Validation of an Analytical Model to Lower the Cost of Solar-Powered Drip Irrigation Systems for Smallholder Farmers in the Mena Region

Proceedings of the ASME 2020
International Design Engineering Technical Conferences
and Computers and Information in Engineering Conference
IDETC/CIE2020
August 17-19, 2020, Virtual, Online

DETC2020-22610

VALIDATION OF AN ANALYTICAL MODEL TO LOWER THE COST OF SOLAR-POWERED DRIP IRRIGATION SYSTEMS FOR SMALLHOLDER FARMERS IN THE MENA REGION

Fiona Grant
Global Engineering and Research (GEAR) Lab
Massachusetts Institute of Technology (MIT)
Cambridge, MA
Email: fionag@mit.edu

Carolyn Sheline
GEAR Lab
MIT
Cambridge, MA
Email: csheline@mit.edu

Susan Amrose
GEAR Lab
MIT
Cambridge, MA
Email: samrose@mit.edu

Elizabeth Brownell
GEAR Lab
MIT
Cambridge, MA
Email: ebrownll@mit.edu

Vinay Nangia
International Center for Agricultural
Research in the Dry Areas
Rabat, Morocco
Email: v.nangia@cgiar.org

Samer Talozi
Jordan University of
Science and Technology
Irbid, Jordan
Email: samerbse@just.edu.jo

Amos Winter, V.
GEAR Lab
MIT
Cambridge, MA
Email: awinter@mit.edu

ABSTRACT

Drip irrigation is a micro-irrigation technology that has been shown to conserve water and significantly increase crop yield. This technology could be particularly beneficial to the world's estimated 500 million smallholder farmers, but drip systems tend to be financially inaccessible to this population. Drip systems require costly components including a pipe network, emitters, a pump and power system. Due to limited access to electricity, many smallholder farmers would require off-grid solutions. Designing reliable, low cost, off-grid drip irrigation systems for smallholder farms could significantly reduce the barrier to adoption.

This paper builds on an integrated solar-powered drip irrigation model that was shown to improve upon an existing software. Field trials of the small-scale drip system were conducted on research farms in Jordan and Morocco for a full growing season. Data collected from these field trials are used to validate the hydraulics portion of the systems-level model. In addition, the insights gained from the field trials were formed into design requirements for future iterations of the model. These include optimizing for the system life cycle cost, as opposed to capital cost, the ability to simulate the system operation over a season, the capability to input a user's irrigation schedule, incorporating locally-available components, and incorporating a system reliability constraint based on more detailed agronomic calculations.

INTRODUCTION

An estimated 500 million smallholder farmers work plots of 2 hectares (ha) or less and produce 80% of the food consumed in Asia and Sub-Saharan Africa [1]. However, only about 10% of global arable land is irrigated, and of that, only 6% uses drip irrigation [2]. Irrigation can improve yields and decrease water usage for farmers working small plots of land. Drip emitters release water and nutrients directly to the root zone of the crop. Pressure compensating (PC) emitters are flow control devices that operate at a relatively constant flow rate above a certain activation pressure. Drip systems with PC emitters can uniformly distribute water to the field, regardless of topology, ensuring that all crops receive the same amount of water. Drip irrigation can reduce water consumption by up to 70% over traditional methods, and has been shown to increase crop yields by 20-90%, depending on the type of crop [3–7]. This is especially important in arid regions that are already experiencing water scarcity.

Despite these benefits, the high capital cost of drip irrigation systems is a barrier to adoption for smallholder farmers [8]. Prior work to reduce the cost of solar-powered drip irrigation systems includes work to reduce the system pressure by significantly reducing the activation pressure of PC emitters, thereby creating ultra-low pressure emitters (hereafter referred to as low-pressure emitters) that need smaller pumps and fewer solar panels to operate [9, 10]. Furthermore, work has been done in [11] to incorporate the low-pressure emitters into a drip system design in order to reduce the system cost. From this work, a Generation 1 systems-level design tool was developed to optimize for the lowest capital cost. The novel Generation 1 system model captures the interdependence of important aspects of a solar-powered drip irrigation system such as the crop water demand, local weather patterns, hydraulic system, pump, and power system configuration. The model incorporates these relationships and also optimizes the power system for capital cost as a Generation 1 design tool.

Other prior work also considers the design and optimization of solar powered pumping systems, but the authors impose limitations on their models [12–16]. Bakelli [12] uses a polynomial fit to model data, rather than fluid mechanics to simulate the system hydraulic behavior. Muhsen [13] proposes a multi-objective optimization scheme that minimizes cost, a reliability metric, and excess water volume, but the three minimization criteria are weighted subjectively. This paper also defines the system components a priori, rather than selecting the components within the optimization scheme. Kelley [14] assesses the feasibility of solar powered irrigation, using average irradiance and maximum crop water requirement for five cases studies. The system designs are not optimized, but local economic data are used to link designs to their locations. Deveci [15] discusses the design of a low-cost, solar powered drip irrigation system for small farms using a systems-level approach. The systems-level approach is useful for framing the problem, but the system description is over-simplified by its assumptions. López-Luque [16] discusses the optimal design for a solar-powered irrigation system using various sub-models to simulate the system while implementing a deficit irrigation scheme and optimizing for profitability. This study shows that with deficit irrigation, the cost of the solar-powered pump is able to be reduced, but the model is limited with a very specific system design that only considers non-pressure compensating emitters. While most of these studies incorporate data sets or collect field data to produce some kind of model validation, none of the studies use these results to produce specific guidelines for updating or improving their models as design tools.

In this paper, the Generation 1 tool from [11] is used to design systems for two field trial locations in the Middle East and North Africa (MENA), specifically Jordan and Morocco. The data from these trials is used to validate the hydraulics portion of the systems-level model and to formulate criteria for improving the Generation 2 model. The aim of this study is to demonstrate that the small-scale hydraulic systems perform as predicted in the field and that the insights from the field trial data can be incorporated into a Generation 2 model to produce lower cost, more robust system designs.

METHODS

In 2018, two solar-powered drip systems of the low-pressure emitters were installed. The systems were sized using the Generation 1 systems-level model. This model optimizes for a minimum capital cost solar-powered drip irrigation system based on a given location and crop. The inputs to the model are the crop agronomic parameters, local weather data, the dimensions and pipe geometry of the hydraulic network layout, and the parameters of the low-pressure emitters. The systems-level model is divided into three main sections: the agronomy and hydraulic simulation, the pump and power system design and the system optimization. The first section calculates the crop water demand and models the behavior of the hydraulic network to determine the system operating point. The second section produces design permutations of the pump and power system capacity. The model calculates the water delivered by each design over a season, using the hydraulic operating point calculated in the first section, and the number of days the design fails to meet the crop water demand as a measure of the design's reliability. The third section is a minimum point search for the minimum capital cost design. The model formulation is described in detail in [11]. The model was shown in simulation to be an improvement over existing software design tools for drip irrigation systems. The goals of the field trials were to demonstrate that the novel low-pressure emitters could be successfully implemented in a small-scale solar-powered drip system, validate the hydraulics portion of the systems-level model, and gain insights from the drip system performance data to improve the next generation of the model.

Selected Locations

Field trials to test the low-pressure emitters have been ongoing in Jordan and Morocco since 2017 [10, 11]. For this set of field trials, a site in Sharhabeel, Jordan and a site in Saada, near Marrakesh, Morocco, were chosen. These countries have arid climates, high solar irradiance, and water scarcity issues that impact the agriculture sector [17, 18]. Both countries also have programs that work on the adoption of drip irrigation technology by smallholder farmers, either through the government or NGOs.

These field trials were conducted with the support of two agricultural research institutions: International Center for Agricultural Research in the Dry Areas (ICARDA) in Morocco and Methods for Irrigation and Agriculture (MIRRA) in Jordan. In Sharhabeel, Jordan the site was a 0.16 hectare field of 64 citrus tree crops, and in Saada, Morocco the site was a 0.52 hectare field of 90 young olive tree crops.

System Configuration

A solar-powered drip irrigation system is made up of a pump that pulls water from a source (reservoir or well), powered by solar panels and possibly batteries, and pushes the water through filters and a fertilizer injector out to a field where a network of pipes and drip emitters are used to deliver precise amounts of water to the root zone of the crop [11]. For these field trials the hydraulic network layout and spacing were predetermined by the agricultural research institutions based on local practices and the arrangement of the crops on the field. These layouts were input into the model to simulate the hydraulic operating point for each system [11]. The Sharhabeel site had a simulated operating point of 7.5m of pressure head and 2.6 $\frac{m^3}{hr}$ of flow and the Saada site had a simulated operating point of 6.5m of pressure head and 2.9 $\frac{m^3}{hr}$ of flow.

The solar-powered systems for each site were designed using the Generation 1 systems-level model, which optimizes the power system design, namely the solar panel, battery, and tank capacities, for capital cost. The simulated operating pressure head and flow for each site are shown in Table 1. The model provides information about the capital cost as well as the design reliability, or the ability of the system to deliver the calculated water demand to the crops. The reliability is measured in number of failure days, and for Sharhabeel the maximum number of failure days is 365, while the maximum is 270 for Saada due to the different growth and irrigation cycles of the crops. The results of the model were shown to be an improvement over the Lorentz Compass software tool, which sizes solar-powered pumping systems based on the system duty point and average, location-specific weather data [11]. For Saada, the systems-level model shows the panel area can be reduced by 38% compared to Compass for a direct drive system, while maintaining 100% reliability (zero failure days). For Sharhabeel, the systems-level model produces a larger optimal panel area than the Compass software as the model is constrained to have 100% reliability. For Sharhabeel the model also shows that the 28% increase in panel area between the two designs results in less than a 1% increase in reliability. The additional reliability information provided by model motivated selecting the smaller panel area for the Jordan design. For both sites, the actual panel area was constrained by the fact that the locally available panels came in sizes of $2m^2$ for Jordan and $1.6m^2$ for Morocco, so two panels with a total area of $4m^2$ and $3.2m^2$ were installed at each site, respectively. In both cases, the model provided insights that enabled the selection of low-cost power system designs.

Instrumentation

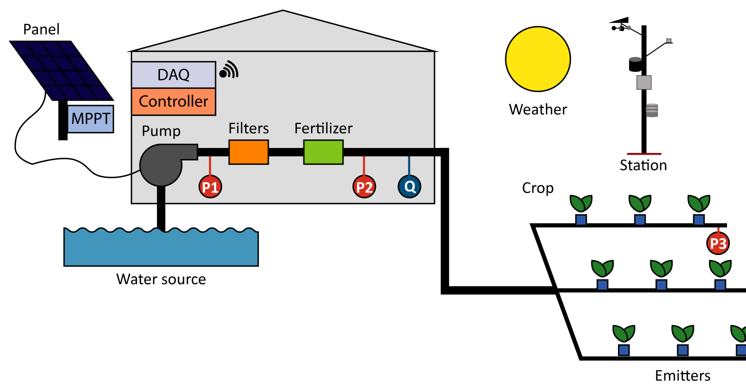


FIGURE 1: Field trial layout and instrumentation. Data recorded by two pressure sensors (P1, P2) and a flow meter (Q) were transmitted every 10 minutes. A manual pressure gauge (P3) was used to verify the last emitter was at activation pressure. The pump operating pressure was set based on the pump house pressure sensor reading when the average flow rate of the last five emitters was at the emitter rated flow, 8Lph.

The hydraulic components - pipes, fittings, valves, sand filter, disk filter and fertigation unit - were obtained and installed through local contractors. The emitters were the custom low-pressure emitters [9]. A Lorentz CS-F4-3 centrifugal surface pump was installed at each site. The PS2-600 pump controller allowed for flow, pressure, or speed control, and allowed the operator to input a total daily water amount for the pump to deliver. A solar-powered Lorentz PS 3G communicator collected pump operation data from the controller and sent it to a server via the cell network. The pump controller data, including the pump pressure and flow rate, were collected and transmitted at ten minute intervals. An online and mobile application enabled the operator

TABLE 1: Comparison of Compass and model results for direct drive panel area calculation.

Location	Pressure & Flow $[m, \frac{m^3}{hr}]$	Max. Daily Water $[m^3]$	Compass Panel Area $[m^2]$	Compass Reliability [# failure days]	Model Panel Area $[m^2]$	Model Reliability [# failure days]
Saada, Morocco	6.5, 2.9	16	4.8	0	3.0	0
Sharhabeel, Jordan	7.5, 2.6	5.0	3.9	1	5.0	0

to remotely control the pumping system and change the irrigation schedule and operating pressure throughout the season. The pump had a BLDC motor and a maximum operating power of 0.7 kW. At both sites, research staff calculated and programmed the system to deliver the crop water demand on a daily basis. After the water demand was met for a day, the system would turn off automatically.

In Jordan, the pump was connected to two Jain (JJ-M672-300Wp) solar panels. The reservoir was located 1.5 meters below the inlet of the pump, which added to the suction lift of the pump. In Saada, the pump was connected to two Canadian Solar (CS6P-270Wp) panels. The reservoir was located 2 meters above the inlet of the pump, and provided some positive inlet pressure. In both locations, a low power shut-off sensor (Lorentz 19-005030) was implemented to shut off the pump during times of low irradiance, and a well probe sensor (Lorentz 19-000000) was implemented to prevent dry running the pump.

In order to monitor the system operation, a flow sensor (Dwyer WMT2-A-C-07-10) and a pressure sensor (Lorentz LPS-500) were placed downstream of the pump. Another pressure sensor was placed downstream of the fertigation unit (SSIP51-15-G-UC-I36-20MA), as shown in Figure 1. The difference between the two pressure sensors measured the pressure drop over the sand filter, disk filter and fertigation unit. Additionally, a manual pressure sensor was placed directly after the last emitter on the farthest lateral from the pump.

A weather station (HOBO U30-NRC) with sensors was placed near each solar pumping system to monitor solar irradiance (HOBOS-LIB-M003), temperature and relative humidity (HOBO S-THB-M00x), precipitation (Davis S-RGF-M002), and wind speed and direction (Davis S-WCF-M003) at five minute intervals. The weather station saved the data locally, and the site research staff downloaded the data periodically via a USB connection.

Experimental Methods

At both sites, the research staff monitored and controlled the pump throughout the season. The staff input the daily water amount based on their agronomic calculations of the crop water demand. The pump turned on whenever there was enough solar irradiance to power the system. After the programmed daily water amount was reached, the pump turned off automatically. The staff adjusted the irrigation schedule after rainfall or dry periods based on their calculations and agronomic expertise.

The simulated system pressure and flow rate from the model was used as a reference to set the pump operating point in the field. Since PC emitters are flow control devices that allow for a constant system flow rate, the pump was pressure-controlled. The operator would increase the pumping pressure through the controller app and measure the flow rates of the last five emitters on the lateral furthest from the pump. When the average flow rate of the last emitters reached the emitter rated flow of 8 Lph, all the emitters were considered to be operating at or above their activation pressure, and therefore at a constant flow rate. This set the pump operating pressure. The operator repeated this calibration procedure periodically during the season to adjust for any fluctuations in the operating point. The pumping pressure was always measured at the pressure transducer downstream of the filters and fertigation, P2 in Figure 1, because the pressure drop across these components changed throughout the season; the filters got dirty over time and the fertigation unit was only connected to the hydraulic loop every two weeks to inject fertilizer for the crops.

Data Processing

For each site, the data was collected from the weather station and the pumping system controller. The pumping system data included the output power from the panel array to the pump, the pump power consumption, the system operating pressure (P1 and P2) and flow rate (Q) in Figure 1, a logical pump on/off variable, and a logical hydraulic system on/off variable. The data CSV files were imported to MATLAB and processed with custom code. The logical variables were used as checks to ensure that the pump and system were always on (logical value of 1) whenever the flow meter recorded a measurement. The script filtered out unreasonably high flow rate measurements that were one or more orders of magnitude greater than the average system flow rate. These readings were likely sensor errors. The script also filtered out pressure measurements that were close to zero during irrigation events, which could have been due to sensor error or leaks in the hydraulic network.

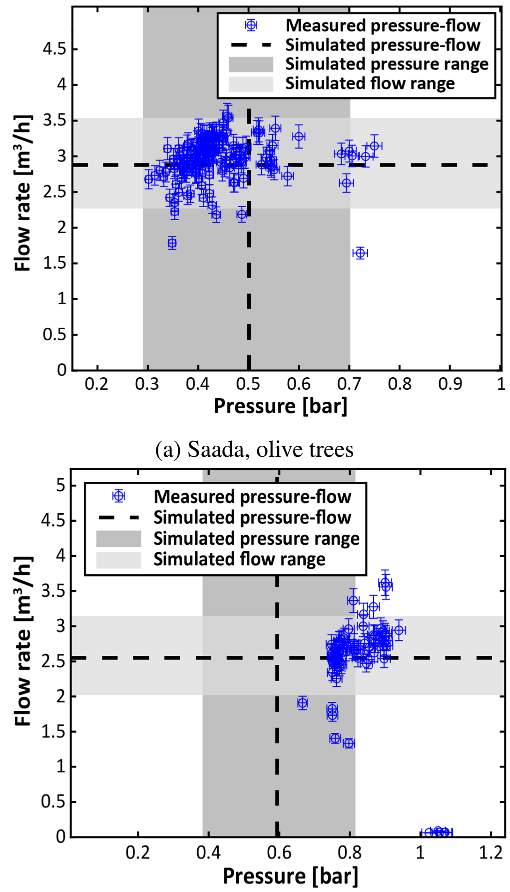
RESULTS

The presented data shows that the novel low-pressure emitters can be successfully incorporated into a small-scale solar-powered drip system, and that the pipe networks of the systems operated largely as predicted by the model for both the Jordan and Morocco sites. This data validates the capability of the system model to accurately predict the hydraulic behavior of a given drip system design. These small-scale systems were also able to meet the water requirement set by the field partners throughout the season, indicating that the designs produced by the model were reasonable for the given conditions and component constraints. In addition to validating the hydraulic simulation results, insights from field trial data on system performance suggest improvements to be implemented in the next generation of the systems-level model.

Hydraulic Network Operation

The operating pressure and flow rate of a hydraulic network were measured in the field trials as the pressure at the pump outlet and the flow rate recorded by the flow meter. Figure 2 shows the operating pressure and flow rate simulated by the model, as well as the expected ranges, and the measured pressure and flow rate during the season. Each measured point is qualified with error bars showing the sensor measurement errors. Ideally, the measured points would collapse onto the intersection of the simulated lines, but both the flow rate and pressure fluctuated. For Figure 2, the simulated pressure limits were estimated based on an assumed pressure drop of ± 0.2 bar across the filters and fertigation unit and verified by checking the difference between the measurements of P1 and P2 (Figure 1). The maximum measured pressure difference across the filters and fertigation unit was 0.40 bar in Saada and 0.25 bar in Sharhabeel. In Saada, the pump was frequently operating below the simulated pressure, but within the expected range, and in Sharhabeel, the pump was operating close to or above the upper end of the expected pressure range. In both cases, the system should deliver water uniformly because all the emitters should be at or above their activation pressure, but the system in Sharhabeel appears to be over-pressurized, meaning it is operating at a higher power than necessary. This indicates that, in future designs, the pressure set point should be better controlled to ensure the system is operating more closely to its ideal operating point as dictated by the PC behavior of the hydraulic network [11].

The simulated flow rate limits in Figure 2 were estimated based on emitter specifications and the known modeling error for the hydraulic network calculation. The low-pressure emitters operate at ±7% of their rated flow rate, which means the system flow rate is expected to vary by this amount [10]. The iterative flow calculation used in the hydraulic simulation estimates the flow rate in a pipe network within ±15% of the actual value, which adds an additional error band to the predicted flow rate [19].



(a) Saada, olive trees

(b) Sharhabeel, citrus trees

FIGURE 2: The simulated and measured pressure and flow rate over the season for olives in (a) Saada, Morocco and citrus in (b) Sharhabeel, Jordan. The blue markers show the measured pressure and flow for an irrigation event with expected error for the measurement. The dashed line intersection shows the simulated operating point, and the grey bands show the expected variation range for pressure and flow.

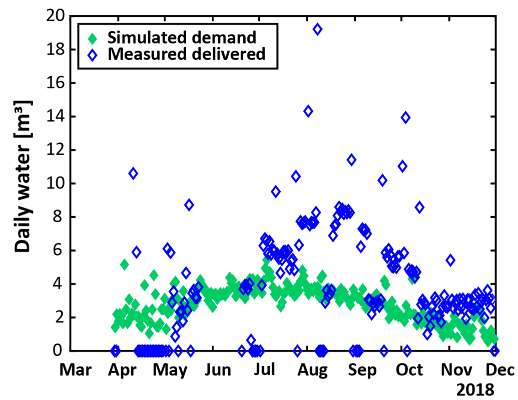
Although most measurements are within the expected range, there are some outliers. The cases where the flow rate is higher than expected are either due to erroneous flow meter readings or a leak in the system, which was occasionally an issue in Sharhabeel. Some of the low flow rate points outside of the expected range correspond to lower pressures (Figure 2). Although these pressures were within the expected range, the required system pressure at that time could have been higher, meaning that the operating pressure was not sufficient for all the emitters to reach activation. This resulted in a lower system flow rate than expected. In Sharhabeel, some of the lowest flow rate points correspond to the highest pressure points, as shown in Figure 2b, which indicates some part of the system was partially closed off or clogged, likely during testing or start-up. The emitters can also clog during the season, which causes a reduction in flow rate, but maintenance was regularly performed on the fields which included cleaning filters, flushing the system with acid, and replacing clogged emitters. The majority of the measured data are within the expected operating range for flow rate and pressure, indicating that the model was able to accurately simulate physics of the hydraulic network.

System Performance

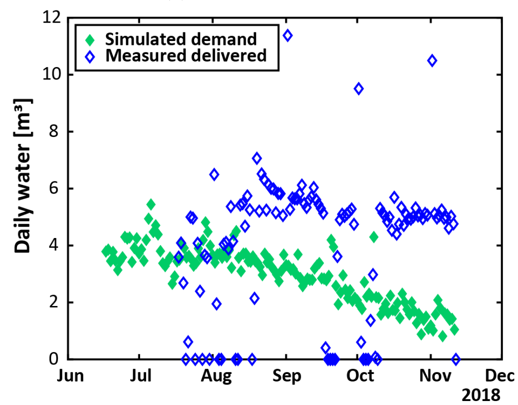
In addition to measuring the hydraulic network behavior, two metrics of overall system performance were recorded: the daily water delivered and the pump operating power. As previously stated, the installed pumps and power systems were not the exact optimal designs produced by the model due to the constraints of component availability, so these performance metrics could not be used to validate design optimization. However, insights gained from this performance data elucidate a number of requirements that will be used to improve the Generation 2 system model.

The daily water demand simulated by the model is plotted with the measured water delivered to the crops according to the field partners schedule in Figure 3. For both sites, the partners reported that the systems were able to meet their scheduled demand for the entire season, meaning that the systems were 100% reliable. The measured water delivered did not exactly match the model-simulated demand because the field partners had control over the irrigation schedule and had more detailed agronomic calculations than those implemented in the model. For example, the partners had more detailed crop parameters and were able to hold off on irrigation based on recent rainfall, surface water availability, or if there was excess water availability from previous irrigation events. Furthermore, the model-simulated demand was based on weather data from a typical meteorological year, whereas the delivered water was based on measured and predicted local weather. Although the differences in irrigation amounts were not enough to cause a failure of the system for these cases, understanding user irrigation practices, and in particular irrigation scheduling, could lead to improvements in the model that produce more robust system designs.

Figure 4 shows the predicted pump power requirement and the measured pump power consumption for each site throughout the season. In both cases the measured pump power is generally within the simulated range, but it can be seen that there are a significant amount of measurements that are outside the simulated power limits. The simulated power limit bands were calculated based on the variations in the pressure and flow rate ranges. As previously discussed, there were irrigation events where the pump operating pressure was set too high, resulting in a higher pump power consumption than necessary to operate the system.



(a) Saada, olive trees



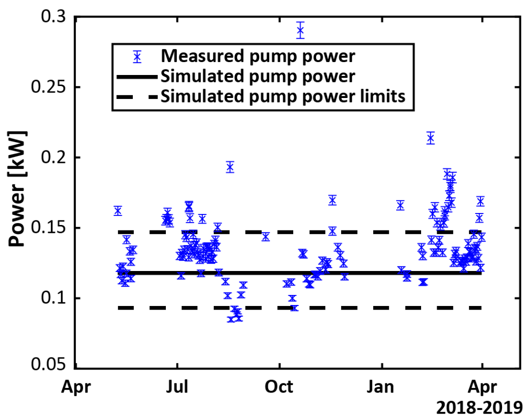
(b) Sharhabeel, citrus trees

FIGURE 3: The measured water delivered during field trials compared to the model simulated demand in Morocco (a) and Jordan (b). The system was able to meet the irrigation needs of the user over the season even though those needs differed from the simulated demand calculated by the system model.

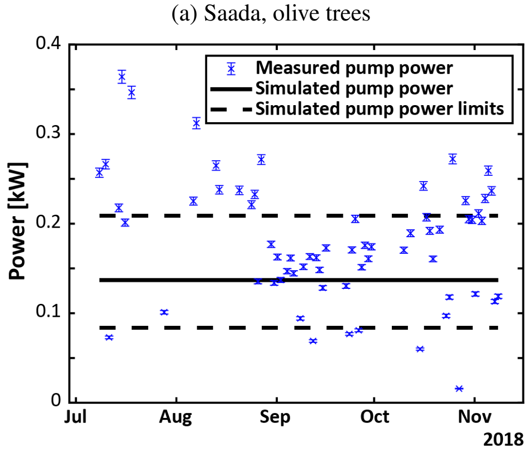
This specific pump model was recommended for these sites by a Lorentz representative, but the pump was oversized. This meant that the pump was operating away from its best efficiency point. The efficiency of the pump was assumed to be higher in the simulation than it actually was in the field trials, which also explains why the operating power consumption of the pump was occasionally higher than the expected maximum for both sites. By further analyzing the data, it was found that the simulated pump efficiency was 36% for Saada and 40% for Sharhabeel, but the average measured efficiency of the pump was 27% for both Saada and Sharhabeel. These results underscore the importance of designing with locally available components and, when selecting a pump, incorporating the pump best efficiency point (BEP) and preferred operation range (POR) in the model simulation. This will ensure that the pumps are more appropriately sized and operate efficiently for the operating range of a given hydraulic

TABLE 2: Summary of daily water, flow rate, pressure, and pump power simulated and measured results.

Location	Daily Water $[m^3]$		Flow Rate $[m^3/h]$		Pressure $[bar]$		Pump Power $[kW]$	
	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured
Saada, Morocco	2.8	3.9	2.9	3.0	0.5	0.4	0.12	0.14
Sharhabeel, Jordan	3.0	4.2	2.6	2.4	0.6	0.8	0.14	0.18



(a) Saada, olive trees



(b) Sharhabeel, citrus trees

FIGURE 4: The measured electrical power to the pump, simulated pump operating power, and expected range. For both sites, the measured power is generally within the expected range. Outliers are most likely due to an oversized pump and differences in measured and simulated irrigation and pump efficiencies

network.

Table 2 summarizes the results from Figures 3-4. The table shows the simulated and measured averages. The ranges and uncertainty of this data are detailed in the previous figures and text. The simulated and measured average results are shown to be generally similar for both locations.

DISCUSSION

Hydraulic Simulation Validation

One of the goals of the field trials was to validate that the Generation 1 systems-level model could accurately simulate the operating behavior of a hydraulic drip network with the low-pressure emitters. The results described in the previous section and shown in Figure 2 show that the model is able to do so. This provides confidence going forward that the systems-level model is able to capture the physics of a given hydraulic network layout, including the behavior of the low-pressure emitters. This means that the hydraulics model can now be used to simulate the behavior of a wide range of cases with different field areas, crops, and hydraulic components in order to asses the scale and bounds of the design space for small farms. As the hydraulic operating point dictates the optimal sizing of pump and power system, this validation is an important step in creating a robust design tool for solar-powered drip irrigation systems on small farms.

Insights for Model Requirements

The field trial results also provide insights on the implementation of small-scale, solar-powered drip irrigation systems that can be incorporated as improvements in the Generation 2 systems-level model. The goal of Table 3 is to share the knowledge gained from the field trials to facilitate and improve the design of solar-powered drip irrigation systems for smallholder farmers. It is important to consider how a design will perform in the real world during the design process, especially when designing for the developing world as many designers are unfamiliar with the conditions of an area that they are designing for. Most of these insights are derived directly from the data analysis, but a few are garnered from observations on the overall process of implementing the field trials. Table 3 provides a summary of these insights and anticipated model improvements, and can be viewed as a design requirements table for the next stage of model development. This is the culmination of simulated results produced with the Generation 1 model, the expansion of that knowledge from building two solar-powered drip systems in Morocco and Jordan, and the experience gained by extensive collaborative work with field partners operating and collecting data from these systems over a growing season.

Data-driven insights First, there is a need to better understand farmers' irrigation practices, in particular irrigation scheduling, and to accurately capture system reliability for those practices. The system performance data in Figure 3 show that the field partners' irrigation schedule, which was produced with more detailed agronomic calculations, adjustments based on concurrent weather patterns, and knowledge of the crop growth history, varied significantly from the schedule produced by the agronomy simulation in the model. This demonstrates the need for a more detailed agronomy model to predict crop water demand and simulate crop yield as well as the capability to input and design to an irrigation schedule produced by the farmer. Incorporating this flexibility into the model will result in designs that meet the crop requirements and user preferences with minimal failures. In order to ensure robust designs, the model must also incorporate a reliability metric that quantifies how well a design meets the water demand required by the calculated or input irrigation schedule over a season. A yield model can show the sensitivity of the reliability metric to design changes, as crop yield is sensitive to the amount of water delivered. This reliability metric should act as a constraint of the optimization such that the optimal design represents the trade-off between minimizing cost and system reliability.

Second, it was observed that the operating point of a drip system will vary over time: emitters clog, filters get dirty, fertilizer is applied periodically through an additional hydraulic component, and even PC emitters will have some variation in their nominally constant flow rate. The model should include a more detailed simulation of the system operation to account for this operating point variation and ensure that the pump and power system are appropriately sized. The assumption that the pump is always operating at a constant value that is within its best efficiency range is not valid in field conditions. As such, the model must use the system operating range to select a pump such that the system nominally operates at the pump best efficiency point (BEP) and, when the operating point varies, it stays within the pump preferred operating range (POR). This will ensure the pump is appropriately sized for the system and will operate efficiently throughout the season. Operating the pump around its highest efficiency will also produce optimal power system designs with lower capacity and therefore lower cost.

In a manual system, users may also set the operating pressure too high, especially as they learn to use the new system. The power consumption data in Figure 4 indicates that the operator set the pump pressure higher than necessary at the beginning of the season, resulting in excess power consumption. This motivates some level of automation of the pumping system control based on the model operation simulations, but implementing that control would depend on the level of automation users are willing to adopt when it comes to making farming decisions.

Implementation observations In addition to the data-driven insights, general observations of the field trial implementation are pertinent to improving the system model. The available solar panels came in discrete sizes that varied in each location. The field trial pump, which was chosen primarily for the data collection capabilities of its control unit, was not locally available for either site. This meant that the solar panel capacity was limited by the available panel sizes, and the pumping system had to be shipped from outside the country. Importing components can increase the cost and potentially make local repairs impossible, either because the replacement parts are not available or local technicians are unfamiliar with the component. Therefore, it is essential to consider locally available components when designing the systems for farms. Some components, such as batteries, also have high replacement costs that will increase the life cycle cost of the system. These observations indicate that incorporating the life cycle cost of locally available components, rather than just the capital cost, would produce more accurate system cost estimations and more feasible designs for a given location. The model must optimize for the minimum life cycle cost, which includes the initial, maintenance and replacement costs of the all the system components. It would also be beneficial to add the capability to input an existing design to facilitate benchmarking. The model can then be used to calculate life cycle cost, simulate operation over a season, and assess reliability of the existing design using location-specific weather and economic data.

Next generation model requirements These insights can be broadly divided into three categories of requirements. The next generation systems-level model must be location-specific, holistic, and flexible. These are summarized in Table 3, which shows the predicted improvement in the model of each insight gained from the field trials. Incorporating locally available components as well as detailed life cycle costs of each component will lead to a design tool that can reduce the life cycle cost of the drip systems, thereby making them more accessible to smallholder farmers. A holistic model that simulates the variability of system operation over the season and accounts for the pump BEP and POR will results in lower cost designs with appropriately-sized system components. Including a detailed water demand calculation and yield calculation in the model will more accurately capture the performance of the system which will allow designers to better analyze the trade-off between system reliability and cost. Finally, having the flexibility to input a user's irrigation schedule will allow designers to compare an optimal design based on current practices to the optimal design based on the agronomic calculations in the model. In addition, the ability to input an existing design into the model and simulate its per-

TABLE 3: Design requirements for Generation 2 systems-level model based on field trial insights.

Model Requirement	Description	Predicted Improvement
Location-specific	Library of available components and their life cycle costs	Produce feasible designs and ensure local repairability or replacement
Holistic	Optimize for life cycle cost (initial, maintenance, replacement)	Better metric for affordability over system lifetime
	Detailed operation simulation	Account for operation variation over season to elucidate further reductions in system cost
	Detailed water demand calculation	Allows for definition of system reliability constraint on cost-optimization
	Yield model	Predicted yield is a metric for the sensitivity of the system reliability to design changes
	Consider pump BEP and POR in pump selection	Select an appropriately-sized pump that operates efficiently throughout the season
Flexible	Ability to input user irrigation schedule	Farmer's irrigation schedule may differ from schedule calculated by model; can design to existing irrigation preferences if necessary
	Ability to input existing design	In addition to finding an optimal design, can calculate cost and simulate performance of existing design for benchmarking

formance can give designers insight on the behavior of specific components. This improved model will not only be able to produce the optimal system design, but also design systems based on a user's operation preferences, while minimize the risk of system failure during operation.

CONCLUSION

A systems-level Generation 1 model was used to design two solar-powered drip irrigation systems for small farms. The model optimized for the lowest capital cost power systems. These systems were built, with modifications based on component constraints, and operated over the course of a growing season in Jordan and Morocco. The field trial results show that the low-pressure emitters could be incorporated into a solar-powered drip system and operated in field conditions, the model accurately predicts the operating point of the drip network, and the performance of the system gives confidence in the model's capability to produce feasible designs. Insights gained from the field trials are summarized and used as criteria for improvements in the next iteration of the systems-level model. The broad requirements are that the model be location-specific, holistic, and flexible. Specifically, components should be locally reparable and replaceable, there should be better metrics for the systems affordability and reliability, modeling detailed operation allows for appropriate and robust system sizing, and consideration of inputs from the user, either farmers or designers, allows for a wider applicability of the model. Additionally, knowledge gained from the field trials is shared to help designers in designing solar-powered drip irrigation systems for smallholder farmers and to help convey a need to consider real world conditions and constraints when designing for the developing world. Future work will involve collecting more detailed information from users about how they operate their irrigation systems and set their irrigation schedules, as well as their willingness to use partially or fully automated systems. The insights from this field work will be incorporated and tested in the Generation 2 systems-level model. This model will be used to design systems for another set of field trials, which will allow for further model validation.

ACKNOWLEDGMENT

The authors would like to acknowledge the staff of Methods for Irrigation and Agriculture (MIRRA), the International Center for Agriculture Research in the Dry Areas (ICARDA), the National Agricultural Research Center (NARC), and the National Institute for Agricultural Research (INRA) for their management of the field sites, data collection, as well as their support and advice. Specifically, Khaled Abu Naser, Khalil Bany Mustafa, Amal Omari, Naem Mazahrih, Rachid Moussadek, Lhassane Sikaoui and Abdulaziz Bouizgaren. The authors would also like to acknowledge Julia Sokol for her drip irrigation experimentation expertise, our partners USAID Cooperative Agreement Number AID-OAA-A-16-00055 (BAA-MWSI-ME-2015) for its backing, and Jain Irrigation Ltd. for manufacturing and conducting preliminary testing on prototype emitters.

REFERENCES

[1] IFAD, "Smallholders, food security and the environment," *International Fund for Agricultural Development (IFAD)*, 2013.

[2] O. Dubois, "The state of the world's land and water resources for food and agriculture: Managing systems at risk.," *Earthscan*, 2011.

[3] J. Burney, L. Woltering, M. Burke, R. Naylor, and D. Pasternak, "Solar-powered drip irrigation enhances food security in the Sudano-Sahel," *Proceedings of the National Academy of Sciences*, vol. 107, no. 5, pp. 1848–1853, 2010.

[4] R. Sivanappan, "Prospects of micro-irrigation in India," *Irrigation and Drainage Systems*, vol. 8, no. 1, pp. 49–58, 1994.

[5] I. Mazher, S. Fayyaz-ul Hassan, H. Tamoor, N. Aadal, M. Azeem, and T. Muhammad, "Evaluation of comparative water use efficiency of furrow and drip irrigation systems for off-season vegetables under plastic tunnel," *International Journal of Agriculture and Crop Sciences (IJACS)*, vol. 7, no. 4, pp. 185–190, 2014.

[6] K. Nkya, A. Mbowe, and J. Makoi, "Low-cost irrigation technology, in the context of sustainable land management and adaptation to climate change in the Kilimanjaro Region," *Journal of Environment and Earth Science*, vol. 5, no. 7, pp. 45–56, 2015.

[7] R. Namara, B. Upadhyay, and R. K. Nagar, *Adoption and impacts of microirrigation technologies: Empirical results from selected localities of Maharashtra and Gujarat States of India*, vol. 93. IWMI, 2005.

[8] G. Rapsomanikis, "The economic lives of smallholder farmers: An analysis based on household data from nine countries," *Food and Agriculture Organization of the United Nations (FAO)*, 2015.

[9] P. Shamshery and A. G. Winter, "Shape and form optimization of on-line pressure-compensating drip emitters to achieve lower activation pressure," *Journal of Mechanical Design*, vol. 140, no. 3, p. 035001, 2018.

[10] J. Sokol, S. Amrose, V. Nangia, S. Talozi, E. Brownell, G. Montanaro, K. Abu Naser, K. Bany Mustafa, A. Bahri, and B. Bouazzama, "Energy reduction and uniformity of low-pressure online drip irrigation emitters in field tests," *Water*, vol. 11, no. 6, p. 1195, 2019.

[11] J. Sokol, F. Grant, C. Sheline, and A. Winter, "Development of a System Model for Low-Cost, Solar-Powered Drip Irrigation Systems in the MENA Region," in *ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, 2018.

[12] Y. Bakelli, A. Hadj Arab, and B. Azoui, "Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept," *Solar Energy*, vol. 85, 2011.

[13] D. H. Muhsen, T. Khatib, and T. E. Abdulabbas, "Sizing of a standalone photovoltaic water pumping system using hybrid multi-criteria decision making methods," *Solar Energy*, vol. 159, pp. 1003–1015, 2018.

[14] L. C. Kelley, E. Gilbertson, A. Sheikh, S. D. Eppinger, and S. Dubowsky, "On the feasibility of solar-powered irrigation," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2669–2682, 2010.

[15] O. Deveci, M. Onkol, H. O. Unver, and Z. Ozturk, "Design and development of a low-cost solar powered drip irrigation system using systems modeling language," *Journal of Cleaner Production*, vol. 102, pp. 529–544, 2015.

[16] R. López-Luque, J. Reca, and J. Martínez, "Optimal design of a standalone direct pumping photovoltaic system for deficit irrigation of olive orchards," *Applied Energy*, vol. 149, pp. 13–23, 2015.

[17] ICARDA, "Ultra-Low Energy Drip Irrigation for MENA Countries: Drip Irrigation in Morocco," *International Center for Agricultural Research in the Dry Areas (ICARDA)*, 2017. internal report, unpublished.

[18] MIRRA, "Economics of the Agricultural Sector in Jordan," *Methods for Irrigation and Agriculture (MIRRA)*, 2017. internal report, unpublished.

[19] F. M. White, *Fluid Mechanics*, ch. 6. McGraw Hill, 2011.