Assessment of Archimedes Screw Power Generation Potential in Ontario

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Abstract

Archimedes Screw Generators (ASGs) are an emerging renewable, low-carbon electricity generation technology. ASGs are appropriate for low head hydro sites, such as existing small dams. Several hundred ASGs have been installed in Europe. There is potential for ASG growth in Canada, which has significant low-head hydroelectric resources. The current state of ASG technology is presented, with details of the University of Guelph's ASG research. The overall ASG generating potential in Ontario is examined. It is found that there is potential to generate approximately 16 MW of low-carbon hydroelectricity in Ontario with minimal incremental environmental impact.

Keywords: Archimedes Screws Generator, Hydroelectric, Hydro Power, Renewable Energy

1. Introduction

Archimedes Screw Generators (ASGs) are a promising form of small hydropower generation that are well suited for low head sites, particularly with already-existing dams. ASGs offer an alternative generator design to typical large-scale hydroelectric power stations that provides higher efficiencies for low head, low flow sites with significant reductions in environmental impacts, both in terms of GHG emissions and effects on the natural environment. Electricity has been generated by utilizing the energy available in water descending in elevation virtually since the beginning of the utilization of electricity for lighting and other purposes. Some of the first large electricity generating stations were hydroelectric power stations, and large-scale hydroelectric power generation is a very mature technology compared to wind- or solar-based electricity generation.

Globally, electricity generated by hydropower plants is the largest non-biomass supplier of renewable electricity, supplying 3-4% of total human energy usage in recent years [1]. It is worth noting that in comparison, fossil fuels have recently comprised approximately 80% of total human energy use. It should be acknowledged that the remaining undeveloped dam sites do not offer the potential additional hydro capacity to replace current fossil fuel usage, even just for electricity generation [2].

A growing number of studies have found that regional to continental scale electricity grids based only on existing hydro, and existing and new wind and solar generation are technically feasible [3][4][5]. In many of these scenarios, wind and solar provide the majority of the generation, and reservoirs at the hydro plants provide a store of energy that is used to supply peaking power. Many scenarios also envision greater use of reservoirs in a pumped storage mode, where water is pumped uphill into the reservoir using surplus electricity at times of low use, and then used to provide additional electricity at high demand times. While details vary from study to study (and region to region), hydropower and hydro reservoirs are an essential component of these decarbonized electricity grids.

In Canada, hydropower makes up a significant portion of the energy mix and plays a vital role in helping meet peak power demand. In Ontario, nearly one quarter of all generated electricity is created through hydropower [6]. Hydropower represents approximately 90% of all renewable energy supplies in the province [7]. Currently, the vast majority of hydropower is produced by Ontario Power Generation, a public company owned by the Government of Ontario, which operates 65 hydroelectric power stations with many of these stations existing on large dams. The capacity of these stations rang e from 800 kilowatts to 1400 megawatts [8].

Historically, hydropower has been considered a zero or low carbon energy source, depending on whether only the actual generation of electricity, or the entire lifecycle of the power plant, is being considered [2]. An operating hydroelectric generator produces essentially no carbon dioxide or other greenhouse gases. The "fuel" of a hydroelectric plant is the potential energy of surface water, which is ultimately supplied by solar energy driving the water cycle.

In the past few decades, investigators have started examining the greenhouse gas generation potential of hydroelectric power plants on a lifecycle basis. The primary sources of greenhouse gasses (GHGs) emissions are construction of large dams and facilities, and flooding due to reservoir filling [9]. Based on mass of materials moved, the large hydroelectric dams are among the most massive individual constructions produced by humans. From a material perspective, large dams consist of concrete and earth or rock fill in varying proportions. Both the production of cement used in concrete, and quarrying and transportation of fill material (by fossil fuel powered equipment) are associated with large CO_2 emissions.

Flooding large areas to form reservoirs can also produce significant GHGs. Once the reservoir is formed, submerged biomass (ranging from trees to soil microorganisms) decomposes, releasing GHGs [10]. The decomposition process generally takes many years, and it is difficult to directly measure the GHG emissions from a large reservoir surface. GHG emissions are highest from tropical reservoirs. In the most extreme cases of tropical reservoirs with a large surface area relative to the hydro generating capacity, GHG emissions from the reservoirs can reach or even exceed the GHG emissions associated with providing equivalent electricity generation using fossil-fuelled thermal generating plants [11].

Damming rivers and forming reservoirs has been found to produce a wide range of other environmental and social impacts, such as mercury contamination of ecosystems, and large changes to river ecosystems, both near and downstream of dams, silt deposition within reservoirs and related delta and shoreline erosion downstream, and disruption of human communities [2].

In Ontario, there is potential for hydropower generation using ASGs at a scale much smaller than typical hydropower stations, which limits many of the aforementioned environmental concerns. There are more than 2600 existing dams in Ontario, located on rivers, streams and tributaries throughout the province [12], which were typically created for flood control or milling purposes. These sit on rivers with power potential much lower than typical hydroelectric stations (well below Ontario Power Generation's smallest 800 kilowatt station). These dam sites represent an untapped energy resource for small-scale hydro projects that would have minimal additional environmental impacts because the dams are already in existence; the negative impacts caused during construction have already been incurred.

Furthermore, many of the dams in North America were constructed several decades ago and are in need of restoration. In the United States, the US Army Corps of Engineers National Inventory of Dams lists 18,140 dams less than 15 feet high in the United States, many of which are deteriorating due to insufficient or deferred maintenance [13]. Management of dam failure in

Ontario is also a concern. The Ministry of Natural Resources estimates that 70% of the dams in Ontario were constructed before 1970 and have expected service lives of 50 to 70 years [14]. This means that 70% of Ontario's dams will need to have major repairs or structural alterations within the next 10 to 15 years [14]. Retrofitting these low head dams with ASGs would provide the capacity to generate low-environmental impact, low carbon electricity. Utilizing the dams would also provide the needed incentive and revenue for repairs and ongoing maintenance. Retrofitting existing dam sites for hydropower production would not only create new energy generation capacity but also help restore structural quality to aging dams, mitigating dam failure risks.

2.0 Hydropower

The purpose of any hydroelectric generating station is to convert potential energy associated with the water in a watercourse passing the station into electrical energy. The available power (P_{avail}) in a watercourse is

$$P_{avail} = \rho g Q h \tag{1}$$

where ρ is the density of water, g is the gravitational constant (9.81 m/s^2), Q is the volume flow rate of water and h is the available head (or "drop") at the site. Large-scale hydroelectric plants are extremely efficient energy conversion systems, capable of converting over 90% of this available energy into useful electrical energy delivered to the power grid. This efficiency includes all hydrodynamic, mechanical and electrical losses associated with the turbine, generator and supporting systems [15].

Microhydro power plants have a capacity of 1 MW or less. Very small plants, on the order of a few kW or smaller, are termed pico-hydro plants. Microhydro generating systems have different environmental impact profiles than larger scale hydro generating plants. Almost all large (megawatt and gigawatt) scale hydro generating stations use impoundment, in the form of reservoirs created by dams, to ensure consistent availability of water and predictability of power output. Many microhydro systems use small reservoirs on smaller scale water courses or are run-of-river, in which the plant uses water available at the time in the watercourse, and does not use a storage reservoir.

A range of turbine technologies are available, with choice of turbine technology depending on the available head, flow, site access and other engineering considerations. For very high head (20 – 100+ m) sites, Pelton and Turgo type impulse turbines are often used. Crossflow, Kaplan or Francis turbines are often used at locations with moderate head (10 m - 30 m). Locations with low head (less than 10 m) are more challenging, since the turbine types listed above need minimum amounts of head in order to operate effectively. Only a few technologies are available for these locations, including undershot waterwheels and Archimedes screws, which are the focus of this study.

3.0 Archimedes Screw Generators

ASGs are a form of renewable hydroelectric power generation that has emerged in the last several decades. ASGs are an adaption of the ancient Archimedes screw pump technology, which has traditionally been used to pump water from low to high elevation under low head conditions such as irrigation [16]. An Archimedes screw is comprised of several helical planes fixated to a central cylindrical shaft. The screw is typically encased in an inclined trough and is free to rotate along the axial length. When used as a pump, the lower end of the screw is placed in water and mechanically rotated. This rotation causes buckets of water to become entrapped between the helical plane surfaces. As the screw rotates, the water buckets are drawn up the axial length of the screw to a higher elevation. Today, Archimedes Screw pumps are still commonly used in wastewater treatment plants [16].

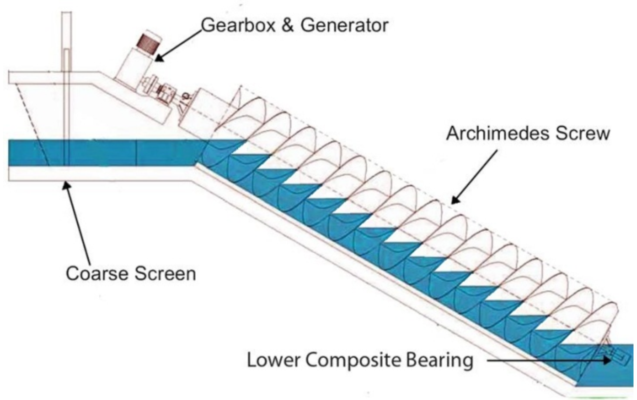

Figure 1. Archimedes screw generator system.

ASGs operate as reversed Archimedes screw pumps. Water is introduced to the top of the screw and allowed to flow through the screw from high to low elevation. As the water transverses the screw, the formed water buckets create a difference in pressure on the opposite sides of the helical planed surfaces. Due to the shape of the plane surfaces, a component of this pressure differential force always acts in a direction normal to the central cylindrical shaft causing the screw to rotate. Attaching a gearbox and generator to the screw shaft, the mechanical rotation can be converted to electrical power.

While Archimedes Screw technology dates back to antiquity, their use as generators is relatively new. The first ASG was installed two decades ago by Brada [16]. Since then, several hundred ASGs have been installed globally [17], with the vast majority being installed in Europe. Currently, there exists one operational unit in North America, installed in Waterford, Ontario Canada [3], but interest in the technology is growing as adoption of renewable energy technology is expanding generally due to concerns over climate change. ASGs are particularly advantageous over traditional hydropower generation technologies for low head sites with heads below 5m. Williamson et al. [18], comparing various forms of micro hydro technology, found ASG efficiency potential remains high even as the head approaches zero, something that is not true for many traditional turbines. Typical ASG efficiency has been found to range between 60 and 80%. Lashofer et al. [17] completed a comprehensive survey, assessing the performance of both ASG field sites and laboratory ASG models for performance. A total of 34 field ASG units located in various European countries (Austria, Germany, Ireland, Italy, Switzerland and the United Kingdom), spanning 7 different ASG designs, were examined. These designs were comprised of both fixed and variable speed generators, with power ranges from 4 to 140 kilowatts, while most ASGs inspected were below 33 kilowatts. Of the 34 ASGs analysed, the measured overall mean efficiency was found to be 69%, with the six top performing plants yielding efficiencies over 75%. For their laboratory tests, Lashofer et al. found efficiencies ranging from 84% to 94% [17]. It was also noted that field ASG units suffered from excessive noise and were subject to stoppages and inefficiencies due to icing in cold weather, however both of these concerns were generally mitigated when the ASG units were housed in an enclosure [17].

Beyond efficiency, ASG technology is gaining traction due to its limited impacts on wildlife and aquatic species. Archimedes Screw pumps are often used in aquaculture industry to transport fish but even when being used as generators are relatively safe. ASGs are particularly fish-friendly because, unlike traditional turbines, fish, debris and other small objects can often successfully pass through the generator without being maimed or destroyed. Generally, if fish pass by the leading edges of the helical plane surfaces at the top of the screw, they will not be harmed. Tests have shown that fish below 1 kg in mass can pass the leading edges without harm under typical operating speeds; rubber bumpers can be utilized to ensure fish up to 4 kg can safely pass without injury [19]. Additionally, it has been shown that all fish species, including salmonoids, trout and eels, can pass successfully unharmed through commercial ASG units in the UK [20].

3.1 Archimedes Screw Theory

Despite being an ancient technology, there are many unexplored research questions surrounding ASGs. The dynamics of Archimedes Screw pumps have been examined within the scientific literature [21][22][23], but significant deficits still exist in both the scientific theory and numerical data (to validate the theory), particularly in the English literature. These deficits mean there is a lack of robust design tools that can aid engineers to properly optimize an ASG for a particular site.

Currently, there have been limited attempts to create predictive ASG performance models. Müller and Senior [24] created a power model that simplified the turbine geometry by assuming the helical planes to be two-dimensional surfaces. Their model assumed the weight of the water trapped between adjacent planes, termed buckets, drove screw rotation. The weight of the entrapped water created a hydrostatic pressure force across the plane surfaces, generating a torque. Müller and Senior's model assumed quasi-static, steady-state flow conditions, neglecting hydraulic energy losses. Furthermore, the mechanical frictional losses from the rotational motion were neglected as well. They did, however, attempt to account for losses that occur due to leakage flow between the screw planes and the containing trough using Nagel's [21] empirically based leakage model intended for pumps. While the Müller and Senior model has limitations, it was the first model to predict ASG performance, and seemed to have general agreement with the initial experiments conducted by Brada [16].

Rorres [22] more appropriately quantified the three-dimensional geometry of an Archimedes Screw and identified the optimal filling bucket volumes, but did not connect this geometry to a power output model. Similarly, Nuernbergk and Rorres [25] extended the geometry model created by Rorres [22] to predict the inflow head level into an ASG based on flow conditions, but again, power output was not calculated.

The University of Guelph's School of Engineering is currently conducting research into the performance of ASGs, both with operational, grid-connected field units and laboratory scale models. The intent is to create predictive models that correctly account for the complicated ASG geometry as well as many of the dynamic energy losses. Lubitz et al. [26] at the University of Guelph have already created an ASG performance model capable of predicting the potential power output of an ASG based on its flow conditions and screw geometry. This model predicts power for varying water levels within the screw, rather than just at optimal filling conditions, which is important because real-world ASG units are often subjected to a range of flow rates. The Lubitz et al. [26] model also assumes quasi-static flow conditions. However, this model was specifically created be used as an engineering design tool. The theoretical model has been implemented as practical software-based design tool. The Lubitz et al. [26] model currently predicts flow and power, and incorporates both the dynamics and losses due to gap and overflow leakage. Research is currently underway using both field ASG units and laboratory scale models to validate and improve this performance model. Additionally, many of the dynamic flow effects neglected in previous models are being incorporated and validated. These effects include entrance and exit hydraulic losses, losses due to varying outlet water conditions, mechanical friction losses, and complete leakage losses (both gap and overflow).

3.2 Case Study: Fletchers Horse World

The University of Guelph has been involved in the development and testing of an ASG installation located at Fletcher's Horse World, on Nanticoke Creek, near Waterford, in southern Ontario, Canada. The ASG was designed and installed by Greenbug Energy Inc. (Delhi, Ontario, Canada) in an existing dam and adjacent building. This ASG was the first commercial ASG installation in North America when it began producing power in September, 2013. The aesthetic impact is low: there is a small addition on one side of the building, a new inlet near the dam, and an outfall below the dam where water is returned to the watercourse.

Figure 2. Site of Fletcher's ASG installation before work began on the site (left) and after installation was complete (right). The access road is located on the dam crest, and the pre-existing dam spillway is visible under the roadway on the left side of both images.

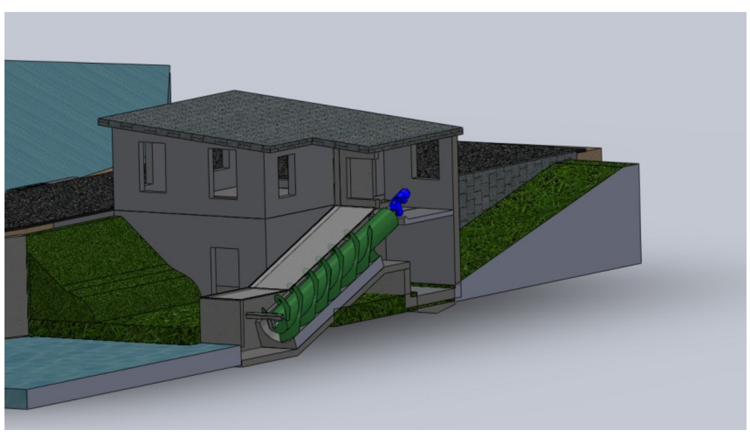

Figure 3. Location of the Fletcher's ASG within the building.

The system was installed in a net-metering configuration due to the large power demands of the property (which include an indoor equestrian arena). Net-metering essentially allows the owner to substitute hydropower from the ASG for electricity purchased from the power grid. Therefore the financial value of the ASG is in reducing costs for electricity purchased from the grid. Each kWh generated by the ASG is therefore worth the avoided retail cost of buying a kWh from the grid (which includes connection charges, taxes and other fees in addition to the actual cost of the electricity). Specifications for the system are given in Table 1.

Table 1. Fletchers ASG Specifications

Parameter	Value
Maximum Output	7.2 kW
Grid Connection	240 V single phase net metered
Max. Design Water Flow Rate	536 L/sec
Design Head	1.7 m
Rotation Speed	41 RPM
Screw Diameter	1.32 m
Screw Length	5.2 m

3.3 Potential ASG Deployment

Hydropower output from all operating hydroelectric generating stations in Ontario averaged approximately 8100 MW in 2013 [7]. This power is primarily produced by OPG's 65 hydroelectric power stations, which are comprised of 240 dams situated on 24 different river systems [6]. The province has long sought to increase the power output from its hydro resources. In 1989, Ontario Hydro issued a Demand/Supply Plan Report that outlined a plan to increase the hydropower supply by approximately 3500 MW by 2014 [27]. It was intended that 1300 MW of this increase would be developed by the private sector [28]. While the realization of this goal did not happen, the province reaffirmed this commitment in 2005, again committing to increase its hydropower output to approximately 9000 megawatts [7]. All of the increases, however, were for sites with potential power output greater than 1 MW as it was deemed sites smaller than this were not feasible [28]. It is estimated that approximately 1000 of the 2600 dams located within Ontario are privately owned by individuals, with the remaining dams owned by the mining industry, Ministry of Natural Resources, OPG, conservation groups and authorities and municipalities [29]. These often overlooked, privately owned dams for low head sites creates a unique opening for the private sector to develop these underutilized hydro resources particularly with ASG technology which is well suited for these sites.

Potential ASG deployment in Ontario were investigated using the Ontario Hydro and Ministry of Natural Resources Water Potential Site database, which contains land, flow and potential power assessments for 2084 dam sites and other locations in Ontario [30]. Included in this data set are the geographical locations of each dam as well as the approximate drainage area, site head, annual flow predictions, development status, and potential power output. Potential power outputs for the individual dam sites were determined through the measured head and predicted annual average flow rates.

Of these 2048, only sites with head less than 5 m and less than 200 kW of generating capacity were deemed suitable for ASG deployment, since most of the currently existing units in Europe have been constructed in this range [17]. Additionally, only sites identified with developments from the past sites were analysed. Using these criterions, approximately 769 sites were identified as suitable for potential ASG deployment. These sites were comprised of 281 developed and 488 undeveloped sites. Developed sites are sites that currently contain hydraulic structures such as dams that are either presently functioning, or functioning at some point in the past. Since ASG deployment would target sites with previously existing dams, only developed sites were taken into account.

The total power output potential for these possible ASG sites is estimated to be 23 MW. The power output potential per site ranged from 0.4 kW to 207 kW, with a mean of 59 kW per site. The average head for these sites was approximately 3.3 meters. Figure 4a shows the locations of current power generating stations in Ontario. Figure 4b shows the 2048 dam sites in the Water Potential Site database that are possible locations suitable for ASG deployment.

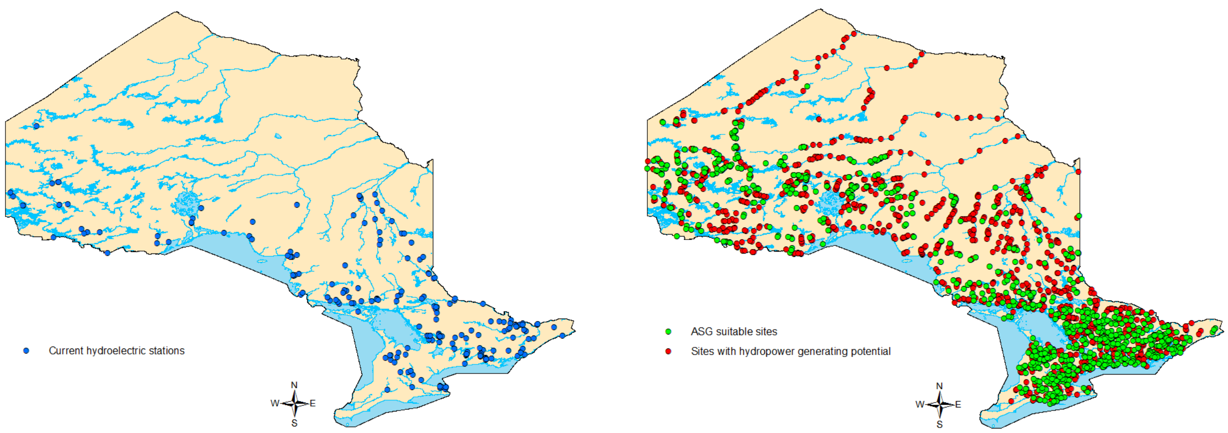

Figure 4. a) Current location of power generating stations in Ontario, Canada. b) Sites identified by the Ministry of Natural Resources capable of hydropower generation. Sites suitable for ASGs are highlighted in green.

Lashofer et al. [17] observed the efficiency of a range of European ASG installations averaged 69%. Using this value, the estimated 23 MW of available energy potential represents 16 MW of potential electrical power output. While most ASGs units installed to date are less than 200 kW, preliminary research at the University of Guelph has suggested that ASGs might remain effective for sites with potential power up to 500 kW. If these sites are included, the power potential of ASGs in Ontario could be expanded to 28 MW, with an operating output of 19 MW. It should be noted that these power approximations are subject to the uncertainty in the estimates of the average annual flow for each site, which can be difficult to predict. Many of the power output estimates were made using site data that dates back to the 1980s. The hydrology of many sites has or can be expected to change in the future. With climate change, site hydrology can be expected to change for many locations with an increase in expected flow due to increased precipitation and snow melt [31]. Additionally, many sites located in increasingly urbanized regions, such as southern Ontario, can expect higher average annual flow rates, particularly during winters due to urban storm water runoff [32].

4. Conclusion

ASGs are a proven hydropower technology appropriate for low head sites. While several hundred ASGs are deployed in Europe, in Canada, and Ontario in particular, the development of small-scale hydro sites is underutilized. In Ontario, it is estimated that approximately 16 MW of low head hydropower power could be generated from ASGs with limited incremental environmental impact. With the emergence of ASGs, previously overlooked small-scale hydro sites could become more attractive to developers and land owners as a means of creating clean energy and economic opportunities. Specifically, ASGs provide a unique opportunity for the private sector, small dam operators, and individual landowners to utilize existing hydropower renewable energy, adding a new source of renewable power into Ontario's energy mix. ASGs can be developed without many of the environmental impacts that accompany large-scale hydropower developments since many of the needed dams already exist. Furthermore, retrofitting already existing dams with ASG units would help improve dam safety, helping to safeguard property, individuals, and the environment from negative impacts of dam failure.

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6. Acknowledgements

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7. Biography

Andrew Kozyn is a Master of Applied Science student at the University of Guelph studying renewable energy under the supervision of Dr. William David Lubitz. Andrew's research is focused on the use of Archimedes screw generators for micro hydroelectric power generation. Andrew graduated from the University of Guelph with a Bachelor of Engineering in Water Resources Engineering in 2012 and a Bachelor of Physical Science in 2014.