Archimedes Screw Generators for Sustainable Energy Development

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***Abstract*—The Archimedes screw has been used as a pump since antiquity and has more recently been used to generate hydroelectric power in plants up to about 200 kW. Archimedes screw generators (ASGs) operate as run-of-river, have low environmental impact and are a uniquely efficient means of generating hydroelectricity at sites with very low head and moderate flow. Experience with ASGs in the developed world suggests they also have the potential to be utilized for rural electrification in developing regions with reliable low head water resources.**

***Keywords*—Archimedes screw, turbine, generator, micro-hydro**

I. INTRODUCTION

The Archimedes screw is a technology that has been in use in a variety of implementations since antiquity. An Archimedes screw (Fig. 1) is a helical array of simple blades that are wrapped around a central cylinder, like a woodscrew. The Archimedes screw may have a single flight, or blade, or multiple flights. It is most common for screws used as pumps or turbines to have either three or four flights of blades.

More recently, the screw has been employed to generate hydro-electricity. In this use, it is often referred to as an Archimedes screw generator (ASG). In its hydro-electric implementation, the ASG is situated within an open trough, and a small gap is retained between the trough and the outer edges of the blades to allow the screw to turn freely.

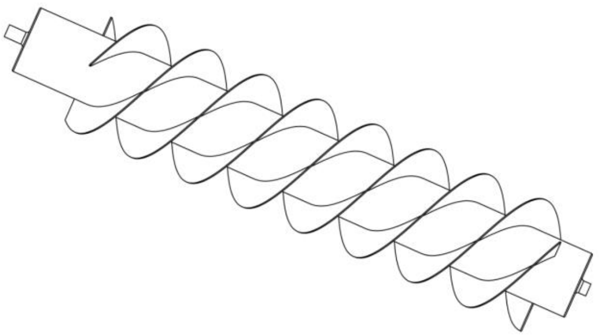

Fig. 1. A three flight Archimedes screw.

When used as either a turbine or a pump, water fills the space between successive blade surfaces, forming volumes of water called a "buckets" [1] (Fig. 2). Since the buckets are relatively large, sediment, debris, and even marine life may pass through the turbine itself. The ASG is considered one of the most environmentally friendly hydropower turbine options [2]. The screw turbine also has a unique low head operational range compared to other hydropower turbines and favorable capital and operating costs. These characteristics lead to it being increasingly proposed as a means to generate hydro-electricity for off-grid communities in the developing world.

II. HISTORY

Though the Archimedes screw has found use as an electricity generator in modern times, it has primarily been used as a pump for most of its history.

A. *Archimedes Screws in Antiquity*

The invention of the Archimedes screw is usually attributed to Archimedes of Syracuse (circa 287-212 BCE), the namesake of the device; however, there is evidence to suggest that the Archimedes screw was invented in the Assyrian Empire under the reign of King Sennacherib (704-681 BCE) in the 7th century BCE [3]. In either case, it seems the device fell out of popular use (or its use was not documented) until its re-invention (or invention) in Ptolemaic Egypt by Archimedes in the mid-third century BCE [3]. Archimedes was reported to have developed an irrigation system in the Nile Delta for King Ptolemy II Philadelphus, and a bilge pump system for King Hiero II of Syracuse using the screw pump design [1]; some historical sources even claim that Archimedes used the device to launch a ship [4].

B. *Middle Ages*

The screw pump found wide use throughout the Roman Empire as a mine drainage pump and was utilized up until the fall of the Western Roman Empire. It saw continued use in the

Iberian Peninsula (Spain) draining mines [5], and in the early Islamic world to irrigate gardens [6]. These examples suggest that the Archimedes screw was still in use in the Middle Ages, although given the general lack of literature from that time period, there is no reliable way to gauge how widely Archimedes screws were deployed until the Renaissance.

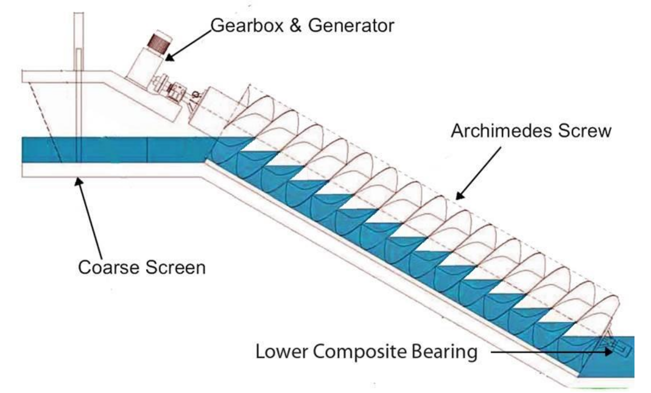

Fig. . Typical Archimedes screw generator. From [48].

C. *Renaissance*

Konrad Kyeser (1366-1405 CE) illustrated the use of Archimedes Screws in the Holy Roman Empire in his *Bellifortis* manuscript [4]; this appears to be the first demonstration of the use of Archimedes screws in the western world since the fall of the Western Roman Empire. Italian Renaissance authors, including Leonardo DaVinci (1452-1519 CE), Gerolamo Cardano (1501-1576 CE), Agostino Ramelli (circa 1531-1610 CE), and Galileo Galilei (1564-1642 CE), outlined the screw-pump and discussed improvements to the design in their respective works [4].

In the Dutch Golden Age of the late 16th and early 17th centuries, massive infrastructure projects were undertaken to drain the Netherlands using Archimedes screw pumps operated by wind mills. A traditional drainage system, the polder mill, is shown in Fig. 3.

The Dutch still employ screw pumps in drainage systems. Kinderdijk, a UNESCO World Heritage Site, uses one of the largest Archimedes screw pumping stations in Europe to maintain water levels and protect the region from flooding [7].

D. *Modern Archimedes Screw Implementations*

The Archimedes screw has been utilized for many purposes in recent times, in applications that utilize its qualities as a robust device that allows transportation of various media through its coarse flights. These include use as fish ladders, land reclamations, injection moulding, heart valve replacement [2], and as a pump for grains, water, and wastewater [8]. The most widespread application of large Archimedes screws is as pumps in wastewater treatment facilities.

The Archimedes screw turbine for generating electricity is a relatively recent application. Karl-August Radlik applied for a patent in 1997 [9] for a power-generating Archimedes screw, with either single or multiple blades, situated within a fixed trough with water flowing in the top and travelling in buckets, turning the screw to capture the energy in the head difference of a waterway [10]. The earliest ASG's for electricity generation were installed in Germany; initial experimentation found the devices to be approximately 80% efficient [11]. After these early installations proved the turbine design, ASGs saw widespread adoption throughout Europe. There are currently hundreds of installations in Europe – mainly in Germany and the UK – that are operating reliably [12]. More recently, the Archimedes Screw Generator (ASG) has become the subject of an increasing number of experimental and simulation-based investigations [13–16].

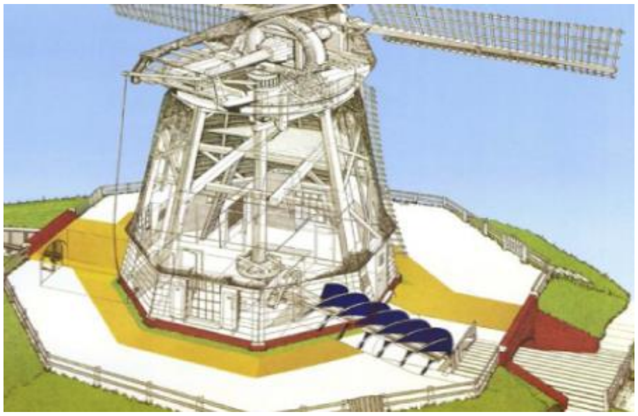

Fig. 3. Traditional Dutch Polder-mill. (*Greenbug Energy Inc., 2016*)

III. ARCHIMEDES SCREW GENERATORS

Many of the characteristics associated with the historical implementations of the Archimedes screw as a pump are also relevant for its more recent utilization as hydro-electric turbine.

A. *Ecological Impact*

Conventional hydropower dams block upstream (and often downstream) fish passage without the aid of fish ladders or elevators. Riverine ecosystems are negatively impacted when fish and other aquatic life lose access to stretches of riverways due to large water impoundments. Pringle et al. found that there have been wide-ranging species extinctions in riverine ecosystems in the temperate areas of the Americas due to large hydropower impoundments [17]. Another study in the Mobile River basin, Alabama, USA, documented the extinction of 38 species, and the near-extinction of another 71 species by 1997, caused by impoundments constricting upstream access by riverine fauna [18].

While conventional dams have adverse impacts throughout watersheds by preventing movement of species, ASGs have been shown to allow fish, eels and other aquatic species to pass directly through the turbine due to the generally coarse spacing between adjacent ASG blades [19]. Between 98% and 99% of all fish passing through an Archimedes screw pump remained unharmed. (Archimedes screw pumps are used to move fish between holding pens in some fish farms.) The dead fish sustained mortal wounds on the head or body, most likely caused by an impact at the inlet of the screw [19]. UK studies of eel and kelt passage through an Archimedes screw generator installation found that both eels and juvenile salmon passed through an ASG had minimal injuries and a low mortality rate. After applying a rubber bumper to the leading edge, the study was carried out again, and found that less than 1% of eels sustained minor, recoverable damage, and 0% of salmon sustained injuries of any sort [20].

The results of this study helped to define the Environment Agency of the United Kingdom's *Hydropower Good Practice Guidelines* which includes key design practices for ASG installations [21]. The guide recommends that screw turbines operating with a tip speed higher than 3.5 m/s should have their leading edge treated with compressible rubber bumpers. The guidelines also suggest a range of ASG diameters that require a trash-rack to screen debris before entering the turbine. Trash racks for ASGs are sized to block passage of large fish and debris into the turbine, that would not fit within the ASG's buckets; this debris and fish are diverted into a spillway or parallel stream [21].

Conversely, the damming of riverways to install traditional hydropower dams blocks the passage of sediment and nutrients into downstream stretches of rivers. The stagnant conditions of the water within the reservoir formed by the dam results in sediments and nutrients settling out of the water column and being deposited on the reservoir bottom, ending movement downstream [22]. Dams are the main cause for the loss of wildlife habitats due to hydropower development. Conventional dams affect the downstream ecology and hydrology both due to changing flow dynamics, and by limiting oxygen, sediment, and nutrient content in the downstream flow, resulting in less nutrient-rich lands downstream [23]. Since ASGs are generally installed as run-of-river systems, no upstream reservoir forms and nutrient and sediment passage continues through the hydropower system.

Reservoirs also release greenhouse gases [24] and methylmercury (MeHg) into river water [25]. GHGs are released when submerged plant life decays in recently formed reservoirs in the absence of oxygen. Large amounts of organic carbon are stored in forests and peatland, and if land is not cleared before it is flooded to form a reservoir, large amounts of CO_2 and CH_4 will be released [26]. Mercury methylation may occur in the flooded lands as well which diffuses MeHg into river flows [25]. Kasper et al. showed that elevated fish MeHg concentrations are evident up to 250 km downstream of a recently impounded reservoir [27]. A recent study projected that Inuit MeHg exposure will double after the flooding of the reservoir at the Muskrat Falls hydropower installation in Labrador, Canada [28]; impoundment for hydropower installations can effect not just aquatic life, but surrounding downstream ecosystems as well. Run-of-river systems limit this negative impact since they generally do not significantly change upstream or downstream flows; it is suggested that ASG installations are unlikely to introduce any significant amount increase in MeHg or GHGs from river systems.

B. *Cost Advantage*

ASGs have low installation and maintenance costs, important considerations for hydropower installations in developing areas. Future Energy Yorkshire compared the costs of microhydro power plants utilizing ASGs or conventional Kaplan turbines. The study found that, though the civil infrastructure costs were similar, the overall cost of the ASG installation was about 10% less than the Kaplan installation and it provided 15% higher energy output. Altogether, the study concluded that the ASG installation was 22% less expensive to install per MWh [29]. Installation costs are normally further lowered by retrofitting old dam sites with ASGs or installing them at existing flood control dams [30].

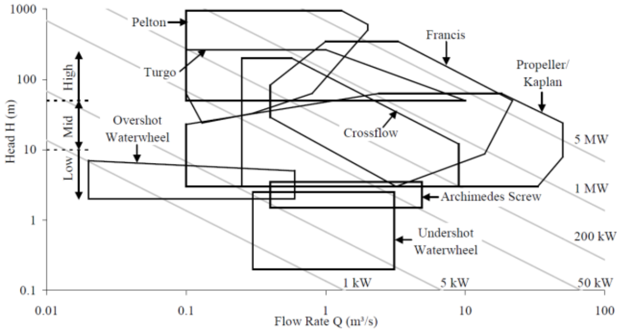

Fig. 4. Operational Range of Hydropower Turbines [49].

Maintenance and operating costs of ASG installations are lower than other available micro-hydro turbines [31]. Regular ASG maintenance is limited to fluid level checks and grease cartridge replacement at the upper bearing and gearbox. Usually the bottom bearing is designed to be sealed for its lifetime, and so it normally operates without any maintenance until it requires replacement [32]. Major maintenance on ASGs is performed after the 20 or 30 year lifecycle of the lower bearing [30]. ASGs operate at a low rotational speed and have few wear points. Generally, only the trough and the blade flights are worn by physical and chemical erosion. Typically, when the lower bearing is replaced, the screw flights are refurbished, and the trough is replaced [33]. Maintenance activities and associated costs are expected to be lower than other turbine options [33].

C. *Operational Range*

ASGs operate in low-head, moderate-flow environments, with typical water-to-electricity efficiencies between 60% and 80% [34], which is comparable to other microhydro technologies. Archimedes screw generators can be installed within systems with heads between 1 m and 6 m, and flow rates between 0.1 m^3/s and 6.0 m^3/s; in these conditions they can be expected to produce between 1.0 and 140 kW of power [12]. Fig. 4 shows the operational range of a range of hydropower turbines.

Fig. 4 shows ASGs are most appropriate for a range of low head and flow rate combinations where most other turbine types do not operate efficiently. The ability to efficiently generate electricity with only a few meters (or less) of head is a particular advantage of ASGs.

ASGs operate within the typical operating ranges of overshot and undershot waterwheels (Fig. 4). ASGs are generally a better choice for these combinations of head and flow. They are more efficient than water wheels: overshot and undershot waterwheels have a maximum mechanical efficiency of 71% and 30%, respectively. Additionally, an ASG is physically more compact than an equivalent waterwheel and would require less material to manufacture. Its higher rotation speed also means smaller, less expensive transmissions are required in the ASG than would be needed to run a generator using a waterwheel.

In most installations, an ASG is inclined at an angle between 26 to 36° [12], and operates as a conventional hydro plant utilizing a difference in head to generate power. However, ASGs may also be installed with the rotation axis horizontal and be used to capture the hydrokinetic energy of tidal systems and river currents; an example of this system is shown in Fig. 5. This implementation is very new, and although it would be expected to be lower overall efficiency than a conventional inclined installation, recent studies have shown promising initial results [35][36][37].

Fig. 5. Hydro-kinetic ASG installation (City University of Hong Kong, 2017).

IV. RURAL OFF-GRID USE IN DEVELOPING COUNTRIES

Rural populations in developing regions often lack access to electricity. Only 29% of the rural population in sub-Saharan Africa has access to electricity [38]. Electricity provides many benefits to society, including increased security, productivity, and health, as well as better access to information, education, and entertainment [39]. Access to electricity was a priority for rural residents in Cameroon [40] – it would reduce reliance on fossil fuels like diesel and kerosene, and increase safety by reducing fire risks and indoor air pollution associated with use of kerosene-based lanterns and wood-fueled cookstoves. Rural areas of Cameroon rely heavily on wood biomass cookstoves for heating and cooking that are estimated to be responsible for 12,900 deaths per year [41].

Small hydroelectric installations, either pico- or micro-hydro systems, offer an option to increase electricity access in developing countries. Small-scale hydroelectric systems have been widely deployed in Asia and Latin America, but they are not common in sub-Saharan Africa [40]. In Cameroon, implementing small hydro systems was found to be difficult due to inaccessibility, corruption and high trade duties [40]. If these barriers can be overcome, however, there is significant potential for small hydro development. In sub-Saharan Africa, only about 5% of available hydropower potential is currently exploited; significant potential exists for implementing small-scale hydroelectric systems [42].

Local availability of turbines and related equipment is a potential limitation to increasing small hydro use in developing regions. Turbines must be either locally manufactured or imported from other countries. Imported systems tend to be much more sophisticated, but costly to import and install, and it is often difficult for locals to maintain complex imported systems. Ho-Yan observed multiple non-operating renewable energy systems in Cameroon that could not be repaired due to inability to access a needed part or the expertise to install it [33]. Local manufacturing of system components avoids these problems, but in practice locally produced systems have often proven to be of poorer quality than imported counterparts [43], increasing costs. Locally manufactured turbines have proven quite successful in some developing countries in Asia, however, and given time local capacity can be developed to produce and operate turbines and hydro plants. It was noted that the current locally manufactured micro-hydro systems required a more robust design [40]. Chan notes that remote communities in Nepal would benefit greatly from the installation of micro-hydro systems, but have difficulties repairing and replacing components due to poor access [44]. ASGs are a promising turbine technology for local manufacture. The turbine and trough are typically manufactured from sheet mild steel. Tight tolerances and precision machining are not required in an ASG. Wear components, such as gearboxes and bearings, can also be sourced or adapted from locally available equipment.

While this discussion has focused on the microhydro generation system, isolated microydro systems must also include turbine controls, distribution lines and connections, and planning of end uses. Unlike solar or wind systems, isolated microhydro installations generally do not include expensive and short-life battery storage. Instead, most microhydro generators operate continuously, and any power that is not needed is dissipated in a dump load (often a resistive heater cooled by river water). Electronic load controllers (ELCs) have been developed to control this process and are usually integrated into the turbine powerhouse. Roodsari et al. [45] proposed an electronic load controller (ELC) system design that could be used to distribute generated power throughout the population of a remote community without access to a power grid. Their load controller system consisted of an ELC at the powerhouse, and a smaller ELC for each home connected to the hydro-system. The individual load controllers were proposed to turn on rice cookers or to heat water tanks when surplus power was produced [46]. Coupling an ASG with such an ELC system could prove practical in remote communities.

While to-date almost all ASGs have been installed in the developed world, particularly Europe, there are now a few recent examples of ASGs being installed in developing regions for rural electrification. A 3-bladed screw was designed for the Arinta waterfall in Ekiti State, Nigeria; to provide the town of Erijiyan with an average of 83 kW [31]. Okamura et al. [47] proposed a small off-grid ASG installation for a town in southern Tanzania. The system was designed to minimize installation costs and provide a 48 homes with enough power to each run one LED light bank and charge one mobile phone daily. The total system cost was estimated to be $460 USD if the system was designed, manufactured, and installed by locally-based companies; costing each family $9.60 USD [47].

While there is still little experience using Archimedes screws to generate power in developing regions, experience to date suggests that this technology could be potentially useful in regions with appropriate low head and moderate flow water resources, and an appropriate level of manufacturing and support infrastructure. The combination of low environmental impact, low mechanical complexity and potential for efficient production of electricity suggest ASGs should be considered as a feasible option when evaluating potential for pico- or micro-hydro development in developing regions.

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