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A Prototype Small Utility-Scale Joint Vertical Axis Wind Turbine and Solar Energy System (VAWT/SES) to Provide Water Pumping in Remote Areas of Uganda

Topic Session FR-EN4: Energy 4: Energy Conversion and Storage for Humanitarian Applications

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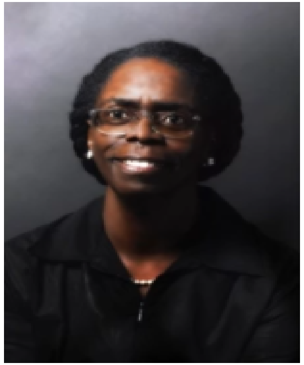

Dr. Jacquelynne Hernàndez

A Prototype Small Utility-Scale Joint Vertical Axis Wind Turbine and Solar Energy System (VAWT/SES) to Provide Water Pumping in Remote Areas of Uganda

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IEEE
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Discussion Outline

Introduction

- Uganda has overcome many internal issues and seeks to move forward to improve the quality of life for its citizens and to develop strong commercial enterprises globally.
- To have a healthy economy, a country needs clean water, access to energy, and a healthy work force.

https://waterjournalistsafrica.files.wordpress.com/2014/04/dsc_2795.jpg

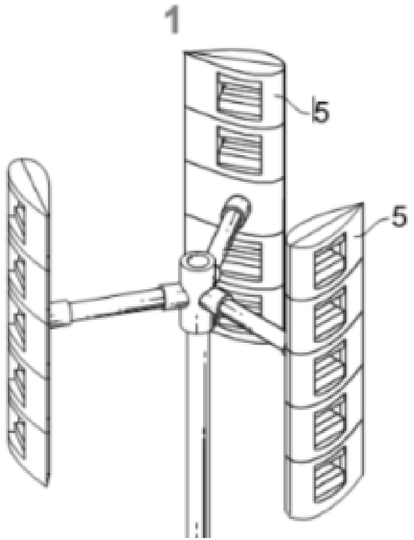
Problem and Thesis Statement

- In Uganda alone nearly 28 million people lack access to safe and clean drinking water. *https://www.waterschool.com/the-problem/ [Accessed April 2021].*
- The authors of this paper propose a VAWT/SES combined with water pumping capabilities to serve as the basis for building a stronger economy in rural Uganda.

https://mapio.net/images-p/2303173.jpg

Description of VAWT/SES

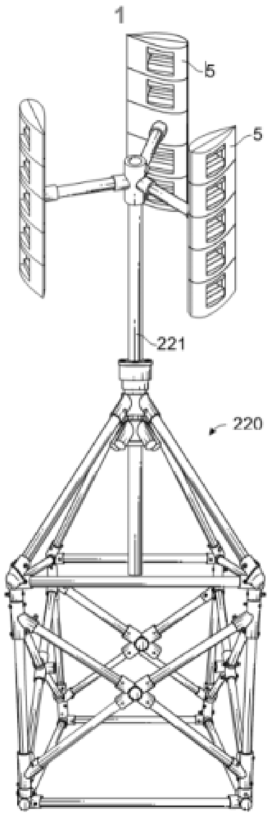
- Small – Medium Scale Vertical Axis Wind Turbines that serve as kinetic solar structures can reduce space for a solar array and combine the two resource collection devices into one structure.
- Wind Power is the main driver of the water pump system with energy generated by the solar cells serving as a backup.
- The solar cells are connected to a slip ring inside a bevel gear system that allows the flow of energy freely through the rotating wires.

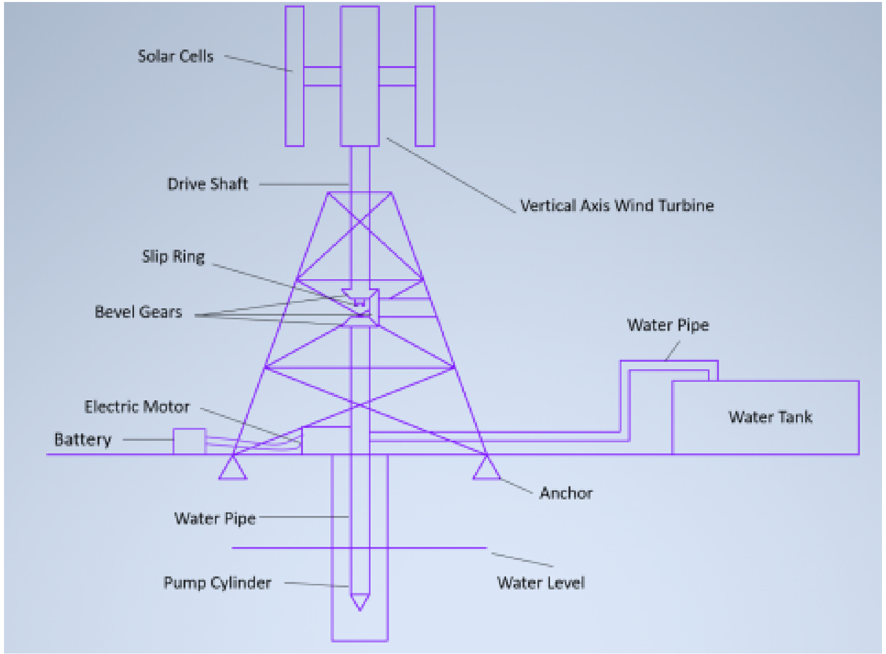


VAWT/SES Construction

- The current design of the VAWT/SES consists of 10 3d printed parts that are assembled.
- Each module has channels for wiring and slots for either solar cells or flexible solar panels.

Composite VAWT/SES System





Literature Review

I. Kumar – outlined wind energy systems, trends, innovations, and global applications

II. Jamaludin – provided analysis on wind speed and water flow from pumps for VAWT systems in Indonesian agricultural regions (comparable to our proposal for Uganda).

III. Mohamed – explored performances of a photovoltaic (PV) water pumping system (Intellectual property associated with this project is a more complex system).

IV. Farah - elaborated on the mechanical and physical properties that affect PLA's stability, processibility, degradation, aging, weatherization, sterilization, etc.

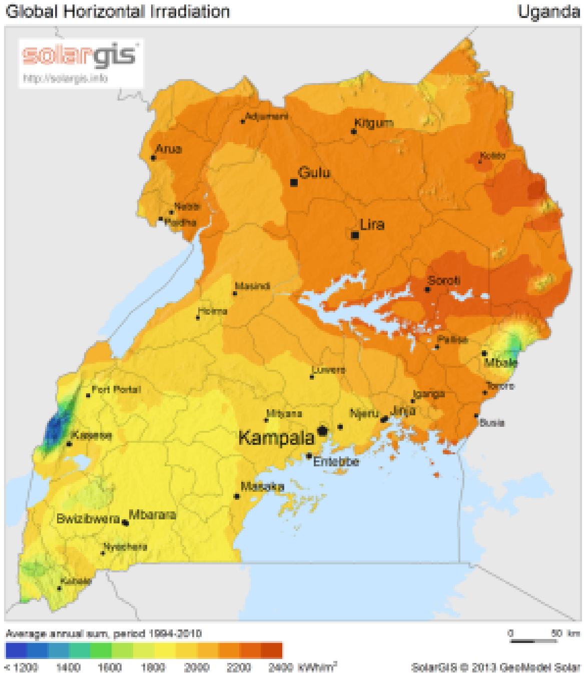
V. Gurulé - U.S. Patent Application No. 17/103,440 - Power Generator System with Modular Blades (This is the utility patent for the VAWT/SES)

Methodology Background

I. Uganda Primary Renewable Energy Viability
II. VAWT/SES Modifications Needed
III. VAWT/SES Application for Water Pumping

Uganda Primary Renewable Energy Viability

- Uganda has 12,700 MW of renewable energy potential
- 4500 MW hydropower
- 1500 MW geothermal
- 1700 biomass
- 5000 MW solar



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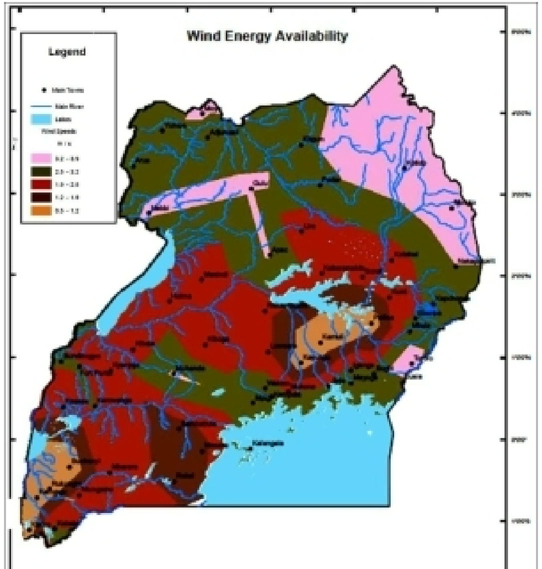

https://www.researchgate.net/profile/Adebayo-Fashina/publication/324986550/figure/fig2/AS:623633345019906@1525697184646/Map-showing-the-availability-of-wind-energy-for-different-sites-across-Uganda-Data.png

VAWT/SES Calculations

1. Sweep area of the turbine

   For HAWT: $A = \pi L^2$

   For VAWT: $A = D * H$

2. Calculate the available wind power

   $Pwind = 0.5 * p * v * A$

3. Find the Efficiency of the turbine

   $\mu = (1-km)*(1-ke)*(1-ke,t)*(1-kt)*(1-kw)*Cp$

4. Calculate the output power

$Poutput = \mu * Pwind$

$\tau = (Poutput/RPM) * (30/\pi)$

For HAWT: $RPM = 60 * v * TSR/(\tau * 2 * L)$

For VAWT: $RPM = 60 * v * TSR/(\tau * D)$

VAWT/SES Application for Water Pumping

- 325, 851 gallons $*$ 8.345 (lbs/gallons) = 2.7M lbs
- 2, 719, 226(f t − lb)/2, 655, 220(f t − lb)/kW h
- Several studies have been conducted to calculate the output of wind water-pumping systems. Measurements of windmill rotation, wind speed, and the amount of water produced show the average windmill of speed 5.6 RPM, wind velocity of 3.6 m/s and water volume of 2034.7 cm3 for one minute (or 2.0347 liters/minute) with 89% efficiency [22].

The Data

- The data analyzed includes the averaged values from 2009-2019 of both Gulu and Soroti’s monthly temperatures, irradiance, and wind speed.
- These predictor variables were used in conjunction with the VAWT performance equations to determine how much water would be theoretically extracted in ft-lbs/hour, as well how much solar and wind power in kWh would be required to deliver that hourly output.

The Analytical Approach

- In order to evaluate the effectiveness of the pump, a sample of averaged monthly temperatures, irradiance, and wind speeds were used as predictor variables in a multiple linear regression (MLR) equation analysis.
- The output variable was the amount of water that could be extracted in ft-lbs/hour, assuming 40% efficiency of the VAWT system.
- The multiple linear regression analysis was conducted in Rscript.
- For the MLR, we assumed a normal distribution and homoskedasticity of the data.
- The result of this approach was to retrieve descriptive statistics for the relationship between variables, especially co-variance.

Results and Discussion

I. Calculations of Output Power, Torque and RPM’s according to Wind Speed
II. Energy and Cost Requirements to Lift or Pressurize Water
III. Multiple Linear Regression Equation Results
IV. Multiple Linear Regression Equation Q-Q Plot
V. Multiple Linear Regression Equation Fit

Calculations of Output Power, Torque and RPM's according to Wind Speed

- The table indicates results of improving output power, torque, and RPMs, where the fixed parameters for the VAWT/SES include turbine efficiency, mechanical loss, and the swept area.
- However, the winds were varied according to the speed in northwest Uganda from the calm to the windiest conditions.
- There is a linear relationship between the output power, the wind, and the RPMs for the VAWT/SES.

Parameter	Calmest	Average	Windiest
VAWT			
Diameter	3 ft	3 ft	3 ft
Height	5ft	5ft	5ft
Windspeed	4.3 mph	5.6 mph	6.8 mph
Available Wind Power	0.006 kW	0.013 kW	0.024 kW
Turbine Efficiency	30%	30%	30%
Wake Losses	5%	5%	5%
Output Power (Before Loss)	0.002kW	0.004 kW	0.007 kW
LOSSES			
Mechanical	0.20%	0.20%	0.20%
Electrical Losses on Turbine	1.50%	1.50%	1.50%
Electrical Losses - Transmission	5%	5%	5%
Time out of Order	3%	3%	3%
EXPECTED OUTPUT POWER			
Real Efficiency	25.82%	25.82%	25.82%
Output Power with Losses	0.00%	0.00%	0.0065
TORQUE			
Tip Speed Ratio	6	6	6
Revolutions per Minute	240.9 RPM	313.7 RPM	380.95 RPM
Torque	0.0605 Nm	0.1052 Nm	0.1552 Nm

Energy and Cost Requirements to Lift or Pressurize Water

- The table shows the energy and cost requirements to lift or depressurize water. It includes efficiency, acre-foot energy conversion, and cost.
- We used calculations that would indicate an overall 100% efficiency of the plant, that is an ideal condition and not something to anticipate in a real system.
- The maximum efficiency one can anticipate from VAWT is 55.9%, which is roughly $0.17/kWh.
- In our system we will assume the lowest overall plant efficiency is $0.25/kWh.

Overall Plant Efficiency (%)	Energy to lift one acre-foot one foot in elevation (kWh)	Cost to lift one acre-foot one foot in elevation ($0.10/kWh)
100	1.02	$0.10
75	1.37	0.137
70	1.46	0.146
65	1.58	0.158
60	1.71	0.171
55	1.86	0.186
50	2.05	0.205
45	2.28	0.228
40	2.56	0.256

Multiple Linear Regression Equation Results

- The results of the multiple linear regression analysis were as follows: β0 was -9.95e+02, β1 was 2.059e+04, β2 3.385e+09, β3 was -3.160e+02.
- The associated p-values were as follows: 0.961, 4.17e-13, ¡ 2e-16, and 0.311 respectively.

```
Coefficients:
                  Estimate Std. Error    t value Pr(>|t|)
(Intercept)     -9.295e+02  1.861e+04      -0.05    0.961
Wind.Speed.Avg.  2.059e+04  1.249e+03      16.48 4.17e-13 ***
Irradiance.Avg.  3.385e+09  1.504e+03 2250913.86  < 2e-16 ***
Air.Temp.Avg.   -3.160e+02  3.039e+02      -1.04    0.311
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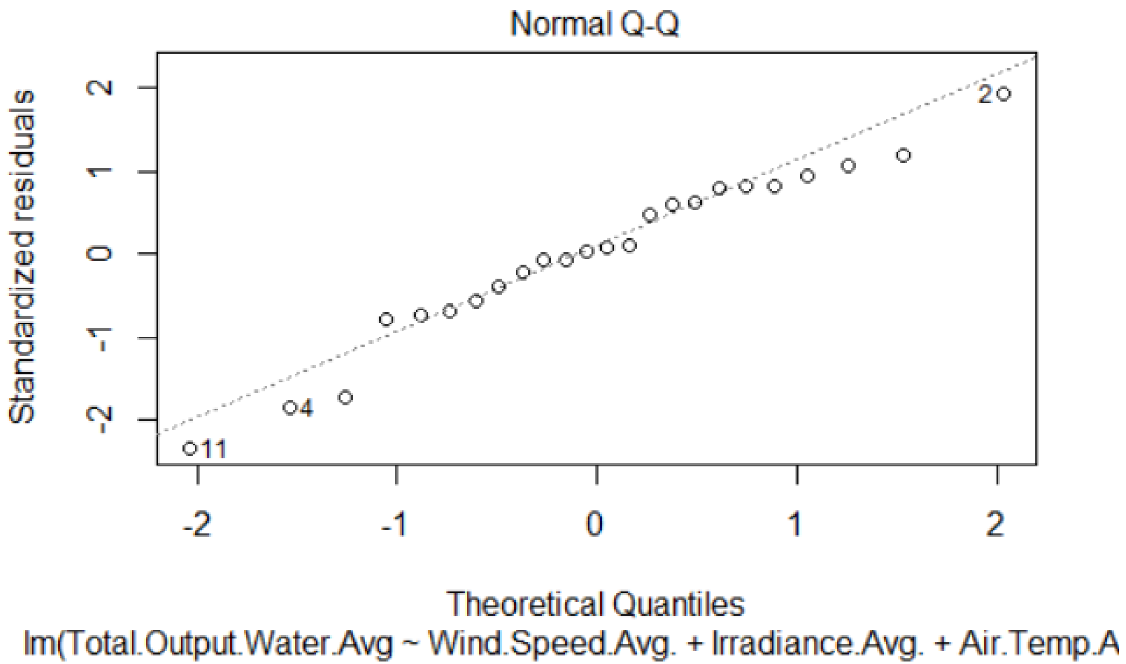
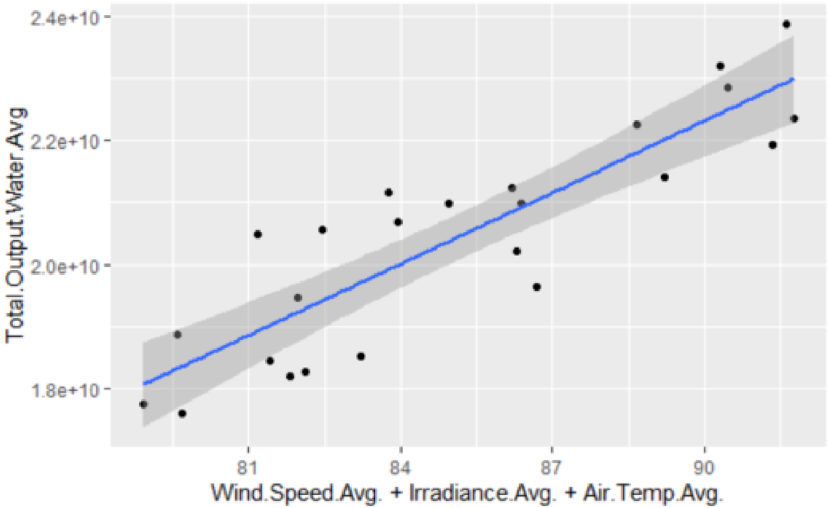
Multiple Linear Regression Equation Q-Q Plot



Multiple Linear Regression Equation Fit

- The correlation between the average temperature and irradiance for the North and Eastern region was 82.866%.



Discussion

- The current prototype we propose for rural areas is untried in the field, but we have made the following observations which are consistent with other in-field tests.
- Using a vertical axis wind turbine resolves the redirection of the turbine torque from the horizontal to the vertical axis that creates large inefficiencies in the HAWT.
- The result is that a VAWT set up creates a basic shaft connection between the turbine and the pump.
- Combining the VAWT water pump system with a high-pressure (HP-VAWP) drip irrigation system can lead, with proper optimization, to two to three times higher efficiency than traditional windpumps.

Discussion Continued

- The strong correlation between temperature and irradiance of 82.866% show that the North and Eastern region of Uganda have the proper solar regime so that the VAWT has redundancy to work properly.
- The wind and the irradiance is effective in influencing the output of ft-lb/hour output.
- The results are consistent with the following solar output variation of 20% (from 4.5 to 5.5 W/m2); 3.7 m/s to 6m/sec require to operate the turbine; and water pumped at the rate of 3748.54 ft-lbs to 42314.72 ft-lbs per hour.

Conclusion and Future Work

- The driving force for the use of a windmill water pump is the need for safe and drinkable water in developing countries and in areas where there is a lack of electricity and an electrical grid.
- The prototype windmill with the blades spinning in a brisk breeze of 15 to 20 MPH will pump on average three gallons per minute or 1500 gallons per day whenever the wind blows for 35% of the day.
- Future studies can be focused on the rigidity of the 3D printed turbine and installation methods.
- Additionally, energy storage capability can be added to store excess power generated for later or other uses.