in macro-vertebrates and fish, migration restriction for fish (Olden & Naiman, 2010), riparian compression, and increased productivity on select plants and algae (Nillson, 1981). Many effects can be mitigated by applying regulations on seasonal releases of water from the dam.

The most important factor to mitigate with the implementation of a dam is the flow regime. Conventional methods to damming have severely altered or depleted stream and river ecology by diverting rivers from their natural, seasonal variation of stream flow. A yearly flow regime depends on five factors: duration, timing, magnitude, rate of change and frequency of water events such as, at their extremes, floods and droughts (Roux, 1980). These factors are greatly affected by conventional damming, as depicted in Figure 2.

Aquatic organisms time the history of their life cycle to the natural flow regime of a stream, as well as the temperature regime. For example, fish tend to migrate in the spring when water is at its highest from spring run-off. Dams can alter the flow regime by stopping flow completely, as well as altering flood duration, timing, frequency, magnitude and rate of change (Roux, 1980).

Changes in the flow regime are not only detrimental for fish and other migratory organisms, but for plants, as well. Riparian organisms lie at the edge of aquatic and terrestrial ecosystems, providing an ecotone between the two and a means of filtering out pollutants and toxins. Riparian structure and composition depend on water levels, velocity, channel morphology and periodic flooding (Nillson, 1981). If the flow regime is altered to where the seasonal variation in water level and water velocity diminishes, it could alter the structure and

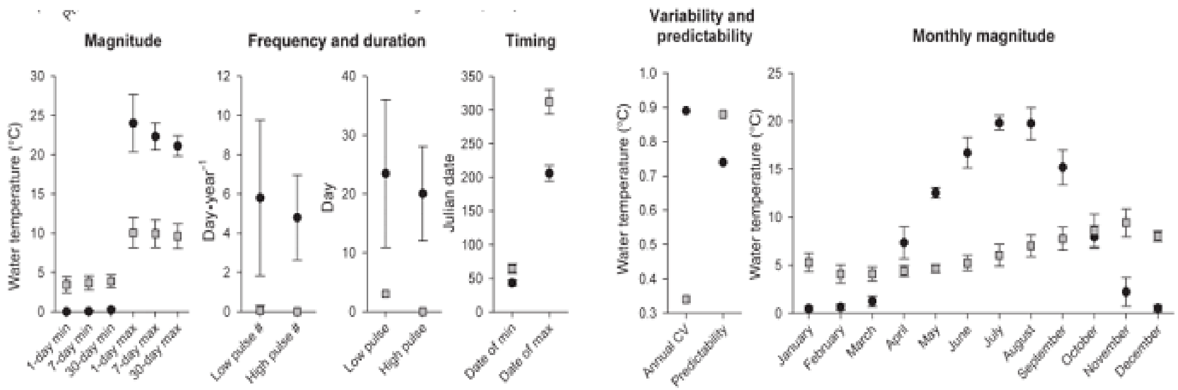

Figure 2: Differences in the magnitude, frequency, duration, timing, and temperature between pre-dam construction (black circles) and post-dam construction (grey squares; Olden & Naiman, 2010*)*.

overall function of the riparian zone. Ultimately, dams reduce the frequency of floods, and droughts can be eliminated, allowing the minimum water levels to increase, compressing all zones and ultimately shrinking the width of the riparian zone (Nillson, 1981). Riparian trees move down towards the water since floods have stopped keeping the trees from moving down towards the water column. Conversely, herbs move up towards the shoreline now that the minimum water level has increased. Reducing the duration and occurrence of floods can also increase the number of trees and shrubs and decrease the density of herbs in the riparian zone due to less saturated soils (Nillson, 1981).

On the Glen Canyon Dam on the Colorado River in Arizona, scientists mimicked spring runoff conditions by letting out enough water to simulate a high flow event. Over the first two years, there were drastic changes in river morphology as well as biotic effects. The second release, another two years later, resulted in stabilizing effects to the ecosystem. A function of high flow events was the building and shaping of sandbars, and the creating of backwater spawning and rearing habitat for fish and other aquatic and semi-aquatic creatures. This experiment proved that high flow events from run-off help shape and keep the river in its naturally functioning state. Damming a river and not allowing these flows is detrimental to the river ecosystem (USGS, 2010).

Dam effects on biota were explored in a separate study, conducted in several North Carolina dammed river systems, showing effects of the dam, and altered flow regimes on amphibian population and species diversity. Researchers found a positive correlation between the distance from the bottom of the dam and overall species diversity, meaning as you traveled farther from the dam the amount and density of different organisms increased in quantity. Above the dam, they saw the same correlation. This is another example of how dams and the disturbance of natural flow regimes can disturb ecosystems (Eskew et al., 2012).

Trophic cascades, defined here as the relationships between predators and prey, are an important consideration, because what affects one organism will affect another, causing a chain reaction in the ecosystem, especially when the original stimulus is something as big as a change in flow regime (Cross et al., 2011). As long as natural variation in annual flow is maintained by intentionally releasing water to simulate seasonal floods, dry periods and temperature fluxes, hydropower could be harnessed while maintaining an approximate natural habitat downstream of the dam.

As dams withhold water in their reservoirs, they also withhold nutrients, such as nitrogen and phosphorous. Consequently, when water is released from the dam, so are the nutrients, causing a large flux in nitrogen and phosphorous in the river system, resulting in large algae blooms, or eutrophication, in the river—namely near the dam's headwaters (Isagirre et al., 2013). Although algae produces oxygen via photosynthesis, they also consume oxygen once they expire, decreasing and potentially eliminating oxygen from a section of the river, most commonly the headwaters, thereby influencing nutrient concentration further downstream, as well. Since algae blooms are seen at the headwaters of the dam, this could cause oxygen deficiency for the whole length of the river (Isagirre et al., 2013). Nutrient fluxes are harder to mitigate, thus other regulations and other means of improvement would need to be implemented, i.e. ways to remove algae at the headwaters to help oxygen levels remain stable downstream. Constant monitoring of stream conditions and the health of its inhabitants should be implemented so that small changes that could escalate to detrimental effects can be identified then mitigated.

Run of River

Run of River (RoR) hydroelectric projects employ the natural elevation gradient of a flowing body of water to generate electricity (Figure 3). Water is diverted from the main channel through a series of pipes that eventually turns turbines in a power plant before returning to the river downstream. This is a method of energy generation that is low impact on all three prongs: economic, social, and environmental. There are limited storage reservoirs and large dams are not required for a project of this nature.

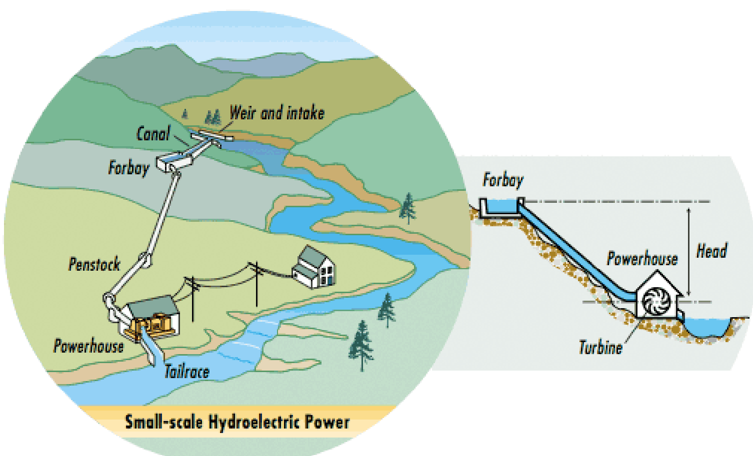

Figure 3: A schematic example of a small RoR project.

One downfall of RoR hydropower stems from water availability during low late season flows. Another stumbling block is that RoR systems are strictly on demand. Because there is no storage of the energy, it is only available as it is generated. This is in contrast to combustion methods of energy generation, where the fuel (coal, wood, and biofuels) can be stored and combusted when energy is needed.

Run of River Economics

RoR systems, like other renewable energy sources, feature a high proportion of upfront installation cost with comparatively lower investments to maintenance. The diversion weir, piping, turbine and generator costs make up 35% of the initial cost while the distribution cables alone comprise 33% of the costs. The other portion of the investment falls under project delivery. Projects with higher peak output require more resources and bigger components that can exponentially scale up in size. Thus, RoR systems have high potential in developing countries or rural areas that don't have large grids or infrastructure. Community scale hydropower projects involve materials small enough to be transported in a pickup truck. Once the materials are on site, the project just needs to be assembled. This can be done with community cooperation, which zeroes the cost of manual labor for installation (Maher et al., 2002).

Furthermore, maintenance is not directly related to the hydro scheme, but rather an indirect effect related to the distribution of power. The components of power generation in RoR systems, in fact, involve virtually no maintenance. The main costs include maintaining the transmission lines that connect the homes to the generator. This maintenance includes trimming trees that may interfere with wires, replacing bad wires, dealing with animals that come in contact with them and keeping the wires off the ground. This further justifies small hydroelectric projects, because the smaller scale suggests that the people using the power will live closer to the turbine and generator, reducing installation and maintenance costs since a lesser length of transmission cable is required.

An example of RoR is found in rural Alaska on the Tazimina River, about 175 miles southwest of Anchorage. A 100-foot elevation gradient achieved through a shaft adjacent to a natural waterfall is harnessed to generate electricity for the rural communities of Iliamna, Newhalen, and Nondalton, home to 600 people. These communities obtain supplies via air or barge and are not connected to the outside world by roads. The project had an upfront cost of $11.7 million. Appropriate sizing is critical when designing a RoR system. Planners must consider the amount of energy needed first and foremost. If the project doesn't produce enough energy, the residents would still rely on diesel generators to create electricity and the project would be considered a failure. Since the rivers in Alaska face reduced flow due to freezing in winter, the lowest flow in a 5-year hydrograph was utilized to determine the size of a turbine the river would probably always be able to turn. The 5-year hydrograph of the Tazimina River showed a low flow of 140 cubic feet per second (cfs) while the turbine only requires 110 cfs to rotate at full capacity. This is a unique workaround for the dilemma of low flow which ensures that the turbine will be able to produce peak power output. It also eliminates the need for battery storage of energy (INEEL, 1998).

Run of River Social Implications

RoR hydropower projects are best applied on small scales with modest power output requirements since they are contingent on being near a river. By coupling a more sustainable method of energy generation and a cultural shift towards using less electricity, strides can be in the direction of protecting a globe where ecology and biodiversity are being negatively impacted.

Significantly less land area is required, reducing social impact because fewer people face the risk of being displaced by the project. Due to their operation on a smaller scale than dams, RoR projects generally require less permitting, planning and rehabilitation.

RoR systems have the potential to provide energy to large urban populations around the world, but most of these areas are already serviced by other methods of energy production. In areas without high population density and well-developed grids, small RoR operations are a cost effective way to provide reliable electricity. The future of electricity generation in developing countries should involve small RoR hydroelectric. In Kenya, for example, 90% of the population does not have access to electricity, and only 2% of the population is connected to the grid. One might argue that hydropower is not viable due to the dry climate or that as people get a taste of electricity they will consume more of it. However, in the 1990s, local television access was broadened and people subsequently bought car batteries to power black and white TVs. This occurrence did not increase the connectivity to the grid and those who were able to access the grid were upper middle class members (Maher et al., 2003). The exciting portion of this application of hydropower is that we don't have to work backwards. If people are not already connected to the grid as we are in the United States they will not be adamantly against remaining off the grid. In fact, they will probably be thrilled to have any electricity at all. If the water resources are available in a given region, small hydropower can be developed in absence of a grid and used to generate sustainable energy.

A specific project in Thima, Kenya proves small hydropower is economically attainable considering a 2.2kW scheme that powers 100 homes costs only $7,800. The elevation gradient is 18m, the flow rate is 28 l/s and the turbine and generator have a combined efficiency of 45%. The furthest house is 800m from the generator. The houses connected to the generator have modest electricity use compared to America (25kW might power 2 homes in America) and have load limiters to prevent one house from using the majority of the electricity. Applications like this are designed to power a few lamps and maybe a TV. By increasing the number of households that are a part of the scheme, the whole project becomes more affordable to each household (Maher et al., 2003).

Run of River Ecology

Run of River projects are considered more environmentally friendly due to the fact that a reservoir is not required. However, flow regime is changed by either diverting water from a particular reach or a diversion dam that impounds a small amount of water behind it. Alteration of flow regime may cause adverse effects to stream biota, but these effects are much less than storage based projects.

Construction and maintenance of single systems still causes a small ecological footprint compared to storage based dams. Considering the lack of pollution in the form of greenhouse gases produced, RoR projects prove to be more sustainable and ecologically friendly. However, the size of the project will determine the size of the disturbance.

An important idea to consider is the overall scale of the RoR project. One small project may have minimal construction requirements, and may not create that big of a disturbance when being constructed. Now consider many of these projects in one particular area, a conglomeration of these systems will pose a much large disturbance on the ecosystem. For example, Plutonic Power Corporation's Bute Inlet project in British Columbia was rejected by the public due to its immensity. This proposal included 17 river diversions, resulting in over 60 km of diverted water. This would require the construction of 476 km of transmission line, 250 km of permanent roads, and over 150 bridges (Chapman, 2008). By themselves RoR projects and other smaller hydropower have low impacts, but grouped together they pose a large threat of disturbance to the environment.

These power systems also pose threats to biota after construction. A study done by Kubecka et al. (1998) in the Czech Republic shows ichthyological and benthic disturbances of bypass hydropower systems. The study was conducted over 23 sites, showing decreased fish biomass, as well as lower reproductive numbers, due to the diversion of water for hydropower. Conversely, mechanical damage by mill turbines and other structures was rare and much lower than large hydropower (Kubecka et al., 1998).

Weirs and diversion dams block channels, posing as migratory obstacles, causing the aforementioned decrease in biomass. A trophic disturbance due to dam obstruction was evident in all streams sampled. One particular reach, on the Cerna River, was dominated by brown trout and the common chub. After construction, the water above the dam experienced a rise in populations of smaller fish species. These species outcompeted the chub, which was the major food source of the trout, resulting in a 30% decrease in biomass of the brown trout in this reach. RoR projects also change the flow regime of the waterway, either by removing water which is diverted to a power station and released back into the stream below, or impounding a small amount of water, altering flow and temperature regime. RoR projects that are installed in smaller waterways have a bigger impact on flow regime and stream health, because there is less water to displace (Kubecka et al., 1998).

The need to enhance fish migration is evident, and current technology is making strides to upgrade fish passage systems. RoR weirs can be retrofitted with fish ladders to alleviate migration disturbance. Fish ladders are a way to slow the flow coming from the large elevation change. Most designs resemble a ladder, which creates small pools between rapids, allowing the fish to rest as they slowly move up the ladder. The figure below, provided by the Australian New South Wales Government, is an example of a rock-ramp fish ladder, which uses a similar design to the pool-weir system. The rock ramp design is ideal for smaller RoR projects, due to the fact that already present rocks can be used for construction. Retrofitting RoR projects with rock-ramp fishways is also feasible due to the nature of this design.

Research by the USGS using sound technology to track movements and behavior of fish will identify better ways to enhance migration and limit mechanical damage done by intakes and turbines. The more knowledge that is collected about migration habits, cues, and disturbances will help assist the construction of more efficient and biota friendly fish passages (US EIA, 2014).

Future Expansion of Hydropower

The world as a whole has potential in multiple ways to increase its infrastructure on large and small scales of hydropower generation. Hydropower already produces a significant amount of energy at one-fifth of the world’s production; more than any other alternative

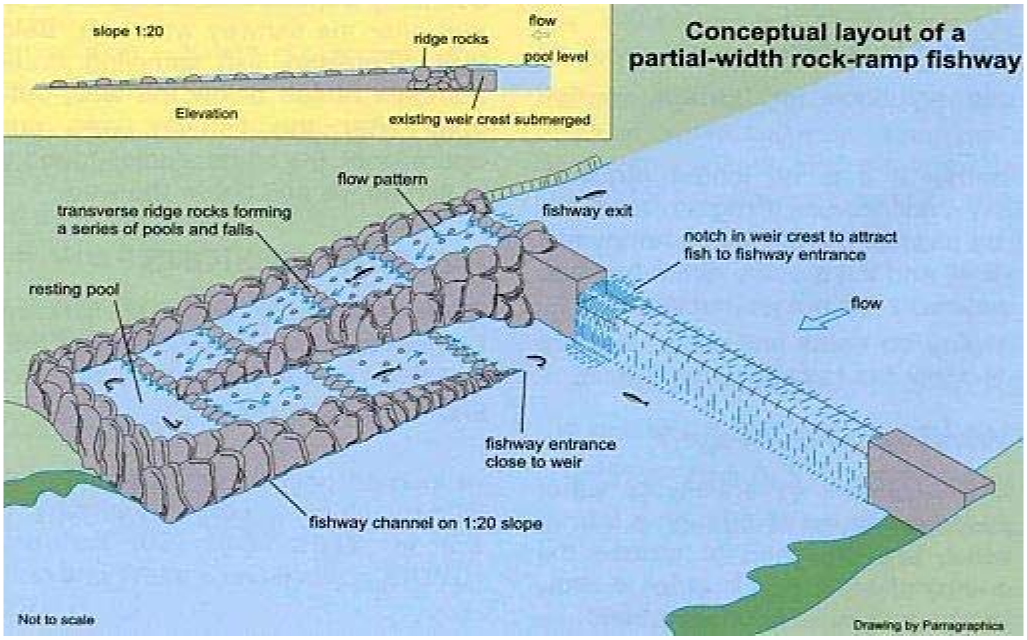

Figure 4: This design of fish passage lowers the gradient, therefore the flow rate making passage easier for migration. The pools, separated by small rapids mimic natural pool riffle systems, making the passage more appealing for fish. (NSW)

energy (Paish, 2002). This greatly reduces CO_2 emissions and reliance on fossil fuels as it is the most efficient energy source. Figure 5 below displays that hydropower has the highest return on investment compared to many other forms of sustainable energy with Run-of-River having an even higher payback ratio than traditional storage based hydropower (Atlason et al., 2014).

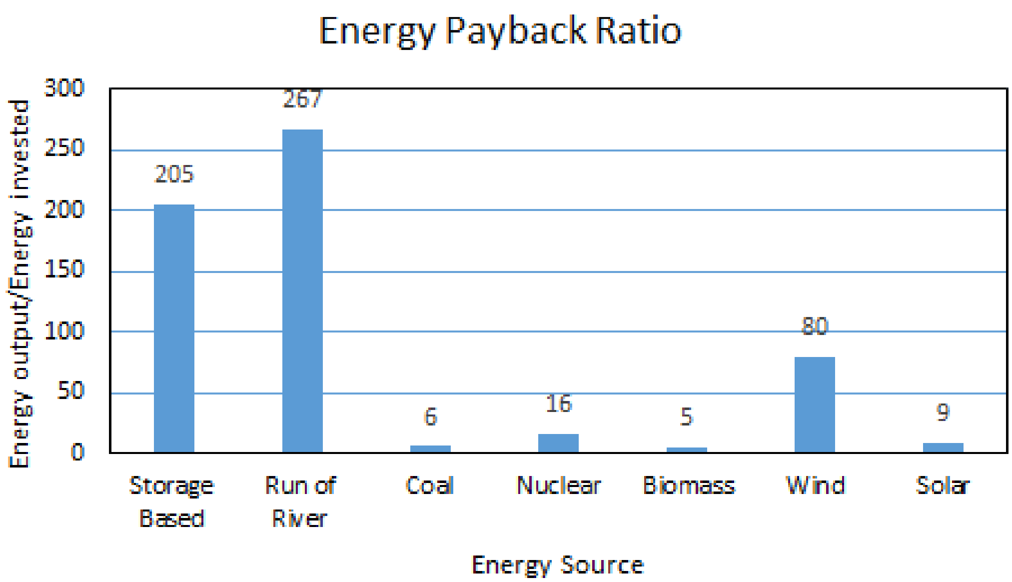

Figure 5: Energy payback ratio of seven common energy sources as a ratio of the gross energy output over gross energy invested into production including construction/production of the power plants (Atlason et al., 2014).

The current extent of hydropower in the US is about 7% of its total power production. This is about 100 GW and more than other renewables (US EIA 2014). The US has exploited most of its large, reservoir-based hydropower from a few dams that impound more water than all the small reservoirs combined, and some of this infrastructure is old and outdated (Paish, 2002). Not only should we increase our energy production from hydropower, but it is imperative that we maintain previous projects and keep them current with present expectations and regulations to continually mitigate ecological interference. President Obama put forth a goal of running the United States off of 80% renewable power by 2035 and increasing hydropower can make this goal attainable (Snyder, 2012). Countries in Europe have also exploited most of their potential for large hydropower, however RoR projects still have potential. One particular dam in China is capable of producing more power than all other renewables combined. China also still has potential for large-reservoir hydropower, as well as India (Paish, 2002).

Some areas of expansion include untapped water supplies, non-powered dams, and pumped storage hydropower. Pumped storage provides a backbone for other alternative energies, and includes two reservoirs and when energy is not at peak demand, energy not being utilized, usually wind or solar, is used to pump water to the higher reservoir to increase gravitational potential energy. With the current infrastructure of hydropower, 20% can be equipped with pump-storage (OEERE, 2013).

Many watersheds have not been utilized for energy production, and construction of new power stations would create more ecological effects. However, it would add 65 GW of hydropower potential. Ninety percent of all dams in the US are not producing energy and are only used for water supply and regulation. If all of these dams were converted to harnessing the gravitational energy of water they could add 12 GW of hydropower energy without adding more significant ecological effects (OEERE, 2013). Each step towards generating more hydropower cuts down the use of fossil fuels, reducing the addition of greenhouse gases to the atmosphere.

Conclusion

Considering the detrimental effects of our current greenhouse gas emissions, it is imperative that, as a society, we reduce our use of fossil fuels to decrease the exponential degradation of our environment. Even with a lower emission of greenhouse gases, atmospheric CO_2 is expected to continue to rise to 500 ppm before the turn of the century (Figure 6). The increased greenhouse gas concentration subsequently leads to the 2-4 ⍰ expected temperature increase in that same time. Figure 6 displays an important aspect of biogeochemistry, which is mean residence time. This term refers to the amount of time that a particle spends in a particular system. Even if CO_2 emissions are reduced, the already emitted percentage would take time to decrease. This makes the expansion of renewable energy and thusly the decrease of future CO_2 important if the global community does not want to deal with the effects of increased climate change (USGCRP, 2009).

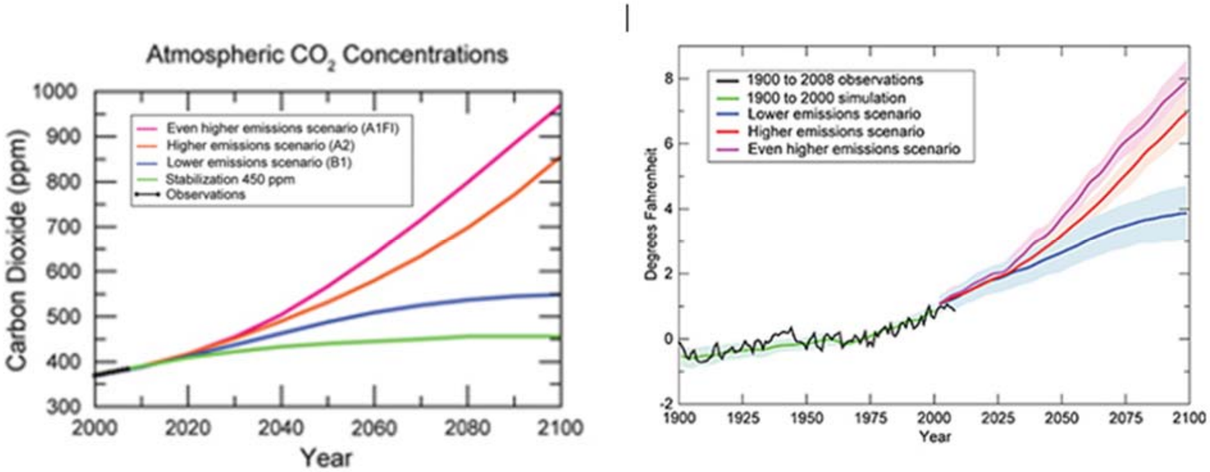

Figure 6: The panels shows expected increase of atmospheric CO_2 concentrations and temperature at various emission scenarios (USGCRP, 2009).

This three-pronged analysis proves hydropower is a viable source of renewable energy. Given the negative ecological effects of damming waterways, RoR and small scale projects can bring about a revolution of small scale renewable energy that would reduce fossil fuel consumption. Smaller scale hydropower will be most useful in remote settings by allowing people living therein to receive clean energy without the drastic environmental changes caused by damming.

Fossil fuel power generation has a large ecological footprint, from power plants, mining sites and refineries to pipelines, and drilling structures. Retrofitting existing dams, which are not currently supplying power, is one step forward in increasing alternative energy supply, while limiting the negative impacts of added facilities, and river disturbance. The utilization of RoR to expand hydropower capabilities is a new and more efficient method to reduce the need for more fossil fuel infrastructure.

Despite acting as the backbone of renewable energy, hydropower alone cannot be expected to act as the solution to the energy crisis facing humanity on its own. The discussion must then shift firstly towards thinking of ways to increase energy efficiency and secondly how to adapt different types of renewable energy to effectively counter the deficit caused by our reduction in fossil fuel consumption.

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