Equation-Based Modeling of Photovoltaic Integrated Water Distribution Systems: A Case Study in Makassar, Indonesia

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Abstract. This paper examines the modeling of an integrated photovoltaic water distribution system (PVWD) application in Makassar, Indonesia. Modeling of these complex systems is often left to more generalized models, which lack the complexity of controllers and the integration between water and power systems. The research develops a PVWD model using Modelica to implement battery controllers and water pumping control accurately. This model was then evaluated using empirical and engineering methods for the fast dynamic performances. While analyzing the model's performance over a month, there is a 4% difference in monthly utility energy usage, demonstrating accuracy within ASHRAE modeling guidelines. These results show the high levels of accuracy the model can achieve at long timescales. Implementing these systems in Modelica allows for 1) highly accurate monthly and yearly simulations; 2) complex integration of existing and new control methodologies; 3) integration of water, electric, and control systems. With this accurate and dynamic model, it is possible to migrate from generalized modeling to more specific and end-use-based analysis of particular systems. Given the specificity allowed in this model, applications and studies can be conducted for more robust control strategies or equipment sizing optimization.

1. Introduction

The use of solar photovoltaic (PV) systems has increased across the globe and is anticipated to continue growing [1]. Alongside this increase, there are more examples of installed community-based water distribution systems to circumvent inadequate access to water [2]. An increasingly growing practice involves integrating photovoltaic (PV) technology and battery storage in these systems, creating coupled photovoltaic-powered water distribution (PVWD) systems [3]. In many urban and low-income areas, such as Makassar, Indonesia, water and electrical infrastructure can be inconsistent and expensive. These systems can help to reduce water distribution costs, improve community knowledge, and reduce utility expenses [4]. These advancements have enabled the creation of equation-based models that support simulation and optimization studies, effectively capturing the systems' multi-physical complexity.

This study proposes a robust multi-physical, equation-based, and variable-timestep model of PVWD systems based on empirical analysis of an existing system implementation in Makassar, Indonesia. By analyzing the existing system operations, the dynamic controls and physics can be compared, as well as monthly energy totals. Such a model can then be used to accurately model, simulate, and optimize new system designs and control implementations.

1.1. PVWD System Components

PVWD systems can include many pieces and components that make the system dynamics complex and challenging to analyze. The least complex types are direct-coupled systems, which directly connect the PV equipment with the water distribution pumping equipment. These systems allow for complete isolation from the local utility grid. They are most suitable for low-head water supply without complex controls [5, 6]. As the complexity increases, distributed systems include the water pumping equipment with other loads met by the PV system. Distributed PVWD systems integrate water pumping equipment alongside other loads powered by the PV system. These applications can consist of battery installations and are typically connected to the utility grid via inverters [7]. The integration of these extra pieces of equipment allows for more robust system performance and the ability always to operate water systems, independent of PV generation peak times [7].

1.2. PVWD System Modeling Methods

For these systems, model and simulation development primarily focuses on accurately modeling either the water pumping systems or the PV generation systems, with minimal emphasis on the intricacies of the multi-physical systems and the rapid dynamics of the system controls. Most of the methods and models were developed with MATLAB and Simulink [8, 9, 10]. This kind of modeling can allow for analysis of a single portion of the system rather than robust handling of multi-physical and dynamic timestep systems, such as a PVWD application. Other simulations and models are focused on longer timescales with little to no consideration for the fast dynamics of the systems or controls [11]. Some models have shown the ability to integrate user water consumption into energy prediction and modeling [8]. These models demonstrate the possibility of integrating specific system components, but they also reveal limitations in modeling control logic and physical characteristics of the water distribution system.

2. Methodology

The first step in developing an advanced integrated model was to analyze and identify existing system characteristics within the installed system. Through site visits and online reporting data, the system size and control operations were identified. This was then followed by the development of an equation-based and multi-physical model utilizing Modelica.

2.1. Existing System

The existing system, as implemented in Makassar, Indonesia, contains distinct equipment configurations to meet the everyday community needs. The electrical equipment installed on the site is shown in figure 1. The system includes an electrical system containing an inverter that is connected to the local utility grid operated by Perusahaan Listrik Negara (PLN), the 5.5 kW PV panel installation, and a 5-kWh battery [12, 13, 14]. This inverter then feeds to output breakers that feed various community loads such as lighting, receptacles, and small aquaculture pumps. Full characteristics of the electrical equipment installed on site are provided in table 1.

(a)

(b) **(c)**

Figure 1. Installed PV panels (a), inverter (b), and battery (c).

Table 1. Installed equipment characteristics.

Equipment Type	Voltage	Maximum capacity	Efficiency	Quantity
PV Panel	47.67 VDC	550W	21.3%	10
Inverter	500 VDC (PV input). 48 VDC (Battery). 230 VAC (Output)	5.5 kW	97% (PV)	1
Battery	51.2 VDC	5 kWh	93% (Battery)	1

Not only is electrical equipment installed on the site, but there is also a community water distribution system. An integrated system schematic was developed to show the interconnections and relationships between the electrical and water systems, as displayed in figure 2. This system includes a 27 m^3 water tower shown in figure 3 and a 2.2 kW water pump that operates at 1 kg/s shown in figure 4. This water serves several uses, including non-potable water to many of the households in the surrounding area and water to the community's fish ponds and aquaponic operations.

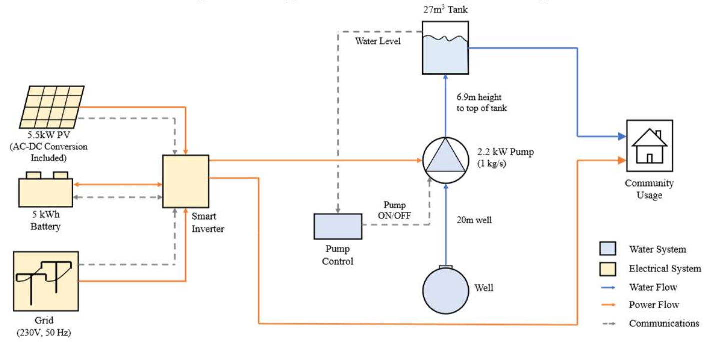


Figure 2. Installed system schematic.

Figure 3. Installed water tower and tank.

Figure 4. Installed water pump.

The final component of the existing system is the battery controller logic. To develop a representative model, it was necessary to accurately model the existing system's inverter controls, which involved determining which power flows to and from each power source. By analyzing the online reporting from the site, a representative battery controller logic could be developed [15]. This logic includes four distinct states in addition to an off operation. The battery can be charged during the day, utilizing the energy generated from the PV panels, or charged at night using a fixed rate from the utility. It can also be used in the later parts of the day to supplement the PV generation to meet community loads. Finally, at night when there is no PV generation, the battery can be discharged when at a specific state of charge (SOC). Switching conditions between these states are shown in figure 5. There is also a built-in curtailment that will switch the battery off and the PV to curtail mode whenever the demanded load exceeds 2000 W.

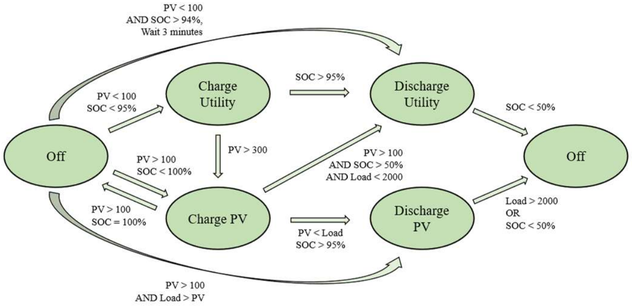


Figure 5. Battery control logic.

2.2. System Model Development

To accurately model the physics, controls, and inter-relationships between the electrical and water distribution systems, these existing conditions were implemented using Modelica. Using Modelica Buildings Libraries and the Standard Libraries, these intricacies could be accurately modeled [16, 17]. Figure 6 demonstrates the integrated model that was developed considering the typical meteorological weather data for Makassar and fixed demanded loads on the system. Using hierarchical modeling, smaller blocks for the control logics and physical systems were developed and connected in a complete system model.

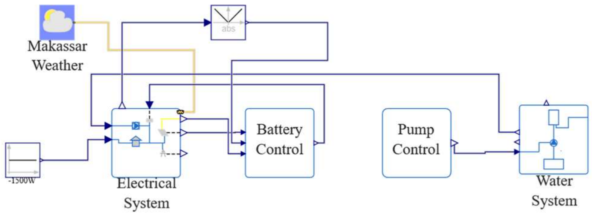


Figure 6. Modelica full system schematic.

The water distribution and electrical system blocks include equipment sized to match that which was found on the site. The equipment blocks from the Building Library were implemented and sized to fit with the operations of the real system. The water distribution block is shown in figure 7 with a pump, water source, water tank, and demanded water load as found on the site. The existing system's control logic and water usage were not given, so based on the spiking of 2.2 kW on the online reporting, a load profile for the water usage and pump operation was developed. Figure 8 demonstrates the electrical system block showing the different loads, including a fixed 1.5 kW community load, a pump load based on operation, and a curtailment block for the PV generation. There are connections to the battery, PV system, and utility grid.

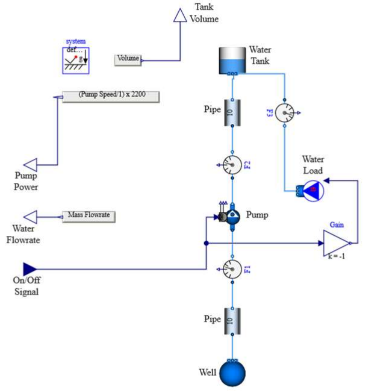


Figure 7. Modelica water distribution system.

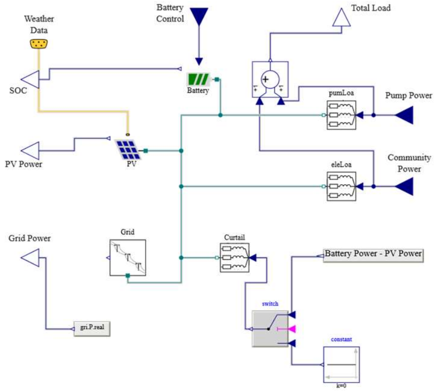


Figure 8. Modelica electrical system.

The final step to developing a functioning model was the implementation of a battery and electrical system controller, as shown in figure 9. Using the logic developed and shown in Section 2.2, states and transitions were implemented into Modelica. This logic allows the system to stage between the five operational stages and control the power flowing in and out of the battery as necessary, depending on the given generation and loading conditions. Short wait times for some transitions were implemented to prevent short cycling of states under dynamic situations and mimic the real-world delay and performance more accurately.

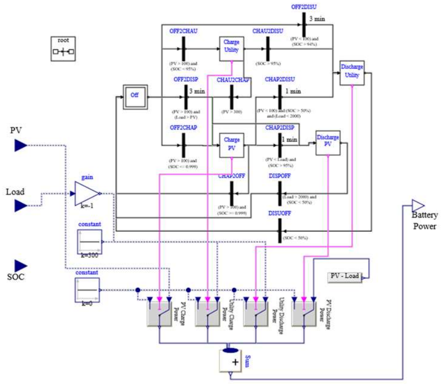


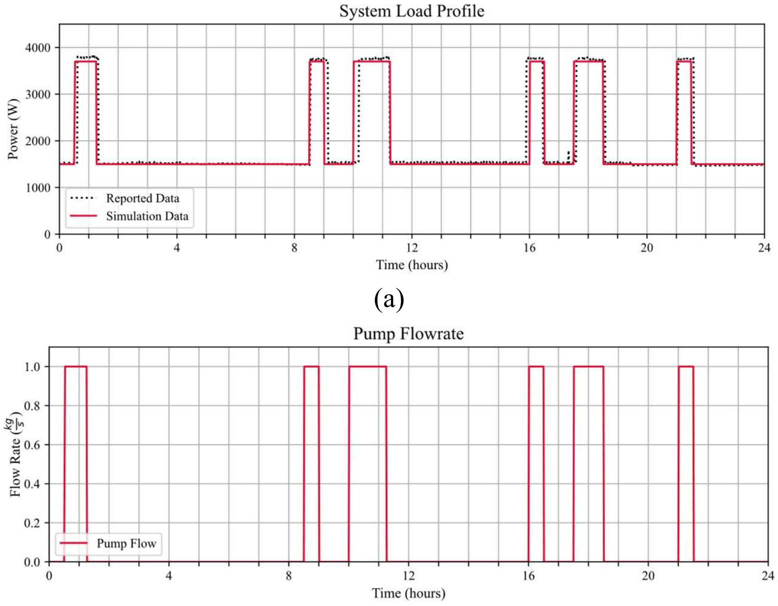
Figure 9. Modelica battery control block.

3. Case Study

Taking a representative day from June, empirical analysis was conducted between the Modelica model and the reported data operation for the same day of the year. Given the inconsistent data reporting and some deficits in the monitoring on the site, empirical analysis was selected to calibrate and test the Modelica performance. Additionally, total energy consumption and generation for June were compared between the reported data and Modelica simulations.

3.1. Dynamic Behaviour

The system's load profile displays a constant 1.5 kW demand from the community loads of receptacles, lights, small pumps, etc. This load profile was based on the most observed load reported from the site, as displayed in figure 12(a). The peak times throughout the day were implemented and determined to occur when the pump serving the community water tower was operating. These peaks were then implemented and used to develop the pump operation profile shown in figure 12(b). Since the pump operations were unknown specifically, they were not compared to the reported data. However, the peak times make sense, as they are approximately at peak times of the day, such as after the workday, during lunch hours, and at night when people are working in the gardens and with the fish.



(a)

(b)

Figure 12. Daily power demand (a) and pump operation (b).

The intricacies of the integrated PVWD system are particularly evident when examining daily behaviors and their rapid dynamics. Given that most studies used a fixed time step, there are fewer capabilities to integrate fast-acting controls and data at a fast time step (such as seconds), in addition to analysis on longer timesteps (such as months). The solar generation from the PV panels is shown in figure 13. The trends shown, particularly around the times of 10:00 to 11:00 and around 16:00, indicate that the proposed model's control represents the curtailment of the PV system. The high peaks of the reported data compared to the smooth curve from the Modelica represent some of the inconsistencies in data reporting from the site and the high-speed dynamics going on during the day when the batteries are charging and losing charge right around the 100% SOC point. This same behaviour is reflected in figure 14, where there are extremely fast peaks in the charging power going into the battery. The model does not have these due to the imposed wait times and lack of power leakage from the battery model used.

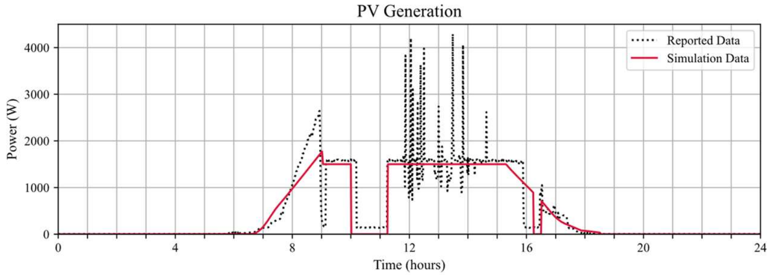


Figure 13. Daily PV generation.

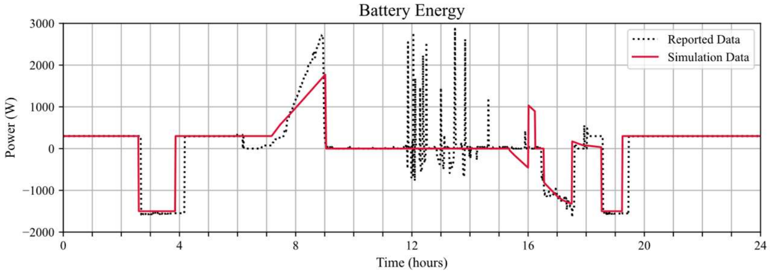


Figure 14. Daily battery performance.

The most critical test of the proposed Modelica model is how well it can implement controls and react quickly. Figure 15 demonstrates that the Modelica model closely mimics the performance of the controls that were implemented on-site. There is again the example of the battery model not having leakage seen throughout the day, where the reported SOC is fluctuating slightly around 100% and the Modelica model maintains 100% the entire time. Otherwise, the performance in the morning and late afternoon is very similar and demonstrates the ability of this model to capture the fast control operations and dynamics of the electrical system, while still providing accurate information on the energy usage and water system operations.

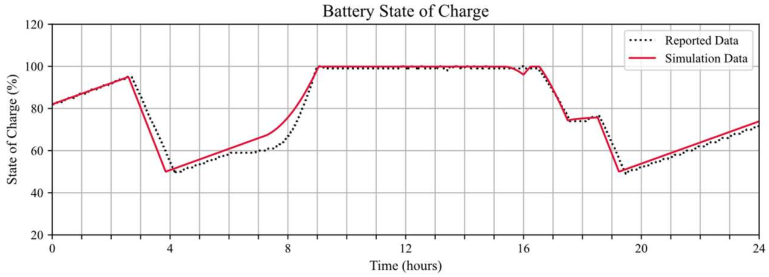


Figure 15. Daily battery SOC.

3.2. Energy Performance

Not only does this proposed Modelica model demonstrate the ability to accurately simulate and model the fast dynamics at finer timescales such as seconds and minutes, allowing for longer-term simulations that can be used for energy savings prediction and optimization. When analyzing the proposed model's performance every month compared to the site's reported data, the two exhibit extremely similar performances. There is only a 4% difference between the simulation results and the reported results when comparing the PV generation on the site. This shows that the model captures the real-world operations at larger timescales very well. Additionally, there is a 9% difference between the utility usage found in the simulation compared the the reported utility usage. This demonstrates that the proposed model has significant accuracy, falling under the 15% standard error from ASHRAE for monthly comparisons [18]. Although there are very minor deviations in the fast dynamics of the simulation compared to the reported information, these results demonstrate that at larger timescales, the model is performing exceptionally well and can be used to accurately predict, simulate, and optimize the performance of real-world installations.

Table 2. Energy results from June.

	Reported Results	Simulation Results	% Difference
PV Generation (kWh)	286.8	314.2	4
Utility Usage (kWh)	1088.1	1043.2	9

4. Conclusions

As PVWD systems are growing in popularity, there is a greater need to simulate and optimize existing or new systems. An integrated model that can handle fast dynamics and long-term energy prediction has become a roadblock to optimized systems. The proposed model utilizing Modelica demonstrates that these characteristics can be captured for accurate engineering analysis. With the capability to accurately model and implement control operations, there are many options to optimize the performance or test control strategies before the installation of a system. Given the option to have accurate long-term energy analysis, there are many new opportunities for optimization of physical or control characteristics within this system. The ability to adapt this model to mimic any proposed or existing systems provides significant potential for optimizing new designs or renovations. It also allows for the implementation and optimization of new control strategies within existing physical constraints. Integration of the physical properties of both electrical and water systems in one model provides the option to analyze different factors, such as energy, utility costs, water usage, and carbon emissions.

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