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Two-phase Energy System

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Abstract

This project explores the technical challenge of sustainability as it relates to solar energy production, storage, and consumption. The challenge is addressed through the design of a two-phase renewable energy system that can provide electrical energy during both day and night without the use of chemical batteries. "Phase 1" is the conversion of solar energy into electrical energy using photovoltaic panels for both immediate supply to the household load and for storage in a fluid based system. "Phase 2" is the conversion of the stored potential energy back into electrical energy for use during the night and at times of peak demand. Methods of energy storage evaluated for this project are pumped-hydroelectric energy storage (PHES) and compressed-air energy storage (CAES), both of which are widely used in large-scale systems such as power plants. The "two-phase" system scales the same idea for practical use at a small scale. Effective methods for converting this stored energy into electrical energy involve the use of a turbine-generator. The system is mathematically modeled in order to determine system parameters to optimize efficiency while meeting constraints on power and total energy output. Based on the results, pumped hydroelectric energy storage was chosen as the method of energy storage, and components were chosen for a prototype. The prototype utilized an electric fluid bench to simulate the system and validate the model. This research may result in an efficient and clean renewable energy system and eliminate the need for a chemical battery in residential photovoltaic systems. Its successful implementation can directly reduce hazardous battery waste and indirectly reduce carbon emissions by decreasing dependency on fossil-fuel burning power plants.

Keywords: Fluid energy storage, Modeling, Solar energy

1. Introduction

Most residential solar energy systems store excess energy collected from sunlight in rechargeable, lead-acid batteries. The energy storage component is essential, as it ensures that power can be drawn from the system consistently throughout the day by supplementing energy when needed during times of peak demand or when there is too little incident solar radiation to support the load. However, the use of chemical batteries in such a system, which is designed to reduce reliance on fossil fuels, is less than ideal. In particular, lead-acid batteries have relatively short lifespans of only around 1000 to 2000 charge-discharge cycles[1]. They are comprised of harmful chemicals, namely sulfuric acid and lead, and must be disposed of properly under Environmental Protection Agency (EPA) regulations[2]. Since 2000, this type of battery alone has accounted for more than two million tons of total waste each year, and in 2008, 20,000 tons of this waste was non-recyclable[2,3]. Moreover, replacement of the batteries is expensive and averages $115 to $160 USD per amp-hour capacity (at 12 V)[4].

The objective of this research is to investigate the feasibility and practicality of implementing a fluid-based energy storage component in place of the traditional chemical battery. This challenge is addressed through the design of a two-phase energy system, where "Phase 1" is the conversion of solar energy to electrical energy for both immediate use and storage (similar to the operation of traditional systems), and "Phase 2" is the conversion of stored potential

energy back into electrical energy. The hierarchical breakdown of the two phases is shown in Figure 1. Ideally, this would improve the environmental sustainability of a residential solar energy system and reduce its cost of implementation over the lifecycle. Another advantage to this approach is that it allows for an indefinite number of charge-discharge cycles, as opposed to the strictly limited number for a chemical battery. This is a limiting factor in a traditional system, as lead-acid batteries should remain charged above 80% capacity to minimize negative effects on storage capacity due to discharge[5]. For this reason, most night-time energy supplied to the load is drawn from the grid in a traditional solar energy system. The described two-phase system would not be limited in this manner.

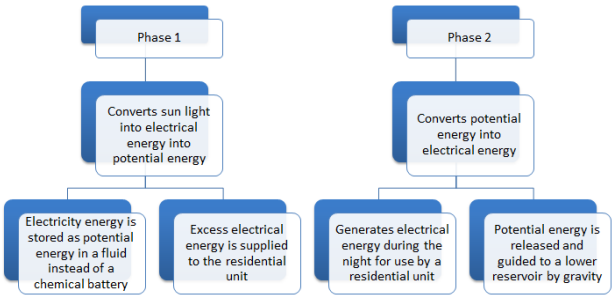

Figure 1: Hierarchical breakdown of two phase system

Large scale adoption of solar energy systems in residences could have a great impact on the expenditure of fossil fuels and associated harmful emissions. About 22% of the total energy used in the United States is consumed in residences, and electricity accounts for 41% of this amount[6]. In 2009, only 10.6% of energy generated in the U.S. originated from renewable sources[6]. This project was supported by the Valley 25x'25 program, a local initiative promoting the adoption of renewable energy sources over conventional ones[7]. The goal of the program is that 25% of the total energy consumed in the Shenandoah Valley comes from renewable resources by the year 2025[7]. According to Zimmerman[6], if 15% of Valley households utilize photovoltaic systems, the associated reduction in carbon emissions would be equal to that produced by about 5,000 average passenger vehicles over a given time period; however, meeting the Valley 25x'25 goal would require 100% adoption. These were great motivating factors for the project, as the two-phase system could help increase adoption rates by reducing the lifetime cost associated with these systems.

2. Current Literature

Fluid based energy storage is not a novel concept. Pumped hydroelectric energy storage (PHES), which uses water pumped to an increased elevation to store energy, was first developed over a century ago[8]. PHES is widely used today and accounts for over 99% of worldwide bulk energy storage[9]. It can prove to be a highly efficient method as well and is cited as being able to reach an efficiency of 80-85% when the pump is powered by electricity[8]. While it is relatively common, it is typically used on a very large scale, such as storage during off-peak hours at power plants[10]. Another highly feasible but less commonly employed method of energy storage is compressed air energy storage (CAES)[11]. Like PHES, this method is usually utilized in very large systems and often exploits geological voids as vessels for air storage[11]. PHES and CAES both are highly reliable and have advantages of producing little negative environmental impact. However, CAES is typically less efficient than PHES and requires greater system complexity[11].

PHES systems have been shown to be feasible on small scales, as well. Cobb and Sharp[12] performed experiments to determine the performance of impulse turbines in a pico-hydro system (one producing less than 5 kW of power). For a 133 mm Turgo and 100 mm Pelton (both measures of the pitch-circle-diameter), turbine efficiencies were measured to be up to 81% and 73%, respectively[12]. Manalokos et al.[13] implemented a stand-alone solar energy system for a village of 13 houses in Merssini, Greece using PHES to store energy, demonstrating the practicality of the two-phase concept. This system used photovoltaic cells to generate electrical energy for the village, while also storing energy by pumping water to a height of about 95 m above the pump[13]. Stored energy was then converted back into electrical energy by allowing the pumped water to flow through the pump in reverse during the night, therefore powering household appliances in the absence of solar energy[13]. The system was the only source of electricity for the village[13]. Cited advantages of the system include reliability in power production, no stand-by

losses, low maintenance cost, and low environmental impact[13]. However, the authors note that initial start-up costs were high and that overall efficiency was poor and would have been higher in a larger system[13].

3. Mathematical Analysis

Preliminary analysis was used to determine the necessary parameters of systems utilizing CAES and PHES. Initially, the energy storage requirement was based on an estimate of the average amount of electrical energy used in a Virginia home during the night. Table 1 displays the fraction of electrical energy used by various household appliances and an estimate of fraction of total usage for each category during the night. Nominal values were obtained from 2009 energy usage data published by the U.S. Energy Information Administration[14].

Table 1: Fraction Of Total Electrical Energy Usage In Virginia Home[14]

Category	Nominal Fraction of Total	Estimated Night-time Fraction of Total
Space Heating	42%	21%
Refrigeration	5%	2.5%
Air Conditioning	6%	3%
Water Heating	18%	4.5%
Lighting and Other Appliances	30%	0%
Total	100%	31%
Total Energy (kWh/home/day)	**36.7**	**11.4**

The night-time contribution to total energy usage of space heating, refrigeration, and air conditioning was considered to be one-half the nominal contribution. Lighting and other appliances were assumed to have no contribution during the night, and water heating was assumed to consume only one-quarter its nominal value during the night. Based on this analysis, the required pressure and volume of stored air for a CAES system and the required water storage volume and reservoir height for a PHES system were calculated such that 11.4 kWh of potential energy is stored. This preliminary analysis served as a basis on which to select the method of energy storage for the two-phase system.

3.1 Analysis Of Compressed Air Energy Storage

The amount of specific energy, energy per unit volume, stored in compressed air is calculated by Equation (1)[15]:

$$w_{theo} = \frac{n}{n-1} P_{in} \left[1 - \left(\frac{P_{out}}{P_{in}} \right)^{\frac{n-1}{n}} \right] \tag{1}$$

where polytropic exponent n is taken as unity for an isothermal system or 1.4 for an adiabatic system, P_{in} is the pressure inside the storage vessel, and P_{out} is the pressure outside the vessel. Theoretically, energy can be extracted as long as $P_{in} > P_{out}$. In reality however, there will be a minimum internal pressure P_m required to drive a turbine or other energy conversion mechanism and produce usable work. Thus, the specific amount of stored energy that is below this usable threshold is obtained by simply replacing P_{theo} with P_m in Equation (1). Defining the resulting equation as w_{thres}, the amount of stored energy that may be extracted and used is[15]:

$$W_{available} = V(w_{theo} - w_{thres}) \tag{2}$$

where V is the volume of the storage vessel.

Using Equations (1) and (2), the required volume of the storage vessel was calculated as a function of internal pressure such that the target of 11.4 kWh was met for minimum pressures of 50, 75, and 100 psi, assuming the process is adiabatic. Ideal results assuming all stored energy can be recovered are shown in Figure 2(a).

As the maximum safe pressure inside the vessel increases, the difference between required volumes for different minimum pressures decreases. Note that for an air vessel only capable of containing pressurized air at 3000 kPa (435 psi), an internal volume of about 7 m^3 (247 ft^3) is required if the minimum pressure for energy extraction is 75 psi. This would be a large structure and would have to be fabricated from high-strength material, likely making the storage vessel itself rather expensive. If a high pressure of 10,000 kPa (1450 psi) is allowable, the vessel would still need to hold about 1.7 m^3 (60 ft^3) of compressed air. This analysis also assumes perfect energy extraction efficiency, which cannot hold true for an actual system. Accounting for the energy lost during Phase 2 (the conversion of stored energy back into electrical energy), the actual amount of energy that can be used to power the household load is:

$$W_{actual} = \eta W_{available} \tag{3}$$

where η is efficiency. Using a typical efficiency value of 36% for conversion of the stored energy back into electrical energy, the amount of available energy must be 31.7 kWh to provide 11.4 kWh to the load[16]. These more realistic calculations are plotted as the "actual" data series in Figure 2(a).

The "actual" results in Figure 2(a) demonstrate that key system parameters are significantly impacted when energy loss is taken into account. If the Phase 2 energy conversion system is 36% efficient, then about 4.6 m^3 of compressed air at 10,000 kPa is now required, versus only 1.7 m^3 for an ideal system. Energy loss in the initial compression of the air (during Phase 1) was not taken into account in this analysis but is an important factor to determine overall system performance. It is expected that the overall efficiency of the system (the ratio of electrical energy out over electrical energy in) would be much less than 36%. It is assumed in this analysis that the available electrical energy from the photovoltaic array will be sufficient to power both the load as well as fill the fluid-based storage component to capacity.

3.2 Analysis Of Pumped Hydroelectric Energy Storage

The total energy stored in a PHES system is a function of the volume and height of the upper reservoir:

$$E_{stored} = \rho V g h \tag{4}$$

where ρ is the density of the water, V is internal volume, and h is height of the upper reservoir above the nozzle exit. The amount of energy that can be provided to the household load as electrical energy is:

$$E_{actual} = \eta_{TG} E_{stored} \tag{5}$$

where η_{TG} is turbine-generator efficiency.

Similar to the analysis for CAES in Section 3.1, Equations (4) and (5) were used to calculate the required volume of water stored as a function of height of the upper reservoir for an energy storage target of 11.4 kWh. The results of the analysis are plotted in Figure 2(b). The minimum and maximum efficiency curves assume 48% and 86% turbine-generator (or energy extraction) efficiencies, respectively.

In addition to the amount of energy that can be stored in the two-phase system, the amount of power that can be generated during "Phase 2" is also an important consideration. The power output of a PHES system is related to the

total kinetic power of the flowing water at the turbine. For impulse turbines, this is the power of the water jet immerging from a nozzle and can be calculated from Equation (6)[17]:

$$P_{jet} = \frac{1}{2}\dot{m}v_j^2 \tag{6}$$

where $\dot{m}$ is the water mass flow rate and v_j is the mean velocity of the water jet at the nozzle exit. For a constant nozzle exit diameter, the jet power is primarily a function of upper reservoir height. The mean velocity of the jet can be approximated by the Torricelli Equation[18], $v_j = \sqrt{2gh}$. Substituting for $\dot{m}$ and v_j, Equation (6) can be rewritten as:

$$P_{jet} = \frac{1}{2}\rho A_n (2gh)^{3/2} \tag{7}$$

where A_n is the area of the nozzle exit. Assuming minimum efficiency of 48%, the required nozzle exit diameter dimension ranges from about 32 to 13 mm to allow for a flow rate capable of meeting a power requirement of 1 kW over the entire plotted h domain of 15 to 50 m.

If a nozzle with an 11 mm exit diameter is used (recommended size for a 204 mm Pelton turbine), then the required upper reservoir height is 42 m to provide 1 kW, based on a maximum expected value of 86%. The reservoir would need to hold about 116 m^3 of water to store 11.4 kWh of total energy at this height and efficiency. Under the same power and energy requirements but at a turbine-generator efficiency of only 48%, the reservoir would need to be 62 m above the nozzle exit and hold 140 m^3 of water. These are large values and indicate that the initial target of 11.4 kWh of usable energy may be unfeasible if the two-phase system is implemented for a single family home.

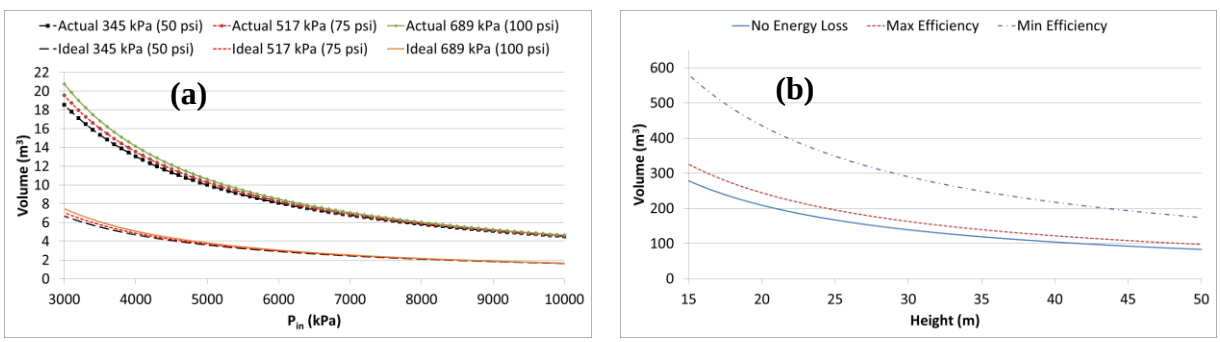

Figure 2: (a) Required volume of air vessel versus internal pressure for 11.4 kWh stored energy and useable energy ($\eta = 0.36$) with P_m = 50, 75, and 100 psi, (b) required volume versus height of upper water reservoir for 11.4 kWh energy stored and 1 kW power with η_{TG} = 1.00, 0.86, and 0.48

3.3 Turbine-Generator Model

Base on the preliminary analysis, PHES was chosen as the method of energy storage for the two-phase system. This was based on the determination that it had much greater potential for efficient operation, could be more easily implemented, and would be safer than CAES. Also, PHES has the advantage of being able to utilize local topography or water sources to construct water reservoirs, whereas CAES would require a large, high-strength tank. To better estimate the output of an actual pico-scale PHES system, a case study analysis was performed with commercially available components. A WindBlue DC-540 permanent magnet alternator (www.windbluepower.com)

and a 204 mm pitch-circle diameter Pelton turbine were mathematically modeled and purchased for testing and model validation.

The force on the vane of a Pelton turbine from an impinging water jet can be determined by considering the rate of change in momentum of the water entering and leaving the bucket (adapted from Thake[17]):

$$F = \dot{m}_b (v_j - v_{\tan})\beta \tag{8}$$

where $\dot{m}_b$ is the mass flow rate of water into the bucket, $v_{\tan}$ is the linear velocity of the bucket (tangential speed of the runner at the bucket center), and β is defined as:

$$\beta = 1 + \zeta \cos\gamma \tag{9}$$

where ζ is an efficiency factor (taken as unity for this model), and γ is the angle of water exiting the bucket relative to the jet centerline[17]. The torque on the turbine driveshaft can then be written from Equations (8) and (9) as:

$$T = r\rho A_n \beta (v_j - r\omega)^2 \tag{10}$$

where r is the distance from the center of the turbine to the center of the bucket, ρ is the density of water, A_n is the area of the impinging water jet (taken as the area of the nozzle exit), and ω is the angular velocity of turbine. The permanent magnetic alternator (PMA) was modeled as a DC motor with a mechanical power input to the armature and a load across the output terminals. Since the transient response of the turbine-generator system was expected to be short and irrelevant to the analysis, the inductance of the motor model was assumed to be negligible. The resistance of the windings of the PMA R_a, the coefficient of bearing damping c, and the torque constant k_T were estimated by curve-fitting test data provided by the manufacturer. Note that the back-emf constant k_b was taken to be equivalent to k_T. The circuit diagram used to develop the model is shown in Figure 3(a).

From Figure 3(a):

$$k_b \omega - i_a (R_L + R_a) = 0 \tag{11}$$

where R_L is the electrical load being driven by the output of the PMA, and i_a is the current through the circuit. The mathematical model of the turbine generator system can then be derived from Equation (11) and the torque balance made using the schematic of the two rotating bodies shown in Figure 3(b).

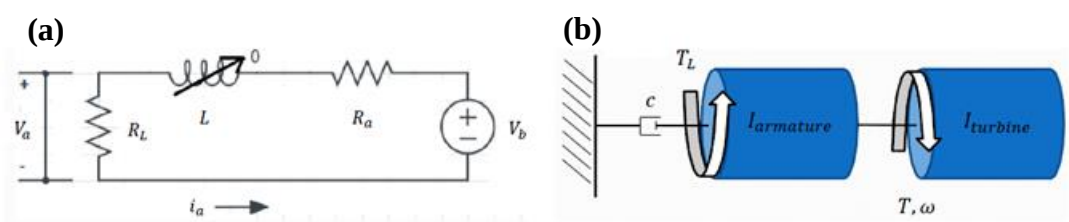

Figure 3: (a) Equivalent circuit for mechanically driven dc motor, (b) free-body diagram of armature and turbine used to develop model equations

The torque balance is:

$$I_e \dot{\omega} = T - T_L - c\omega \tag{12}$$

where I_e is the equivalent moment of inertia of the armature and turbine, and T_L is the load torque ($T_L = k_T i_a$). Substituting the expressions for T and T_L and solving for the steady-state angular velocity of the turbine and armature, when $\dot{\omega} = 0$, gives:

$$\omega_{ss} = \frac{1}{2A_n \beta \rho r^3 R_T}\left[\pm\sqrt{cR_T + k^2}\sqrt{4A_n \beta \rho r^2 v_j R_T + cR_T + k^2} + 2A_n \beta \rho r^2 v_j R_T + cR_T + k^2\right] \tag{13}$$

where $R_T = R_L + R_a$ and $k = k_T = k_b$.

The model was then used to determine optimal system parameters of nozzle diameter and load to maximize efficiency at various reservoir heights. Table 2 gives the modeled results for heights of 20, 30, and 40 m, given a constraint that the turbine-generator must output 250 W electrical power. The power requirement used here was reduced from the prior 1000 W target as it was determined to be too large to be reasonable for such a small system.

Table 2: Modeled System Parameters To Optimize Efficiency

Height (m)	Nozzle Diameter (mm)	R_L (Ω)	Mass Flow Rate (kg/s)	Output Power (W)	Turbine-Generator Efficiency
20	19.28	25.48	5.78	250.00	22.04%
30	12.20	30.00	2.84	250.00	29.95%
40	9.21	43.99	1.87	250.00	34.15%

The system parameters shown in Table 2 were then used to plot the modeled turbine-generator efficiency as a function of power output for heights between 10 and 60 m, shown in Figure 4. Each curve is based upon one of the three rows of values shown in the table (250 W is achieved at $h = 20$, 30, or 40 m, respectively). The plot shown in Figure 4 shows how various system parameters affect the system based on the design height chosen. The power output of the system is largely dependent on the mass flow rate. A system optimized to provide 250 W at 20 m versus one optimized to provide the same amount of power at 40 m will require a much greater flow rate (and thus require a larger reservoir if a target amount of total energy is to be stored). This model provides insight into how actual system efficiency may vary with overall size. In general, efficiency decreases with increasing height for static system parameters of nozzle diameter and load, but a system optimized for a greater overall head (reservoir at a greater height) for a power need will drastically increase overall system efficiency. The results of the model are supported by the general idea that the efficiency will increase with system size, as previously cited[13]. Overall efficiency for parameters used, however, is lower than the expected range of about 48-86%. Note that these calculations are independent of reservoir volume.

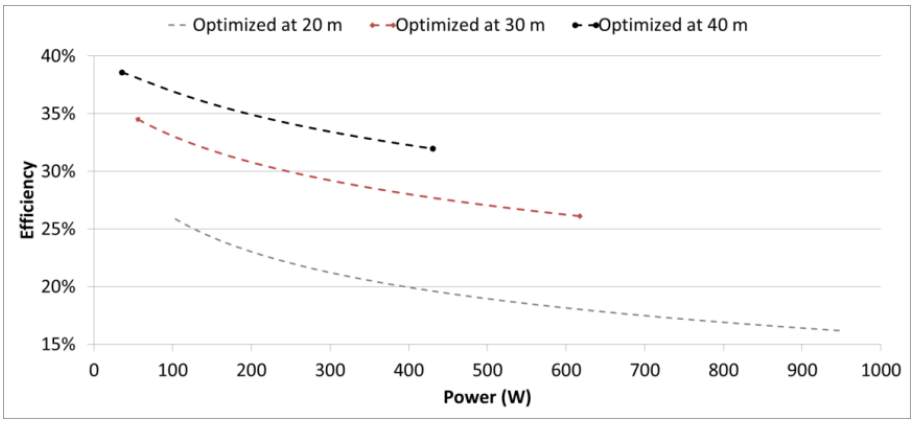

Figure 4: Modeled turbine-generator efficiency versus power for system parameters optimized at $h = 20$, 30, 40 m

4. Results and Validation

The case study model was tested and validated using an electrically driven fluid bench to simulate the hydraulic head of a raised PHES reservoir. The net head provided by the fluid bench pump can be directly determined from flow and pressure measurements at the nozzle. A schematic of the test set-up is shown in Figure 5(a).

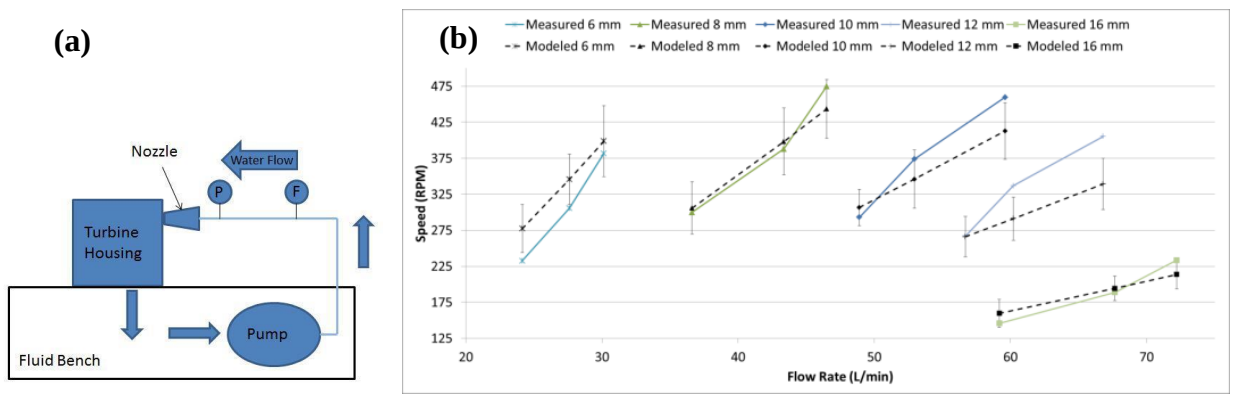

Figure 5: (a) Schematic of test set-up for model validation, (b) measured and modeled turbine speed versus flow rate with $R_L = 61.2\ \Omega$ using test set-up

Pressure was measured just before the nozzle in the test set-up. Assuming energy losses in the nozzle are negligible, the net hydraulic head of the water jet is then:

$$H_n = z + \frac{P}{\rho g} + \frac{v_j^2}{2g} \tag{14}$$

where z is the elevation difference between the point of measurement and the nozzle exit, and P is pressure[18]. Model validation was performed by measuring steady-state turbine speed at three fluid bench pump speeds with electrical loads of 61.2, 72.4, and 83.6 Ω and five different nozzles with exit diameters of 6, 8, 10, 12, and 16 mm. Results for the 61.2 Ω load are shown in Figure 5(b). Measured data is shown as solid, colored lines, while modeled speeds are shown as black, dashed lines. The error bars indicate the range of modeled speed response that can be calculated given the uncertainty in measured flow rate and load. The average error between modeled and measured speeds for all testing was about 8.8%.

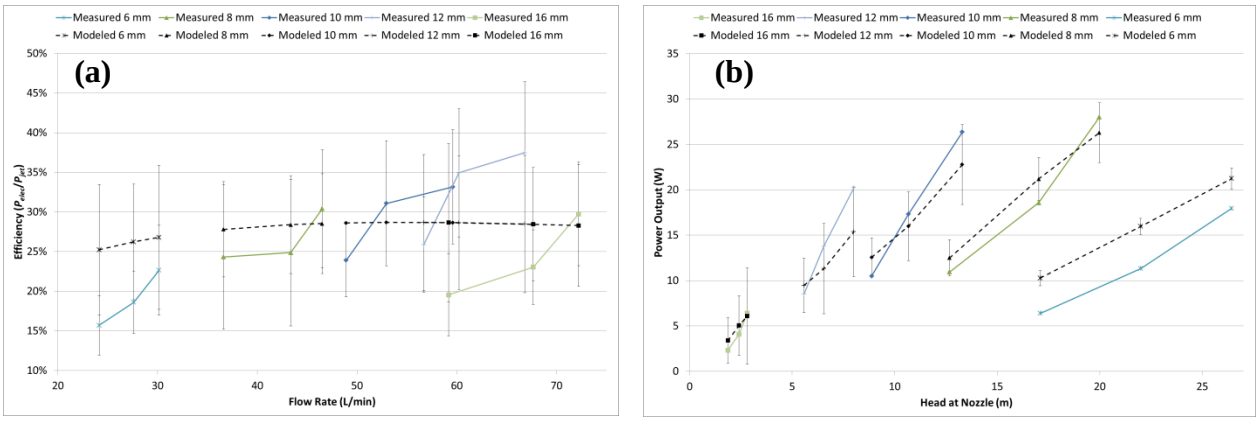

Figure 6: (a) Measured and modeled turbine-generator efficiency versus measured flow rate and (b) measured and modeled electrical power output of PMA versus measured hydraulic head at nozzle inlet

The significant results of testing are measured efficiency values, as the feasibility of PHES on a small scale depends on the ability to generate a usable quantity of power while storing as little water at as low a height as possible. Figure 6(a) shows measured and modeled efficiencies of the Pelton turbine-generator system, and Figure 6(b) shows modeled and measured electrical power outputs of the PMA as a function of hydraulic head at the nozzle inlet. Measured efficiency was found to be as high as 37.5% for a flow rate of 66.8 ± 4.8 L/min using a 12 mm nozzle, which is about 9% greater than the corresponding modeled value. This corresponds to a head at the nozzle inlet of 8.0 m and a power output of 20.2 W. This indicates that a reservoir placed at a height of only around 8 m would create similar flow conditions, thus stored energy can be converted to electrical energy with relatively high efficiency.

5. Discussions of Results

Modeled results show that the efficiency of a PHES system can be greatly improved be increasing the height of the upper reservoir, which aligns with the convention that efficiency can be improved by increasing system size. Moreover, reducing the power requirement can vastly improve energy extraction efficiency. Although it may be impractical to design a single-home system that stores enough energy to power a Virginia household during the entire night, results obtained from both the model and physical testing show that reasonable turbine-generator efficiency can still be achieved with a pico-PHES system. Instead of designing a system for a specific load requirement, the cost-benefit of the system could be improved by designing for a small but efficient power output. If the system is to be used in a grid-connected home, then the two-phase system could be used to replace energy normally supplied by the grid if net-metering cannot be employed.

The Valley 25x'25 program is a local initiative to reach a goal of 25% renewable energy in the Shenandoah Valley by the year 2025. The two-phase energy system is designed to aid in meeting this goal through implementation on existing single family homes in the Valley. According to Zimmerman[6], if 100% of owner-occupied housing units (139,990 residences) utilize 5 kW PV systems, then the Valley 25x'25 goal would be met by this electricity alternative alone (would produce 24.6% of the Valley's total energy needed). Implementation of the two-phase energy system, which trades compact storage of energy for extended lifetime, increased safety, and reduced costs, would require fewer new PV system implementations to meet the same goal. The major difference between the two-phase system and conventional solar energy systems is that energy is not usually drawn from the batteries unless it is required due to a grid outage or shortage in PV supplied energy, but the number of charge-discharge cycles of a PHES system is indefinite. Therefore, if a 5 kW solar array is expanded slightly to provide energy for the day-time pumping of water, additional energy could be supplied each night. Even a very small PHES system would have a big impact on the number of adopters required to meet the Valley 25x'25 goal. For a 30 W system that can run for 2 hours operating with 30% turbine-generator efficiency (7.3 m^3 or 1940 gal of water stored), the number of system adopters is reduced by 349. For a larger, 86 W system capable of running for 2 hours at the same efficiency (21 m^3 or 5500 gal water), the number is reduced by 1000 adopters.

A potentially excellent application for the two-phase system is an implementation in poor, remote, or developing locations where grid-supplied energy is limited or non-existent. This system would be especially appropriate where local topography would allow for inexpensive and easy installation of a raised water reservoir. Once installed, the system would require very little maintenance and could be used to provide a valuable source of electrical energy in the absence of sunlight. More than 20 W of electrical power was measured during testing for an approximate head of only 8 m, while less than this is needed to power efficient electrical lighting like LEDs or to charge portable electronics such as cell phones.

6. Conclusions

Through mathematical analysis, PHES was chosen as more a feasible method of energy storage for a small-scale system to replace chemical batteries in a residential photovoltaic system. A model was created based upon a small, commercially available permanent-magnetic alternator and Pelton turbine to better determine how various system parameters such as reservoir height and nozzle size effect performance. The model was validated by simulating a PHES system in a physical test set-up using the components modeled. It was determined that the initial goal to store 11.4 kWh of energy and provide 1 kW of power may not be practical, but system could be used for low-power applications effectively.

7. Future Work

Presently, testing and model validation has only been performed by simulating a PHES system with an electrically-driven fluid bench, which can only provide a limited hydraulic head. Future work will include a site implementation to develop a system control scheme, investigate scalability of the model, and determine actual practicality and potential return on investment.

8. Acknowledgments

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