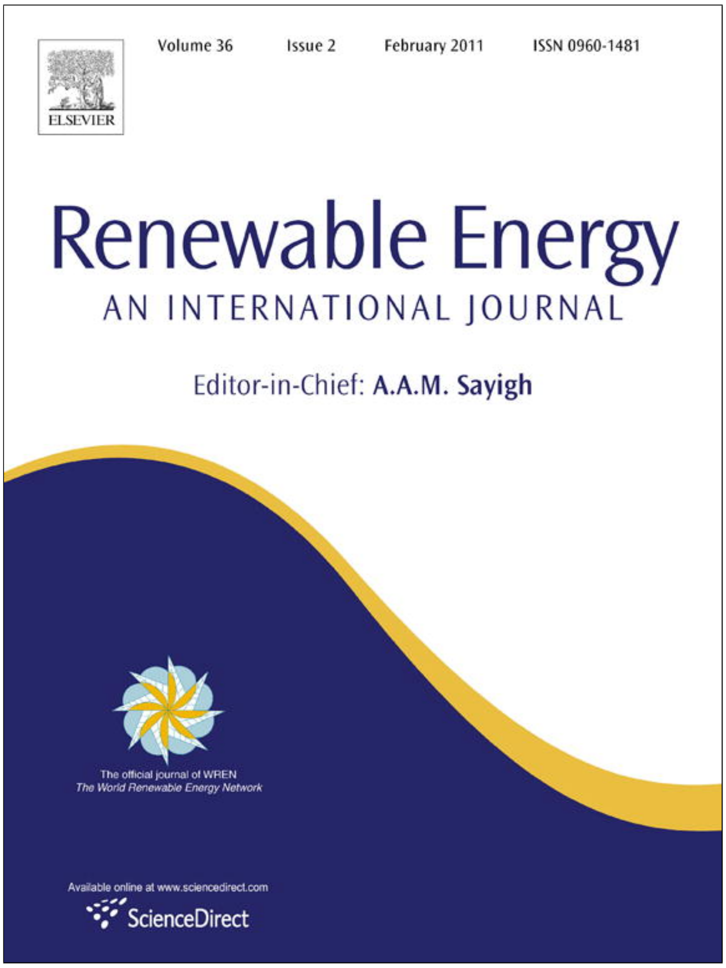

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Hydrokinetic power for energy access in rural Ghana

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ABSTRACT

Approximately half of Ghana's overall population has access to electricity and, of this, much of it is in urban areas. Often in regions where modern energy is not available, kerosene lamps, for example, are used for indoor lighting. This produces harmful emissions, leading to poor respiratory effects. Implementation of hydrokinetic power (HKP) within nearby streams can provide low impact, robust energy to rural communities. Such a system lends itself to a simple design with ease of maintenance, which can be used as a stand alone power system (SAPS). With Ghana's renewable energy policies coming to fruition, it is sought to establish the economic viability and sustainability of this technology. This paper discusses site selection and the HKP technology in rural areas of Ghana.

1. Introduction

Currently, about 54% of households in Ghana have access to electricity, with rural access at only 24.9%, compared to 81% for urban households [1]. A review of the Ghanaian topography map and population density map [2,3], in combination with Ghanaian electrification, demonstrates that Ghanaian electrification actually neglects over 50% of the overall population [4]. As part of the UN Millennium goals, the national development planning commission of Ghana has outlined energy development as a priority, since it is tied to so many aspects of general well-being, such as health, prosperity, and gender equality [5,6]. Hydrokinetic power (HKP) generation is a new type of hydropower energy that extracts kinetic energy rather than potential energy. Potential energy extraction is the mode of energy generation currently used in almost all large and small hydropower systems. These will be referred to as hydropotential power (HPP) systems to aid in clarification among the hydropower types. HKP systems avoid many of the problems encountered with HPP, such as large population displacement, high infrastructure costs, and large decreases in downstream flow. They utilize a simple design, and can be maintained by local residents for low cost. Furthermore, HKP can be easily installed into a stream and modified with small effort to enhance energy extraction. HKP and small HPP are competing technologies due to their similar power extraction amounts, but the benefits of HKP far outweigh HPP, due to HPP systems' more complicated infrastructure and associated maintenance issues.

Approximately 70 sites, with a total potential of 800 MW, have been identified for small HPP in Ghana; however, none of these sites have been utilized to date [7,8]. A main reason for this is lack of necessary policy backing, while other reasons include minimal small HPP technology knowledge and absence of financial support [8]. The lack of policy backing for HPP is largely due to the amount of infrastructure cost (in terms of economics, social impact, and the environment) compared with the amount of energy available from the system. HKP has a lower cost per unit of energy extracted than HPP systems, and is economically comparable with other distributed systems, such as solar, making it a better candidate for policy support. Note that the micro hydropower outlook in Ghana was explicitly developed for small hydropotential, but the projection is that these sites will be more suitable for HKP [9]. The stream level can decrease during the dry season, making HKP much more viable in this setting since it involves turbine placement in the stream to extract flow or kinetic energy, and does not require a dam or weir structure to create a reservoir. This results in fewer changes to the downstream locations, such as not completely removing the water source. Additionally, the implementation of a renewable energy law is under review in Ghana to provide support for future renewable energy development and expansion of rural electrification [9]. Policies are shifting to give renewable energy technologies, like HKP, further support by creating opportunities for investment in them.

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Because of the system's less complex infrastructure, HKP has been identified as a key remote energy technology for developing countries [10]. HKP has been a proven technology in certain isolated cases [11–15]. A successful rural application of HKP has been in operation for at least a decade to provide electricity to a health center in central remote Brazil [16,17]. It has already improved quality of life in this region [17]. Furthermore, HKP can help improve access to electricity in peri-urban and remote rural areas. Studies have shown that it is cheaper to electrify communities using decentralized systems like hydrokinetic power when they are more than 20 km from the electric grid [18].

2. Electricity in Ghana

Large scale HPP, in the form of two dams, has been a significant contributor to Ghana's energy sector, providing more than 1100 MW of the total 2200 MW supply in the country [4]. However, these types of power plants are not the focus for Ghana's future energy development due to both environmental and social reasons [4]. Severe environmental impacts have been exhibited by the two dams in operation. 243,000 ha of cocoa plantation have been flooded, and two million oil palm plantations have been destroyed. Additionally, lagoons naturally supplied by the Volta River dried up, allowing aquatic weeds to grow. This has slowed the river, and these weeds have provided a place for disease vectors to form. One result is that the lower part of the river has been declared a schistosomiasis endemic area [9], where the disease rate tripled within a year [19]. Further environmental impacts have not been investigated for both large and small HPP in Ghana, but could include decrease in fish populations, flora and fauna destruction from changes to the overall flow regime and temperature, and a decrease in bird populations [20–23]. While this is not the direct focus for this paper, it points to the added benefit of employing a technology with a smaller environmental impact.

The best area in Ghana to implement these technologies is in the northern region for two reasons: 1. It has the highest poverty [24]; and 2. It has the poorest electrification [4]. The population density [2], in combination with the river/micro hydropotential [9], indicates that the White Volta River is a viable option for HKP implementation. During the dry season, this river does dry up; however, partial electrification is still an improvement, and addresses many of the reasons why this technology is needed, such as residential lighting and vaccine refrigeration. The Ghanaian government shares this perspective: for example, the Bui Dam is scheduled to be operational in February 2013. It will provide around 300 MW after having been constructed for approximately $400 million, but is only expected to operate at 25% capacity due to the dry season.

3. Regulatory and policy framework

In Ghana, the Public Utilities Regulatory Commission (PURC) was established in 1997. PURC is an independent body set up to regulate and oversee the provision of the highest quality of electricity and water services to consumers. The Energy Commission (EC) was also created in 1997, and is required by law to regulate, manage and develop the utilization of energy resources in Ghana, primarily through providing the legal, regulatory and supervisory framework for all providers of energy in the country. More specifically, this is done by the granting of licenses for the transmission, wholesale, supply, distribution and sale of electricity and natural gas, including refining, storage, bulk distribution, marketing and sale of petroleum products and related matters. In order to introduce competition in the power sector, the government has introduced Independent Power Production (IPP) schemes and reforms, such as increasing low electricity tariffs toward international levels. Ghana's current low tariffs and the delays in establishing a sustainable tariff regime are discouraging many potential power sector investors.

Since the mid-1980s, the Ghanaian government has been financing projects using small levies on petroleum products. The money is paid into an energy fund and used to promote renewable energy and energy efficient projects. A strategic national energy plan was adopted earlier this decade, and covers the period 2006–2020. In this plan, government hopes to achieve 15% penetration of rural electrification through decentralized renewable energy by 2015, expanding to 30% by 2020. The energy plan also sets a target of 10% overall contribution from renewable energy by 2020. Presently, there is no clear policy or regulatory framework to support this renewable energy investment. However, a renewable energy law is being drafted and will soon be passed to parliament for adoption.

4. Technology

HKP was originally developed to overcome the myriad of problems associated with dams throughout the world. This technology avoids destruction of nearby lands, and results in lower changes to the overall flow regime, so as to not contribute to large differences in stream biology, i.e. allowing weeds to grow in streams. In addition to these benefits, HKP systems reduce the flora and fauna destruction associated with traditional HPP systems, since they do not require a reservoir.

HKP encompasses both tidal and river applications. Within the context of this paper, the focus is on river HKP, since it is suitable for energy generation at remote locations. There are many ways in which to extract kinetic energy from either tidal or river settings, including axial turbines, cross-flow turbines, and vortex shedding. Much of this has been inspired by wind energy extraction and may involve different augmentation schemes to increase energy extraction and efficiency. Most research to date has indicated that cross-flow turbines have the potential for the highest energy extraction within river environments [13,25]. Since HKP implementation is very site-specific, the turbine type and size can vary. The calculations and modeling presented here will be used in combination with site parameters to determine the appropriate turbine specifications. Our previous work provides more details about the different types of hydrokinetic devices [11,12].

A water wheel river current turbine (RCT) is selected as a representative technology to demonstrate an energy extraction analysis. Fig. 1 depicts a water wheel RCT in a riverbed. In the figure, the river moves from the left, rotating the device, and continues into the page and to the right. The top surface is designated as the river–air interface. The bottom surface is the riverbed, while the side furthest from the turbine is a river bank or side wall, and the side closest to the turbine is the mid-plane in the river. To accurately model this for implementation, a power extraction analysis is completed first, followed by a full computational fluid dynamics (CFD) model.

Power extraction is estimated initially using a simplified energy equation:

$$P_{\text{ideal}} = 0.5\rho A V_i^3 C_p \tag{1}$$

In this equation, is the surface area from one water wheel RCT turbine arm, is the inlet velocity to the device, and is a turbine power coefficient, which is calculated using Equation (2):

$$C_p = \frac{\left(1+\frac{V_0}{V_i}\right)\left(1-\frac{V_0^2}{V_i}\right)}{2} \tag{2}$$

where $V_0$is the outlet velocity from the device. This is an approximation of the amount of energy that can be extracted, and is based

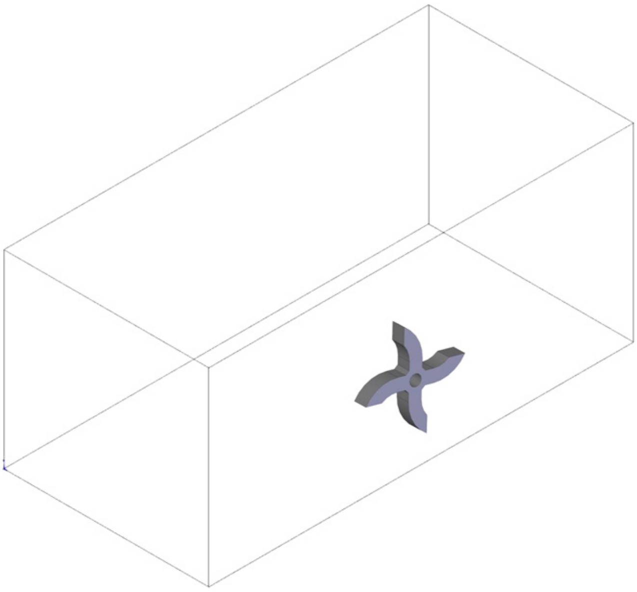

Fig. 1. Water Wheel RCT – River Schematic.

on wind turbine correlations. A detailed analysis with blade shapes and surfaces, and the corresponding fluid interactions, would give more accurate results [26], as does the CFD model. Through a simplification of mass conservation, tends to reach a Betz limit of 0.59, which allows for a check of the estimate of the outlet velocity. However, the final outlet velocity check is from the system CFD model. Power extraction analysis details are given in Miller and Schaefer [11,12].

The river velocity will depend on the site in which this technology is placed, and, in turn, the resultant turbine specifications. For an initial HKP system, we will assume 500 W (100 W per turbine) energy extraction is needed and a 0.3 m/s river velocity is present. With an initial outlet velocity assumption of 0.1 m/s, the RCT would need to have a 10 m swept area.

To verify and advance the RCT energy analysis, Fig. 1 was analyzed using a commercial CFD software package, FLUENT. The mesh was created in Gambit, and contains 1,788,345 cells. Within FLUENT, continuity and the Reynolds equations for turbulent motion are used to simulate a river [27,28]:

$$\rho\nabla\cdot\overline{V} = 0 \tag{3}$$

$$\rho\frac{D\overline{V}}{Dt} = \rho g - \nabla\overline{p} + \nabla\cdot\tau_{ij} \tag{4}$$

$$\tau_{ij} = \mu\left(\frac{\partial\overline{u}_i}{\partial x_j} + \frac{\partial\overline{u}_j}{\partial x_i}\right) - \rho\overline{u}_i'\overline{u}_j' \tag{5}$$

The isotropic turbulence model, $k-\epsilon$, is used to account for the fluctuating velocity term:

$$k := \frac{1}{2}\left\langle\left|\overrightarrow{u}_i'\right|\right\rangle, \epsilon := \frac{\nu}{2}\left\langle\left|\nabla\overrightarrow{u}_i' + \nabla\overrightarrow{u}'^{T}_i\right|^2\right\rangle \tag{6}$$

In this model, the bottom edge and side furthest from the turbine are defined as walls, and the top edge and side closest to the turbine are defined as symmetry, while the edge to the left is the flow inlet, set to 0.3 m/s, and the edge to the right is an outlet. In order to properly account for an interaction between the river and air in FLUENT, a symmetry boundary is used for the top edge. This is a method commonly used in CFD to impose a no-shear condition. The no-shear condition is needed to ensure a proper open-channel velocity profile. Other defined parameters include atmospheric pressure and water density at atmospheric pressure and 20 °C.

Fig. 2 shows the velocity contours of a water wheel RCT. The different colors represent velocity magnitudes, where the *y*-direction is the distance toward the top river surface and the *x*-direction is the distance down the river channel. Fig. 2 is a vertical cross-section showing the velocity through the RCT and around it. In this figure the river is flowing from the right to the left as is also the case for the next two figures. The velocity profile, upstream of the turbine, is typical of open-channel flow. Peak velocities of 2–5 m/s can be seen at locations near the turbine blades, where high velocity is a result of turbine rotation. Additionally, decreases in the velocity to a low of 0.15 m/s, can be seen after the turbine due to energy extraction in the stream. Finally, to provide further details, the velocity vectors of a water wheel RCT are given in Fig. 3. Some circulatory flows and high velocity regions are seen as a result of the device rotation. These figures show the initial outlet velocity estimates are accurate. Furthermore preliminary experimental results have shown agreement with these CFD models.

5. Implementation details

A potential energy extraction scheme for implementation of the technology using RCTs is shown in Fig. 4. It contains a series of turbines connected to a common shaft, which is then connected to a generator and storage system, followed by a possible electrical connection to the local village. It is likely that implementation of a simple storage/charging system (such as batteries) will be appropriate, since the RCTs are constantly extracting energy. This is commonly known as a Stand Alone Power System (SAPS). The stored energy can then be collected by local inhabitants for individual use. The turbines can be constructed using common materials such as fiberglass and steel rods for the blades and shaft, respectively. However, if aluminum is more readily available, it would be the blade material of choice, because it is light, less toxic, and easily formable.

The focus of this study is to attempt to meet a portion of Ghana's energy need. It is calculated an average household will need annually. Based on a population density of 45 per square km and a hydrokinetic energy system able to reach those within a 5 km radius, the amount of households reached per system is 693, assuming 5 persons to a household. To meet this scenario, 16 turbines that extract each need to be installed at each site.

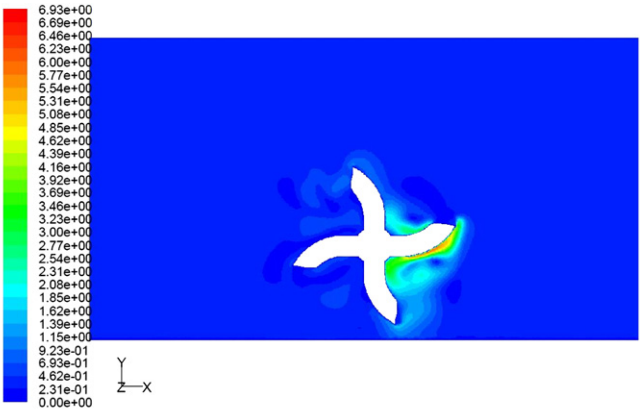

Fig. 2. Water Wheel RCT Velocity Contours, Vertical Cross-Section.

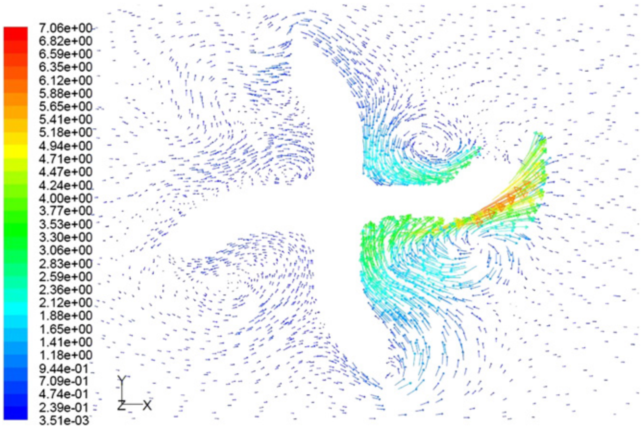

Fig. 3. Water Wheel RCT Velocity Vectors, Vertical Cross-Section.

From a high level, the cost breakdown of HKP can be disaggregated into material, installation, labor, and maintenance costs. Per turbine, the material cost is estimated at $360. Installation costs, including site preparation, are expected to be $4750 per site, and labor costs per site total $1276. The total expected cost per site calculated with an average of number of 16 turbines per site is therefore $12,743.90. Maintenance and overhead costs are expected to be 5.5% and 2.5% of annual revenues respectively. To achieve a reasonable break-even period since, the premise of this energy system is to function at a non-profit level, the cost to users would be $0.035 per kWh, giving a break-even point of about six years.

6. Discussion

The implementation of hydrokinetic turbines for energy access in rural Ghana will benefit society in many ways, thus contributing toward a global impact. Energy access can make everyday tasks simpler and safer. It also has a direct link to a community's health. For example, electrification is important for rural health centers in maintaining vaccine refrigeration. Cheap, widespread electricity directly addresses the UN Millennium goals of eradicating extreme poverty and hunger, promoting gender equality and empowering women, and improving maternal health.

The mathematical model shown in Section 4 can be used in combination with the implementation details, given in Section 5, to assess turbine type and amount for a given energy extraction location and associated site parameters. As mentioned in Section 5, the system of 16 turbines is given as an example of a system size, which can be altered based on the specific energy need at the implementation site. Additionally, consideration would need to be given to the configuration based on site parameters such as flow rate, depth, and width. Further analysis can verify series and parallel effects from the turbine system, since installing a matrix configuration of the turbines will affect their individual performance. However, estimates developed for an individual turbine does give an initial point of reference for how it will operate, and turbine spacing can also be adjusted to minimize the system effect.

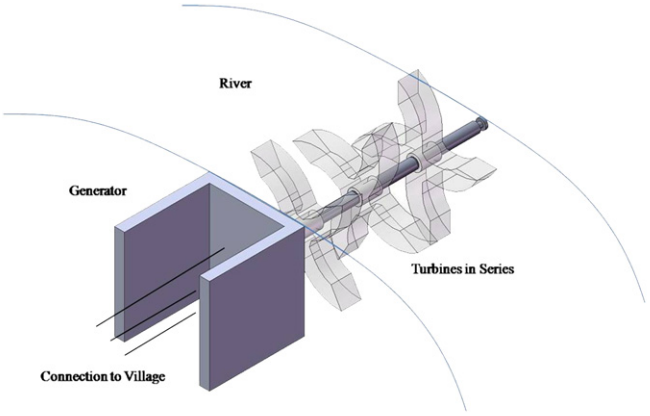

Fig. 4. HKP Schematic for an Energy Extraction Site.

HKP's innovation succeeds where previous methods fell short. The cost of running power from the power producing regions of Ghana to the far reaching rural areas is cost prohibitive. By bringing the power generation facilities closer to the end user, HKP gives opportunity for even the poorest of regions to gain access to affordable power. The cost savings is anticipated to be 2.5 cents per kWh which is a substantial amount. It is anticipated that the government of Ghana will subsidize these poorest of consumers, similar to their current policy for the established utilities, therefore allowing even those with the greatest need access to electrical power [4].

In addition to these important benefits, it is also crucial to ensure environmental sustainability, another of the UN Millennium goals. Preliminary studies show that HKP generation can result in minimal environmental impact. Using one metric, Poff et al. have defined the parameters of any functioning stream as the flow rate, average flow rate over a given time period, amount of time for excessive or recessive flows, flow predictability, and flow stability [23]. In reviewing the potential changes to these parameters, HKP will produce an overall smaller effect on the stream, with, for example, less than a 70% flow rate decrease compared with large and small HPP. It is also proactive to implement such an environmentally benign energy type in a developing country, keeping overall global emissions and CO contribution under control. Developing countries that lack a solid energy infrastructure generally contribute less to global climate change, but will be affected most by climate change. They cannot afford to develop an infrastructure that might be controlled or prohibited by future environmental standards. It is in the best interest of everyone's future to build a base of sustainable technologies.

7. Conclusions

There is a clear need for remote energy in rural Ghana. Many sites have been identified for small HPP which could also be used for HKP. In the past, these sites have not been utilized; however, the Ghanaian parliament is setting forth new policies to remedy this. HKP can be implemented easily into rural Ghana, due to its simple mechanical to electrical conversion system and ease of electrical storage. Possible implementation in the White Volta region is discussed and a general HKP scheme for the region is presented. There is a clear need for remote energy extraction in rural Ghana, and HKP is a robust technology that can alleviate this deficiency.

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