Energy Research and Development Division

FINAL PROJECT REPORT

Decision Support Tool to Reduce energy and Water Consumption in Agriculture

Appendices A-D

California Energy Commission

Gavin Newsom, Governor

March 2019 | CEC-500-2019-022-APA-D

Energy Research and Development Division
Product

LIFE CYCLE ASSESSMENT (LCA) MODEL FOR WATER MEASUREMENT

Appendix A

Prepared for: California Energy Commission
Prepared by: UC Santa Barbara

JUNE 2017
CEC-14-081

PREPARED BY:

Primary Author(s):
Kevin Langham, UC Santa Barbara
Roland Geyer, UC Santa Barbara

Institute for Energy Efficiency
University of California, Santa Barbara
2316 Phelps Hall
Santa Barbara, CA 93106-5160
http://www.iee.ucsb.edu/

Contract Number: EPC-14-081

Prepared for:

California Energy Commission

Anish Gautam
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

I wish to thank Stan Knutson and Olivier Jerphagnon (PWE) for consulting on all PWE system details, and providing a mechanical meter for LCA purposes. Many thanks to Dr. Zoldoske at CSU Fresno for providing regular feedback and for advising on the pump sampling strategy, and to Arman Shehabi (LBNL) for providing email and phone consultation on estimating GHG impact from cloud computing. Additional thanks to McCrometer and Seametrics employees for providing all requested product information.

ABSTRACT

Considering recent California legislation, growers will be required to measure and report the volume of water used. It is difficult to accurately measure water, and many farmers do not currently have measurement infrastructure in place that meets these legislation standards. To meet compliance stipulations farmers will be required to invest in new equipment to comply with regulations. Hence, there is a need for new forms of measurement that will not require high investments and provide the level of performance required by the legislation.

This document aims at comparing three different forms of metering which meet the legislation standards for measurement. These include the use of a mechanical flow meter with manual readings, a magnetic meter with a telemetry system and PowWow Energy's (PWE) solution to measure volume of water pumped from a well.

To accomplish this task, Life Cycle Assessment (LCA) methodology will be used. In LCA, a functional unit is defined which ensures that each system being compared fulfills an equal amount of work. The functional unit is the reporting of annual volume of water pumped at a farm using a meter with at least 10% accuracy and the transmission of that data to the state.

The results from comparison are presented in the table below. The PWE system has the lowest environmental impact, and the easiest logistics associated with installation and use. There was not enough available data to estimate the environmental impacts of the magnetic meter. The mechanical meter has the lowest annual cost followed by the PWE system, while the magnetic meter is almost a factor 4 higher than the mechanical meter and factor 2 higher than the PWE system. Water measurement accuracy is the only category where the PWE system did not match up to the mechanical and magnetic meters, with greater range of percentage error. However, it does support the maximum field error requirement from Title 23 of the California Code of Regulations. It should be noted that the PWE system accuracy was based off measurements in the field whereas both other meters were based off lab rated accuracy. We collected field measurements of mechanical meters in the field, and some had significant error beyond 10%.

Variable	Mechanical Meter	Magnetic Meter	PWE System
Environmental Impact (kg CO2 eq.)	36.65	N/A	0.48
Cost (USD)	$638	$2,497	$1,040
Logistics (Qualitative)	Difficult/Moderate	Moderate/Easy	Easy
Statistical Accuracy (% error)	1%-2%*	1%-2%*	1%-10%

* *These are lab rated errors. Field error is often greater without proper management.*

Keywords: water, life-cycle assessment, sustainable groundwater management act, smart meter, mechanical meter, magnetic meter, greenhouse gas emissions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

1.1 The water resource or “the Tragedy of the Commons”

California is facing the worst drought in recorded state history. All of California’s 39 million residents are experiencing the deleterious effects of that drought to one extent or another, and the agricultural sector is no exception.

Growers who have relied on surface water to grow crops were forced to use groundwater to make up the deficit in surface water. Pumping water extensively from aquifers leads to increased energy costs and threatens long-term water reserves. Increased reliance on groundwater had has caused historically stable water tables to fall and put the sustainability of farming at risk.

In 2014, California growers were expected to extract an additional 5 million acre-feet of groundwater from aquifers to compensate for the lack of surface water and rain, resulting in an additional 454 million dollars of energy costs for water pumping. Agriculture is a 45-billion-dollar industry and represents more than 8% of the California energy footprint. There are more than 80,000 farms in California with an average of 1.3 pumps per farm. Agricultural energy demand is a significant fraction of power usage, and currently peaks in August, when total grid energy needs are highest. Groundwater usage is a good illustration of Garrett Hardin’s “Tragedy of the Commons”.

Hardin was an ecologist and microbiologist whose most famous work is his 1968 essay, “The Tragedy of the Commons” [1]. Hardin’s essay focuses on herders sharing a common parcel of land on which each can graze their sheep. According to Hardin, the land could provide adequately if the number of herders grazing cattle on it was kept in check, through natural population control mechanisms such as war and disease. If the numbers were to increase as a result of those natural population control mechanism being overcome, the land would be no longer sufficient to support the population. Each person sharing the land, acting in self-interest, would continue to tax the resources of the commons, despite the fact that if enough people do so, the land will be damaged and unable to support them. To avoid inappropriate use of the water common, California state had to adopt new policies.

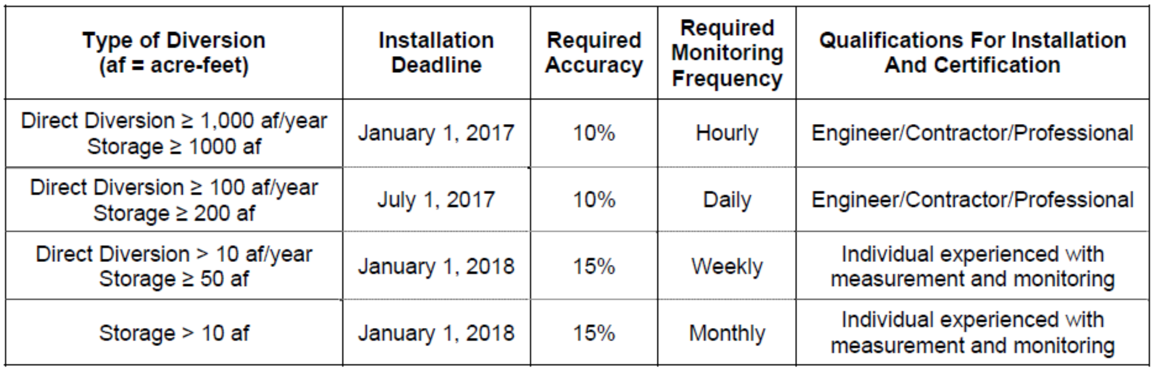
1.2 Recent regulation on surface water and groundwater management

1.2.1 Diversion of surface water

On January 19, 2016, the State Water Board adopted an emergency regulation for measuring and reporting water diversions (Senate Bill 88). The measurement requirements of the regulation apply to all water right holders who divert more than 10 acre-feet of water per year. The annual reporting requirements in the regulation apply to all statement holders as well as persons authorized to appropriate water under a permit, license, registration (small domestic, small irrigation, or livestock stockpond), or certificate for livestock stockpond use.

SB-88 set expectations for both the accuracy of measurement devices as well as the monitoring frequency of the device (Table 1). The regulation links both device accuracy and monitoring frequency to the volume categories.

Table 1. Required accuracy for measurement and frequency for monitoring



Type of Diversion (af = acre-feet)	Installation Deadline	Required Accuracy	Required Monitoring Frequency	Qualifications For Installation And Certification
Direct Diversion ≥ 1,000 af/year Storage ≥ 1000 af	January 1, 2017	10%	Hourly	Engineer/Contractor/Professional
Direct Diversion ≥ 100 af/year Storage ≥ 200 af	July 1, 2017	10%	Daily	Engineer/Contractor/Professional
Direct Diversion > 10 af/year Storage ≥ 50 af	January 1, 2018	15%	Weekly	Individual experienced with measurement and monitoring
Storage > 10 af	January 1, 2018	15%	Monthly	Individual experienced with measurement and monitoring

1.2.2 The Sustainable Groundwater Management Act

Unsustainable management of groundwater resulted in California Governor Jerry Brown signing three laws: Assembly Bill (AB) 1739 and Senate Bills (SB) 1168 and 1319 (collectively referred to as The Sustainable Groundwater Management Act of 2014 (SGMA).

SGMA applies to all groundwater basins (i.e. 515 basins), but contains special requirements for basins or sub-basins that the Department of Water Resources (DWR) designates as medium- and high-priority basins (i.e. 127 basins, representing about 96% of groundwater extraction). For these basins, Groundwater Sustainability Agencies (GSAs) will have to be formed by June 2017.

GSAs will be responsible for developing and implementing a Groundwater Sustainability Plan (GSP) to manage basins by defining a sustainable yield. GSPs will include restrictions such as the maximum quantity of water that can be withdrawn annually from a groundwater supply without causing an undesirable result. GSAs have 3 to 5 years to develop and begin implementing their GSP and have 20 years to achieve sustainability.

Even though GSPs will not be implemented for a couple of years, SGMA will require groundwater elevation to be monitored [2]. To some extent, the common understanding is that growers will have to monitor groundwater extraction at their farms. For now, DWR has not released what is a valid method for recording groundwater usage.

1.3 Comparison of Three Measurement Systems Using LCA

In light of recent California legislation, growers who divert more than 10 acre feet of surface water per year will be required to measure and report the volume of water diverted. The common understanding is that growers will have to monitor water extraction on their farms to comply with SGMA and SB-88. It is very difficult to accurately measure water on a commercial scale without breaking the bank. Many farmers do not currently have measurement infrastructure in place that meets these existing and potential legislation standards, and they will be required to invest in new equipment to comply with new regulations.

Hence there is a need for new forms of measurement that will not demand high investments and provide the level of performance required by the legislation. This document aims at comparing three different forms of metering which meet the legislation standards for measurement. These include the use of a mechanical flow meter with manual readings, a magnetic meter with a telemetry system and PowWow Energy's (PWE) solution to measure volume of water pumped from a well. It is important to understand the costs and benefits associated with each different measurement technique. This document will analyze each of the three systems for water measurement under the lens of environmental impacts, cost, logistics/ease of use and statistical accuracy.

When comparing the three systems, it is essential to account for the impacts over the entire life of the product, and to ensure that all systems being compared are equal. To accomplish this task, Life Cycle Assessment (LCA) methodology will be utilized. In life cycle assessment, a functional unit is defined which ensures that each system being compared fulfills an equal amount of work. To define the functional unit of this study, accuracy measurement requirements of California Code of Regulations Title 23 will be used. By using LCA methodology, this analysis thoroughly compares the three systems under several categories, throughout the entire product lifecycle.

2. Environmental impacts: LCA Analysis of Water Measurement

The purpose of this LCA analysis was to compare the environmental impacts (GHG emissions) of using three different systems for water measurement and reporting. The systems that were compared include a standard mechanical flow meter with manual readings, a magnetic meter with telemetry system and PWE's solution to measure water volume pumped using existing utility meters. The LCA analysis was done in GaBi ts, and data from the EcoInvent Database was also used. This document follows ISO 14044 (2006) standards where applicable.

The results are a small part of the much larger goal of quantifying the water and energy savings from using the PWE's solution instead of the status quo. Without conducting life cycle based analysis, it is difficult to accurately quantify the total energy and water burden from the manufacture, installation and use-phase of these three methods for measuring water. These results are meant to illuminate the different environmental impacts associated with each system. The results should only be used to compare the three systems in this analysis and not extrapolated to other measurement systems.

2.1 Function and Functional Unit

The function of the systems being compared in this study is to measure the volume of water pumped, convert that information for transmission, and transmit that information to the state. To define the functional unit, Title 23 in the California Code of Regulations (CCR) will be used. This legislation outlines specific requirements for water measurement devices.

Title 23 also outlines water measurement requirements for agricultural water suppliers. This study assumes that the surface water accuracy standards will hold true for groundwater monitoring, even though the new regulations for groundwater have not been released. The water measurement standard requires monitoring devices in the field within 10%-15% accuracy depending on the volume of diversion (if using a non-laboratory certification). [3]

Therefore, the function that we are fulfilling is the regulation requirements for water reporting. Thus, the functional unit is the reporting of annual volume of water pumped from a single pump on a farm using a meter with at least 10% accuracy, and the transmission of that data to the state. Each system in this study will have slightly different measurement frequencies within the year.

2.2 System Boundary

Due to the fact that this is a comparative LCA, we will only model unit processes that are likely to differ between our two systems. In the case of this specific comparison, it is assumed that all three product systems transmit data to the same California government servers. In order to comply with Title 23 of the CCR, one must be able to transmit water-use data in a form that is readable by Microsoft Excel, Microsoft Access or another software program. Thus, the environmental impacts from transmission of data to the state will not differ for each system, and they are excluded from this model. Additionally, it is difficult to make accurate assumptions about shipping distances for the different physical products. For this study shipping impacts will not be included in the model.

2.2.1 The Product Systems

This comparative LCA estimates the environmental impacts in terms of kg CO_2 equivalence of three different methods for measuring and transmitting volume of water over one year. The first, assumed to be the traditional method, utilizes a bolt on saddle mechanical flow meter with manual meter readings [25]. The second is the Smart Meter technology used by PWE, which uses existing utility electricity meters and an algorithm to convert spent energy to volume of water pumped at approximately 10% accuracy [21]. The PWE solution takes advantage of the Green Button initiative to retrieve data from utility meters, and does not require the installation of additional infrastructure. The final is a Seametrics magnetic flow meter equipped with a WiseConn telemetry system [26]. It is assumed that the magnetic and mechanical flow meters will last 5 years. Each product system in this study is discussed in further detail below.

2.2.1.1 Mechanical Flow Meter

The product system for the mechanical flow meter is described below (Figure 1). This system requires the installation of new infrastructure necessary to measure the volume of water consumed. Thus, the manufacture of the mechanical flow meter is modeled in the meter manufacture unit process. The installation unit process does not include any human energy spent (e.g. non-electric tools) but includes other forms of energy spent (e.g. diesel generator).

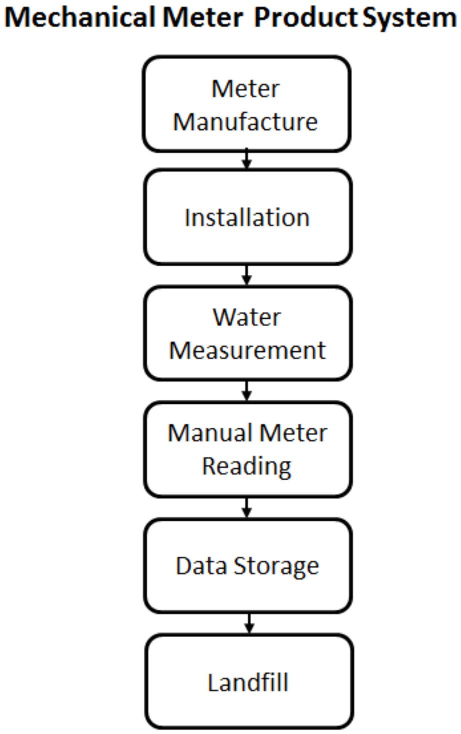


Figure 1. Process flow diagram representing all unit processes being modeled in the product system of a bolt on saddle mechanical flow meter. Shipping is excluded from the model.

The ‘use-phase’ of this system includes the measurement of water volume that passes through the pipe, followed by the manual reading and recording the data on a desktop PC. It is assumed a farm worker will drive a small passenger vehicle a total of 2 miles roundtrip to retrieve the water data from the meter. A sensitivity scenario is presented in the results for various distances traveled. A small passenger car is modeled for transportation to the meter, as it is a middle ground between the two more common forms of transportation on a farm, a pickup truck and ATV. The manual meter readings occur once per week, or 52 times per year or functional unit.

The weekly data gathered from manual readings is stored in an excel file on a desktop PC. To store the data, it is assumed that a person will operate a PC for 10 minutes, once per week to input the data. Energy consumption for storage is calculated by taking the average wattage of a desktop PC, and multiplying it by the total use time per functional unit. Average wattage of a desktop DC is assumed to be 100 W, based on research from Baliga et al (2010) for a modern midrange computer [4]. The total energy used is multiplied by an emission factor for the California (CA) grid mix. The CA emission factor used in this study is 0.354 kg CO2 eq/kWh, which aligns closely with estimations based on recent studies from the California Public Utility Commission (CPUC), California Energy Commission (CEC) and California Air Resources Board (CARB) [13, 14, 15].

The mechanical flow meter does not require any additional electricity to measure the water flowing through the pipe, and consequently does not have any impacts associated with measurement. The end-of-life is considered to be landfill; however, a recycling sensitivity scenario is modeled in the results.

2.2.1.2 Smart Meter and Mathematical approach

The PWE Smart Meter system functions by converting kWh of electricity usage from booster and well pumps into volume of water applied. Before this data reaches the customer, it must first travel to two different locations (Figure 2). The energy use is measured at the utility smart meter, transferred to utility servers, then sent to PWE’s cloud servers at Amazon where the data is converted to volume of water, and finally transferred to the customer via email. It is important to understand the path of the data, in order summarize the important unit processes to model.

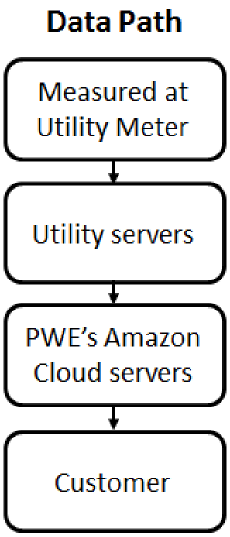


Figure 2. Representation of the path the data takes starting from measurement at utility smart meters, and ending at the customer. It is assumed that transfer is over the public internet.

The product system including relevant unit processes for the PWE Smart Meter System is described below (Figure 3). Unit processes consist of two instances of data transfer, and storage/computation in the Amazon cloud servers. Data measurement and transfer from the utility meter to utility servers is not modeled as these processes would occur independently of PWE involvement. Each of the unit processes are described in greater detail in the following subsections.

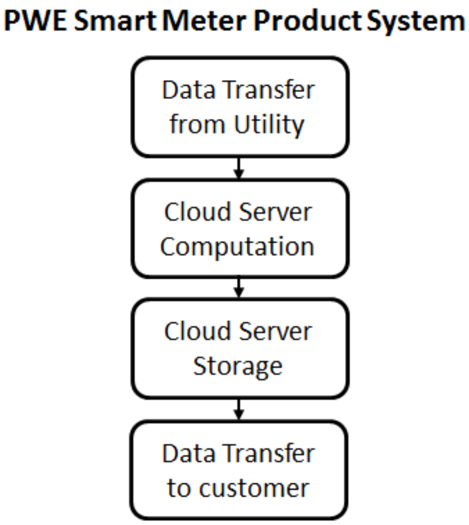


Figure 3. Process flow diagram representing all unit processes being modeled in the PWE Smart meter product system. Data measurement is not included in this model as Utilities will measure electricity usage regardless of PWE usage of their data.

Data Transfer

Within the Smart Meter system being modeled there are two instances of data transfer, illustrated in the product system (Figure 4). The first is the transfer from Investor Owned Utility (IOU) computers to the PWE servers, and the second transfer occurs from the PWE servers to the customer via email. To calculate the impact from both data transfer stages, secondary research was conducted. From this research, the energy impact per GB of data transferred or the 'energy factor' was determined. The energy factor is multiplied by the total GB of data transfer within the functional unit, and then multiplied by a California emissions factor (see Impact Calculation at the end of section 2.2.1.2) to estimate GHG impacts for data transfer. The details of this calculation are outlined in the following paragraphs.

There have been numerous studies published that estimate the energy consumption of data transfer over the internet [5, 7, 8, 9, 10, 11, 12], providing values ranging from 0.0014 kWh/GB [7] for transfer through metro and core networks, to 3.5 kWh/GB for transfer through Customer Premise Equipment (CPE), Digital Subscriber Line Access Network (DSL), IP core network and large data centers [8]. The specific components of the Information and Communications Technology (ICT) network modeled vary in these studies, resulting in contrasting estimations for data transfer. Considering this finding, the specific stages of transmission included in our model are clearly outlined in Figure 4. Malmodin et al. (2014) provide the most detailed, transparent and current estimation of the energy burden for data transfer [5]. This publication was recommended as the most current and accurate data transfer estimation by cloud data center researchers at Lawrence Berkley National Lab [6]. Of the estimated impact, values used in this study from Malmodin et al (2014) were higher than other estimates, providing more conservative results.

There are several ways to interact with the ICT network, broadly described as the 'internet', depending on the user device and the task at hand. To begin estimating the impacts of data transfer, the specific path from cloud data center to user PC within the ICT network must be defined. Figure 4 shows the map of data transfer used in this analysis. The map is modified from Malmodin et al. (2014), who describe the path for data transfer using a fixed broadband xDSL subscription from a home PC [5]. This data path is assumed to be the best representation the two data transfer unit processes being analyzed in this study.

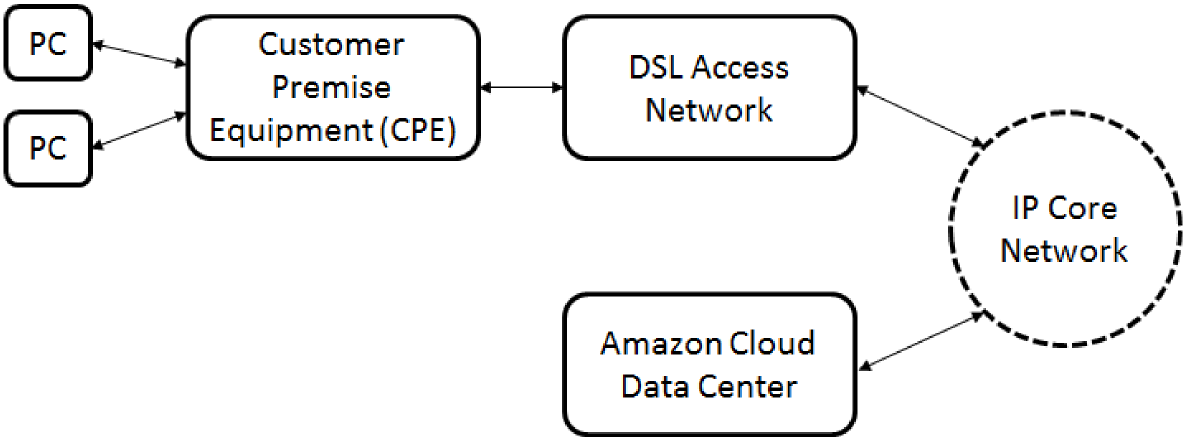


Figure 4. Map of the data path being modeled in for data transfer in this analysis.

For stages of data transfer described in Figure 4, average required infrastructure was assumed in order to estimate energy burden. For an in-depth description of the infrastructure modeled in each stage of data transfer, reference Malmodin et al. (2014) and the supporting information available on the web (Section 6.5) [5].

Impacts for data transfer have been calculated in terms of energy use per gigabyte (GB) of data. A list of the estimated energy consumption per GB of data transfer for each stage described in Figure 4 is shown in Table 2. The resulting energy factor of 0.46 kWh/GB will be used in this study to calculate the energy burden of data transfer (Table 2).

Table 2. Comparison of the kWh/GB impacts for each stage of data transfer from cloud data centers to user device. Differences between the primary research reference [5] and this study. kWh = kilowatt hour. GB = Gigabyte

Transfer Stage	**Malmodin (2014) [kWh/GB]**	**This Study [kWh/GB]**
PC	1	*Not Included*
CPE	0.3	0.3
Fixed DSL	0.08	0.08
IP Core Network	0.08	0.08
Cloud Data Center	1	*Not Included*
Total	**2.46**	**0.46**

The calculations for total impact per GB of data transferred are 2 kWh lower than the estimation by Malmodin et al. (2014) (Table 2). This is because the impacts from the use of the user PC and the data center operation have been omitted in the data transfer unit process. PC impacts have been omitted as they were calculated in a way that does not fit the calculation of the functional unit in this study. They were calculated by dividing the average data transferred per customer (400 GB) by the average total annual computer usage per household (395 kWh). In the product system described in this study, the PC users would operate their computer for less than one minute to transfer the data. Therefore, including the estimation from Malmodin et al of PC impacts would result in an overestimation of energy burden of the data transfer unit process. The energy consumption from data centers is included in the data storage and calculation unit processes within the system boundary.

To calculate total energy burden, the total MB data transfer for our functional unit was estimated (Table 3). Transfer from the utility to PWE's Amazon Cloud servers occurs daily, and contains information on total energy use at the pump. This data has been estimated to be 3 MB [16]. The total data transfer per functional unit amounts to 1095 MB (3MB * 365 days) for transfer from utility servers to PWE cloud servers. Transfer from the cloud servers to the customer is estimated to occur once per week, via a 100 kB email [16]. Therefore, transfer of 5.2 MB is necessary per functional unit for distribution of water data to the customer.

Table 3. Calculations and estimations for total data transferred per year (functional unit) in this study. kB = kilobyte. FU = Functional Unit (discussed in section 2.1.1). MB = megabyte. PWE = PowWow Energy.

Transfer	Size of transfer (kB)	Total transfers per FU	Total transferred per FU (MB)
Utility to PWE	3000	365	1095
PWE to customer	100	52	5.2

Data Computation

Once the electricity consumption data have been transferred to the Amazon Cloud servers they must be converted to total volume of water pumped via the PWE algorithm. This computation is done in servers inside an Amazon virtualized cloud data center. Amazon does not release detailed information about the specifics of their data centers, and many informed assumptions had to supplement this lack of information. Most assumptions were based on the most recently published analysis of the energy impact of U.S. data centers [17] and personal conversation with the lead author and data center energy expert, Arman Shehabi [6]. Assumptions for the calculations of the energy burden of computation are compiled from Table 4 below.

Table 4. List of cloud data center assumptions used in the calculation of the total energy burden of computation per functional unit.

Variable	Description	Quantity	Unit	Source
P_m	Maximum server power draw	118	W	[17] p. 9
SU	Average server utilization	45	%	[17] p. 10
DR	Server dynamic range	44	%	[17] p.11
PUE	Power use effectiveness	120	%	[17] p. 23-24
h	Annual server runtime	8760	hours	[6]
N/A	Users per server	1	N/A	[6]

All of the required computations for PWE can be completed in a single socket unbranded volume server inside of the data center. In reality, these servers are shared among several clients (one of the core aspects that make cloud computing so efficient). However, in this estimation we make the conservative assumption that PWE is responsible for the entire burden of the server. Shehabi et al. (2016) define the maximum power of a single socket unbranded volume server to be 118 watts (Table 4) [17].

The average power draw is based on the server utilization and dynamic range (DR) of the server. In this study, we assume the average utilization is 45% based on the average utilization of volume servers in hyperscale data centers from 2000-2010 [17]. The DR of a volume server is the ratio of the lowest power level at idle power, and the maximum power draw [17]. The DR used for this analysis is 44%, which is based on the average for volume servers reported in the SERT[1] database [17].

The power use effectiveness (PUE) is a metric used to measure the energy efficiency of a data center. This variable is a ratio between the power draw from IT equipment and the power draw from the entire data center. The closer this value is to 1, the more efficient the data center. This experiment will use a conservative value for hyperscale data center PUE of 1.2, even though numerous large data centers already claim PUE of closer to 1.1 or lower [17, 18, 19]. A PUE of 1.2 indicates that the IT equipment consumes 80% of the energy, while other external equipment such as air conditioners consume the other 20%.

The variables listed in Table 4 are used to calculate the energy consumption from computation in volume servers in a virtualized cloud data center. Idle power draw is calculated by multiplying the maximum power draw by the dynamic range (Table 5). To calculate the average power draw equation 1 was used:

$$P_a = SU * P_m + (1 - SU) * \ DR * P_m \qquad [1]$$

For this equation, we assume power draw increases linearly from idle power (P_i) to max power (P_m) draw. To calculate the average power draw we first multiply the difference of P_m and P_i by the server utilization (SU = 45%). We then add this value to P_i to get the average power draw, which amounts to 81.66 W

Table 5. Calculations for the total energy use from the computation of water pumped using the PWE algorithm. Other inputs for these calculations are listed in Table 4.

Variable	Description	Quantity	Unit
P_i	Idle Power Draw	51.92	W
P_a	Average Power Draw [1]	81.66	W
TP	Total pumps	1000	#
TEC_c	Total Energy use per year [2]	858,368	Wh

---

[1] SERT is The Server Efficiency Rating Tool used in the US Environmental Protection Agency's Energy Star program. This tool collected a large pool of power consumption data which is managed by the Information Technology Industry Council.

EC_c	Single pump annual energy consumption from computation	858	Wh

Once average power draw has been established, the annual run time needs to be defined. The assumption was made that the server is constantly running at average power draw, despite the fact that PWE computations only require a small fraction of the day to complete. The total energy use from the system is calculated in equation 2 below:

$$TEC_c = P_a * PUE * h \qquad [2]$$

The average power draw is multiplied by the PUE and the total hours in a year, resulting in an estimated energy consumption of 858 kWh per year. However, the functional unit in this study only includes the burden from a single pump. Assuming the data from 1000 total pumps are being processed, we allocate one one-thousandth of the energy burden to our functional unit, amounting to 858 Wh per year. This burden will be converted to kg of CO_2 equivalent in the results section of the analysis using the emission factor for CA of 0.354 kg CO_2 eq. defined in section 2.2.1.1

Data Storage

Once the energy use data has been converted it is stored within the same cloud data center where computation occurred. For this project, a 2-socket volume server is rented from Amazon Web Services for the storage of data. The maximum power draw of 2+ unbranded volume servers in hyperscale data centers is 365 W [17]. The storage capacities of these servers vary due to the potential installation of additional external storage in the form of solid state drives (SSD) or hard disk drives (HDD). For the pump data, PWE has purchased 100 GB of storage on an SSD. Therefore, we assume the capacity of the server to be that of an average SSD, as recommended by industry experts [6]. The average storage capacity of an SSD in 2017 is approximately 2 TB/drive [17].

PWE elects to store the raw power data from utilities and the results from the algorithm for future reference. Data centers are very efficient at storage and are able to compress the data to 10% of its original size before long term storage. For each meter, 10 kB of post processed data is stored per day for quick access, and 0.3 kB of compressed power data is stored for situational access. Only the 10 kB will be included in this model as the compressed data is insignificant.

The energy burden from storage is allocated to our functional unit based on the proportion of the total storage capacity that is taken by PWE at any given point. For an entire year, storage energy consumption changes daily, because the quantity of data stored increases by 10 kB per day. To calculate the cumulative energy consumption from storage over a year, the following equation is used:

$$EC_s = \sum_{i=1}^{365} \left[P_m * \left(\frac{Ds * i}{C_m} \right) \right] * h * PUE \qquad [3]$$

The variables used in equation 3 are defined in the following table:

Table 6. Description of the variables used in equation 3 to calculate the energy consumption from storage of algorithm data in hyperscale cloud servers.

Variable	Description	Quantity	Unit
P_m	Maximum server power	365	W
Ds	Daily storage quantity	10	kB
C_m	Maximum capacity of the server	2000	GB
h	Hours per day	24	hours
PUE	Power Use Effectiveness	120	%
i	Days per year	365	days
EC_s	Energy consumption from storage	3.51	Wh

Using equation [1] we calculate the energy burden for storage to be 3.51 Wh per pump per year. The system consumes such a low quantity of energy, because the digital storage is minimal.

Impact Calculation

Impacts from this section will be calculated differently from other product systems in this comparative analysis. Instead of modeling the unit processes in GaBi ts and estimating the CO_2 equivalent from all stages, the energy burden from unit processes will be calculated, and the environmental impact will be based exclusively on energy use. Estimating the impacts from other life cycle stages such as infrastructure manufacture and end of life are not in the scope of this project. To develop an emission factor, the California grid mix as reported by California E-Grid (2014) [20] was modeled in GaBi ts to yield an emission factor of 0.354 kg CO_2 eq./kWh. This factor represents a California average, as the location of the modeled system could occur anywhere in the state. The estimation of environmental impact per kWh aligns closely with estimations based on recent studies from the California Public Utility Commission (CPUC), California Energy Commission (CEC) and California Air Resources Board (CARB) [13, 14, 15].

2.2.1.3 Magnetic Meter and Telemetry System

For this study, the level of publicly available information on the magnetic meter and the associated telemetry system was not complete enough to perform an LCA on the systems. Seametrics and WiseConn were contracted and additional data was requested so that this LCA may be completed. Representatives from each of these companies seemed compliant and willing to share information, but the necessary information (bill of materials and mass of each material) was never received. The environmental impacts were not calculated for the magnetic meter or telemetry system in this study as necessary data was not obtained.

2.2.2 Cutoff Criteria & Allocation

When modeling each product system, a mass based cutoff criteria of 1% will be used. This means that if any one input makes up less than 1% of the mass, it will not be considered in the study.

2.2.3 Data Sources

For this analysis data will be used from PowWow Energy employees, manufacturers, Gabi ts and EcoInvent databases, online sources and conversations with farmers within our project who use the products in the model. Ideally, primary data from manufacturers and farmers will be used where available. However, when no primary data is available, assumptions will be made based on the best available online resources. For raw material data, general processes from EcoInvent and GaBi ts will be used. Missing data will be documented, and assumptions will be made to fill the data gaps.

For the mechanical flow meter, mass data for each component will be gathered manually by taking apart the meter and weighing each component. Assumptions will be made when pieces cannot be easily separated for weighing.

2.2.4 Comparison between Systems

When comparing two systems, it is essential that the equivalence of both systems be evaluated. In the case that the meters do not fulfill the functional unit equally, differences will be identified and reported.

2.3 Results

In LCA, various environmental impact indicators are used to quantify environmental impact. For the purpose of this study, the primary concern was global warming potential (GWP). GWP results for the mechanical flow meter are presented using the TRACI 2.1 impact category, Global Warming to Air including biogenic carbon (kg CO_2 equivalent). The kg CO_2 equivalent was estimated for the PWE system through calculating energy burden and multiplying that burden by an emission factor of 0.354 kg CO_2 equivalent to determine overall GWP impact. Analysis of other impact categories are outside the scope of this analysis.

2.3.1 Comparison of three systems

The environmental impact for the three systems in terms of kg CO2 equivalence has been estimated below in Figure 5. Sufficient data was not available to calculate the impact of the magnetic meter with telemetry system, and the impacts remain unknown. The environmental impact from using the PWE system is only 1.3% of the impact from using a mechanical meter to measure volume of water pumped over an entire functional unit. The PWE system benefits from economies of scale in the large cloud servers, and does not require the manufacture of any infrastructure reducing the impacts when compared to the mechanical meter. Additionally, the PWE system does not require driving vehicles to check meters, which was responsible for over 80% of the mechanical meter emissions. Sensitivity scenarios and the details of the calculations of each system's environmental impact are calculated in the following results sections.

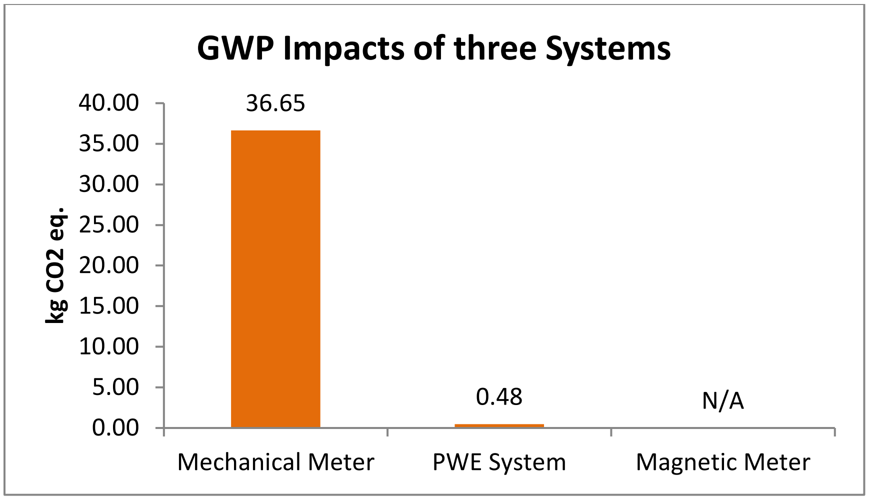


Figure 5. Comparison of the GWP 100 impacts of three systems for measuring volume of water pumped from a single pump for an entire year. Mechanical meter impacts calculated using Traci 2.1 impact category, and PWE systems impact calculated by estimating energy burden and multiplying by an emissions factor of 0.354 kg CO2 eq.

2.3.1.1 Mechanical Flow Meter

The GWP impacts of using a mechanical flow meter to measure, manually read, and transmit data for one year (functional unit) has been calculated in Figure 6. The total GWP impacts per functional unit for the mechanical flow meter amount to 36.65 kg CO_2 eq. The process with the highest impact per functional unit was the meter reading, which produced 30.11 kg CO_2 eq. or 84% of total emissions (Figure 6). There may be impact associated with installation of the meter, however necessary data for this calculation was not available at the time of this study. The majority of impacts stem from requiring an employee to drive to the site for installation, however calculating these impacts were outside the scope of our project. Water measurement was found to have no GHG emissions as it is completed without the use of energy. Impacts from meter manufacture were divided by 5 due to the fact that the product is assumed to last five years.

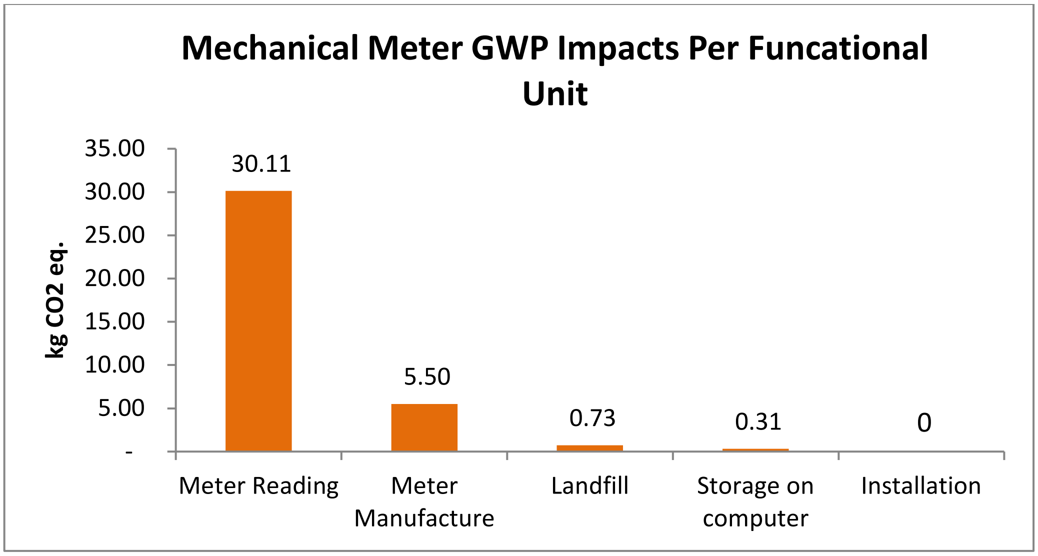


Figure 6. GWP impacts per functional unit (annual measurement, reading, and transmission of volume of water pumped) for the different unit processes of a mechanical bolt on saddle flow meter. Results were calculated using TRACI 2.1 impact categories.

2.3.1.2 Mechanical Meter Manufacture

The manufacture of the mechanical flow meter was modeled in GaBi ts, and estimated to have a cradle to gate GWP_{100} impact of 26.48 kg CO_2 eq. Each component of the meter was modeled separately to understand which had the largest impacts (Figure 7). The aluminum canopy had the highest proportion of total GWP impacts, and was responsible for nearly 50% of the GWP emissions.

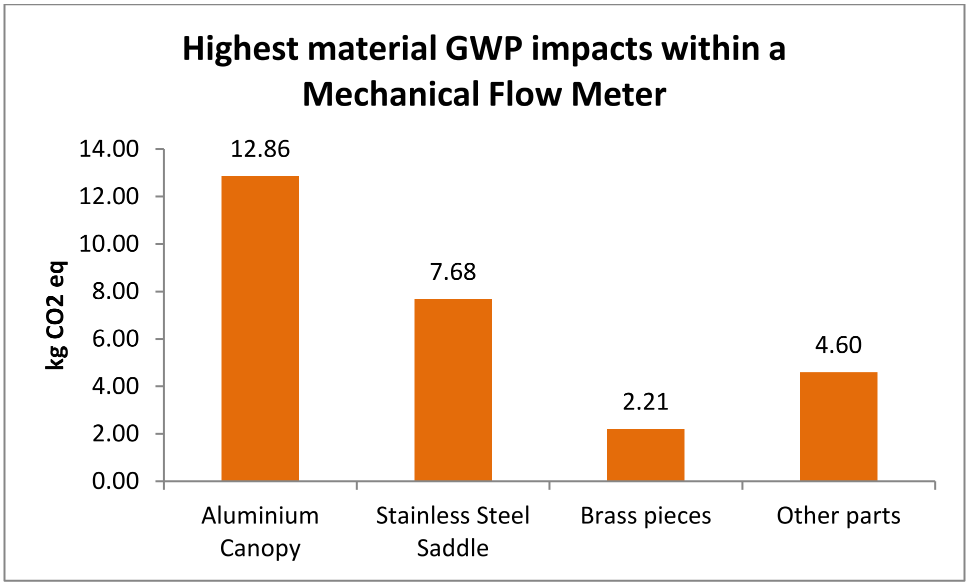


Figure 7. Estimated CTG GWP 100 impact of a mechanical bolt-on-saddle meter. Impacts were estimated using GaBi ts and TRACI 2.1 GWPs.

2.3.1.3 Mechanical Meter Scenario Analysis

Two scenarios were tested with the mechanical meter model. The first was varying the distance driven in a passenger vehicle to manually read the meter. It was assumed for the baseline that a farm employee would drive 2 miles round trip to check the meter. Because this distance is likely to vary between different ranches, total GWP impacts were calculated per functional unit with 1, 2 and 4 mile roundtrip distances (Figure 8).

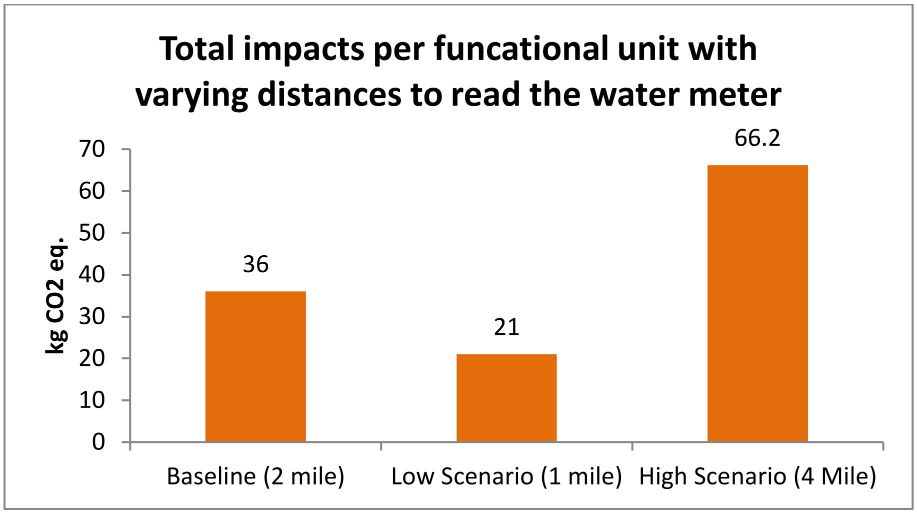


Figure 8. Total GWP impact for a mechanical meter per functional unit with varying distances to travel roundtrip to check the meter. Distances tested included 1, 2, and 4 miles round trip. It was assumed that a farm employee traveled in a small passenger vehicle. Impacts were calculated using TRACI 2.1 impact categories.

Changing the distance traveled drastically altered the GWP for the mechanical meter functional unit. The low scenario decreased impacts from the baseline by 41%, and the high scenario increased impacts by 84%.

The second scenario that was tested was to assume recycling for the end of life of the meter. In the modeled recycling scenario, it was only assumed that aluminum, steel, stainless steel, brass and high impact polystyrene were recycled. There was not enough mass of other materials in the meter, or they were not commonly recycled enough to be considered in the recycling scenario in this analysis. The recycling processes were assumed to have a 90% material recovery efficiency, and the avoided burden method was used to allocate savings from recycling. Applying the recycling scenario resulted in a savings of 23.1 kg CO_2 equivalent from the baseline over the lifetime, or a 4.62 kg CO_2 equivalent savings per functional unit. This savings decreases functional unit GWP impacts by 13%.

2.3.2 PWE Software System

The GWP impacts for using the PWE smart meter system for measuring the volume of water applied from a pump over an entire year are calculated in Table 7. The impacts per functional unit amount to 0.484 kg CO_2 eq.

Table 7. Calculated energy use and environmental impact for each unit process per functional unit for the PWE smart meter system. The environmental impact is estimated by multiplying the total energy use by the emission factor. The Emission factor was calculated based on a grid mix from 2014 California E-Grid data and modeled in GaBi ts.

Unit Process	Energy Use (Wh)	Emission Factor (kg CO2 eq/kWh)	Envy. Impact (kg CO2 e.)
Data Transfer from Utility	503.70	0.354	0.178
Cloud Server Computation	858.37	0.354	0.304
Cloud Server Storage	3.51	0.354	0.001
Data Transfer to Customer	2.39	0.354	0.001
Total	**1367.97**	**N/A**	**0.484**

Over 99% of the impact from this system comes from a combination of the data transfer from the utility to the cloud server, and the computation within the server (Figure 9). Cloud server storage is minimal because only a small portion data (2.92 MB) are stored over a year due to efficient data compression. Additionally, the data transfer to the customer is a single 100 kB email per week, whereas the data transfer from the utility is a 3MB email each day. Computation resulted in the greatest burden because the impacts were modeled so that PWE was responsible for the use of a large volume server for an entire year. In reality these servers are split between multiple customers, and the burden would be less.

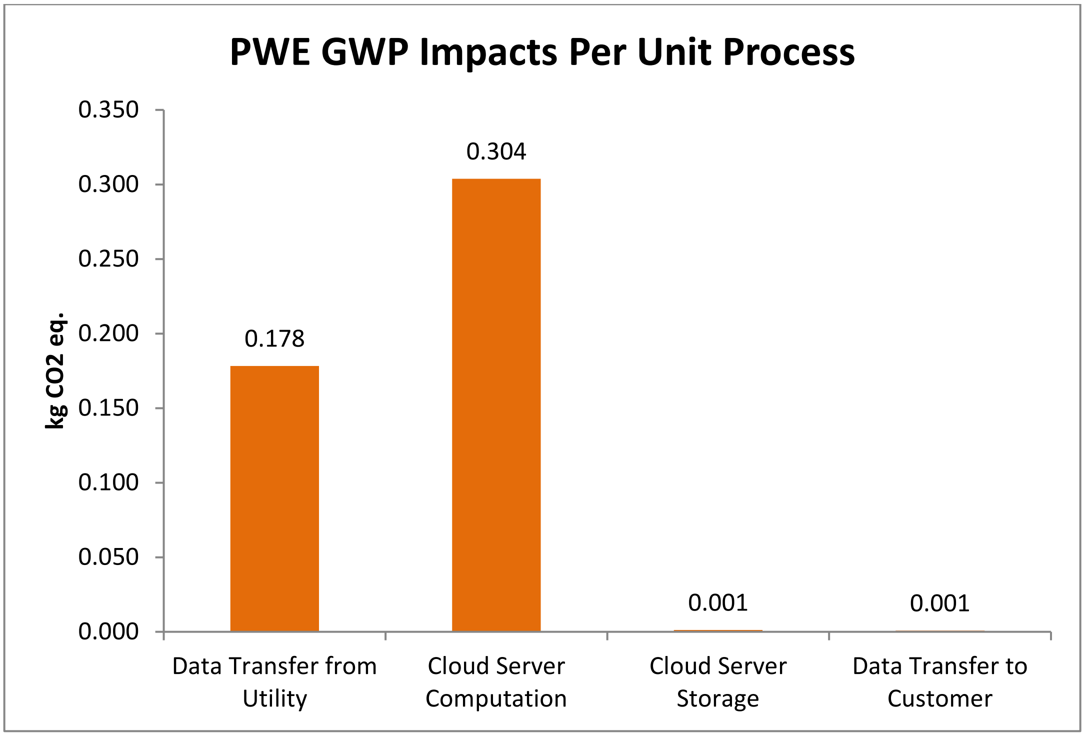


Figure 9. Estimated GWP impacts for the unit processes involved in the PWE methodology for measuring water applied from a smart meter. These are normalized per functional unit described in section 2.1 of this analysis. GWP was calculated based on estimated energy consumption for each unit process and converted for this graph using an emission factor of 0.354 kg CO_2 eq./kWh, discussed in section 2.2.1.2.

2.3.2.1 PWE System Scenario Analysis

Different scenarios were tested with the PWE system to gauge the relative effect on the overall environmental impact. First the impact of storing more data per pump was tested and the results are presented in Table 8. Energy consumption increased linearly for additional data storage modeled. While the energy use does increase, the environmental impact remains small <0.2 kg CO_2 eq for the entire functional unit, because the overall energy use is quite insignificant. An increase in data stored from 10 kB per year to 1000 kB per year could increase the impact of the system by 25%, however the overall impact of the system does not surpass 1 kg CO_2 eq.

Table 8. Energy use and the relative environmental impact of the storage unit process in the PWE system using three varying quantities of storage per day: 10kB, 100kB and 1000 kB.

Variable	Energy use (Wh)	Emissions Factor (kg CO2 e/kWh)	Env. Impact (kg CO2 e)
Storage per day (10 kB)	3.51	0.354	0.0012
Storage per day (100 kB)	35.11	0.354	0.0124
Storage per day (1000 kB)	351.07	0.354	0.1243

A second scenario was tested to gauge the impact of increasing the size of the email to the customer. This scenario may be the case in the future if PWE decides to include more information such as images, with their water report sent weekly. The results from increasing the size of the email are presented in Table 9. Similarly, to the previous sensitivity analysis, the energy use increase linearly based on the size of the email. Increasing the email size from 100 kB to 10000 kB would cause the environmental impact of this specific unit process to increase significantly, however the increase for the overall PWE system would only be increased by 17%. Increasing the size of the emails would cause an increase in the impact of the transmission unit process, but the overall impact would still remain very low at < 1 kg CO_2 eq.

Table 9. Energy use and the relative environmental impact of the transmission to customer unit process for three varying sizes of emails: 100 kB, 1000 kB and 10000 kB.

Variable	Energy use (Wh)	Emissions Factor (kg CO2 e/kWh)	Env. Impact (kg CO2 e)
Size of Email (100 kB)	2.39	0.354	0.0008
Size of Email (1000 kB)	23.92	0.354	0.0085
Size of Email (10000 kB)	239.2	0.354	0.0847

2.3.3 Magnetic Meter with Telemetry System

There was insufficient data available to estimate the GWP impact from the use of the magnetic meter and telemetry system.

3. Costs

This section covers the differences in cost for the three methods for measuring volume of water applied in this analysis. Costs for hardware, installation and labor, and the use cost for each of the meters is compared. The mechanical meter cost is estimated from a quote from McCrometer [22], magnetic meter and telemetry system cost is estimated from an invoice given to PWE [24], and PWE cost is available on their webpage [21]. The total upfront and annual cost for each system is summarized in the Table 10, and discussed in detail in the following sections. Hardware and installation/labor costs were divided by the lifetime of the products (5 years), as our functional unit is a single year, and these are onetime fees.

Table 10. Estimated total cost for three different systems for measuring volume of water on a farm. Annual fee is for a single year. The estimations in this table are subject to change and are case specific. Price estimations come from product quotes, product invoice from purchase, and conversation with company representatives.

	One-time fees		*Annual Fee*	
Meter	**Hardware**	**Installation and Labor**	**Service and Subscription**	**Total per year**
McCrometer 6" Bolt-on-saddle flow meter	$1,192.00	$2,000.00	$0.00	**$638.40**
Seametrics 8" AG2000 Irrigation Magnetic Meter & WiseConn Telemetry system	$5,411.00	$1,006.25	$1,213.33	**$2,496.78**
PWE Smart Meter solution	$0.00	$200.00*	$1000.00	**$1040.00**

**This is an estimated cost for a pump test. Test cost varies, and will often be reimbursed by local utility.*

3.1. Hardware costs

The cost for the hardware of each of the products was estimated from vender quotes or conversations with farmers who recently purchased the meter equipment (Table 11).

Table 11. Pre-tax cost estimations for the three methods for measuring volume of water pumped over a year. The additional cost column will be described in text below the table. McCrometer quote received on 11/8/2016. Magnetic Meter costs gathered from PWE invoice from purchase and installation equipment. PWE costs were gathered from their webpage on 2/21/2017. All prices are subject to change and may not accurately reflect the current price of equipment.

Meter	**Hardware Cost**	**Additional Cost**	**Total**
McCrometer 6" Bolt-on-saddle flow meter	$1,112.00	$80.00	$1,192.00
Seametrics 8" AG2000 Irrigation Magnetic Meter & WiseConn Telemetry system	Mag Meter = $2809; Telemetry = $2602	$0.00	$5,411.00
PWE Smart Meter solution	$0.00	$0.00	$0.00

The McCrometer hardware comes in $1,192 total [22]. The additional cost encompasses a canopy cover and a 3-year warranty on the product. This extended warranty may reduce the cost of part replacement over time. This specific product was slated for the use of exclusively non-potable water.

The pricing of the Seametrics magnetic meter and WiseConn telemetry system amounts to $5,411. The magnetic meter costs a total of $2809; $1979 was paid for the meter itself, and the rest of the cost came from installation equipment, a square wave pulse and a 40-watt solar panel [24]. The telemetry system cost $2602 in total; $1382 was spent on the GRPS unit, $799 on the node and the rest on cables and expansion boards [24].

Unlike the mechanical and magnetic meters, the PWE system requires no hardware, thus no cost for hardware. The only cost for this system is a subscription to their web application which will be covered in section 3.3.

3.2 Labor costs

The installation of the mechanical meter requires additional payments for setup including freight, pipe measurement, cable-run evaluation, equipment start-up and end user training [22]. McCrometer offers a one day installation and training per meter priced at $2000, however the McCrometer sales representative suggested that reaching out to a local contractor may be more cost efficient [22].

Table 12. Cost estimations for installation and labor of the three water measurement systems in this study. An order was required to get a cost estimation for McCrometer installation. Seametrics installation price may vary based on numerous different factors.

Meter	Installation & Labor Cost
McCrometer 6" Bolt-on-saddle flow meter	$2000.00
Seametrics 6" AG2000 Irrigation Magnetic Meter & WiseConn Telemetry system	$1006.25
PWE Smart Meter solution	$200.00*

The magnetic meter required around ~$1000 for installation and labor. This was made up of a $600 labor fee for welding the flow meter onto the pipe, and a $406 fee for system integration and installation.

The PWE system does not require and additional costs for any installation. However, in order to calibrate the PWE algorithm, a current pump test is required. The cost of these tests varies but is typically around $200. This payment can likely be subsidized by utilities such as PG&E (Advanced Pumping Efficiency Program (APEP)) if a pump test has not been administered for several years [23]. PG&E offers subsidies for pump tests at $200/test for pumps not tested in the last 47 months, $100/test for pumps not tested in the last 23 months, and $50/test for pumps in series with another pump (well and booster) [23].

3.3 Telemetry and data hosting costs

The annual cost for data hosting, subscriptions, service and cell phone plans are aggregated in table 13 below.

Table 13. Estimated prices for data hosting, service fees, software subscription and other annual costs associated with the three meters in this study.

Meter	Software Subscription	Annual Service fee	Other	Total
McCrometer 6" Bolt-on-saddle flow meter	$0.00	$0.00	$0.00	$0.00
Seametrics 8" AG2000 Irrigation Magnetic Meter & WiseConn Telemetry system	$0.00	$850.00	$363.33	$1,213.33
PWE Smart Meter solution	$1000.00	$0.00	$0.00	$1000.00

There are no known costs for McCrometer annual service or software subscription. The magnetic meter with telemetry system requires three different annual fees. WiseConn requires $203.33 for an annual monitoring fee on their system, and $160 for a cellular service data plan. Seametrics charges $850 per year for annual service of the equipment. Finally, PWE charges an annual subscription fee of $1000 as its only cost. The price of this subscription varies based on the horsepower of the pump the customer submitting. For the purpose of this study we are assuming a medium sized pump (35HP < xHP < 135HP), resulting in an annual cost of $1000 per meter. The prices range from $600 for <35 HP pump and $1300 for a pump with HP > 135 [21].

4. Logistics

4.1 Introduction

This section aims to compare the three meters in this analysis (mechanical, magnetic and PWE method) in terms of logistic requirements. Two sections including ease of installation and ease of use will be examined to ultimately determine the differences between the three meters. Table 14 shows the subjective overall assessment of each of the systems in the study. Reasoning behind each of the assessments are detailed in the two sections below.

Table 14. Qualitative assessment of the logistical difficulty of the three meters in this study based on ease of installation and use. Assessments are subjective and may vary for different parties.

Meter	Installation	Use	Overall
Mechanical Meter	Difficult	Moderate	Difficult/Moderate
Magnetic Meter	Moderate	Easy	Moderate/Easy
PWE System	Easy	Easy	Easy

4.2 Installation

Mechanical Meter: Difficult

Installation of the mechanical bolt on saddle flow meter typically requires the aid of a trained professional. A quote from McCrometer stated that they will need to visit the site to measure the pipes, perform cable run evaluations, install, and check that everything is running properly [21]. A 6-inch meter must be installed at least 30 inches downstream from any obstruction, and in a pipe that has a full flow and no swirling of water. Water swirling can be caused by centrifugal sand separators or two elbows in different planes. The flow of the water in the pipe and the maximum pressure must be known to select the proper meter to install.

An interesting clause in the installation contract states that the buyer will, "provide McCrometer employees with all Personal Protective Equipment (PPE) and information and training required under applicable safety compliance regulations and Buyer's policies." Additionally, the buyer will pay the McCrometer employees a standard hourly rate to attend necessary safety classes for work on a given property. McCrometer offers a day long service that includes installation and training, however the installation can also be done by local contractors. The classification of difficult has been given because installation likely requires multiple visits from a trained professional, and potentially providing staff with extra pay and equipment.

Magnetic Meter: Moderate

Once a location is selected where the pipe will be full when water is running, a flat compressible gasket must be installed on both sides of the meter. Special instructions are required for installing on metal vs plastic pipes. Once the meter is installed a telemetry system can be added to the setup. The magnetic meter is equipped with an option to have a power input and pulse output for a telemetry system. A Wiseconn RF-X1 node can be easily installed on the magnetic meter for storage and transmission of data. The classification of moderate has been given to the magnetic meter, because it requires the installation from a trained professional, and potentially a separate professional to train and install the telemetry system.

PWE Smart Meter Solution: Easy

Installation for the PWE Smart Meter is not necessary, because this system functions using existing infrastructure. The only necessary on-boarding requirement includes a pump test on the well or booster, and inputting utility account information on the PWE web application. The classification of easy has been given to the smart meter because the only onboarding requires the setting up a pump test, submitting it online, and entering utility account information.

4.3 Use

Table 15 shows the assessment for ease of use for each of the three meters.

Table 15. Qualitative assessment of the logistical difficulty of the three meters in this study based on ease use. Assessments are subjective and may vary for different parties

Meter	Use
Mechanical Meter	Moderate
Magnetic Meter	Easy
PWE System	Easy

In order to get readings from the mechanical meter, someone is required to drive to the meter and read the dial. They then must store the data electronically. Magnetic meters with telemetry systems have an advantage in that they transmit the data wirelessly, removing the requirement for meter readings. For the PWE system, the team will send emails monthly that include the total water used as calculated by their algorithm. Aside from actual readings, all meters will measure the water flow autonomously. Maintenance may be necessary for the mechanical meter throughout its lifetime. Maintenance is limited for magnetic meters, as there are less moving pieces. The PWE method required limited maintenance once the pump test has been recorded.

5. Statistical Accuracy of Measurements

The reading error associated with the three meters in this analysis is presented in Table 16. Values for the mechanical and magnetic meter come from lab rated error in spec sheets, which may vary in the field. PWE error estimation was completed by PWE employees through numerous field tests, and verified independently by UCSB. Details of UCSB verification and results can be seen in Appendix A.

Table 16. Summary of accuracy associated with the three meters in this analysis.

Meter	Error in readings	Source
Mechanical Meter	± 1-2%[1]	*Spec Sheet [25]*
Magnetic Meter	± 1-2%[1]	*Spec Sheet [26]*
PWE system	± 1-10%[2]	*Independent Verification by UCSB §5.4.2*

[1] *These are lab rated errors. Field error is often greater without proper management.*

[2] *95% of sampled error (n = 69) fell within this range of error (sample mean = 4.1, std. dev. = 2.78%).*

5.1 Measuring Water is Challenging

While many systems are calibrated to maintain minimal water measurement error in the lab, these error ranges often increase in the field. PWE gathered data comparing the flow rates of installed mechanical meters and the flow rates measured by APEP certified professional pump testers. The average error comparing the customer installed meters to the pump tester readings was around 10% (see Figure 10). This is an observed example where the field measured error (0%-80%) is much higher than the lab rated error (1-2%).

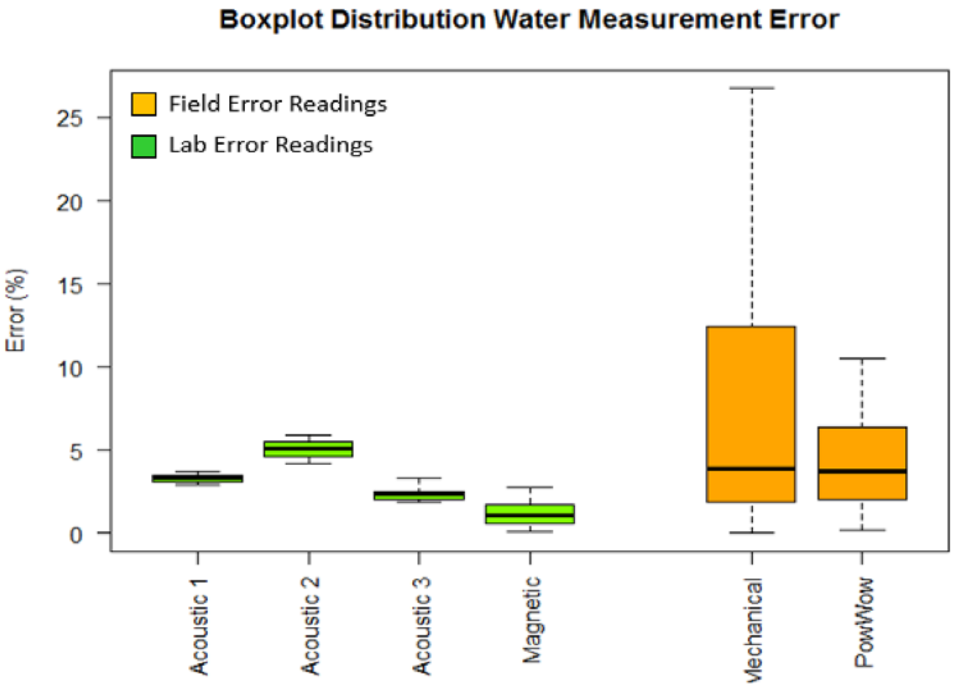


Figure 10. Comparison of measurement error of acoustic and magnetic meters used in the Fresno State CIT lab (green), and of mechanical meters and electrical meters with PWE algorithms (orange). The plot shows median, the middle 50% of data, and 100%-tile range. This graph does not show calculated outliers. There was one outlier for the mechanical meter at 80% error.

One of the principal factors that causes increased error is the fact that each pump is uniquely configured, and configurations do not always offer ideal conditions for meters. Water turbulence, cavitation, unclean pipes, and changes in pressure all occur often in pumping systems and have the potential to increase error of a meter system. Additionally, lack of proper maintenance can compound the error. The PWE system should maintain rated error throughout the season, unless there are changes to the operating conditions that are not covered by the most recent pump tests. This could include damage or wear and tear on the pump, change in the water table, or change in pressure. All the real-world variations cause the average error of most meter systems to be greater than their lab rated values.

5.2 Mechanical Meter

Accuracy estimation was taken from the spec sheet for the 6” McPropeller bolt-on-saddle flowmeter M0300 online [25]. The spec sheet specifics that accuracy is ± 2% throughout the full range, ± 1% on reduced range with ± 0.25% or better repeatability. Accuracy of these mechanical meters is only guaranteed when the flow in the pipe is totally full, and there is no swirling of water. Water swirling can be caused by centrifugal sand separators or two elbows in different planes. The proper flow must be known for accuracy to be maintained. Typically, the meter is accurate to a range of 15:1 for the maximum flow and the minimum flow. As mentioned in section 5.1, PWE gathered data on field accuracy of the mechanical meters and revealed an error range of 0% - 27% with an average error of 10%. There was one outlier recorded at 80%, where the meter was likely broken and in need of repair.

5.3 Magnetic Meter

The primary accuracy estimation was taken from the Seametrics AG2000 spec sheet [26]. Accuracy is claimed to be ± 1% of reading for flow between 10% and 100% of max flow, and ± 2% of reading for flow from cutoff to 10% of max flow. When a pipe is not totally full of water, it can be difficult for magnetic meters to measure the water flow. A 10" Seametrics AG2000 magnetic flow meter was put through calibration at Fresno State Center for Irrigation Technology (CIT). Twenty flow readings were taken and compared against CIT system, which is calibrated to be 99.5% accurate. When compared with the CIT system, error ranged from -1.89% to -0.051%, with a mean error of -1.19%. This confirms that the meter is within the error bounds stated on the spec sheet. One interesting fact was that on every single measurement, the magnetic meter measured less water than the CIT system. There was no data available to PWE to estimate the field accuracy of the magnetic meter.

5.4 PWE System

5.4.1 Method

The accuracy of the PWE algorithm was tested by measuring a full day of irrigation for 20 different pumps covering several water basins. The 20 sample pumps were selected to exhibit variety in nameplate horsepower (HP), motor setup (single (SSP) vs variable speed pumps (VSP)), utility provider (PG&E/SCE) and type of pump tests. A single data point was defined as a 24-hour water use measurement from midnight to midnight. For the 20 pumps, there were 69 full days of measurement recorded for the error estimation sample dataset. To calculate error, the estimated water use calculated by the PWE algorithm was compared with measured values taken by Seametrics jwave acoustic meters and Seametrics magnetic meters. These meters were calibrated at Fresno State Center for Irrigation Technology to have minimal error. PWE has set the goal of error to be +/- 10% error in order to meet standards in California Code of Regulations Title 23[2].

See Appendix: Water Measurement Report for more information on method used to compare daily water measurement with daily water use estimated with PWE's solution.

5.4.2 Water measurement verification performed by Bren School of Environmental Science and Management at UCSB

This section aims to verify the accuracy of the algorithm used by PowWow Energy (PWE), which converts kWh of electricity usage to volume of water pumped. The set of data gathered for this study illustrates that the PWE algorithm is capable of measuring water from wide range of pump nameplate HP, pump test types, pump configurations and pump operating conditions. The data suggest that error is likely to be under 10% if pump tests are properly administered and recorded (max error = 10.5%, min error = 0.225%, mean error = 4.01%, standard deviation =

---

[2] California Code of Regulations, Title 23. Waters. Division 2. Department of Water Resources Chapter 5.1. Water Conservation Act of 2009 Article 2. Agricultural Water Measurement. §597.3 Range of Options for Agricultural Water Measurement

2.78%, n = 69). This study has also shown that estimation errors do not differ significantly between VSP and SSPs, and that the error spread has decreased in the most recent Version 3 of the PWE algorithm. In cases where the pump test does not cover an operating HP for a pump, for example when a pump is used at low efficiency or when a pump starts to cavitate and should be repaired, PWE will send an alert to the farmer letting them know that the PWE measurement method may be inaccurate. This is a unique trait of the PWE measurement method, which allows for better maintenance of measurement methods compared with traditional solutions (magnetic or mechanical devices). It should also be noted that damage to pump bowls, or significant changes to a pump will merit a new set of pump tests.

The PWE method has its limitations. This method relies on accurate pump tests. During this experiment, consultation with one of the APEP certified pump testers revealed that three of the pump tests PWE purchased likely had incorrect data entered in them. PWE should aim to utilize their expertise in machine learning to develop an algorithm to check the accuracy of pump tests. If a pump test is entered incorrectly, it can cause the PWE algorithm to estimate results with a high error. Another limitation is that PWE (like mechanical and magnetic meters) cannot provide water estimation for all pump configurations. The current algorithm cannot estimate total water volume pumped on meters shared with solar arrays, meters that have multiple pumps, or most surface water lift pumps. PWE is working on improving their system to accommodate all configurations with future testing.

See Appendix: Water Measurement Report for more details on the measurement and verification.

6. Discussion and Review

The previous sections have detailed the comparison of the three meters in the study through the lens of environmental impact, cost, logistics and statistical accuracy. Table 17 summarizes the results for each of the meters. The PWE system has the lowest environmental impact (of the two systems calculated) emitting less than 2% of the impact of the mechanical meter. In terms of cost, the mechanical meter is the lowest followed by the PWE system, while the magnetic meter with telemetry system runs almost a factor of 4 greater price than the mechanical meter and factor 2 greater than the PWE system. This higher price covers greater reliability and removes the need to manually check for meter readings. The logistics for the mechanical meter are considered the most difficult, due to the installation requirement and the need for manual readings. The PWE System falls into the easiest category as the installation is simple and there is no need for manual readings. The accuracy of readings is the only category where the PWE system falls behind other systems. However, it should be noted that lab rated error ranges represent the lower end in range of error, and water meters often exhibit higher ranges of error in the field. Field tests of Mechanical meters revealed error from 0% - 27%, with one outlier data point at 80% error. None of these three options for measuring water can accurately measure water usage across all pump configurations and throughout time.

Table 17. Summary of the environmental impact, cost logistics and statistical accuracy of a mechanical meter, magnetic meter and the PWE system for measuring volume of water pumped from a well or booster pump. Details of calculations can be viewed in the previous sections of this analysis.

Variable	Mechanical Meter	Magnetic Meter	PWE System
Environmental Impact (kg CO2 eq.)	36.65	N/A	0.48
Cost (USD)	$638.40	$2,496.78	$1040
Logistics (Qualitative)	Difficult/Moderate	Moderate/Easy	Easy
Statistical Accuracy (% error)	1%-2%	1%-2%	1%-10%

GLOSSARY

Term	**Definition**
AB	Assembly Bill
APEP	Advanced Pumping Efficiency Program (PG&E)
CA	California
CARB	California Air Resources Board
CCR	California Code of Regulation
CCR	California Code of Regulations
CEC	California Energy Commission
CIT	Center for Irrigation Technology
CPE	Customer Premise Equipment
CPUC	California Public Utility Commission
DR	Dynamic Range
DSL	Digital Subscriber Line
DWR	Department of Water Resources
FU	Functional Unit
GB	Gigabyte
GHG	Greenhouse Gasses
GSA	Groundwater Sustainable Agency
GSP	Groundwater Sustainable Plan
GWP	Global Warming Potential
HDD	Hard Disk Drive
ICT	Information Communication and Technology
IOU	Independently Owned Utility
IP	Internet Protocol

ISO	International Organization for Standardization
kB	kilobyte
kWh	Kilo-watt hour
LCA	Life Cycle Analysis
MB	Megabyte
OPE	Overall Pumping Efficiency
PG&E	Pacific Gas & Electric Company
PPE	Personal Protective Equipment
PUE	Power Use Effectiveness
PWE	PowWow Energy
SB-88	Senate Bill 88
SCE	Southern California Edison
SGMA	The Sustainable Groundwater Management Act
SSD	Solid State Drive
SSP	Single Speed Pump
SU	Server Utilization
TDH	Total Dynamic Head
TDH	Total Dynamic Head
VFD	Variable Frequency Driver
VSP	Variable Speed Pump

REFERENCES

[1] Hardin G., The Tragedy of the Commons, Science, New Series, Vol. 162, No. 3859, Dec. 13, 1968, pp. 1243-1248.

[2] California Code of Regulations, Title 23. Waters. Division 2. Department of Water Resources. Chapter 1.5. Groundwater management. Subchapter 2. Groundwater Sustainability Plans. § 354.16. Groundwater Conditions

[3] California Code of Regulations, Title 23. Waters. Division 3. State Water Resources Control Board and Regional Water Quality Control Boards. Chapter 2.8. Measuring and monitoring. §933. Measuring Device Requirements

[4] Baliga, J., Ayre, R. W., Hinton, K., & Tucker, R. S. (2011). Green cloud computing: Balancing energy in processing, storage, and transport. *Proceedings of the IEEE*, *99*(1), 149-167.

[5] Malmodin, J., Lundén, D., Moberg, Å., Andersson, G., & Nilsson, M. (2014). Life cycle Assessment of ICT. Journal of Industrial Ecology, 18(6), 829-845.

[6] Personal communication with Arman Shehabi, Research Scientist, Energy Technologies Area, Lawrence Berkeley National Lab.

[7] Weber et al. 2010b. The Energy and Climate Change Impacts of Different Music Delivery Methods. The Journal of Industrial Ecology. vol. 14, no. 5. October. pp. 754–769.Available at: http://dx.doi.org/10.1111/j.1530-9290.2010.00269

[8] Center for Energy Efficient Telecommunications (2013). The Power of The Wireless Cloud: An Analysis of Energy Consumption of Wireless Cloud. Bell Labs and the University of Melbourne.

[9] Masanet, E. Shehabi A. Liang, J. Ramakrishnan, L. Ma, X. Hendrix, V. Walker B. & Mantha, P. (2014). The energy efficiency potential of cloud-based software: A us case study. Lawrence Berkeley National Lab.

[10] Malmodin, Jens, et al. "LCA of data transmission and IP core networks. "Electronics Goes Green 2012 (EGG), 2012. IEEE, 2012.

[11] Baliga et al 2009, Energy Consumption in Optical IP Networks. IEEE. Journal of Lightwave Technology. Volume 27, issue 13

[12] Coroama, V., L. Hilty, E. Heiri, F. Horn. 2013. The direct Energy Demand of Internet Data Flows. *Journal of Industrial Ecology* 17(5):680-688

[13] California Public Utilities Commission. Decision Adopting Greenhouse Gas Allowance Revenue Allocation Formulas and Distribution Methodologies for Emissions-Intensive and Trade- Exposed Customers. Rulemaking 11-03-012. ALJ/JMH/vm2/jt2.

[14] California Energy Commission. Draft 2016 Integrated Energy Policy Report Update. General/Scope. Publication #CEC-100-2016-003-CMD

[15] Personal communication with Mihoyo Fuji, CalEPA, Air Resource Board. (2016).

[16] Personal communication with Stan Knutson, VP Software Development, PowWow Energy (2016).

[17] Shehabi, Arman, et al. (2016). United States Data Center Energy Usage Report. Lawrence Berkeley National Lab, Berkeley California. LBNL =1005775 (2016).

[18] Masanet, E., Shehabi, A., Ramakrishnan, L., Liang, J., Ma, X., Walker, B., & Mantha, P. (2013). *The Energy Efficiency Potential of Cloud-Based Software: A US Case Study*. Lawrence 51 Berkeley National Laboratory, Berkeley, California

[19] Google 2015. "*Our energy-saving data centers*." https://www.google.com/about/datacenters/efficiency/internal/

[20] California Environmental Protection Agency (2014). eGRID 2014 Summary Tables – State Resource Mix. Created 1/13/2017.

[21] PowWow Energy Webpage. Retrieved from: https://www.powwowenergy.com/products/pump-monitor on 2-21-2017

[22] Josie Gardner (2016). Quotation for 6" M0300 bolt-on-saddle mechanical flow meter. McCrometer. Quote received on 11/8/2016. Quote number: 148086.

[23] Advanced Pumping Efficiency Program. Policies and Procedures Manuel. Pacific Gas and Electric Company. Version produced on 1/20/2016. Retrieved on 2-23-2017 from http://www.pumpefficiency.org/

[24] Western Ag and Turn Inc. Invoice for installation of 2 nodes, 2 Well sensors, one flow meter (Seametrics), 3 pressure sensors and 2 energy monitors. Invoice #81860. May 5th, 2016.

[25] McCrometer 6" McPropeller Bolt-on Saddle Flow Meter. Available online at: http://www.mccrometershopping.com/6-Mc-Propeller-Bolt-on-Saddle-Flow-Meter_p_30.html

[26] Seametrics AG 2000 8" Magnetic Flow Meter. Available online at: http://www.seametrics.com/product/ag2000-magnetic-flow-meter

APPENDIX

Appendix A: WATER MEASUREMENT REPORT

1.1 Introduction to the methodology to estimate the algorithm error

Here we describe the strategy by which we will evaluate the accuracy of the method used to generate daily water records from interval energy data captured by Independent Owned Utilities (IOU) with smart meters. There are more than 80,000 farms in California and irrigation represents up to 8% of the energy load of the grid depending on the season during dry years.

We will calculate statistical accuracy of our method by choosing a relevant sample of pumps in California. The pumps in this study include:

1. Type: single speed (SSP) and variable speed pumps (VSP)
2. IOU: PG&E and SCE
3. Application: deep well for extraction, or booster for application
4. Impact of variation of water table and discharge pressure: horse power, water flow, and total dynamic head (TDH) are related via pump performance curves (pump acts as a generator) and system curves (irrigation acts as a load)

For this study, we randomly choose one day to measure a full day (midnight to midnight) of irrigation for a sample of n = 20 pumps (15 SSP and 5 VSP) at three different locations under the CEC project (Site 1, Site 5 and Site 6), and two additional ranches (Figure A-1). In addition, pumps were selected to represent a variation of nameplate horsepower (HP) and pump configuration.

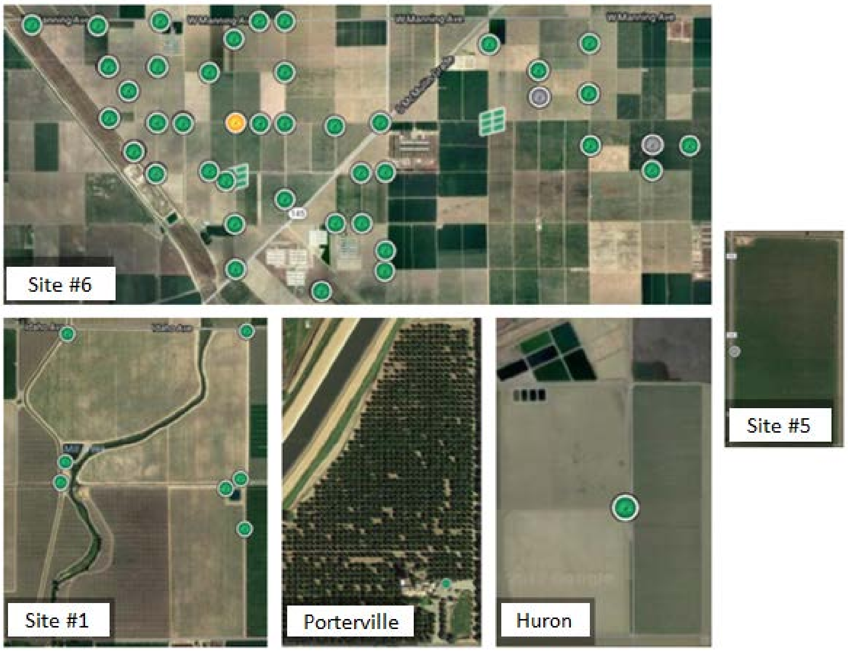


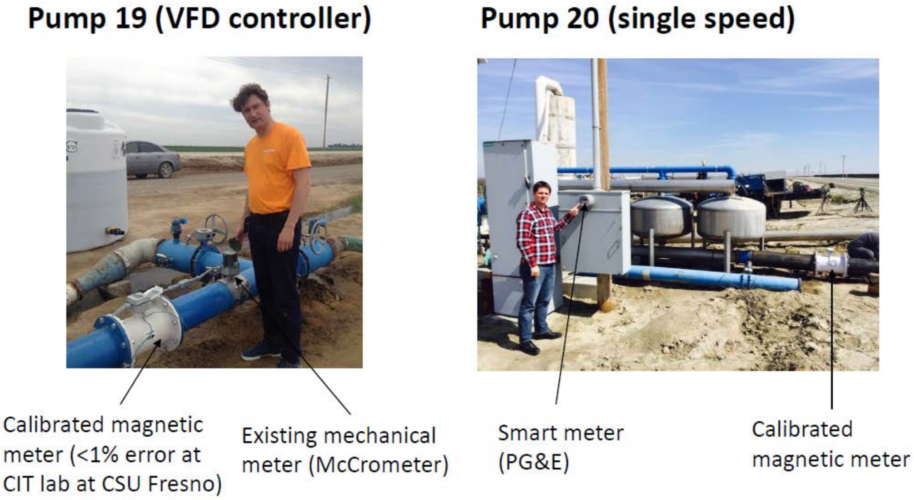
Figure A-1. Farms where the water measurements were taken across different groundwater basins.

1.2 “Ground-truth” measurements (PWE)

The hypothesis is that the accuracy of tests will be below our goal of ± 10% error according to California Code of Regulations Title 23[3]. Daily water usage estimations from smart meters will be compared to daily measurement performed with acoustic and magnetic flow meters calibrated at the Center for Irrigation (CIT) at Fresno State. The data is logged by the device and downloaded from a smart phone via email (Figure A-2).

Figure A-2. Daily water measurement performed with jWave acoustic meter from Seametrics.

We also installed long-term telemetry equipment at one single speed pump (SSP) location and one variable speed (VSP) location to measure accuracy over time (Figure A-3). The data is logged on the server of the telemetry vendor (WiseConn). Long term measurement is important because the water table can change significantly over time. The data can also be used for 24-hour measurement although it is primarily used for algorithm development. To measure long term data, we installed higher-accuracy magnetic meters that were calibrated to less than +/-1% error by CIT.



Pump 19 (VFD controller)

Pump 20 (single speed)

Calibrated magnetic meter (<1% error at CIT lab at CSU Fresno)

Existing mechanical meter (McCrometer)

Smart meter (PG&E)

Calibrated magnetic meter

Figure A-3. Magnetic meters from Seametrics installed with telemetry for continuous measurement of flow (gpm), discharge pressure and water table (feet) along with energy from smart meter (kWh)

---

[3] California Code of Regulations, Title 23. Division 3, Chapter 2.8, Sections 931-938.

1.3 Background on the measurement method (PWE)

There is an inherent relationship between the kinetic energy of the volume of water traveling through a pipe, and the mechanical energy of the engine used to rotate the bowls. From the principle of energy conservation, they are equal minus friction losses in the form of heat in the engine, mechanical shaft, and the water due to occasional turbulence. Conservation of energy tells us the integral of water pumped (total water volume over a day) is related to the integral of electrical energy in that day (Figure A-4).

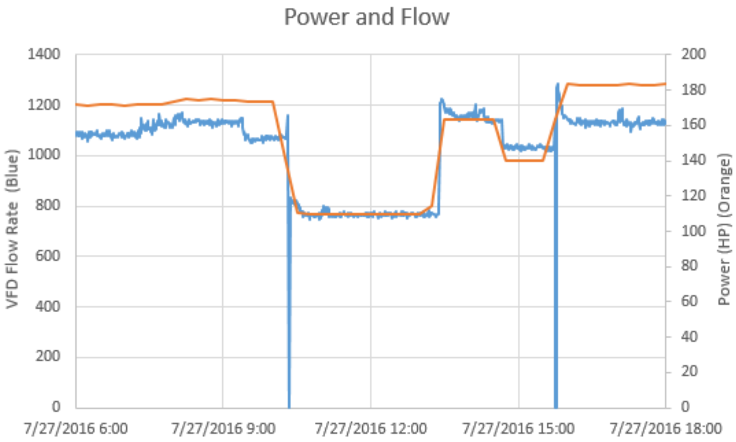


Figure A-4. Pump cycle representing the energy conservation. The flow rate (blue line; primary y-axis) and the power usage (orange line; secondary y-axis) show similar shapes.

1.3.1. Measurement for SSP case

In the case of a SSP, the relationship between energy and water use is set by Overall Pumping Efficiency (OPE), which is a function of the pump performance curve; the pump can only work at fixed flow (gallons per minute) and TDH (feet). Pumps are usually installed to work at their maximum OPE. However, the operating condition can change over time (Figure A-5).

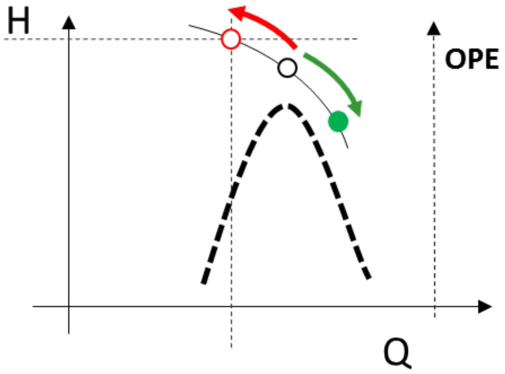
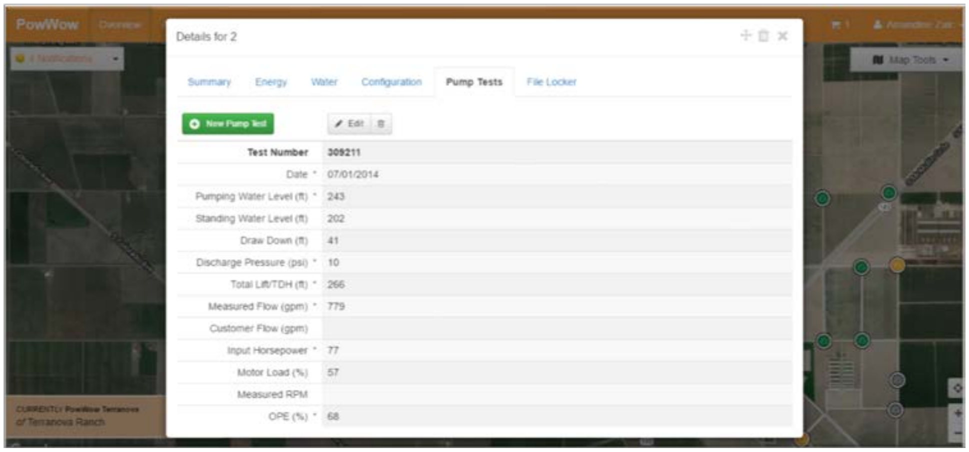


Figure A-5. Single speed pump curve. The motor adapts to the pump performance curve and the overall pumping efficiency (OPE) varies. The variables are water flow (Q) and total head (H).

The current version of the PowWow algorithm recommends a 3-point pump tests for SSP cases to cover large range of water flow. Pump tests are entered on the web portal (see Figure A-6).



Test Number	309211
Date *	07/01/2014
Pumping Water Level (ft) *	243
Standing Water Level (ft)	202
Draw Down (ft)	41
Discharge Pressure (psi) *	10
Total Lift/TDH (ft) *	266
Measured Flow (gpm) *	779
Customer Flow (gpm)	
Input Horsepower *	77
Motor Load (%)	57
Measured RPM	
OPE (%) *	68

Figure A-6. PowWow web application with pop-up “Pump Tests” tab

1.3.2 Measurement for VSP case

In the case of VSP, the relationship between water and energy use is not set by the pump performance curve. The rotation per minute (RPM) is adjusted by the variable frequency driver (VFD) to change the pump curve so OPE stays high even if the pump is used at a different flow rate. The operating is set along the system curve and not the pump curve in this case.

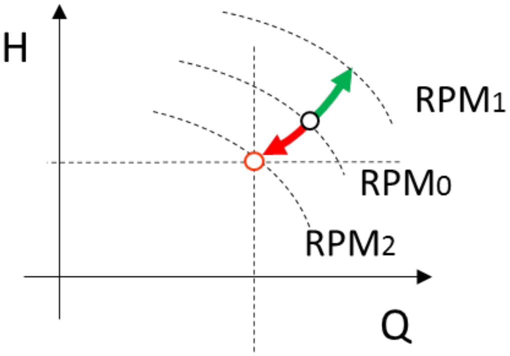
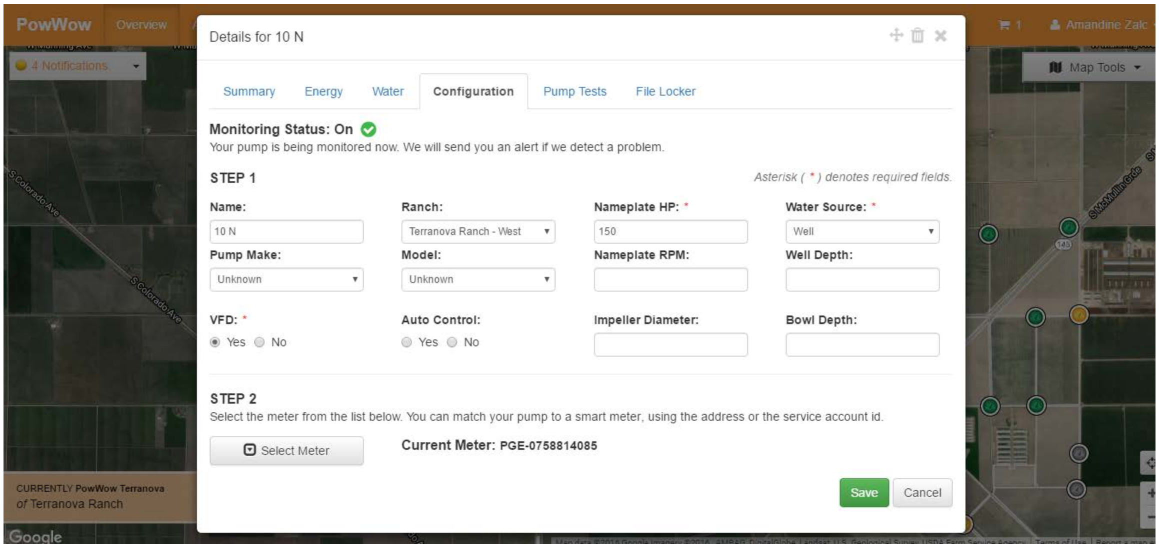


Figure A-7. Variable speed pump curves. Variable Frequency Driver (VFD) changes the rotation per minute (RPM) of the engine and the pump with different rpm.

PWE requires a minimum of 2 pump tests at high and low RPM to calibrate water measurement from energy data on VSP. It is important to set the right configuration in the web portal (see Figure A-8). The algorithm for VSP case is different from SSP case.



Details for 10 N

Monitoring Status: On ✓
Your pump is being monitored now. We will send you an alert if we detect a problem.

STEP 1

*Asterisk (*) denotes required fields.*

Name: 10 N
Ranch: Terranova Ranch - West
Nameplate HP: * 150
Water Source: * Well
Pump Make: Unknown
Model: Unknown
Nameplate RPM:
Well Depth:
VFD: * ● Yes ○ No
Auto Control: ○ Yes ○ No
Impeller Diameter:
Bowl Depth:

STEP 2

Select the meter from the list below. You can match your pump to a smart meter, using the address or the service account id.

Current Meter: PGE-0758814085

Figure A-8. PowWow web application with pop-up "Configuration" tab

1.4 Water measurement verification (Bren School at UCSB)

Introduction

PWE has developed an algorithm to calculate total volume of water usage from well and booster pumps using only pump horsepower (HP) data as an input. The algorithm is based on recent multi-point pump tests administered by Advanced Pumping Efficiency Program (APEP) certified pump testers. This algorithm has gone through several iterations as more data has become available, to address new and unique pump configurations. The purpose of this analysis is to estimate the error associated with the current version of the algorithm.

Error is estimated by comparing the water use calculated by the PWE algorithm with ground truth measurements from acoustic and magnetic meters. Ground truth measurements and pump tests of various types have been applied to 25 well pumps across California with a range of configurations and operating conditions. PWE attempted to vary the characteristics of the samples to demonstrate the algorithm's capability to estimate water usage across a wide range of conditions. The document will cover information on the PWE algorithm, ground truth data verification, dataset specifics, statistical error results, and a discussion of the error and experimental process.

PWE algorithm

The PWE algorithm uses big data and machine learning to estimate the water usage based on multi-point pump tests. The pump tests provide information on pump characteristic curves, which PWE recreate to estimate the relationship between power and flow. The current version of the PWE algorithm uses three different equations to fit curves to pump tests based on several factors. The specific equation used to generate a curve is based on proprietary classification of pump curves based on pump tests.

In order to maximize algorithm accuracy, industry standard best practice pump tests as defined by APEP are taken at the pumps. For single speed pumps (SSPs) a three-point test is recommended, and for variable speed pumps (VSPs), a 2-point pump test is recommended. The SSP test should cover all operating conditions of the pump, ideally over a large range of HP inputs. The VSP pump test must have a point at high RPM and a point at low RPM. The algorithm can still compute water use estimations with 1 or 2-point pump tests. However, if only one or two pump test points are provided, the range of HP variation that PWE's algorithm can cover is limited. A three-point pump test covering all operating conditions allows for PWE to estimate water pumped outside of the pump test range. When operating conditions fall out of the range covered by the pump tests and the algorithm, PWE will send an alert to the farmer. The alert capability is made possible by utilizing machine learning software associated with the product. In single point cases, it is recommended that additional pump test points be administered, or ground truth verification of power and flow be completed.

Ground Truth Data

Ground truth data was gathered by JWave acoustic meters[4], and magnetic meters[5], both of which were manufactured by Seametrics. JWave meters were used for short measurements of 24 hours at various pumps, and the magnetic meters were used for longer term measurements. All meters used for ground truth measurements were calibrated at Fresno State Center for Irrigation Technology (CIT) to have a lab error of less than 5% (Figure A-9). This boxplot graph was included to show the meters were professionally calibrated, but also to illuminate the fact that they do not generate perfectly accurate estimations of ground truth water usage data.

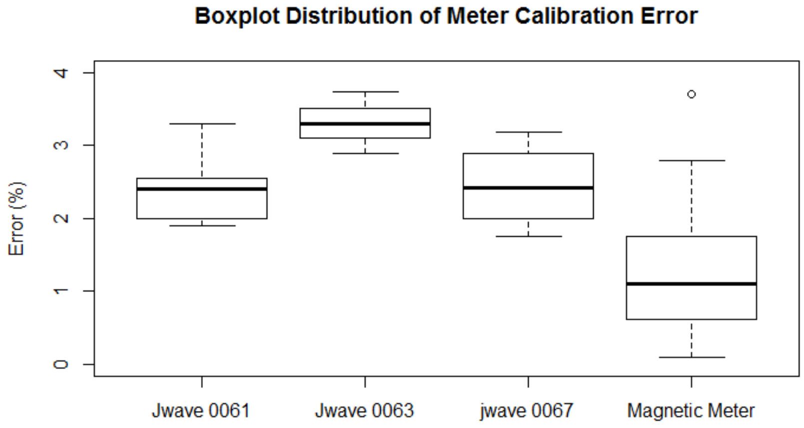


Figure A-9. Boxplot representing the range of error from calibrations tests across four meters measuring ground truth data. Sample error for each unit varied during calibration: jWAVE 0061 (n=15), jWAVE 0063 (n=3), jWAVE 0067 (n=15), Magnetic Meter (n=15).

---

[4] http://www.seametrics.com/sites/default/files/product_downloads/LT-14233r2.0%2020160608%20jWAVE%20Spec.pdf

[5] http://www.seametrics.com/sites/default/files/product_downloads/LT-65650278-AG2000-RevA.pdf

Jwave acoustic meters were installed for a minimum of 24 hours (one entire day 00:00 – 00:00) on pumps to measure water use. These meters measure flow for various time intervals (approximately every minute depending on measurement duration). The flow rate was multiplied by duration of that flow rate to estimate a total volume of water pumped over a 24-hour period. Staff installing the meters were trained by experts and verified that meters were installed correctly. During the data gathering process, one meter was sent back to Seametrics for repair (JWave 0061), due to the fact that it was gathering unrealistic ground truth data (flow rates that were 1000GPM above the rated flow, and flow rates that were constant to 2 decimal points over several hours). No data from this meter was included once anomalies were identified.

There were several instances where ground truth data was rejected, and PWE had to recollect the ground truth data on a different day. Bad meter readings are commonly caused by turbulence in the water, old equipment in the pipe, pipe cavitation, or setup errors. It was clear when meters were malfunctioning due to the fact that flow would shift drastically over short periods of time. PWE was consulted by Seametrics engineers to determine which datasets had poor data. Only complete and accurate data was included in the final dataset for error analysis.

Omitted Pumps

Ground truth measurements were gathered for 25 pumps across several water basins and pump configurations. Pumps were selected so that a wide variety of nameplate HP, configurations, and water basins were included. Of the 25 pumps measured, five were omitted from this analysis due to issues with ground truth measurement or pump tests. A list of the pumps omitted, their pump characteristics, and the reason for omission is covered below in Table A-1.

Table A-18 Table showing information on the 5 pumps that were omitted from our study, due to errors in the ground truth measurement or the pump testing.

Ranch	Pump Name	Type (SSP or VSP)	HP	Status	Notes
[redacted]	Ag well	VSP	20	Rejected	Pump tests did not cover high and low operating RPM (requirement for VFD)
[redacted]	Ag well + Domestic	SSP + SSP	40 + 2	Rejected	Algorithm not calibrated to work with two pumps on same well. This feature will be added in next release.
[redacted]	29-6	SSP	200	Rejected	Pump test only covered flood output while farmer only uses drip output
[redacted]	27	SSP	200	Rejected	JWave unit died early and only gathered a partial day of measurement
[redacted]	F-4	VSP	250	Rejected	Pump test had incorrect measurements verified by tester (Mid Valley Pump & Water Testing)

There were several 24-hour measurements where a pump was not used, and the PWE algorithm correctly estimated 0 water use. All of these days were also excluded from the dataset as to not artificially reduce the average reported error.

Dataset analysis

The final dataset included 20 pumps from 5 different water basins and 69 full days of measurement (Table A-2). The dataset includes 5 variable speed pumps (VSP) and 15 single speed pumps (SSP). Pumps Terranova 19 and Terranova 20 were set up for long term measurements with magnetic meters. Fewer data points are included for Terranova 20, because this pump has a second output with an ad-hoc diesel pump not tracked by any meter. Days were excluded from the dataset for pump 20 when the secondary, untracked output was used. Some other pumps have multiple days of measurement at different dates.

Table A-19. Classification of all pumps based on pump type, nameplate HP and the number of samples gathered, number of pump test points and the source of the pump test. SSP = Single Speed Pump; VSP = Variable Speed Pump; PT = Pump Test administered by an APEP certified tester; PT - PWE = PWE Administered PT with acoustic meter; PT – Telem. = PT administered by PWE using Telemetry systems and magnetic meters.

Pump Count	Existing data cases	Pump Type	Nameplate Horsepower	# 24-Hour Measurement	# Pump Test points	Pump test source
1	[redacted]	SSP	50	1	1	PT - PWE
2	[redacted]	SSP	125	2	1	PT - PWE
3	[redacted]	SSP	125	1	1	PT - PWE
4	[redacted]	VSP	150	2	3	PT - PWE
5	[redacted]	SSP	150	2	1	PT- PWE
6	[redacted]	SSP	200	1	1	PT - PWE
7	[redacted]	SSP	250	1	1	PT - PWE
8	[redacted]	VSP	250	1	2	PT - PWE
9	[redacted]	SSP	125	1	3	PT - PWE
10	[redacted]	VSP	150	32	2	PT – Telem. #1
11	[redacted]	SSP	10	1	3	PT #1
12	[redacted]	SSP	125	1	2	PT #2
13	[redacted]	SSP	125	1	3	PT #2
14	[redacted]	SSP	125	1	3	PT #2
15	[redacted]	SSP	125	1	3	PT #2
16	[redacted]	SSP	150	6	3	PT #3
17	[redacted]	SSP	150	1	2	PT #2
18	[redacted]	SSP	250	10	3	PT #2
19	[redacted]	VSP	300	1	3	PT #2
20	[redacted]	VSP	500	2	2	PT – Telem. #2

Table A-2 indicates that there were different sources for pump tests, and different numbers of pump points per test. Several pump tests were administered by PWE using acoustic meters (PT – PWE). These pump tests were administered on a different day and with a different unit from the ground truth measurements. Most other pump tests were administered by APEP certified professionals (PT #x). In two cases, pump tests were administered by PWE using a magnetic meter to estimate flow, the utility smart meter to estimate power use, and a telemetry system to calculate total dynamic head (TDH). All pump tests provided baseline data on the operating characteristics of a pump, that PWE utilize in their algorithm.

In addition to variety in the source of the pump test, the number of pump test points gathered varied from 1 to 3 different operating points. It can be difficult for even experienced pump testers to gather multiple points if the farmer has not given him permission to run the pump on multiple outputs. Different operating points can be artificially generated by increasing the pressure in a pipe through tightening a value, however these valves do not always exist, and there is not always a place to measure flow where the valve would increase the pressure in the pipe. In order for PWE to extrapolate operating conditions outside of the pump test range for SSPs, a three-point test is required. For SSPs with 1 or 2 pump test points, the algorithm only covers a limited range of HP. Alerts will be sent to the customer when the operating range is outside the pump test range.

There is a large variety of nameplate power capacity for pumps used in agricultural operations in California. PWE collected samples from a wide range of pump nameplate HP capacity, to demonstrate that their algorithm generates estimates across a range of pump HP. Figure A-10 below shows a histogram of pump HP included in this study sample. The majority of pumps are in the 100-200 HP range, which is a common nameplate HP for medium sized pumps in the California Central Valley, where the greatest number of PWE customers reside.

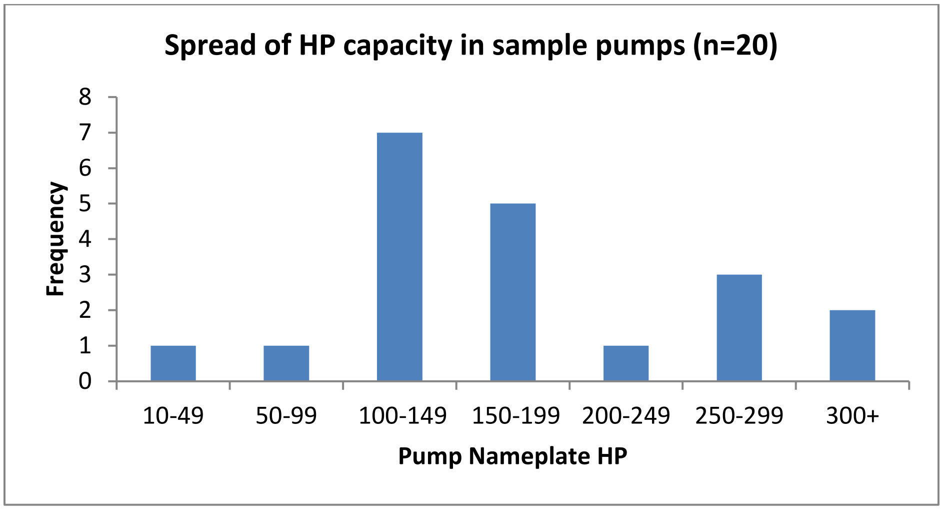


Figure A-10. Histogram showing the distribution of pump nameplate horsepower (HP) in the study sample. Full list of pumps shown in table A-2.

Results

PWE algorithm error is defined as the difference between algorithm estimates and flow meter readings. Error was calculated for the 20 pumps for 69 days of 24-hour measurement by comparing algorithm output to the ground truth measured by acoustic and magnetic meters. Only the absolute value of the error was considered for these results, as the sign of the error is not as important as the magnitude. General measures of central tendency are presented in Table A-3 below. Mean error is 4% and the mean error plus two standard deviations is 9.57%. This estimation indicates that 95% of the data will be below 10% error.

Table A-20. Measures of central tendency for PWE algorithm error calculated from the dataset of 20 pumps and 69 days of measurement.

Variable	Quantity
Mean Error	4.02%
Median Error	3.61%
Standard Deviation	2.78%
Mean + 2 Std. Dev. (95%)	9.57%

Due to the fact that only the absolute value of error has been considered, the dataset is positively skewed. The histogram in Figure A-11 illustrates the skewness of the dataset.

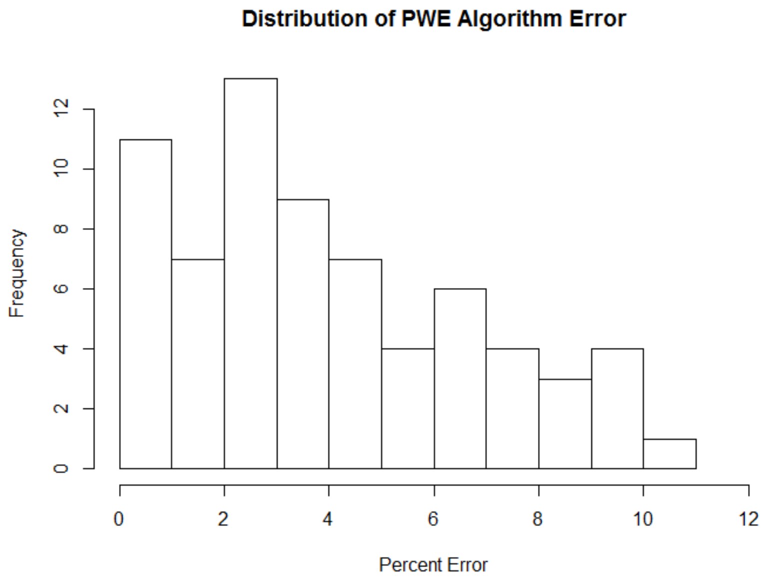


Figure A-11. Histogram of PWE algorithm error (n = 69).

For datasets that are skewed and not normally distributed, boxplots can provide a more informative visual representation of data spread. A boxplot was generated to explore the range of the absolute value of error (Figure A-12). The boxplot shows the median error at 3.61% with an interquartile range (IQR) of 4.25%, where the upper bound of the IQR is 6.17% and the lower bound is 1.92%. The IQR is a representation of the rank-based middle 50% of the data. There is one data point out of the 69 sample data points that is above 10% at 10.5%. PWE has noted that the single instance of 10.5% error likely has ground truth measurement issues, and the ground truth will be re-measured at a later date. Because ground truth error hypothesis could not be confirmed by a re-measure before this report was documented, the data point was still included.

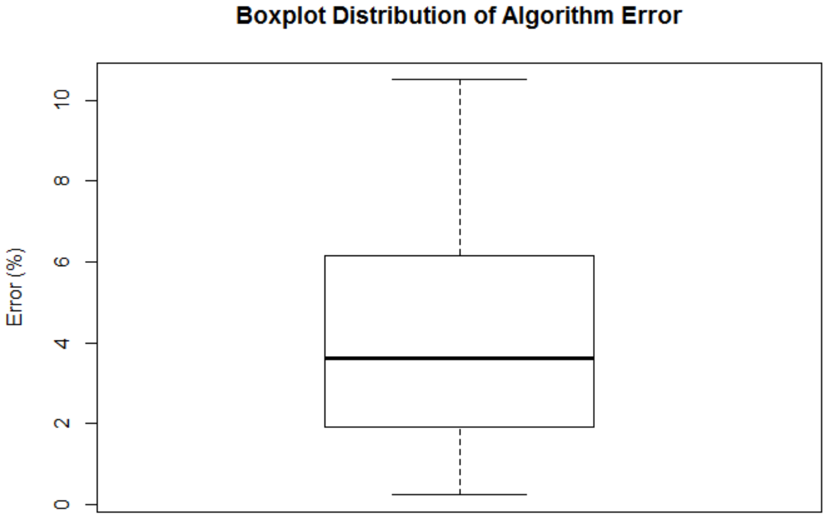


Figure A-12. Boxplot distribution of PWE algorithm error (n = 69).

Comparing results of VSP and SSP pumps

PWE uses different algorithms for variable speed and single speed pumps (VSP & SSP). Different algorithms are used because these pumps behave differently in terms of their power-flow relationship. Measures of central tendency were calculated for the SSP and VSP pumps to compare error (Table A-4). While there were three times as many SSP pumps, the number of total days sampled is relatively close. Mean error is 13% less for the VSP cases, however this is difference likely insignificant.

Table A-21. Measures of central tendency for single speed pumps (SSP) and variable speed pumps (VSP)

Variable	SSP	VSP
Total Pumps	15	5
Total Days Sampled	31	38
Mean Error	4.3	3.8
Median Error	3.7	3.6
Standard Deviation	2.9	2.7

Boxplots were also generated to visualize the difference in the data spread between VSP and SSP error (Figure A-13). The total error range was greater for the SSP (0.28% – 10.51%) compared with VSP (0.22% – 8.86%), but the IQR was greater for the VSP (4.73%) when compared with the SSP (3.6%). The higher error value for SSP could be due to the fact that there is more pump configuration variety in the SSP dataset.

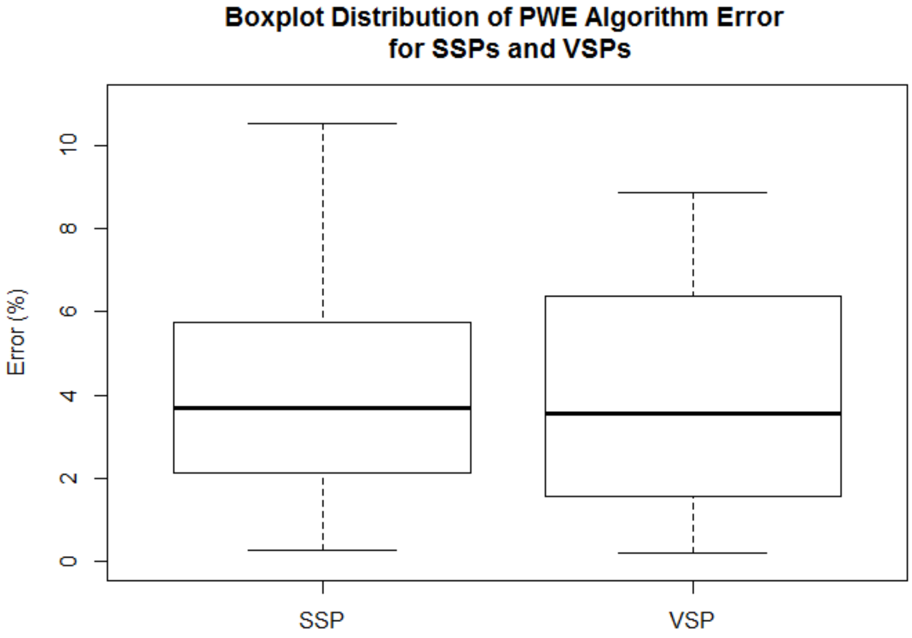


Figure A-13. Boxplot distribution of PWE algorithm measured error for single speed pumps (SSPs) and variable speed pumps (VSPs).

To determine if the error is significantly different between the SSP and VSP samples, a t-test could normally be used. However, the raw data has been transformed using only absolute value versions of the data, resulting in a dataset that is not normally distributed (non-parametric) and highly positively skewed (Figure A-11). For unpaired, non-parametric datasets, a Mann-Whitney U test can be used to determine if two datasets are significantly different. The null hypothesis of a Mann-Whitney U-test is that there is no difference between the ranks of the two samples. A Mann-Whitney U test revealed that there was no significant difference in the error associated with SSP (median = 3.7%) and VSP (median = 3.6%; p = 0.45; CL = 95%).

Comparing All Versions of the PWE Algorithm

There have been three different versions of the PWE algorithm that have been deployed. The first version added the capability to track VSPs. Version 2 improved the VSP algorithm, and included variable TDH in the SSP calculation. The current version, Version 3, expanded the types of algorithms to better account for pump configuration variation and estimating the water use outside the range of the pump tests.

Error for each version of the algorithm has been compared over a set of 12 pumps. These 12 pumps were selected based on the fact that they were the only pumps that had accurate pump tests and ground truth measurement for each iteration of the algorithm. For pumps with multiple days of measurement, an average error was calculated over the entire set of sample days. There has been a noticeable reduction in the spread of error for each version (Figure A-14).

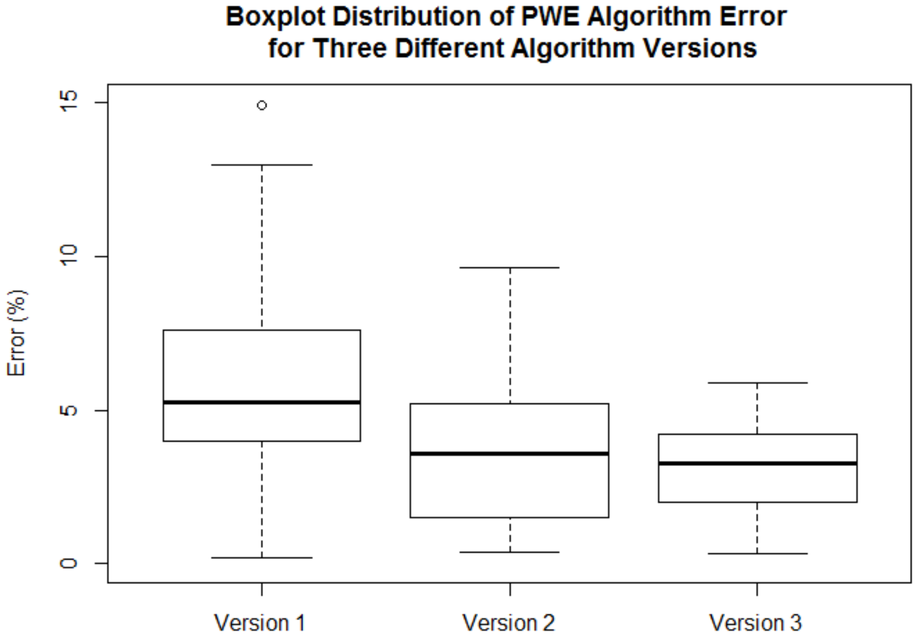


Figure A-14. Boxplot comparison of different algorithm versions for daily measurements of the same pumps. Twelve pumps were selected because PWE had the same valid ground-truth for each version analysis.

The boxplot clearly shows a decreasing trend in the maximum error for these pumps. Additionally, the IQR is the smallest for Version 3 of the algorithm, while the median remained similar to Version 2. This is likely because the newest version has the capability to account for the largest variety of pump configurations, impeller design, and nameplate HP. There were some cases where Version 3 produced slightly higher error than Version 2, but notably reduced error on other pumps. For example, pump 17 had an error of 9.6% in Version 2, and only 2.2% with Version 3.

Comparing Different Methods for Measuring Water

Measuring water accurately is difficult; this has become abundantly clear through working with acoustic, mechanical and magnetic meters in the field. There are several pump configuration variations that cause meters with low lab tested error to result in a much higher error in the field. PWE compiled data for the lab rated error for their acoustic and magnetic meters, and compared them with the field test error of this version of the PWE algorithm, and field tests for mechanical meter error. Mechanical meter error was estimated by analyzing the difference in measured flow from APEP certified pump testers, and the customer flow read from mechanical meters already present on customer pumps. The difference in the error distribution spread is shown in Figure A-15.

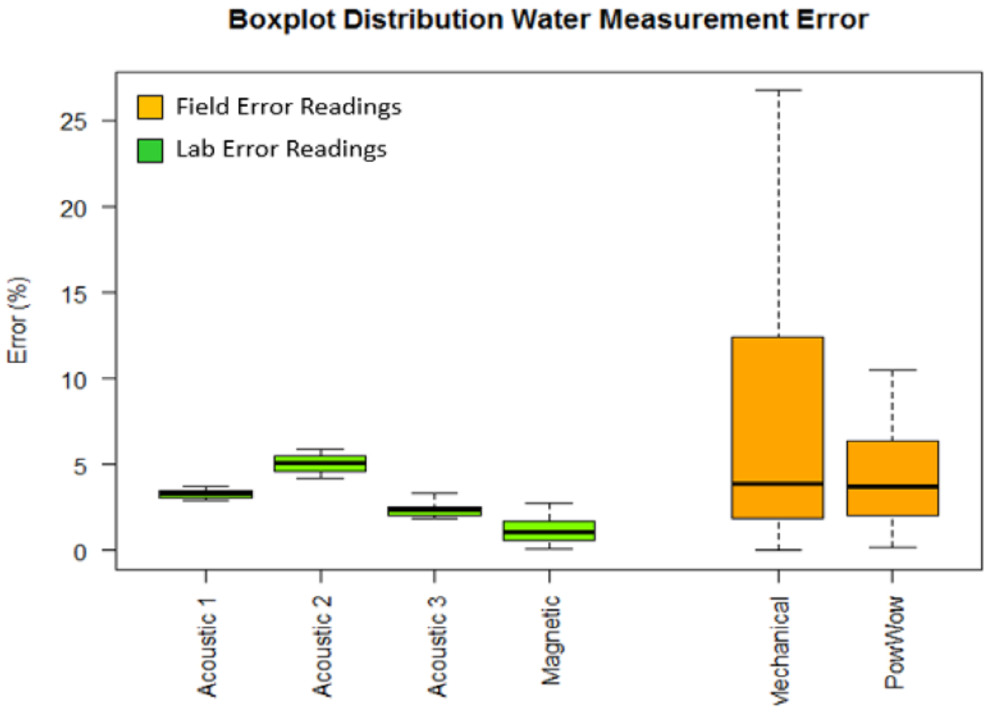


Figure A-15. Boxplot distributions of lab calibrated error for 3 acoustic meters and 1 magnetic meter versus the error in the field on operating pump for mechanical meters and the current version of the PWE algorithm. Outliers were excluded from this image for visual purposes. There was one outlier for the mechanical meter dataset at 80% error.

The error for the field readings is much higher than the lab calibrated readings. Increased error in the field is to be expected. The median error between the PWE and the mechanical error is nearly the same, however the mean is quite different between the mechanical meter field readings (~10%) and the PWE field readings (~4%).

Discussion

The set of data gathered for this study illustrates that the PWE algorithm is capable of measuring water from wide range of pump nameplate HP, pump test types, pump configurations and pump operating conditions. The data suggest that error is likely to be under 10% if pump tests are properly administered and recorded. This study has also shown that estimation errors do not differ significantly between VSP and SSPs, and that the error spread has decreased in the most recent Version 3 of the PWE algorithm. In cases where the pump test does not cover an operating HP for a pump, PWE will send an alert to the farmer letting them know that their measurement method may be inaccurate. This is a unique trait of the PWE measurement method, which allows for better maintenance of measurement methods compared with traditional solutions (magnetic/mechanical). It should be noted that damage to pump bowls, or significant repairs or upgrades to a pump will merit a new set of pump tests.

The PWE method has its limitations. This method relies on accurate pump tests. During this experiment, consultation with one of the APEP certified pump testers revealed that three of the pump tests PWE purchased likely had incorrect data entered in them. PWE should aim to utilize their expertise in machine learning to develop an algorithm to check the accuracy of pump tests. If a pump test is entered incorrectly, it can cause the PWE algorithm to estimate results with a high error.

Another limitation is that PWE cannot provide water estimation for all pump configurations. The current algorithm cannot estimate total water volume pumped on meters shared with solar arrays, meters that have multiple pumps, or most surface water lift pumps. PWE is working on improving their system to accommodate all configurations with future testing.

PWE has made an effort to gather data and test their algorithm on a variety of different pumps. The dataset collected for this analysis covers a wide range of pump nameplate HP, VSP and SSP, different pump test types and pump test points. However, this dataset does not cover all the pumping configurations and characteristics owned by farmers in California. As PWE continues to gather data on new pumps, it is encouraged that this dataset be expanded, and that error estimations be updated. PWE plans to install 8 long-term magnetic meter monitoring stations capable of measuring all relevant pump test variables continuously. Access to this level of data will allow for deeper investigation into the ability of the algorithm to accurately predict water usage over a range of operating conditions.

Energy Research and Development Division
Product

LIFE CYCLE ASSESSMENT PROTOCOL FOR MEASURING THE IMPACT OF OPTIMIZED IRRIGATION SCHEDULING

Appendix B

Prepared for: California Energy Commission
Prepared by: UCSB

MAY 2016
CEC-14-081

PREPARED BY:

Primary Author(s):
Kevin Langham, UCSB
Roland Geyer, UCSB

University of California, Santa Barbara
Santa Barbara, CA 93106
Phone: (805) 893-8000
http://www.ucsb.edu/

Contract Number: EPC-14-081

Prepared for:

California Energy Commission

Leah Mohney
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

Many thanks to Olivier Jerphagnon, PowWow Energy for consulting on proper content and providing detailed information for methodology development. Additional thanks to UCD colleagues Teresa Carrilo-Cobo, Israel Herrera and Kate Scow for consulting on experiment results, and working together to develop the best experiment. Thanks to the farmers that worked with us and maintained constant communication about farm status, especially James "Jimmy" Nichols. Finally, thank you to the several experts that consulted on the normalization factors in this project, we could not have done it without you.

ABSTRACT

This document summarizes a protocol designed to quantify the water and energy intensity changes from implementation of two treatments at five test sites. Within the scope of this study, there are two stages within a farm where resources are converted; energy is converted into water in the irrigation infrastructure (well pumps, lift pumps, booster etc.) and water is converted into yield in the plants. Two treatments were applied which aimed to improve those efficiencies. PowWow's Pump Monitor software was applied on pumps to reduce the energy intensity to pump water (kWh/ac-ft), and optimized irrigation schedules were applied to crops to improve the irrigation water intensity (ac-ft/ton yield). Optimized irrigation schedules varied per site and crop type and included: full evapotranspiration (ET), ET with soil moisture monitoring (ET-SMM), or partial ET with deficit irrigation (Carrillo-Cobo, 2015). Data sources for comparison include records from various sources (cloud service data, on-site sensors, or farmer irrigation notes) and available online under the Software-as-a-Service (SaaS) provided by PWE for the experiments.

Comparison of treatments and controls are done differently for each system. Pump energy intensity is compared annually as this is an appliance system that is subject to minimal external factors. Irrigation water intensity is compared within the same year, and near-by fields as there are numerous external factors that affect the yield of a crop. Analysis of the potential impact of external factors is explored, though quantification of the influence is outside the scope of the project. Results of the experiment are presented in the attached appendices.

Keywords: Life Cycle Assessment, water footprint, carbon footprint, functional unit, comparison

Langham, Kevin; Geyer, Roland. (UCSB). ***Life Cycle Protocol for Optimized Irrigation Scheduling.*** California Energy Commission. Publication number: CEC-500-YYYY-XXX.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.1 Introduction

PowWow Energy has developed two programs that aim to reduce the water and energy intensity on farms: optimized irrigation and smart pump monitoring. These programs are facilitated by a data analytics platform developed by PWE that integrates numerous measurements at the farm level such as pump energy records, aerial imagery, evapotranspiration (ET) estimates, stem water potential, and soil moisture monitoring. The principal purpose of this deployment project is to validate a hypothesized 20% improvement in energy and water efficiency from the two programs by applying them to commercial and demonstration fields. Five test sites have been selected that span over 1500 acres and include pistachio, almond, tomato and alfalfa crops to test these programs.

This protocol will present a framework to measure the water and energy intensity between existing farming practices and optimized practices through PWE programs. These PWE programs will be referred to as ‘treatments’ and status quo will be referred to as ‘control’. Within each site, some fields will be subject to treatments and others will be run as the farmer sees fit (control). Water and energy intensity reductions from various smart irrigation strategies will be measured by comparing treatment fields and control fields within the same growing season. Historical comparison is avoided when considering yield, due to the fact that there are too many external factors affecting annual yield.

1.2 Project Goals

The goal of this project is to develop the Life Cycle Assessment (LCA) protocol for measuring the impacts of water and energy intensity treatments during one growing season. The principal treatment is a smart irrigation treatment to fields based on plant evapotranspiration (ET). The fundamental process that a plant uses to regulate its temperature, the rate of carbon capture from the atmosphere, and nutrients from the soil is ET [1]. Due to the daily variance of ET in response to weather, plants require varying amount of water each day. Irrigating crops based on this daily change in ET can provide an avenue for significant water/energy savings. This method avoids deep percolation in the soil (drip irrigation and surface irrigation) or run-off from the field (surface irrigation) associated with over watering.

We are particularly interested in comparing the water and energy footprint at five test sites in order to compare two different forms of irrigation scheduling: existing irrigation practices using limited information, and optimized irrigation practices leveraging advanced data analysis and modern communication tools. The baseline irrigation will be defined as ‘farmer preference’, which will likely vary between each site as the farmer sees fit. The treatment irrigation will be selected by the farm manager after consultation with PWE and the UC Cooperative Extension (UC-CE). Three treatment irrigation choices are offered: full ET (ET), ET with Soil Moisture Monitoring (ET-SMM), or partial ET with Regulated Deficit Irrigation (RDI) to minimize yield losses [1].

The energy intensity change from the pump monitoring treatment will be calculated and the methodology will be presented in the energy intensity section. Estimating the savings from this treatment is an auxiliary calculation, but is still important to consider.

Water and energy footprints will be compared between the baseline and the treatment irrigation strategies to test PowWow's hypothesized 20% water and energy savings. The detailed data and results from this study are not intended for the public; however the aggregate site water and energy savings may be distributed to the public. Results should not be used to compare with other agriculture sites outside of this project, as many factors may be different.

1.3 Project Scope

1.3.1 Functional unit

In order to compare baseline and treatment impacts, a functional unit must be defined that encompasses the service provided by the product system [2]. When analyzing agricultural impacts from a life cycle perspective, special attention must be given to the selection of this functional unit. In an analysis of agricultural LCA methodology, Haas et al. suggested that agricultural functional units can include: the entire farm, a specific area (Ha), or product (ton yield) [3]. Because yield is important to consider in this project, the functional unit for this study will be based on yield. Due to the fact that crop type varies between each site, the specific functional unit for each site will be different based on crop (Table 1).

Table 1: List of different functional units specific to each test site. Functional units have been chosen based on the Yield Measurement Workshop involving UCD, UCSB and PWE held in 2015 [4].

Site Number	**Site Name**	**Functional Unit**
Site #1	Nichols: Drummond	1 ton pistachio edible nuts + shells with <12% moisture
Site #2*	Nichols: AKE	1 ton pistachio edible nuts + shells with <12% moisture - or - tons edible almond nuts/tons hulls (dry wt.)
Site #3	Russell Ranch	1 ton red tomato (wet wt.)
Site #4	Meeks	1 ton red tomato (wet wt.)
Site #5	Button &Turkovich	1 ton total dry alfalfa biomass (dry wt.)

** Because Site #2 contains parcels with almond and pistachios, each crop will utilize individual functional units based upon crop type*

In traditional comparative LCA, the product systems which fulfill the functional unit are compared through various impact categories. For the purposes of this study, the functional unit at each site will be compared in terms of water use per functional unit (ac-ft/ton yield) and energy use per functional unit (MWh/ton yield). While it is important to have a functional unit that encompasses yield, this may cause results to show a comparative percent change that differs from the direct applied water or energy percent change (Table 2)

Table 2: Tables 2-A & 2-B illustrate two scenarios where a 20% savings in water use results in a percent change in functional unit (highlighted in yellow) that differs from the actual percent change of water use. The Percent change row was calculated by diving the 2016 value by the 2015 value and subtracting the difference by 1.

Table 2-A.					*Table 2-B.*			
Year	**Water Use (ac-ft)**	**Yield (t)**	**ac-ft/t**		**Year**	**Water Use (ac-ft)**	**Yield (t)**	**ac-ft/t**
2015	100	25	4		**2015**	100	25	4
2016	80	30	2.67		**2016**	80	20	4
% Change	↓20%	↑20%	↓**33%**		**% Change**	↓20%	↓20%	**0%**

Table 2 shows two sample scenarios which illustrate how a decrease in water use of 20% can have varying comparative results when using a yield-based functional unit. Table 2-A represents a scenario with a decrease in water use by 20% coupled with an increase in yield of 20%. The cause of this increase in yield cannot be determined; it may have been caused by better nutrient uptake, or another factor not related to irrigation scheduling. The resulting comparison between the functional unit shows a 33% savings (yellow highlight), while the actual water savings are only 20%. Conversely, Table 2-B represents a scenario where water use decreases by 20% and yield also *decreases* by 20%. Thus, the difference in the functional unit is 0% (yellow highlight). With this in mind, the functional unit comparison should not represent absolute water or energy savings, but rather 'effective water or energy savings', to account for the yield normalization.

1.3.2 Project Study Sites

This comparative LCA will include energy use and irrigation records from groundwater, surface water and rainfall at all sites within this study. Due to the fact that each site includes numerous fields, it is necessary to specify which fields within each site will be included in this study (Table 3). Fields were included from each site as specified by PWE. Site #1 has three fields of pistachios that were planted in 2014 and have yet to reach maturity. Because of this, they will not be included in the comparative LCA. Measurements of water use and energy use will be compared between control and treatment fields.

Table 3: List of the fields being analyzed for water and energy savings as specified by PowWow energy.

Site number	**Site Name**	**Included Fields**	**Acres**
Site #1*	Sierra View	Drummond C,D,E,F,G,H & J	238

Site #2	Nichols	AKE A, Ake B, AKE C1, AKE C2, AKE C3, AKE D North Ake D South	830
Site #3	Russell Ranch	Demo Field E	8.8
Site #4	Meeks	Field 56 (West/East)	150
Site #5	Turkovich	Field 12 (North/South)	75
**** Drummond A, B & I were omitted from site #1 as they have not reached maturity yet.***			

As mentioned in the introduction, there are various types of irrigation strategies and methods for impact comparison at each site. Irrigation application varies between flood, drip or subsurface drip irrigation. Irrigation application method is determined by farmer preference and crop type. Furthermore, the treatment for each site may be one of three types: full evapotranspiration (ET), ET with soil moisture monitoring (ET-SMM), or partial ET with regulated deficit irrigation (RDI). These specifications for each site are aggregated in Table 4 below. The almond fields do not have a farmer preference control field and instead, a treatment of full ET will be compared to regulated deficit irrigation.

Table 4: The irrigation strategy, method of comparison and treatment irrigation for each site in the study.

Site number	Type of Irrigation	Method of comparison	Treatment Type
Site #1	Flood/Drip	Side by Side: *Control (Drummond E) and Treatment*	ET/partial ET
Site #2			
Almond	Flood/Drip	Side by Side: *Treatment ET (AKE-C3/C4) Treatment (AKE-D)*	ET-SMM
Pistachio	Drip	Side by Side: *Control (AKE-A) and Treatment (Rest)*	ET/partial ET
Site #3	Subsurface Drip	Side by Side: *Control (every other line) and Treatment (every other line)*	ET Partial ET
Site #4	Subsurface Drip	Side by Side: *Control (West) and Treatment (East)*	ET
Site #5	Flood	Side by Side: *Control (North) and Treatment (South)*	Flood & Flood with limited runoff

Due to the fact that each site is a commercial field not insured by the project, the farmer has the right to change irrigation practices at any time. The farmer may decide at any point to change the treatment type as to preserve the value of his crop. While not expected, any changes will be noted and listed in an updated version of this document.

1.4 Data Sources

The data analytics platform has access to three types of data to optimize irrigation scheduling:

- Historical records for planning at the beginning of the year:
    - Historical pump records provided by PWE using the Pump Monitor product to understand existing irrigation schedule.
    - Historical ET records from California Irrigation Management Information System (CIMIS) to compare ET schedule with existing irrigation schedule and identify possible mismatch that can cause water waste or yield losses.
    - Historical images that are post processed to provide Normalized Differential Vegetation Index (NDVI) to identify areas that under-irrigated or over-irrigated

- Data services that are integrated by PWE using the Irrigation Advisor product during the season
    - Pump records
    - ET forecasts from National Weather Services (NWS)
    - Monthly aerial images (pistachio, almond, and alfalfa) or weekly aerial images (tomato)

- For some of the fields on-site sensors are installed to provide more insights:
    - Soil Moisture Monitoring (SMM) sensors provided by Irrometer
    - Actual ET (ETa) sensors irrigation efficiency using renewable surface method provided Tule
    - Stem Water Potential (SWP) measurements done manually with a pressure chamber
    - In the case of surface irrigation, a temperature system provided by Hobo to detect the progress of the flood of water across the field.

1.5 Water Use Intensity

The change in water use intensity will be calculated by comparing the water use (ac-ft) per functional unit (ton yield) between treatment and control fields. Total water use of the field will be defined by aggregating the water applied to the crop from three potential sources, groundwater irrigation, surface water irrigation and rain. Yield will be gathered for each site in the format outlined in SubTask 7.5 Yield Measurement Requirements and will be reported separately for control and treatment fields. The protocol for measuring water applied from each of the three sources is outlined in the sections below.

1.5.1 Groundwater Irrigation

The majority of the sites in this project irrigate their crops primarily from groundwater, which is pumped from wells to the surface. This water is frequently distributed into reservoirs before it is allocated to specific fields through booster pumps (Sites 1 & 2). Groundwater irrigation to crops will be gathered from a selection of four data sources: PWE smart meters, Tule pressure switches, flow meters and farmer irrigation records. A summary of the data sources available to estimate water applied for each site is presented in Table 5.

Table 5. List of the different data sources available at each site to estimate total volume of water applied to each of the fields within the study.

Site	Water Data Sources
Site #1	1. PWE Smart Meter 2. Irrigation Records 3. Tule Pressure Switch
Site #2 Pistachio	1. PWE Smart Meter 2. Irrigation Records
Site #2 Almonds	1. PWE Smart Meter 2. Irrigation Records
Site #3	1. PWE Smart Meter 2. Small and Large Flow Meters
Site #4	1. PWE Smart Meter 2. Irrigation Records 3. Tule Pressure Switch
Site #5	1. PWE Smart Meter 2. Small Flow Meters

PWE has ensured there are smart meters installed at each site, which allow for the energy usage (MWh) to be converted into water applied (ac-ft). Small pressure sensors on all fields containing a Tule sensor will also gather data on hours a pump is applying water through a drip irrigation system. Some fields are equipped with flow meters that provide a more detailed report of total water applied. Additionally, farmers manually record irrigation data that will be used to corroborate meter readings. All of these data sources will be used to maximize data accuracy and robustness of water applied to each field. In the case where two sources do not align (ex. smart meter calculations and irrigation records) and it cannot be determined which source is more accurate, an average will be taken and error will be presented based on the range between the two values.

Accuracy of smart meter measurements using version 2.0.3 of the PWE algorithm were tested by Cal Poly at Site #6, Terranova Ranch and processed/verified by UCSB. The results from these tests can be viewed in the appendix of SubTask 7.3 Water Measurement Report. The results from this verification study revealed that the mean error of this version of the smart meter algorithm is between 5.37% and 10.61% when calculating total volume of water pumped. In 2017 a new presumably more accurate version of the algorithm will be released, and will be re-verified using the same methodology.

1.5.2 Surface Water Irrigation

Surface water use will vary between measured sites in the 2016 growing year. When it is available, many farms will utilize surface water for irrigation. In 2015, most sites in this study did not apply any surface water due to a lack of availability, and will continue to avoid surface water for irrigation. Table 6 indicates predicted surface water allocation in 2016 and the method for measuring surface water use.

Table 6: Predicted surface water allocation for the 2016 growing year and the measurement method for total surface water applied.

Site number	Predicted 2016 surface water use?	Measurement Method
Site #1	no	N/A
Site #2	no	N/A
Site #3	no	N/A
Site #4	no	N/A
Site #5	no	N/A

Sites 3 and 4 utilize only sub surface drip irrigation that is fed exclusively by groundwater. The owners at Site 1 and 5 agreed to use no surface water in order to provide a reasonable comparison between sites.

1.5.3 Precipitation measurement

Precipitation measurement can be done using rain gauges, and multiple online sources are available for this data. However effective precipitation (Pe) must be calculated to accurately measure water available to crops. Effective precipitation is the amount of precipitation that infiltrates the soil and is stored in the root zone so that it may be used by the plants [5]. When rain falls, some runs off on the surface, and some will percolate below the root zone. Thus, only a portion of the water is actually available to be absorbed by the plant, and that is known as effective precipitation. When the soil is dry and the rain events are not heavy, the total precipitation and effective precipitation are approximately equal. The USDA Soil Conservation

Service has developed an equation that accounts for surface runoff and deep percolation past the root zone of the plants. The equation to estimate P_e is as follows:

$$Pe = P - RO - D_P$$

Where P is total precipitation, RO is runoff and D_P deep percolation past the root zone during rain events. Losses due to RO and D_P cannot be controlled. We will only count P_e as contribution from rainfall. It should be noted that the P_e calculation does not include other factors such as evaporation or soil absorption that are based on weather. However, P_e is accepted in academic studies and will suffice for our definition of precipitation in this study.

Precipitation will be tallied with separate methods for tree crops (Almond & pistachio) and row crops (alfalfa & tomato). Tree crops will have the 2016 rainfall calculated from Nov 1st 2015 – November 1st 2016. The reason a November 1st cutoff date was selected is that it generally corresponds with the harvest for these two crops. Row crops are typically removed after harvest, thus an annual summary of rainfall is not appropriate. For row crops at Sites #3/4/5, soil moisture at the time of transplant was measured by UC Davis (UCD). That quantity of water in the soil will be added to the total precipitation measured during the growing season to generate a value for the total water applied to the crop from rainfall.

Due to the limited rainfall in 2016, UCD advised that P_e and total precipitation would be essentially equal. Therefore, in the presentation of 2016 results, total precipitation is presented. Total precipitation was measured by the Data Transmission Network (DTN), the Progressive Farmer Agriculture Division.

1.5.4 Sensors used to optimize irrigation scheduling

Each site has numerous sensors installed to aid in the application of ET based irrigation. Sensors require hardware to be either transported by car (Stem Water Potential) or permanently installed with a telemetry system (SMM or ETa) at each site. Table 7 describes the known hardware being used at each test site.

Table 7: List of known hardware required for PowWow treatment scheduled irrigation at each site.

Site Number	Site Name	Hardware Installed
Site #1	Sierra View	3 ETa sensors with telemetry equipment
Site #2	Nichols	2 SMM sensors with telemetry equipment
Site #3	Russell Ranch	2 SMM sensors
Site #4	Meeks	2 ETa sensors, 2 SMM sensors
Site #5	Turkovich	2 ETa sensors, 2 SMM sensors, and 1 Hobo Temp System

While there may be an additional energy and water burden associated with the manufacture, use and end of life of these sensors, the calculation falls out of the scope of this project.

1.6 Energy Use Intensity

1.6.1 Measuring Energy Use

Energy is generally consumed on a farm in four ways:

- application of groundwater through well pumps and boosters
- application of surface water through lifts
- farming equipment
- embodied energy of infrastructure such as sensors

At the sites in this study, well and booster pumps were the primary consumer of energy. Data for electricity usage of wells and boosters came from utility smart meters attached to the pump units. To allocate an energy burden to individual fields, the total well/booster energy usage will be multiplied by the ratio of water applied to the field and total water pumped. In other words, the field will be allocated the same proportion of energy as water applied.

Surface water is not scheduled to be applied to any of the fields in the study. However, if surface water is applied, it will be measured and considered as an external factor affecting the overall energy intensity results for a site. Estimating the energy burden of farming equipment (tractors, harvesting equipment etc.) and the embodied energy burden from sensors is not in the scope of this study. The energy impact from data transfer and storage using PWE software will be estimated in Sub Task 7.3 LCA for Water Measurement.

1.6.2 Defining Farm Energy Intensity

In order to develop a methodology for calculating the energy intensity of farms, ‘energy intensity’ must first be carefully defined. On a farm, energy is consumed to pump water to fields, where the crops consume the water and produce yield; i.e. the input to the farm system is energy and the output is yield. Therefore, energy intensity of a farm is defined as the energy consumption (MWh) per ton yield (our functional unit). To calculate this definition of energy intensity on the farm, we take the product of the pumping energy intensity and the irrigation water intensity (***Figure 1***).

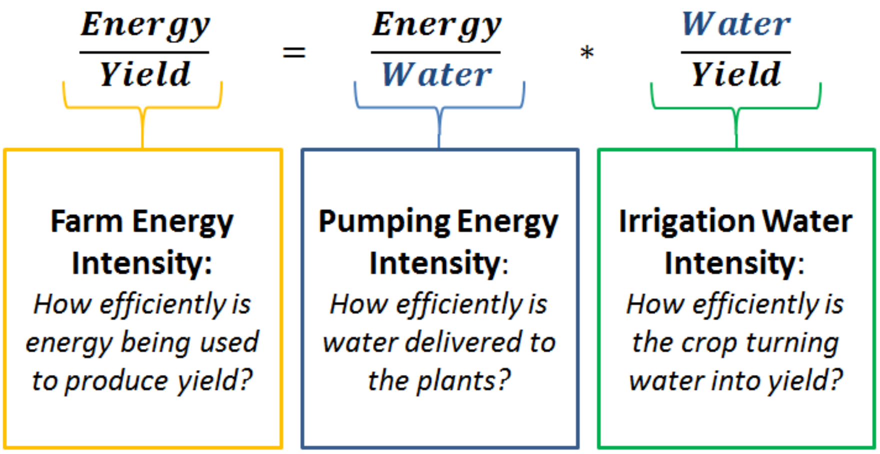


Figure 1. **Visualization of the relationship between the two components of farm energy intensity. The input to the farm is energy, and the output is yield, and water is the factor that connected both of these flows.**

Pumping energy intensity is a measure of how much energy is required to pump water to the crop. Pumping infrastructure can be very simple (Ex. Site #3, where 1 groundwater well pumps water to a single field) or complex (Ex. Site #2, where 4 groundwater wells and 3 surface water pumps deliver water into a reservoir, where 3 booster pumps deliver water to 7 fields). Farms such as Site #2 with additional water pumping equipment will have a comparatively higher energy intensity.

Irrigation water intensity is a measure of how much water is required to produce a ton of yield; or rather, how efficient a plant is at converting water into yield. Therefore, the energy intensity on a farm is the product of the pumping energy intensity and the irrigation water intensity. The energy intensity on a farm can be estimated on any scale (ranch or field) with these two variables.

1.6.3 Calculating the Energy Intensity Change from Treatments

PWE applied two separate treatments to reduce energy intensity at each site. The first was a smart irrigation schedule, which aimed to minimize excessive watering of crops and ultimately improve plant efficiency. This treatment is the principal focus of this experiment. The second PWE treatment was smart pump monitoring. Both of these treatments were considered separately, and the impacts were measured with individual methodologies as one is a physical system (pump) and the other involves a biological system (plant). The following sections will define the two methodologies developed to estimate the true energy intensity change from pump and irrigation efficiency treatments.

1.6.3.1 Methodology for Calculating the Energy Intensity Change of Smart Irrigation

PWE Irrigation Treatment

The treatment applied by PWE to reduce irrigation water intensity is the use of smart irrigation strategies based on plant evapotranspiration (ET). Many farmers apply more (or less in some cases) water than necessary as a ‘safety net’ to their crops. It can be difficult to determine the precise amount of water that should be applied without help from technology, as it is based on numerous external factors. PowWow Energy offered farmers a smart irrigation schedule so that they could get an idea of how much water the plant needs. Applying irrigation based on plant ET allows farmers to apply only the amount of water necessary for the plant to grow and maintain yield.

How to calculate energy intensity per field

To calculate the reduction in energy intensity from treatment irrigation, the energy intensity for treatment and control fields will be calculated using the equation in Figure 2. Thus, to estimate energy intensity for each field the irrigation water intensity and the pumping energy intensity will need to be calculated.

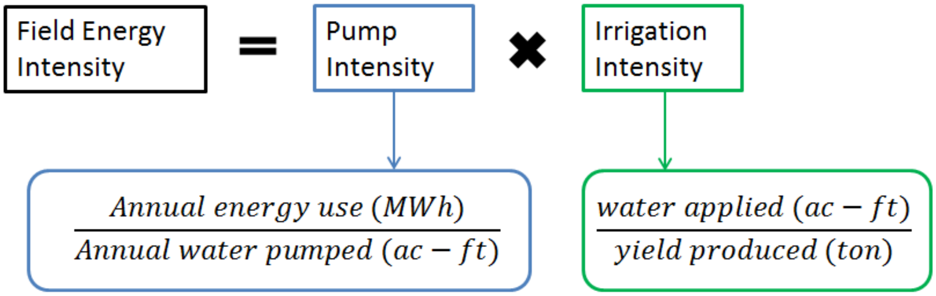


Figure 2 Equation used to calculate energy intensity per field

Irrigation Water Intensity Methodology

The methodology to calculate irrigation water intensity per field has been outlined in Section 1.5 of this document, and those values will be used in this equation.

Pump Energy Intensity Methodology

To estimate pumping energy intensity, the total water pumped (ac-ft) and energy consumed (MWh) by the pump/boosters in a calendar year will be aggregated and the ratio MWh/ac-ft will be used as the value for pumping energy intensity. For sites where wells feed reservoirs and boosters feed the crops, the energy intensity of each appliance will be calculated separately and aggregated to estimate overall energy intensity of the water application infrastructure

How to calculate the reduction in energy intensity

Once the energy intensity for each field has been calculated, treatment fields will be compared with control fields to calculate the percentage change in energy intensity (Figure 3). Unlike appliance energy efficiency, no historical baselines will be included.

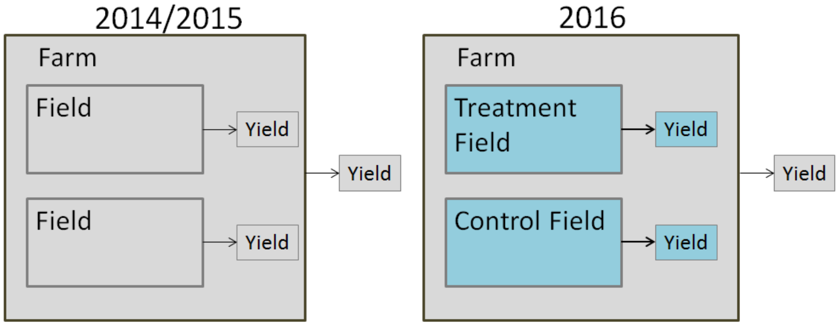


Figure 3. Visual representation of the final methodology developed for measuring the impact treatments on the energy intensity of farms. The blue shapes indicate what is being included in the comparison, while data in grey is excluded from the comparison.

1.6.3.2 Pumping Energy Intensity Methodology

The treatment applied by PWE to improve pumping energy intensity on farms is their Pump Monitor product. This product turns a utility smart electricity meter into a water meter, and monitors energy records daily to find leaks, falling water tables, or issues with a pump. Alerts are sent to the farmer via text message or email when one of these issues is detected. The application of Pump Monitor will cause changes in energy intensity of a pumping system by inducing a behavioral change in a farmer. Behavior changes can manifest in a number of ways and will differ on a case by case basis.

Measuring the precise impact of behavioral change is difficult. In this project, the change will be estimated by comparing the total water pumped (ac-ft) per unit of energy consumed (MWh) on an annual basis. Results can be affected by external factors, which will be analyzed in the report. This method is similar to the traditional methods used by utilities to measure energy improvements in buildings or appliances.

To calculate energy intensity improvements, 2016 data at Sites #1/2 will be compared with 2014 values, and 2016 data at Sites #4/5 will be compared with 2015 values. Site #3 did not have the pump monitor treatment applied. The quantity of energy consumed will be measured from smart meters on the pump, and the total water applied will be calculated by the PWE algorithm. The most current version of the PWE algorithm will be used to calculate historic values for energy and water use. Annual values will be aggregated for the calendar year.

1.7 Normalization of Results

1.7.1 Normalization of Farm Energy Intensity and Irrigation Water Intensity

In order to determine if the improvements in water and energy intensity were due to treatments, all factors that could significantly affect the three variables (yield, energy and water use) need to be either proven to be equal between control and treatment, or normalized for. The first step is to identify all the factors that might have a possible effect on each variable. Table 8 summarizes the list of all possible factors that were confirmed by farmers and experts to potentially have an effect on yield or energy use. Due to the fact that water use and energy use are inherently related, they share the same list of factors that may influence them.

Table 8. List of all the factors that may cause yield energy or water use to vary. To create the list, experts were contacted from UC Davis, PWE, and the farmers of the ranches in this experiment. The factors in this table need to be proven equal or normalized for when estimating the impact of an energy efficiency treatment.

Energy/Water Factors	Yield Factors
Temperature	Soil Fertility
Rainfall	Soil Type
Surface Water Allocation	Root Stock
Other Field Irrigation	Crop Variety
Pump Issues	Evapotranspiration (ET)
Overall Pump Efficiency	Weather Events
Distribution Uniformity	Pests
Soil Variability	Disease
Water Table Level	Crop Age
	Fertilization
	Irrigation Water Quality
	Timeliness of Harvest

Additionally, a separate table of yield factors specific to the crops in the PWE experiment has been identified in Table 9. Experts of these crops expressed that these variables would potentially have a significant effect on yield, which may not be the case for other crops.

Table 9. List of all the factors that could cause significant variation in the yield for crops specific to the PWE experiment. For tomato factors Israel Herrera (Russell Ranch Facility Manager) and Timothy Hartz (UCD Tomato Expert) were interviewed. Alfalfa factors were specified by Mike Button (Button & Turkovich farms) and Israel Herrera. For Almond and Pistachio factors James Nichols (Nichols Ranch Irrigation Manager) was interviewed.

Tomato Specific	Alfalfa Specific	Almond/Pistachio Specific
Wind > 20 mph when budding	Number Cuts	Winter Chilling
Excessive heat during fruit set	Rain after Cut	Alternate bearing
Soil Ph (5-7 preferred)	Early/Late rain	Canopy Light Interception
Historical Crop rotation	Insects	
Soil Salinity	Weeds	
Weed presence	Year of crop	

Unlike physical systems such as buildings, biological systems have an immense quantity of variables that can affect the yield (Tables 8 & 9). However because the experiment was performed in the same location and year, some factors become the same (ex. atmospheric conditions) and numerous factors can be considered likely the same (ex. fertilization, pests/disease, timeliness of harvest etc.) between control and treatment fields (Table 10).

Table 10. A list of all the factors affecting water/energy use and yield categorized into their likelihood differing between control and treatment fields in experiments that are held in the same geographical location and same time period. These are

assumptions based on the data from this experiment, and conversations with farmers. Factors may change categories in specific cases, this list is a general estimate.

Classification	Same	Likely Same	May be different
General			
	Temperature	Overall Pump Efficiency	Pump Issues
	Rainfall	Crop Variety	Distribution Uniformity
	Other Field Irrigation	Pests	Soil Type
	Surface Water Allocation	Disease	Soil Fertility
	Weather Events	Crop Age	Evapotranspiration (ET)
	Root Stock	Fertilization	Water Table Level
	X	Irrigation Water Quality	X
	X	Timeliness of Harvest	X
Tomato Specific			
	Wind > 20 mph when budding	Soil Ph (5-7 preferred)	Historical Crop rotation
	Excessive heat during fruit set	Soil Salinity	X
	X	Weed presence	X
Alfalfa Specific			
	Number Cuts	Insects	X
	Rain after Cut	Weeds	X
	Early/Late rain	X	X
	Year of crop	X	X
Almond/Pistachio Specific			
	Winter Chilling	X	Alternate bearing
			Canopy Light Interception

In an ideal experiment, all factors in the 'may-be-different' or 'likely-same' columns would be normalized for, or proven equal with empirical data. However, the resources may not be available to gather precise scientific data on all factors. Where this is not possible, conversation with farmers and educated assumptions will suffice. Reducing the external factors that need to be considered is essential in order to create an experiment with meaningful results.

To account for potential unintended effects from external factors, efficiency experiments should be designed with the matrix of external influential factors in tables 8-10 in mind.

Supplementary evidence should be gathered to ensure that these factors do not differ between control and treatment fields. Additionally, results should be contextualized with the matrix of factors outlined earlier in this section so that it is clear to the audience when an external factor may have had an effect on the efficiency changes.

1.7.2 Normalization of Pump Energy Intensity

The pump energy intensity deals strictly with appliances and does not encompass biological systems, limiting the number of external factors that have the potential to influence results. The PWE treatment specifically aims to manage for external factors that might increase the pump energy intensity such as leaks, cavitation, dropping water table, or a drop in pressure. There have been three external factors identified in this project to have a potential effect on the pumping energy intensity: water table level, surface water allocation, and the use of other pumping equipment (boosters or transfer pumps) to deliver water to the field. Each of these factors are outside the control of PWE and have the potential to increase or decrease pump energy intensity.

In the current CA drought, water table depth is likely to increase from year to year, as most farms are drawing more groundwater than is being replenished. Increase in water table depth will increase the energy intensity of the pump as it requires more energy to bring water to the surface. Water table depth is best tracked by annual pump tests from the same pump tester and at the same time of year. If this data does not exist, public water table levels can be analyzed from the California Statewide Groundwater Elevation Monitoring Program (CASGEM).

Surface water allocation has the potential to reduce the overall pump energy intensity. Pumping surface water typically has a lower energy intensity as a lift pump does not have to pump water from deep in the earth. The energy intensity of a ranch will be reduced as the proportion of annual irrigation from surface water increases. There is no expected surface water use in 2016 of this project at any site.

While the majority of sites have pressurized well pumps that deliver water directly to the fields, Sites #1/2 have a slightly more complex system. At these sites, well pumps deliver water into reservoirs, and booster pumps deliver the water to the individual fields. Because there are two appliances being used, the relative energy intensity is higher than other sites. When comparing 2016 to previous years, this will not have an effect on results, as the boosters have been in place for several years. However, when comparing site to site, Sites #1/2 will have comparatively higher energy intensity due to the presence of these boosters.

APPENDIX

2.1 2016 Project Results

The water and energy use intensity of each site was calculated and is summarized in the table below using the methodology outlined in section 7.1. Irrigation schedules achieved up to 9% reduction in energy and water use intensity at Site #2 A, 3 and 5. Sites #1, 2P and 4 had data issues or experimental errors preventing robust results. The pumping energy intensity decreased up tp 24% at Sites #1, 2 and 5; Sites #3 and 4 did not have robust data. Details of these calculations are reviewed in the subsections below.

Table 11. Overall average results in energy and water use intensity from treatments in this project. In cases where there were multiple treatments, the maximum savings is presented in this graph (Site #3). Cells with an X indicate there were data or experimental issues preventing accurate data from being gathered.

Site	Irrigation Water Use Intensity Change (Average %)	Irrigation Energy Intensity Change (average %)	Pump Energy Intensity (average %)
Site #1	X	X	-4%
Site #2 P	X	X	-1%
Site #2 A	-8%	-8%	-1%
Site #3	-3%	-3%	X
Site #4	X	X	X
Site #5	-9%	-9%	-24%

2.1.1 Water Use Intensity (WUI)

The water use intensity results for control and treatment fields in 2016 are summarized in Table 12. These were calculated by summing the total water applied (groundwater + surface water + rainfall) and dividing it by the total yield (ton) from the experimental plots. Contextualization for site specific results are covered in the sections below the data table.

Table 12. Results for the water use intensity of all sites in 2016. Methodology for results is discussed in Section 1.5 of this document. The water use intensity is a measure of the total water applied to the crop from all sources over the tons of yield from the crop. Control fields are highlighted in orange. Results from Sites #1 and Site #2 P misrepresent the truth as the control field was not subject to alternate bearing, and all of the treatment fields were. Site #2 P represents pistachio fields, and Site #2 A represents almond fields at Site #2.

Site	Treatment	Fields	WUI (ac-ft/ton)	Change from Control (%)
Site #1				
	Control	Drummond E	2.91	Control
	Treatment #1	Drummond CDFG	1.61	-44.74%
	Treatment #2	Drummond HJ	1.20	-58.83%
Site #2 P				
	Control	AKE A	2.56	Control

	Treatment #1	AKE B	6.67	160.14%
	Treatment #2	AKE C1C2	3.93	53.39%
Site #2 A				
	Treatment #1	AKE C3C4	2.86	Considered control
	Treatment #2	AKE D	2.64	-7.69%
Site #3				
	Treatment #1	Demo Field (East)	0.0433	3.73%
	Treatment #2	Demo Field (West)	0.0418	Control
	Treatment #3	Demo Field (East 8 PSI)	0.0379	-9.28%
	Treatment #4	Demo Field (West 8 PSI)	0.0398	-4.79%
Site #4				
	Control	Field 56 West	0.0492	X
	Treatment #1	Field 56 East		X
Site #5				
	Control	26 Checks	0.58	Control
	Treatment #1	10 Checks	0.53	-9.25%

Site #1

The results at Site #1 are misrepresented due to the effect on an external factor: alternate bearing. At this site, the control field was not mature enough to exhibit alternate bearing, while the treatments fields did exhibit alternate bearing. The treatment fields were on an, 'on-year' in 2016 meaning they produced more yield than the control field. This external factor causes the water use intensity in Table 12 to appear artificially low for Site #1 treatment fields when compared to the control field. Site #1 is planned to be retested in 2017 with control and fields that are on the same alternate bearing schedule.

Site #2 (Pistachio)

Similar to Site #1, the results from the pistachio fields at Site #2 are misrepresented due to alternate bearing affecting treatment fields and not the control field. However at this site, the treatment fields were on an 'off-year', meaning they produced much less yield relative to the control yield. Due to alternate bearing, the WUI results on treatment pistachio fields at Site #2 are artificially high.

Site #2 (Almonds)

The WUI results from the almond fields at Site #2 were fairly robust. It should be noted that there was not a traditional control or 'farmer preference' field for these trees. Instead, the treatment field is compared with AKE C3/C4 which received a full ET irrigation treatment. These results show that the deficit irrigation reduced WUI by 7.69%. This result suggests that further reduction in irrigation from ET may be beneficial for almond field efficiency.

Site #3

Similar to Site #2 almond fields, there was no traditional control or farmer preference field at Site #3. Instead, treatment sections with various levels of deficit irrigation were compared to a section receiving a full ET irrigation treatment. The section with the most deficit irrigation had the greatest reduction in WUI of 9.28% when compared with the full ET treatment. This suggests that additional reduction of irrigation under ET for the last few weeks before harvest may be beneficial for tomato water efficiency.

There was an experimental error at this site. During the beginning of the season when each section was supposed to receive equivalent irrigation, the east side received 2 inches more than the west. The east side still received the scheduled 20% deficit irrigation later in the season. Despite this experimental error, meaningful results were still generated from the site, as deficit irrigation was applied in the last weeks before harvest. Site #3 is set to be retested in 2017 with irrigation applied according to the planned methodology.

Site #4

There were 2 issues with the experiment at Site #4 in 2016 that prevented results from being generated. The farmer at Site #4 did not follow recommended irrigation quantities for the season and mid-season experimental design changes prevented some data from being gathered from the control side of the field.

The farmer at Site #4 did not follow PWE recommendations and watered both control and treatment sides of the field similarly for several weeks. He did not follow recommendations for the first week because he thought the irrigation would not reach the roots of the transplants. The farmer did not follow recommendations for future weeks because of soil variation within his 150 acre plot, claiming that if he irrigated based on ET, the plants in the sandy patches would be too stressed.

There were changes made to the experiment in the middle of the growing season that prevented data from being separately gathered for control and treatment sections of the experimental field. Pressure switches were only installed on the treatment side, and yield was only gathered on the treatment side. Due to the errors covered above, the experiment is being repeated in 2017 with only a few rows.

Site #5

WUI was reduced on treatment checks at Site #5 by nearly 10%. This was due to a combination of reducing water applied to treatment checks and gathering higher yield on treatment checks. UC Davis colleagues working on this experiment advised that the variation in yield was likely random and not a result of irrigation variance.

2.1.2 Energy Use Intensity

Energy intensity reductions were achieved from two PWE treatments, smart irrigation based on ET and smart pump monitoring. The energy intensity improvements from both of these treatments are summarized in the two sections below. The methodology developed for the calculation of these results is detailed in section 1.6 in the main body of this paper. The original methodology was not able to accurately generate results for these sites. Therefore, the methodology at some Sites 1, 2 and 5 was manipulated slightly from the planned methodology to maintain more accurate results. The original methodology results and the deviations are described in detail in the results sections below.

2.1.2.1 Pumping Energy intensity

The percent change in pump energy intensity for each site has been calculated in Table 13. This table summarizes the results which are presented in more detail in the sections below.

Sites #1/2 compared 2016 pump energy intensities with 2014 values, while Site #5 compared 2016 intensities with 2015 values. The PWE pump monitor treatment was not applied to the pump at Site #3, and thus no results are presented for that site. There was no reliable data available for total water pumped in 2015 at Site #4, thus an annual comparison of energy intensity was not possible. Results for Sites #1,2 and 5 had unanticipated inaccuracies using in the original methodology. In an attempt to calculate results closer to the truth, alternative methodologies were used for each of these sites. The results from the original methodology and the alternative methodologies are detailed in the sections below.

Table 13. The change in pumping energy intensity (MWh/ac-ft) for each site in the study, The 'Original Methodology' column was calculated using the methodology outlined in section 1.6.3.2 of this study. The 'Alternative Methodology' results were calculated using new methodologies outlined in the sections below.

Site	Original Methodology (Energy Intensity % change)	Alternative Methodology (Energy Intensity % change)
Site #1	9%	-4%
Site #2	0%	-1%
Site #3	X	X
Site #4	X	X
Site #5	7%	-24%

Results from Original Methodology

The energy intensity for boosters and well pumps at each site in this experiment are summarized below for years 2014 – 2016 using the methodology discussed in section 1.6.3.2 (Table 14). The energy intensity is calculated annually based on the total water pumped and the total energy consumed by boosters or well pumps respectively. For sites that have well pumps and booster pump, the total energy intensity was calculated by added the individual energy intensities of the booster and well pumps. The energy intensity at each site was compared with the most recent year where the farmer was not using the PWE smart pump monitor. Data on pump energy use and water use were only available for Sites #1/2 in 2014. Site #3 only has data presented for 2016, because the PWE pump monitor treatment was not applied to the large pumps at Russell Ranch. Site #4 does not have data presented for 2015 water pumped, because no accurate source of data was available.

Table 14. Table showing the total energy use, water pumped and energy intensity from well and booster pumps at the 5 sites in this experiment for 2014-2016 using methodology detailed in section 1.6.3.2. Booster and well intensities are added together to produce the overall annual site energy intensity. Sites #1/2 are compared with 2014 data, while Sites #4/5 are

compared with 2015 data. Data for energy use came from utility smart meters and water pumped was calculated from the PWE algorithm using the most current pump tests and algorithm version available. Historical data (2014 & 2015) likely have data inaccuracies due to expired pump tests, water alerts, multiple pumps on one meter and pump repairs.

	2014		2015		2016	
Site #1	**Booster**	**Well Pump**	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)	146,754	560,017	128,495	412,044	169,962	499,964
Water pumped (ac-ft)	764	1,384	764	1,013	942	1,059
Energy intensity (MWh/ac-ft)	0.19	0.40	0.17	0.41	0.18	0.47
Total (MWh/ac-ft)	**0.60**		**0.58**		**0.65**	
					Energy Intensity Change (%)	**9%***
Site #2	**Booster**	**Well Pump**	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)	364,942	1,301,013	375,242	1,248,959	459,900	1,136,598
Water pumped (ac-ft)	2,116	2,666	2,171	2,599	2,657	2,335
Energy intensity (MWh/ac-ft)	0.17	0.49	0.17	0.48	0.17	0.49
Total (MWh/ac-ft)	**0.66**		**0.65**		**0.66**	
					Energy Intensity Change (%)	**0%***
Site #3	**Booster**	**Well Pump**	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)	X	206,095	X	137,589	X	168,495
Water pumped (ac-ft)	X	X	X	X	X	429
Energy intensity (MWh/ac-ft)	X	X	x	X	X	0.39
Total (MWh/ac-ft)	**X**		**X**		**0.39**	
					Energy Intensity Change (%)	**X**
Site #4	**Booster**	**Well Pump**	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)	X	X	X	218,952	X	177,467
Water pumped (ac-ft)	X	X	X	X	X	451
Energy intensity (MWh/ac-ft)	X	X	X	X	X	0.39
Total (MWh/ac-ft)	**X**		**X**		**0.39**	
					Energy Intensity Change (%)	**X**
Site #5	**Booster**	**Well Pump**	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)		X	X	113,019	X	14,770
Water pumped (ac-ft)	X	X	X	933	X	114

Energy intensity (MWh/ac-ft)	X	X	X	0.12	X	0.13
Total (MWh/ac-ft)	**X**		**0.12**		**0.13**	
					Energy Intensity Change (%)	**7%***

**These results were deemed to misrepresent reality. Alternative methodology and new results are presented in following sections.*

Using this methodology, the pump energy intensity change ranged from 0% (Site#2) to 9% (Site #1). While these results may suggest that the pump monitor increases energy intensity at the pump, the data increases were influenced by external factors such as shifting water table level. An analysis of water table levels for each pump is presented in the water table section 2.2.2 of data normalization. Alternative methodologies were utilized for the pumping energy intensity of Sites #1, 2, and 5 due to data inaccuracies and influence from external factors.

Energy intensity results at Sites #1/2 are the highest because those farms require a well pump to deliver water into reservoirs, and boosters to deliver the water to individual fields. This additional appliance causes the overall energy intensity to increase by about 0.175 MWh/ac-ft or 60% of the well energy intensity. In 2016, Site #5 had the lowest energy intensity. This lower intensity was likely caused by the fact that the water table is only 60 feet below the surface, which is much closer to the surface than all other pumps in this study. Shallower water tables reduce the distance the pump lifts water against gravity (pumping water level), and thus minimize energy requirements.

Site #1 Alternative Methodology

In the original calculation, the pumping energy intensity in 2016 was compared with 2014 values. The year 2014 was selected as the baseline because this was the first full year of energy use data before pump monitor was utilized. 2016 was initially selected as the treatment year because it was the year the irrigation schedule treatments were deployed. However upon analysis of the data, a comparison of 2015 and 2014 provides a better estimation of savings because this was the first year the Pump Monitor treatment was implemented, and when behavioral changes were noted. Additionally, influence from external factors was greater in 2016 as there were 2 years of water table change, and the use of an additional pumping equipment (transfer booster). See section 2.2.2 for a full discussion of external factors.

The new calculation of change in pumping energy intensity can be seen in Table 15 below. Instead of a 9% increase in energy intensity, the calculation now shows a decrease of 3.63% energy intensity. This reduction is likely due to a behavioral change, where after seeing the Pump Monitor data, the ranch manager decided not to use Pump Drummond A North in 2015, as it was having issues. This meant that the more of the water was pumped from more efficient well pumps, reducing the overall intensity.

Table 15. Calculation of pumping energy intensity (MWH/ac-ft) for the irrigation infrastructure at Site #1 in the study. Energy use data was taken from utility smart meters and water pumped data was taken from PWE algorithm using the most current software version and pump tests.

	2014		2015	
Site #1	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)	146,754	560,017	128,495	412,044
Water pumped (ac-ft)	764.4	1383.5	764.1	1012.6
Energy intensity (MWh/ac-ft)	0.19	0.40	0.17	0.41
Total (MWh/ac-ft)		**0.60**		**0.58**
		Energy Intensity Change (%)		**-3.63%**

Site #2 Alternative Methodology

Similar to Site #1, the initial comparison for pumping energy intensity was between 2014 and 2016. The data in 2016 was found to be affected by external factors. After the experiment was completed, it was discovered that there was surface water used in 2016 at Site #2. One of the lift pumps used 13,167 kWh to pump ~404 ac-ft of water to the reservoir that feeds the booster pumps, which would have been otherwise delivered from a well pump. The surface water consumption is not included in Table 15 above, because this lift was not used in previous years thus an annual comparison would be meaningless. However, using a lift pump instead of a well pump to deliver water to the reservoir reduces the ranch level energy intensity, as the energy intensity of the lift pump is much lower than well pumps (Table 16). The result is that in 2016, Site #2 was able to pump more water for less energy, despite the fact that the individual well and booster energy intensities hardly changed (well energy intensity decreased by 0.28% and booster energy intensity increased by 0.37%). The resulting ranch level energy intensity with the lift pump information included has been recalculated below in Table 16, to be used when calculating the total energy intensity change on a farm level.

Table 16. Table recalculating the ranch level energy intensity for Site #2 including surface water pumped from a lift pump on site. A weighted average was taken between the well and lift pump based on total volume pumped, and added to the booster energy intensity to calculate total ranch level energy intensity.

Site #2 (2016)	**Booster**	**Well Pump**	**Lift Pump**
Energy Use (kWh)	459,900	1,136,598	13,167.71
Water pumped (ac-ft)	2657.3	2335.35	403.96
Energy intensity (MWh/ac-ft)	0.17	0.49	0.03
Weighted Average (MWh/ac-ft)	N/A	0.42	
Total Energy Intensity (MWh/ac-ft)	**0.59**		

To calculate the new energy intensity including the lift pump, a volume-weighted average was taken for both the energy intensity of the well pump and the lift pump based on total water pumped. The inclusion of the lift pump data brought the weighted average energy intensity down from 0.49 MWh/ac-ft to 0.42 MWh/ac-ft, a reduction of 13.7%. When summed with the energy intensity of the booster pump, the total ranch level energy intensity to deliver water to the field in 2016 was 0.59 MWh/ac-ft (Table 16).

To minimize the impact of external factors, the pumping energy intensity was recalculated to compare 2015 and 2014 annual pumping energy intensities (Table 17). The impact of the project was measured similar to the original result, showing a reduction of -1.07%. This slight reduction likely came from a repair that was made to well pump AKE A during the 2015 growing season, preventing the use of this pump. Pump tests show that the overall pumping plant efficiency (OPE) at AKE A increased from 52.5% in 2014 to 66.3% 2016. In 2015, the other well pumps had an OPE of 66%, 67% and 59%. The reduction in energy intensity would have been higher, however there was a slight drop in water table level between these two years, increasing the energy intensity (see section 2.2.2).

Table 17 Calculation of pumping energy intensity (MWH/ac-ft) for the irrigation infrastructure at Site #2 in the study in 2014 and 2015. Energy use data was taken from utility smart meters and water pumped data was taken from PWE algorithm using the most current software version and pump tests.

	2014		**2015**	
Site #2	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)	364,942	1,301,013	375,242	1,248,959
Water pumped (ac-ft)	2116.3	2665.8	2171.1	2599.0
Energy intensity (MWh/ac-ft)	0.17	0.49	0.17	0.48
Total (MWh/ac-ft)		**0.66**		**0.65**
		Energy Intensity Change (%)		**-1.07%**

Site #5 Alternative Methodology

At Site #5 there was a lack of a pump test or irrigation record data in 2015 to corroborate well algorithm output, creating significant error with the algorithm estimation for 2015 total water pumped. To reduce error, an alternative method was used to estimate total water pumped in 2015. Instead of volume of water data, PWE was given dates that the pump was used to irrigate the specific field in our experiment. Total energy use and water use for 2015 and 2016 were only included if they occurred on a date that the pump was used on our specific experiment field. To estimate total volume in 2015 from flood dates, the average flood event in 2016 was first calculated to be 0.71 feet of water (max flood volume = 0.84 ft; min flood volume = 0.65 ft). The total acre-feet of flooding per event in 2015 was assumed to be the same as the average volume in 2016 (0.71 ft). The energy intensity for the pump in 2015 using this value comes out to 0.16 MWh/ac-ft (Table 18). The resulting percent change in pump energy intensity changes from +33% using the original methodology, to -24% using the alternative methodology.

Table 18. Recalculated results of pump energy intensity at site #5 using the alternative methodology described in this section.

Site #5	**Booster**	**Well Pump**	**Booster**	**Well Pump**	**Booster**	**Well Pump**
Energy Use (kWh)		X	X	53,297	X	11,122

Water pumped (ac-ft)	X	X	X	330	X	91
Energy intensity (MWh/ac-ft)	X	X	X	0.16	X	0.12
Total (MWh/ac-ft)	**X**		**0.16**		**0.12**	
					Energy Intensity Change (%)	**-24%**

As a sensitivity test, the 2015 energy intensity was also calculated using the 2016 maximum (0.84 ft) and the minimum (0.65ft) flood volume to gauge the impact of variation on the energy intensity (Table 19). When compared with the 2016 pumping intensity, the max, average and min values resulted in an 11% reduction in energy intensity from the max flood volume, a 24% reduction from the average flood volume, and a 31% reduction from the minimum flood volume. While there is not primary data on the total volume of water pumped onto the Site #5 alfalfa field in 2015, this sensitivity analysis shows that a range of plausible values still resulted in a reduction of energy intensity of 11% - 31%.

Table 19. Sensitivity test to show how the pump energy intensity could change in 2015 if the maximum, average and minimum flood quantities had been used selected for calculation.

Irrigation Value	Volume per Flood Event (ft)	Intensity (MWh/ac-ft)	Intensity Change in 2016 (%)
2015 Average Irrigation	0.71	0.16	-24%
2015 Maximum Irrigation	0.84	0.14	-11%
2015 Minimum Irrigation	0.65	0.18	-31%
2016 Irrigation	0.65-0.84	0.12	N/A

Data Uncertainty

Two sources of primary data were required for the pump energy intensity calculation: energy use (MWh) and water pumped (ac-ft). The energy use data came directly from utility smart meters on the pumps, which have been proven to be reliable as utilities rely on them to charge customers for their energy use. The water pumped data was likely far less accurate. The current version of the PWE algorithm had been validated in the appendix of subtask 7.3 to show an expected mean error of 5%-10%. In addition to this calculated error, there were complications with the pumps at several sites. Table 20 below shows the estimated total water pumped from each well pump and booster at each site as calculated by the PWE algorithm. Cells highlighted in yellow have a potential data complication; specific complications are covered below.

Table 20 Table of algorithm estimations for total water pumped from each booster and well at every site in the project for years 2014 – 2016. Highlighted cells indicate there is an additional potential complication which may have reduced accuracy of value. Specific complications are labeled by letter and are covered in the text below the table.

Site	Pump	Ac-ft (2016)	Ac-ft (2015)	Ac-ft (2014)
1	Drummond B Well	96	304 [a]	358
1	Drummond F Well	120 [a]	240	59
1	Drummond West Booster	679	502	476
1	Drummond A North Well	310	10	317
1	Drummond A South Well	177 [b]	33 [b]	215 [b]
1	Drummond A Booster	263 [b]	262 [b]	288 [b]
1	Drummond I Well	355	426	435
1	***Total***	**2,001**	**1,777**	**2,148**
2	AKE A Well	25	2	90
2	AKE B Well	1,093	985	964
2	AKE C1 Well	493 [c]	773 [c]	878 [c]
2	AKE C1 South Well	307	X	X
2	AKE D Well	418	838	734
2	AKE Boosters	2,657 [d]	2,171 [d]	2,116 [d]
2	AKE C1 Lift Pump	404	0	X
2	***Total***	**5,397**	**4,770**	**4782**
3	K3 Well	261	X	X
3	J3 Well	167	X	X
3	***Total***	**428**		X
4	**UCD 56 Well**	**451**	**578** [e]	X
5	**Field 12 Well**	**114**	**933** [f]	X

a. There were two pump alerts issued at Site #1 that may have caused algorithm results to differ from the ground truth. The alert was fixed within 2 months at Drummond B in 2015.

b. The Drummond South A Well and the Drummond A Booster are connected to the same smart meter. Therefore, disaggregating water pumped data had to be done by hand by PWE, and may have a different accuracy than the validated algorithm.

c. AKE C1 Well has a variable frequency drive which added some complication to the algorithm calculation. The current estimation was calculated as if the pump was a single speed pump, adding an unknown level of error to the estimation.

d. AKE has 3 boosters of different horsepower (hp) connected to the same meter (154.62 hp, 154.22 hp & 60 hp). Water pumped cannot be measured reliably from the algorithm because two of the pumps are nearly the same hp. Estimations for water pumped were generated by considering the two pumps that have nearly the same hp as a single 308 hp pump.

e. There was a pump repair in 2015 to lower bowls and repair for cavitation in pipes. There is no pump test before the repair to estimate properly the water pumped before the repair. This calculation was done using the newest version of the PWE algorithm and a different pump test, however the algorithm is not able to properly calculate total volume pumped before or during the cavitation.

f. PWE has recognized this estimation to incorrect, as a pump test from 2016 is being used. Additionally, there are no irrigation records available to corroborate the pump estimation.

2.1.2.2 Energy intensity change from Irrigation Treatments

As discussed in Section 1.6, the energy intensity for each field has been calculated as the product of the irrigation water intensity and the ranch level pumping energy intensity (Table 21). Irrigation water intensity has been previously calculated using the methodology in section 1.5, and the results in section 2.2.1. The pumping energy intensity was calculated using methodology in section 1.6.3.2 and results were presented above in 2.1.2.1. All experimental issues outlined in Section 2.1.1 for each site hold true for these results, as they use WUI values as one of the primary inputs.

Table 21. Table showing the irrigation water intensity, pumping energy intensity and the resulting field energy intensity. The percent change shows the percentage increase or decrease of the energy intensity of any field compared with the control field on that site. Pumping energy intensity was estimated at a ranch level and held constant for each field, to isolate the impact of the irrigation strategy. For sites where a control field was not available, treatment fields were compared with the field receiving full ET irrigation. Site #4 experienced an experimental issue preventing comparison between treatment and control impossible.

Site	Treatment	Fields	Irrigation Water Intensity (ac-ft/ton)	Pumping Energy Intensity (MWh/ac-ft)	Field Energy Intensity (MWh/ton)	Change from Control (%)
Site #1						
	Control	Drummond E	2.91	0.65	1.899	Control
	Treatment #1	Drummond CDFG	1.61	0.65	1.050	-45%
	Treatment #2	Drummond HJ	1.20	0.65	0.782	-59%
Site #2 P						
	Control	AKE A	2.56	0.59	1.520	Control
	Treatment #1	AKE B	6.67	0.59	3.953	160%
	Treatment #2	AKE C1C2	3.93	0.59	2.331	53%

Site #2 A						
	Treatment #1	AKE C3C4	2.86	0.59	1.694	Considered control (ET)
	Treatment #2	AKE D	2.64	0.59	1.563	-8%
	Control*	HOME B	2.79	X	X	X
Site #3						
	Treatment #1	Demo Field (East)	0.0433	0.39	0.017	4%
	Treatment #2	Demo Field (West)	0.0418	0.39	0.016	Considered control (ET)
	Treatment #3	Demo Field (East 8 PSI)	0.0379	0.39	0.015	-9%
	Treatment #4	Demo Field (West 8 PSI)	0.0398	0.39	0.016	-5%
Site #4						
	Control	Field 56 West	0.0492	0.39	0.019	X
	Treatment #1	Field 56 East				
Site #5						
	Control	26 Checks	0.58	0.12	0.071	Control
	Treatment #1	10 Checks	0.53	0.12	0.064	-9%

The energy intensity per ton was lowest for tomatoes (mean = 0.017 MWh/ton), and pistachios had the highest mean energy intensity (mean = 1.922 MWh/ton). A disparity in results such as this can be credited to the fact that tomatoes are much heavier than nuts like pistachios and almonds.

There is a large range of relative impacts from treatment irrigation strategy on field energy intensity, which mirror the impact of water use intensity. The relative impact for Site #1 and Site #2 pistachios are misrepresented because the control fields were not subject to alternate bearing like treatment fields. Excluding results from Site #1/2 pistachios, treatment fields showed change in energy intensity of -9% to 4% when compared with control fields (Table 21). Almond fields receiving partial ET deficit irrigation of 20% showed an energy intensity reduction of 7.68% when compared with the fields receiving the full ET treatment. Tomato treatments at Russell Ranch Demonstration Fields at Site #3 were able to achieve up to a 9% reduction in field energy intensity on the treatment rows which received the greatest reduction in irrigation from ET (~20%). At Site #5, the alfalfa experiment resulted in an 9.28% reduction in energy intensity on checks being monitored with temperature sensors to reduce runoff. The treatment checks in this experiment produced 5% more yield than control checks. UCD advised that this variation may not have been caused by irrigation treatment, and may have just been caused by random variation in yield within the field. 2.2 2016 Normalization Results

2.2.1 Normalization of Farm Energy Intensity and Irrigation Water Intensity

The farmers at each site, PWE employees, and agronomic experts were interviewed to discuss all factors that might influence the results in this experiment. Each of the factors outlined in the section 1.7 of the document were explored to understand if they varied between treatment and control fields. Table 22 and 21 below provide the best estimate for determining if a factor was either the same, probably the same, different or unknown between control and treatment fields. The influence of external factors on each site will be covered in the sections below.

Table 22. Matrix of external factors that may have had an effect of yield or energy/water use in this experiment. Each factor has been categorized as 'same', 'probably same', 'different', 'unknown' or 'X' between control and treatment fields. 'Same' means factors were definitely the same between control and treatment, 'probably same' means that factors were highly likely the same, but we do not have evidence to be certain, 'different' means we have evidence to prove that the factor differed between control and treatment, 'unknown' means we were not able to determine if factors were the same between control and treatment and 'X' means that the factor does not apply to the specific site.

Energy/Water Use Factors (Sites #1 & #2)

Meta	Factor	Site #1	Site #2 (P)	Site #2 (A)
General	**Temperature**	Same	Same	Same
	Rainfall	Same	Same	Same
	Surface Water Allocation	Same	Same	Same
	Other Field Irrigation	Same	Same	Same
	Source of water	Different - Managed	Same	Same
	Overall Pump Efficiency	Different - Managed	Probably Same	Probably Same
	Distribution Uniformity	Same - Managed	Same - Managed	Same – Managed
	Soil Variability	Different	Different	Different

Yield Factors (Sites #1 & #2)

Meta	Factor	Site #1	Site #2 (P)	Site #2 (A)
General	**Soil Fertility**	Unknown	Unknown	Different
	Soil Type	Different	Different	Different
	Root Stock	Same	Unknown	Probably Same
	Crop Variety	Same	Different	Same
	Evapotranspiration (ET)	Different	Unknown	Unknown
	Weather Events	Same	Same	Same
	Pests	Same	Different	Same
	Disease	Same	Same	Same
	Crop Age	Different	Different	Different
	Fertilization	Different	Different	Different
	Irrigation Water Quality	Same	Same	Same
	Timeliness of Harvest	Same	Same	Same

Alfalfa Specific				
	Number Cuts	X	X	X
	Rain after Cut	X	X	X
	Early/Late rain	X	X	X
	Insects	X	X	X
	Weeds	X	X	X
	Year of crop	X	X	X
Tomato Specific				
	Wind > 20 mph when budding	X	X	X
	Excessive heart during fruit set	X	X	X
	Soil Ph (5-7 preferred)?	X	X	X
	Historical Crop rotation?	X	X	X
	Soil Salinity	X	X	X
	Weed presence?	X	X	X
Pistachio/Almond				
	Winter Chilling	Same	Same	Same
	Alternate bearing	Different	Different	Unknown
	Canopy Light Interception	x	x	Unknown

Energy/Water Use Factors (Sites #3, #4 & #5)

Meta	**Factor**	**Site #3 (Tomato)**	**Site #4 (Tomato)**	**Site #5 (Alfalfa)**
General	**Temperature**	Same	Same	Same
	Rainfall	Same	Same	Same
	Surface Water Allocation	Same	Same	Same
	Other Field Irrigation	Same	Same	Same
	Source of water	Same	Same	Same
	Overall Pump Efficiency	Same	Same	Same
	Distribution Uniformity	Same - Managed	Same - Managed	Same – Managed
	Soil Variability	Probably Same	Different	Unknown

Yield Factors (Sites #3, #4 & #5)

Meta	**Factor**	**Site #3 (Tomato)**	**Site #4 (Tomato)**	**Site #5 (Alfalfa)**
General	**Soil Fertility**	Same F	Same F	Probably Same
	Soil Type	Probably Same F	Different	Unknown
	Root Stock	Same	Same	Same

	Crop Variety	Same	Same	Same
	Evapotranspiration (ET)	Probably Same	Probably Same	Same
	Weather Events	Same	Same	Same
	Pests	Same	Same	Same
	Disease	Same	Same	Same
	Crop Age	Same	Same	Same
	Fertilization	Same	Same	Same
	Irrigation Water Quality	Same	Same	Same
	Timeliness of Harvest	Same	Same	Same
Alfalfa Specific				
	Number Cuts	X	X	Same
	Rain after Cut	X	X	Same
	Early/Late rain	X	X	Same
	Insects	X	X	Same
	Weeds	X	X	Same
	Year of crop	X	X	Same
Tomato Specific				
	Wind > 20 mph when budding	Same	Same	X
	Excessive heart during fruit set	Same	Same	X
	Soil Ph (5-7 preferred)?	Probably Same	Probably Same	X
	Historical Crop rotation?	Same	Same	X
	Soil Salinity	Probably Same	Probably Same	X
	Weed presence?	Same	Same	X

Site #1 – Pistachio

The treatment and control fields at Site #1 were subject to some variation in external energy factors between control and treatment. The source of water was slightly different for Drummond H/J and Drummond C/D/F/G/E due to the fact that there are separate reservoirs and boosters that feed each grouping of fields. Additionally, the OPE of the booster for the east side was lower than the booster on the west side, requiring net more energy per unit of water delivered to the crops. The water source was managed by PWE by minimizing the stress on fields, and the OPE was managed by the method in which energy was allocated to each field. Energy was allocated to the field by looking at the total energy burden and water use, rather than calculating the east and west sides of the ranch individually. The farmer also specified that the parent material of the soil is the same, but there are streaks of variation throughout out the fields on the ranch.

There were several external factors that could have had a potential effect on the yield at Site #1. We found that soil type, ET, crop age, fertilization and alternate bearing were all different between control and treatment at site #1.

- **Soil Type**: There are streaks of different soil through the equivalent parent soil. The effect is likely minimal on overall yield.

- **ET**: Actual evapotranspiration (ETa) was measured by Tule sensors at fields D, H and E. The reported ET was highest at H, and lowest at E with an annual difference of ~ 7 inches. Higher ETa indicates greater transpiration within the plant which could indicate the potential for greater yield.

- **Crop Age/Alternate Bearing**: While trees in all treatment orchards were planted in 1984, the trees on the control orchards were planted in 2007. Because of this, the control orchard was not subject to the alternate bearing effect, which affects mature trees of around 10 years. As a result, the control field produced a slightly lower than average yield of a mature tree (2,624 lbs/acre), and the treatment fields produced a much higher yield (Drummond C/D/F/G = 4,144 lbs/acre; Drummond H/J = 5,816 lbs/acre). This crop age and alternate bearing issue had a considerable effect on the yield, causing 2016 results to be less meaningful.

- **Fertilization**: The farmer informed us that fields are fertilized differently, based on projected productivity of the field for that year. The result was that Drummond H/J received more fertilizer than other fields. This may have increased the chance for Drummond H/J to be more productive.

We were not able to determine if the soil fertility was different between control and treatment fields by talking to the farmer or PWE employees. Drummond has records of soil content, however the records were not available to us.

Site #2 – Pistachio

The pistachio fields at Site #2 were subject to several of the same factors being different as Site #1, as the sites are fairly close and run by the same organization. In terms of energy use factors, the only factor that was different is the soil variability. Like site #1, the parent soil is the same, but there are streaks of variation within the fields. OPE and surface water allocation is likely the same, but could not be confirmed.

The yield of pistachio trees at this site had many more factors influencing them than energy use, as is typical. The soil type, crop variety, disease, crop age, fertilization and alternate bearing all differed between control and treatment.

- **Soil Type**: There are streaks of different soil through the equivalent parent soil. The effect is likely minimal on overall yield.

- **Crop Variety**: Control field is Golden Hills and treatment fields were Kerman. Golden Hills is a more recent cultivar released to the industry in 2005 that can have harvest around 2 weeks earlier than Kerman. A presentation by UCD showed that Golden Hills variety had a higher yield (lbs/acre) than Kerman in a 5 year study [10].

- **Pests**: Navel orangeworm invested 20-30% of Ake C1/C2 (treatment fields). The farmer said this likely had an effect on yield results; however he was not able to quantify the level of effect.

- **Crop Age/Alternate Bearing**: AKE A (control) was planted in 2008, AKE B (ET treatment) was planted in 1989, and AKE C1/C2 (partial ET treatment) was planted in 1995. Because of this, the control orchard was not subject to the alternate bearing effect, which affects mature trees of around 10 years. As a result, the control field produced a slightly lower than average yield of a mature tree (2,518 lbs/acre), and the treatment fields produced a much lower yield (AKE B = 1,049 lbs/acre; Ake C1/C2 = 1,601 lbs/acre). This crop age and alternate bearing issue had a considerable effect on the yield, causing 2016 results to be less meaningful.

- **Fertilization**: The farmer informed us that fields are fertilized differently, based on projected productivity of the field for that year.

We were not able to determine if soil fertility, root stock or ET was equivalent at each field. AKE Ranch has records of soil content that provide measures of nutrients in the soil at various depths among other common measurements. The AKE ranch soil expert told us that the electrical conductivity of the soil at AKE B and AKE C2 was significantly different, likely reducing the yield potential at AKE B. Due to the fact that this soil data was not gathered for AKE A (the control field), the classification of understanding remains unknown between control and treatment. There were no Tule devices at these fields to measure ETa.

Site #2 – Almond

The only external factor affecting the energy use of almond orchards that was different between control and treatment was the soil variability. There was not empirical evidence available to OPE were equivalent. Factors potentially affecting yield include, soil fertility, soil type, crop age and fertilization.

- **Soil Fertility**: PWE conducted early studies on the site to prove that soil fertility differed between each of the treatment almond orchards at site #2. Actual concentrations of crucial nutrients such as phosphorous nitrogen and potassium were not available. The impact of this variance on overall yield cannot be estimated without consultation with soil experts.

- **Soil Type**: There are streaks of different soil through the equivalent parent soil. The effect is likely minimal on overall yield.
- **Crop Age**: Fields C3/C4 were planted in 2008 and field D was planted in 2009. The overall effect of this variance on yield is likely minimal.
- **Fertilization**: The farmer informed us that fields are fertilized differently, based on projected productivity of the field for that year.

Tule stations were not available on these fields, and thus ETa was unable to be calculated. The farmer did not know precisely about rootstock, but thought they were likely the same between both almond fields.

Two almond specific factors were distinguished late in the experiment after conversation with Dr. Ken Shackel (UCD): alternate bearing and canopy light interception. Dr. Shackel advised that almonds can have a 10-20% variance in yield due to alternate bearing [11]. Evidence suggests that this variation is only sometimes present in almond orchards [12]. Dr. Shackel also pointed out the potential significant effect of light interception on yield. Evidence suggests that canopy light interception and yield are positively related [13]. Unfortunately, there was not empirical evidence to prove equivalence between control and treatment for either of these variables, however they should be considered in future experiments.

Site #3 – Processing Tomato

Site #3 was the most consistent field in our study between control and treatment fields. There were no factors affecting energy or yield that were proven to be different between the different treatments. This is likely due to the fact that the field is much smaller than other sites in the study, and it is located in the UCD demonstration field at Russell Ranch, making it the only non-commercial field in the study.

The only factors that were potentially, but unlikely different were soil type, ET, soil Ph and salinity. There were no measurements of soil variability, soil ph or soil salinity, but Israel Herrera informed us that he would guess they were pretty consistent throughout the field.

Site #4 – Processing Tomato

Site #4 was similarly consistent as Site #3, however due to its larger size there was significant soil variability within the field. The farmer described 8 acre sections in the 150 acre field that have sandier soil than the surrounding soil. Because of this, the farmer has traditionally overwatered the huge irrigation sections to make up for this variation in soil. This variation was one of the reason the farmer didn’t follow recommended reductions in irrigation, because he thought irrigating based on ET of the tomatoes, would cause these sandier sections to die. Like Site #3, there were no evidence to ET, prove soil salinity or pH were equivalent or different.

Site #5 – Organic Alfalfa

Our alfalfa site was similarly consistent between treatment and control fields. There were no studies done specifically on treatment and control checks to prove soil content was similar. When asked, the son of the farmer, Mike Button, said that soil content is fairly similar, and likely did not have a significant impact on yield. Many of the alfalfa specific factors were automatically the same based on the design of the experiment, and we confirmed that the rest were equivalent though interview with Mike.

2.2.2 Normalization of Pump Energy Intensity

The three variables that were identified to have a potential effect on pumping energy intensity in this study are outlined in Table 23. Surface water allocation was different at Sites 4 and 5, water table level was likely different at all sites, and use of extra pumping equipment was the same at every site for the years compared.

Table 23. Matrix of factors that may have had an effect on pumping energy intensity at the sites in this study. Each factor has been categorized as 'same', 'different' or 'probably different' between control and treatment fields. 'Same' means factors were definitely the same between control and treatment, 'different' means we have evidence to prove that the factor differed between control and treatment and 'probably different' means that we have reason to believe the factor differed between control and treatment, but no direct evidence to support it.

Site	Years compared	Surface water allocation	Water Table Depth	Additional pumping equipment
Site #1	2014 - 2015	Same	Probably Different	Same
Site #2	2014 - 2015	Same	Probably Different	Same
Site #3	N/a	Same	Probably Different	Same
Site #4	N/a	Different	Probably Different	Same
Site #5	2015 - 2016	Different	Probably Different	Same

Surface Water Allocation

While Sites #1 and #3 used no surface water in any year, while Sites #4 and #5 did use different amounts. Site #2 had allocation of 404 ac-ft surface water in 2016 (17% total use), however for pumping energy intensity 2015 was used as the treatment year to avoid impact from this external factor. In 2015, Site #4 had some additional water sent over in a ditch from another field, as the farm's infrastructure could not support the demand for water. Site #5 had surface water allocation in 2016 for sections of Field 56 not included in our experiment. The result is that the pump was used more in 2015 to supplement a lack of surface water. This surface water use likely had little to no effect on results as no surface water was applied to our experimental field section.

Pumping Water Level Analysis

An important annually-variable external factor that has the potential to affect pumping energy intensity is the depth a well is required to pump water. The depth of the water table is measured as standing water level (ft from surface). When a pump turns on, there is an effect called the drawdown effect, which causes the total distance pumped to be greater than the standing water level. This distance is known as the pumping water level. The pumping energy intensity increases as the pumping water level increases, because the distance water is pumped against gravity increases.

Managing the pumping water level is out of the control of PWE and needs to be normalized for or considered when contextualizing results. Water level data was available in this project through pump tests. However, only some sites had pump tests completed for all 3 years. Unfortunately, in 2015 the pump tests were administered by a third party instead of Southern California Edison, who administered tests all other years. The standing water table levels in 2015 do not make sense with the drought and energy records. The data here (Table 24) show the water table rising (17% average), when there was no local recharge program to our knowledge and precipitation was far below the annual average [6]. This increase was likely due to variation in equipment used to measure the water table between SCE and the third-party tester.

Table 24. Table showing the standing water level at each of the well pumps at Site #2 AKE ranch. Data was taken from pump tests administered to the wells. AKE C1 South Well was not used before 2016. An 'X' means a pump test was not administered for a given year, or we did not have access to them. Pump tests were completed in August or September for every year.

Site #2 Wells	2014 (ft)	2015 (ft)	2016 (ft)
AKE A Well	262.4	243	283.7
AKE B Well	261.7	263	292.6
AKE C1 Well	243.7	235	x
AKE C1 South Well	x	x	280.2
AKE D Well	261.8	229	278.7

Additionally, reliable water table data was not available through pump tests for sample years at other sites. In lieu of reliable pump test data public water table data available through California Statewide Groundwater Elevation Monitoring Program (CASGEM) can be analyzed to understand the difference in water table level near our test sites for our experimental years [7]. Data was pulled from multiple CASGEM wells close to the experimental Sites #1, 2, and 5 to understand the trends of water table level. Figure 4 below shows the average annual water table elevation for Sites #1, 2, and 5 from 2013 to 2017. The data was calculated from 3 to 5 wells at each site within 4 miles of the test site.

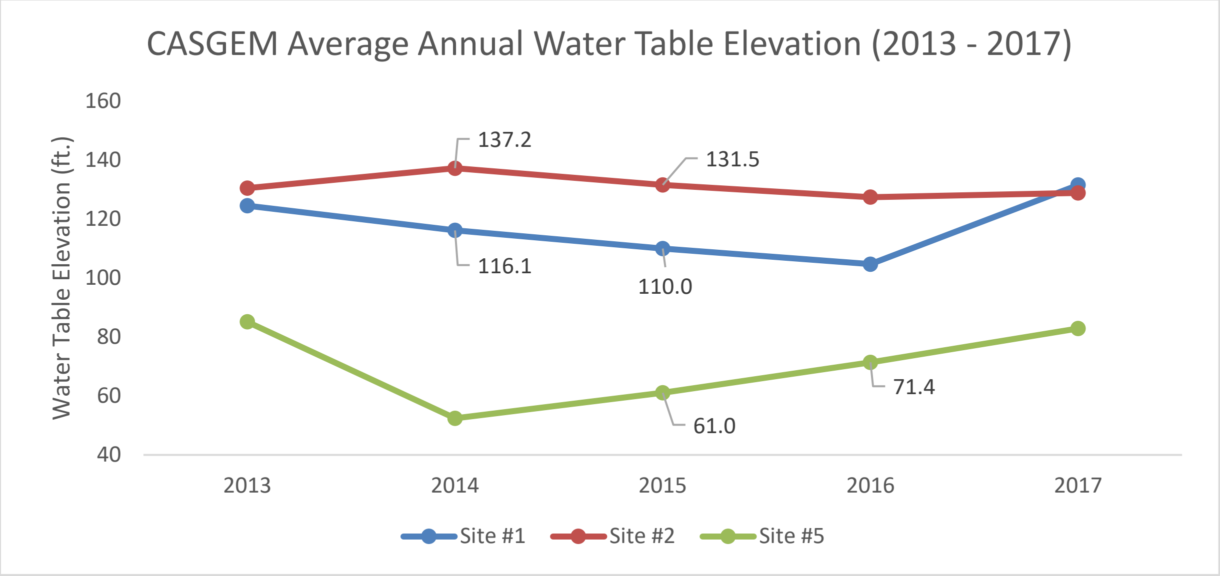


Figure 4. Average water table elevations for Sites 1, 2 and 5 from 2013 to 2017. Data was calculated from averaging water table elevation from 3-5 CASGEM wells within 5 miles of each site. Each data point was taken in September or October for reasonable annual comparison. Data is publicly available from the DWR CASGEM webpage [7].

Tables are presented below for each of these sites that show groundwater elevation and detailed data that went into Figure 4 above. In this case, as groundwater elevation decreases, the distance from the groundwater to the pump increases. It should be noted that these represent trends of nearby wells, and no not necessarily represent the water table trends of the wells in our experiment.

At Site #1, nearby CASGEM wells show a clear trend of decreasing water level for all years in the drought, and a substantial increase in the water level in 2017 after the wet year (Table 25). This trend is expected based on annual hydroclimate reports. Between 2014 and 2015, the water table dropped by an average of 6.1 feet or 5% at this Site. This drop would have increased the pumping energy intensity of the groundwater wells at Site #1.

Table 25 All data was taken directly from the CASGEM web page [7] using the data gathered in October of each year.

CASGEM Well ID	Distance from Experiment Site (Mi)	Groundwater Elevation (ft)				
		2013	2014	2015	2016	2017
15928	1.34	139.7	131.7	125.9	125.3	134.7
47894	1.95	123.8	114.8	106.6	94.9	150.9
33024	2.22	109.9	101.8	97.4	93.9	108.9

For Site #2, there was some more variability in the groundwater elevation over the years, however the trend between 2014 and 2015 was consistent – the groundwater elevation decreased by an average of 5.6 feet or 4% (Table 26). This increase in the distance to pump water likely increased the energy intensity of the well pumps at Site #2.

Table 26. Data was gathered directly from the CASGEM web page [7] using data gathered in September/October of each year.

CASGEM Well ID	Distance from Experiment Site (Mi)	Groundwater Elevation (ft)				
		2013	2014	2015	2016	2017
34448	0.89	119.7	114.7	111.3	108.8	107.5
19840	1.6	x	146.7	141.1	137.1	125.9
36063	2.67	141.22	150.22	142.22	136.22	153.22

There was a different trend observed at Site #5 in northern CA of a decrease in water elevation from 2013 to 2014, followed by a slow rise in elevation from 2014 through 2017. Between 2015 and 2016 when our experiment was conducted, the elevation decreased by an average of 10.6 feet or 13.9% across CASGEM wells analyzed (Table 27). This decrease in water table level explains one of the reasons the reduction in pumping energy intensity at Site #5 was so high at ~24%.

Table 27 Data was gathered directly from the CASGEM web page [7] using data gathered in September/October of each year.

CASGEM Well ID	Distance from Experiment Site (Mi)	Groundwater Elevation (ft)				
		2013	2014	2015	2016	2017
7751	1.27	102.28	69.98	74.38	104.58	103.98
29121	2.07	100.19	X	77.19	89.09	104.89
7619	1.54	86.29	X	52.19	60.29	76.59
30536	1.55	73.28	50.28	54.18	62.28	72.68
29416	3.7	63.48	36.98	47.28	40.78	56.08

SCADA data at Site #3 reported the total pumping level of the well pump J3 throughout the year (Table 28). The results from this data corroborate the CASGEM data indicating an increase in water table elevation in this area.

Table 28. Total pumping level for the J3 well at Russell Ranch (Site #3) in 2015 and 2016. Data was available through August in 2015, however the date range for 2015 and 2016 were only calculated through May 01 to June 20, because that was the date range of available data in 2016.

Site #3 Pumping Levels	2015	2016
Average Pumping Level (ft)	147.2	135.6
Maximum Pumping Level (ft)	95.0	78.3
Minimum Pumping Level (ft)	200.9	186.9

2.3 Methodology to Measure Energy Efficiency Improvements in Agriculture

2.3.1 Introduction

Numerous government and private organizations have developed programs to improve energy efficiency as minimizing energy use becomes an essential priority in the face of climate change. The agricultural sector has been the focus of several of these programs, due to the fact that it is responsible for over 8% of California's energy consumption [8]. Private and public organizations continue to publish claims of energy efficiency improvements from various innovative programs; however their methodologies for measuring efficiency improvements are inconsistent. Claims of efficiency improvements calculated using different methodologies are not comparable, and inhibit the public from discerning which programs are the most effective. This analysis aims to develop a new universal methodology for accurately measuring the effect of energy efficiency treatments in California agriculture through redefining energy efficiency on farms using life cycle assessment (LCA) techniques.

2.3.2 Agronomic and Utility Efficiency Methods

Before developing a new methodology, it is important to explore what methods have been traditionally accepted as efficiency improvements in California agriculture. The agricultural and the energy sectors currently employ contrasting efficiency measurement methods. Typically, California Investor-Owned Utilities (IOUs) such as Pacific Gas & Electric (PG&E) will offer rebates for energy efficiency improvements through deemed measures (fixed rebate per project; ex $200 towards a pump test) or retro commissioning (rebates based on savings from a historical baseline; $0.09/kWh saved from a 1 year historical baseline) [9]. Retro-commissioning rebates are often awarded for the reduction in total energy usage after a treatment compared with the energy usage of a historical baseline. For agronomists, efficiency improvements in energy or water take into account farm yield, as it is the most important factor for farmers. Water efficiency has been termed 'crop per drop' which is measured as yield (ton)/water used (ac-ft), and is measured between control and treatment fields within the same year. In agriculture, water use and energy use are closely related as pumping water is the biggest consumer of energy on a farm. To develop a new methodology, both the agronomic and the utility definition of efficiency improvements were reconciled.

2.3.3. First Methods Developed

Two methodologies were developed using an LCA perspective to measure the impact on energy efficiency from treatment programs on farms, which reconcile the agronomic and utility understanding of energy efficiency. The first is a ranch level comparison of energy use(kWh)/yield(ton) in the current year, to a historical baseline. This method will further be referred to as the 'Ranch Level' method. The second is the same comparison as the Ranch Level, except energy use and yield are measured on a field level, on only fields that received an irrigation treatment. This second methodology will further be referred to as the 'Field Level' method. The Field Level allocates energy burden to a specific field based on the ratio of water applied to the field, and total water pumped from a booster. The field is allocated the same proportion of the energy burden as water applied. To better understand these two methodologies, see Figure 5 below. The only significant difference between both methodologies is that the Field Level considers the data exclusively from treatment fields, giving the results more resolution, but reducing the accuracy.

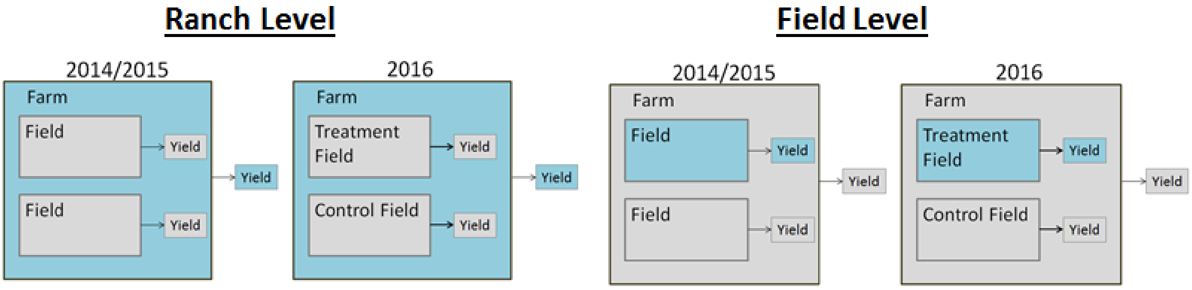


Figure 5. Visual representations of the two new methodologies for measuring energy efficiency in agriculture; Ranch Level and Farm Level. The blue shapes indicate what is being included in the comparison, while data in grey is excluded from the comparison.

2.3.4 Preliminary Results and Lessons Learned

The 2016 results for each site in this experiment using both LCA methodologies are summarized below in Table 29. While these methods provide insight into energy efficiency improvements, they are not perfect. The Ranch Level method shows an 85% improvement for Site #5, which is a gross overestimation on the truth. At this site, the farmer used his pump for numerous additional fields in 2015, and used the pump exclusively on our experiment field in 2016. This discrepancy illuminates an issue with the Ranch Level method, in that it includes energy use not associated with our experiment.

Table 29. Summary of efficiency improvements from treatments in the PWE project as calculated by the Ranch Level and Field Level methodologies for all sites. Site #2 is split into those fields which have pistachios and those which have almonds. Site #3 has no historical data (thus N/A) and Site #2 Ranch Level has N/A because it does not make sense to aggregate the yield from two different crops into one number.

Site Number	*Ranch Level*	*Field Level*
Site #1	23%	23%
Site #2 (P)	N/A	32%
Site #2 (A)	N/A	18%
Site #3	N/A	N/A
Site #4	-8%	11%
Site #5	85%	50%

The Field Level method contains issues as well. One requirement is that all data sources have to align. At Site #1 the total water applied to the fields as measured by the irrigation records report 22% less water than the smart meter on the boosters. The Field Level method requires data from both of these sources in order to allocate energy to fields. Because these sources do not align, there is a large level of uncertainty associated with the efficiency estimations for Site #1. Additionally, this method requires metadata about results from previous years that is not always readily available.

2.3.4.1 Technical Advisory Committee Feedback

When these methods were presented to agronomic experts David Zoldoske (Director CIT), Allan Fulton (UC-CE irrigation and water resources advisor) and Don Cameron (Terranova Ranch director) two other important issues were identified. A paramount issue with these methodologies is that there are several factors that can cause annual variation in yield, which are not normalized for or accounted for in either of these methodologies. Because these exist, it becomes very difficult to determine if efficiency changes as measured through energy use/yield are due to treatments, or other external factors. Another issue is that these methods attempt to combine efficiency changes from two treatments: advanced pump monitoring and treatment irrigation based on ET. Claims of efficiency improvements would be more precise if the impacts were disaggregated for these two efficiency treatments.

2.3.5 Redefining Energy Efficiency on a Farm

In order to solve the issues exposed by agronomic experts, we needed to define energy efficiency on farms more specifically. First, rather than look at energy efficiency we are really looking at the energy intensity of the farm. There are two separate classes of resource intensity that make up overall farm energy intensity: pumping energy intensity, and irrigation water intensity (Figure 6). Pumping energy intensity is a measure of how much energy is required to pump water to th6 plants. Irrigation water intensity is a measure of how much water is required to produce a ton of yield; or rather, how efficient a plant is at converting water into yield. Therefore, the farm energy intensity is the product of the pumping energy intensity and the irrigation water intensity, and can be estimated on any scale (ranch or field) with these two variables.

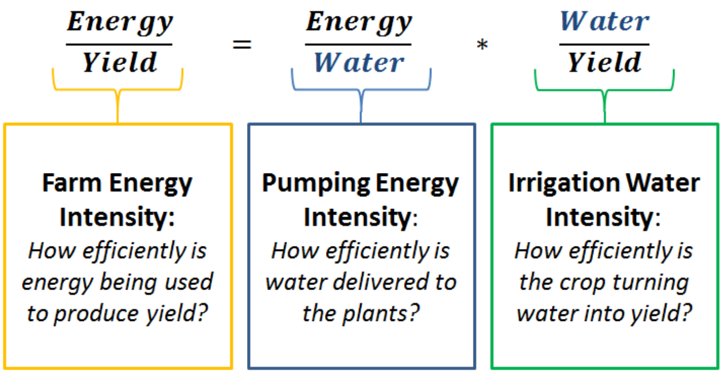


Figure 6 Visualization of the relationship between the two components of farm energy intensity. The input to the farm is energy, and the output is yield, and water is the factor that connected both of these flows.

When estimating the energy impact of treatments on a farm, one needs to categorize their improvements within the category of pumping efficiency or irrigation efficiency to better define their outcome.

2.3.6 Two new Methodologies

2.3.6.1 PWE Energy Intensity Treatments

PWE applied two separate treatments to improve energy efficiency at each site. The first was a smart irrigation schedule, which aimed to minimize excessive watering of crops and ultimately improve irrigation efficiency. The second PWE treatment was smart pump monitoring. Both of these treatments need to be considered separately with individual methodologies as one is a physical system (pump) and the other a biological system (plant). The following sections will define the two methodologies developed to estimate the true energy efficiency impact from pump and irrigation efficiency treatments.

2.3.5.2 Irrigation Intensity Methodology

PWE Treatment

The treatment applied by PWE to improve irrigation efficiency is the use of smart irrigation strategies based on plant evapotranspiration. Many farmers apply more water than necessary as a ‘safety net’ to their crops in order to minimize risk of under-watering and reducing yield. Applying irrigation based on plant ET allows farmers to apply only the amount of water necessary for the plant to grow and maintain yield.

How to calculate energy efficiency per field

To calculate the change in energy intensity from treatment irrigation, the energy intensity for treatment and control fields will be calculated using the equation in Figure 7. Thus, to estimate energy intensity for each field the irrigation water intensity and the pumping energy intensity will need to be calculated.

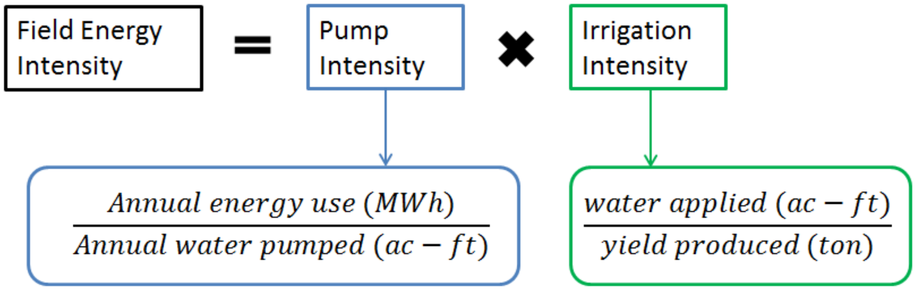


Figure 7 Equation used to calculate energy intensity per field.

The irrigation water intensity per field methodology has been outlined in section 1.5 of this document, and those values will be used in this equation. To estimate pumping energy intensity, the total water (ac-ft) and energy use (kWh) for the calendar year will be aggregated and the ratio MWh/ac-ft will be used as the value for pumping energy intensity. The range of variance for the pump throughout the entire year will be presented with these results, to contextualize them and be transparent about how the pumping energy intensity may have changed throughout the year. However typically, pumping energy intensity is relatively constant throughout a single year.

How to calculate the improvement in energy intensity

Once the energy efficiency for each field has been calculated, treatment fields will be compared with control fields to calculate the percentage improvement or decrease in energy intensity (**Figure** 8). Unlike appliance energy efficiency, no historical baselines will be included.

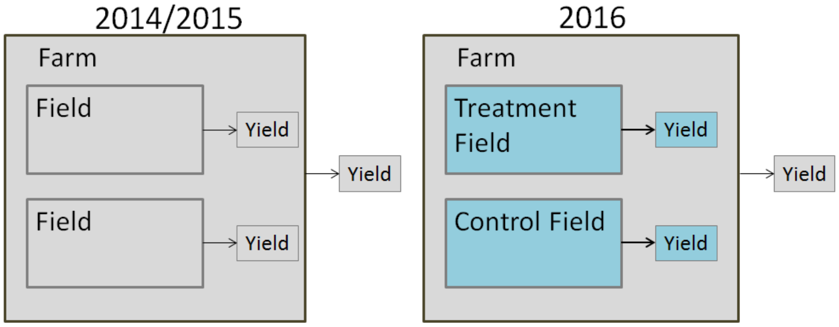


Figure 8. Visual representation of the final methodology developed for measuring the impact of energy intensity treatments on farms. The blue shapes indicate what is being included in the comparison, while data in grey is excluded from the comparison.

2.3.5.1 Pumping Energy Intensity Methodology

The treatment applied by PWE for improving pumping energy intensity on farms is smart pump monitoring. PWE helps farmers improve or maintain their pumping energy intensity by monitoring for leaks, changes in total dynamic head (TDH) and requiring current pump tests on farm infrastructure. To measure the level of impact from this program, the total water pumped (ac-ft) per unit of energy consumed (MWh) will be compared on an annual basis. This method is similar to the traditional methods utilities use to measure energy improvements in buildings or appliances. Annual analysis is the best avenue for comparison of pumping energy intensity, because there are minimal external factors that have the potential to influence the ratio of water use per unit energy consumed, that are not part of the treatment.

To calculate energy intensity improvements, Sites #1/2 will be compared with 2014 values, and Sites #4/5 will be compared with 2015 values. Site #3 did not have the pump monitor treatment applied. The quantity of energy consumed will be measured from smart meters on the pump, and the total water applied will be calculated by the PWE algorithm. The most current version of the PWE algorithm will be used to calculate historic values for energy and water use. Annual values will be aggregated for the calendar year.

2.3.7 Results Normalization

Normalization

One of two paramount critiques of the original methodology was a lack of acknowledgement of the potential effect on results from external factors. In order to determine if the improvements in intensity were due to treatments, all factors that could significantly affect the three efficiency variables (yield, energy and water use) need to be either proven to be equal between control and treatment, or normalized for. The first step is to identify all the factors that might have a possible effect on either variable. Table 30 summarizes the list of all possible factors that were confirmed by farmers and experts to potentially have an effect on yield or energy use.

Table 30. List of all the factors that may cause yield energy or water use to vary. To create the list, experts were contacted from UC Davis, PWE, and the farmers of the ranches in this experiment. The factors in this table need to be proven equal or normalized for when estimating the impact of an energy efficiency treatment.

Energy/Water Factors	Yield Factors
Temperature	Soil Fertility
Rainfall	Soil Type
Surface Water Allocation	Root Stock
Other Field Irrigation	Crop Variety
Pump Issues	Evapotranspiration (ET)
Overall Pump Efficiency	Weather Events
Distribution Uniformity	Pests
Soil Variability	Disease
	Crop Age
	Fertilization
	Irrigation Water Quality
	Timeliness of Harvest

Additionally, a separate table of yield factors specific to the crops in the PWE experiment has been identified in Table 31.

Table 31. List of all the factors that could cause significant variation in the yield on crops specific to the PWE experiment. For tomato factors Israel Herrera (Russell Ranch Facility Manager) and Timothy Hartz (UCD Tomato Expert) were interviewed. Alfalfa factors were specified by Mike Button (Button & Turkovich farms) and Israel Herrera. For Almond and Pistachio factors James Nichols (Nichols Ranch Irrigation Manager) was interviewed.

Tomato Specific	Alfalfa Specific	Almond/Pistachio Specific
Wind > 20 mph when budding	Number Cuts	Winter Chilling
Excessive heat during fruit set	Rain after Cut	Alternate bearing
Soil Ph (5-7 preferred)	Early/Late rain	
Historical Crop rotation	Insects	
Soil Salinity	Weeds	
Weed presence	Year of crop	

Unlike physical systems such as buildings, biological systems have an immense quantity of variables that can affect the yield (Tables 30 & 31). Because we are performing the experiment in the same location and year, some factors become the same (ex. atmospheric conditions) and numerous factors are likely the same (ex. pump issues, pests/disease, timeliness of harvest etc.) between control and treatment fields (Table 32).

Table 32. A list of all the factors affecting water/energy use and yield categorized into their likelihood differing between control and treatment fields in experiments that are held in the same geographical location and same time period. These are

assumptions based on the data from this experiment, and conversations with farmers. Factors may change categories in specific cases, this list is a general estimate.

Classification	Same	Likely Same	May be different
General			
	Temperature	Overall Pump Efficiency	Pump Issues
	Rainfall	Crop Variety	Distribution Uniformity
	Other Field Irrigation	Pests	Soil Type
	Surface Water Allocation	Disease	Evapotranspiration (ET)
	Weather Events	Crop Age	X
	Root Stock	Fertilization	X
	X	Irrigation Water Quality	X
	X	Timeliness of Harvest	X
Tomato Specific			
	Wind > 20 mph when budding	Soil Ph (5-7 preferred)	Historical Crop rotation
	Excessive heat during fruit set	Soil Salinity	X
	X	Weed presence	X
Alfalfa Specific			
	Number Cuts	Insects	X
	Rain after Cut	Weeds	X
	Early/Late rain	X	X
	Year of crop	X	X
Almond/Pistachio Specific			
	Winter Chilling	X	Alternate bearing

In an ideal experiment, all factors in the 'may-be-different' or 'likely-same' columns would be normalized for, or proven equal with empirical data. However, the resources may not be available to gather precise scientific data on all factors. Where this is not possible, conversation with farmers and educated assumptions will suffice. Reducing the external factors that need to be considered is essential in order to create an efficiency experiment with meaningful results.

To account for potential unintended effects from external factors, the experiment should be designed with the matrix of external influential factors in mind. Supplementary evidence should be gathered to ensure that these factors do not differ between control and treatment fields. Additionally, results should be contextualized with the matrix of factors outlined earlier in this section so that it is clear to the audience when an external factor may have had an effect on the efficiency changes.

2.3.8 Discussion

Through this deployment project, numerous significant lessons were learned about how to calculate energy intensity on a farm. We learned that farms are very complicated, and that they cannot be subject to the same efficiency methodology as buildings. The energy intensity of a farm is a combination of appliance energy intensity (pump) and biological water intensity (plant). PWE applied one appliance efficiency treatment (smart pump monitor) and one biological efficiency treatment (smart irrigation strategy), and the impact from both of these treatments need to be measured separately. Energy savings through the pumping efficiency treatment can simply be measured through annual comparison of total water pumped per unit of energy spent. The intensity impact of the irrigation treatment is a much more complicated system that varies significantly geographically, temporally and for different crops. A method was developed that calculates the energy intensity of a field by taking the product of the irrigation water intensity and the pumping energy intensity, to produce the energy intensity of the field as a whole.

It was shown that it is essential to include yield when measuring irrigation energy intensity change on farms as it is not a question of if we can produce less to save energy, but how to produce more with less. To account for variation in yield a method was presented in this analysis that provides a matrix of factors to consider when estimating energy intensity or efficiency, to grant insight as to the true efficiency gains from a treatment. Without accounting for the variation factors, it is impossible to determine if intensity/efficiency changes were caused by the treatment, or other external factors.

Ideally, the methodology defined in this paper will be used to meaningfully design experiments and contextualize agricultural energy intensity/efficiency claims so that projects from different sectors can be compared. Clarification of the separation of pumping energy intensity and irrigation water intensity can provide insight to where easy efficiency improvements can be discovered. Further research should be done to estimate the impact of energy and yield factors on overall results where more data is available, so that normalization for these factors is possible.

GLOSSARY

Term	Definition
Ac-ft	Acre feet (referred to as a measure of volume of water)
CIMIS	California Irrigation Management Information System
CLEER	Cloud Energy Emissions Research Model
CO2 eq.	Carbon Dioxide Equivalent
Dp	Deep Percolation
DTN	Data Transmission Network
ET	Evapotranspiration
ETa	Actual ET
ET-SMM	Evapotranspiration with Soil Moisture Monitoring
GHG	Greenhouse Gas
Ha	Hectare
IOU	Investor Owned Utilities
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MWh	Megawatt Hour
NDVI	Normalized Differential Vegetation Index
NWS	National Weather Services
OPE	Overall Pump Efficiency
P	Precipitation
Pe	Effective Precipitation
PWE	PowWow Energy
RDI	Regulated Deficit Irrigation
RO	Runoff
SaaS	Software-as-a-Service
SWP	Soil Water Potential

TDH	Total Dynamic Head
UC-CE	University of California Cooperative Extension
UCD	University of California, Davis
UCSB	University of California, Santa Barbara
USDA	United States Drug Administration
WUI	Water Use Intensity

REFERENCES

[1] Carrillo-Cobo, Teresa; Zaccaria, Daniele; Scow, Kate (UCD). ***Partial Irrigation Schedules.*** California Energy Commission. 2015.

[2] Standard, I.S.O. Environmental Management Life Cycle Assessment Requirements and Guidelines. Vol. 14044. ISO. 2006.

[3] Haas, Guido, Frank Wetterich, and Uwe Geier. Life cycle assessment framework in agriculture on the farm level. The International Journal of Life Cycle Assessment 5.6: 345-348. 2000.

[4] Torbert, Emma. Et al. Yield Measurement Workshop. Sub Task 6.1. PowWow Energy. 2015.

[5] Carrillo-Cobo, Teresa, Daniele Zaccaria, and Kate Scow**.** ***Rational Irrigation Scheduling***. Sub Task 3.2. California Energy Commission. 2015.

[6] Anderson, Michael. Hydroclimate Report Year 2015. California Department of Water Resources. Office of the State Climatologist. Fall 2016. Retrieved from: https://www.water.ca.gov/LegacyFiles/climatechange/docs/2016/a3037_Hydroclimate_report_v11.pdf

[7] California Department of Water Resources. CASGEM Online System. Last Modified 11/13/2017. Retrieved from: https://www.casgem.water.ca.gov/OSS/(S(d3rumuw55zlhd4zoqvjb14vv))/Public/ApplicationHome.aspx

[8] Younghein, Meredith. Water & Energy. California Ag Water Stewardship Initiative. Retrieved from: http://agwaterstewards.org/practices/water_energy/.

[9] Center for Irrigation Technology, California State University, Fresno. Advanced Pumping Efficiency Program – Policies and Procedures Manual. Pacific Gas and Electric Company. Retrieved from: http://www.pumpefficiency.org/incentive-rebates/

[10] Kallsen Craig. Pistachio Cultivars. U.C. Cooperative Extension. 5th Pistachio Short Course, 2008. Retrieved from: http://fruitsandnuts.ucdavis.edu/files/74174.pdf

[11] Conversation with Ken Shackel, P.h.D. Plant Physiology. http://www.plantsciences.ucdavis.edu/faculty/shackel/shackel.htm

[12] Tombesi, S., Lampinen, B. D., Metcalf, S., & DeJong, T. M. (2011). Relationships between spur-and orchard-level fruit bearing in almond (Prunus dulcis). *Tree physiology*, *31*(12), 1413-1421. Retrieved from: https://academic.oup.com/treephys/article/31/12/1413/1693983/Relationships-between-spur-and-orchard-level-fruit

[13] Shackel, Ken; Doll, David; Fulton, Allen; Lampinen, Bruce; Sanden, Blake. Almond ET/Yield Production Function. Research poster for UC Davis Plant Sciences. Viewed in the UC Davis Plant Sciences Building on March 15th, 2017.

[14] Arman Shehabi, Ben Walker and Eric Masanet. The energy and greenhouse-gas implications of internet video streaming in the United States. Environmental Research Letters. 2014.

[15] Coroama, Vlad C., and Lorenz M. Hilty. Assessing Internet energy intensity: A review of methods and results. Environmental impact assessment review 45: 63-6. 2014.

Energy Research and Development Division
Product

RATIONAL IRRIGATION SCHEDULES

Appendix C

Prepared for: California Energy Commission
Prepared by: PowWow Energy

JANUARY 2016
EPC-14-081

PREPARED BY:

Primary Author(s):
Teresa Carrillo-Cobo, UC Davis
Daniele Zaccaria, UC Davis
Kate Scow, UC Davis
Olivier Jerphagnon, PowWow Energy

PowWow Energy
425 Broadway
Redwood City, CA 94063
Phone: 415-658-7125
http://www.PowWowEnergy.com

Contract Number: EPC-14-081

Prepared for:

California Energy Commission

Leah Mohney
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

We would like to acknowledge the information provided by the University of California, Division of Agriculture and Natural Resources (ANR), and the various vendors of sensors that we talked to.

ABSTRACT

This document describes the relevant parameters necessary to develop rational irrigation schedules for the specific crops selected within the present project, i.e. processing tomatoes, alfalfa, pistachios and almonds. Rational irrigation schedules provide irrigators with information about the water applications, timing, frequency and duration of irrigation events that are required to fulfill the crop water needs and offset the water losses due to irrigation inefficiencies, while preventing the occurrence of water deficit and excess to the crops and minimizing on-farm water and energy usage.

Different approaches can be followed to schedule irrigation with remote sensing: 1) ET-based irrigation scheduling, and 2) Soil moisture-based (SMM) irrigation scheduling. Plant-based measurements can also be used to adjust irrigation scheduling.

For the specific purposes of this project, we plan to leverage the combination of ET-based and SMM-based irrigation schedules. Partial irrigation is covered in another document.

Cumulative crop evapotranspiration minus effective rainfall will be considered as the crop water need. Average values of application efficiency for the different irrigation methods, soil water holding capacity and soil moisture will also be factored in to define the depth, timing, frequency and duration of irrigation to apply to the different crops.

Keywords: Irrigation scheduling, crop evapotranspiration, irrigation frequency, soil moisture monitoring, plant water status

Carrillo-Cobo, Teresa; Daniele Zaccaria; Kate Scow (UCD). 2015. ***Rational Irrigation Scheduling.*** California Energy Commission. Publication number: CEC-500-YYYY-XXX.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Introduction

In the face of increasingly limited and impaired water supplies resulting from the severe drought facing California over the past few years, agriculture is under scrutiny to achieve higher water use efficiency through improved irrigation management practices.

Long standing irrigation practices based on traditions can sometimes come in the way of adopting new irrigation methods. Hearing a grower saying “I have been farming for more than 25 years. I look at the weather every day, and I use a shovel if I need to check the moisture of the soil” is not uncommon. It denotes a dedication to the land and an intimate knowledge of the crop. However, can we do better?

Irrigation based on actual data can help rationalize the adoption of new irrigation schedules that can save water and improve yield. The main goal of irrigation scheduling is to define the adequate amounts of water to apply to cropped fields with the proper irrigation timing, frequency and time duration to avoid the occurrence of water stress (deficit and excess) during the crop cycle.

We review here a number of rational irrigation techniques based on information that can be collected and analyzed with modern technology tools. Evaporation and Transpiration (ET) are the fundamental mechanisms by which a plant grows, matures and also adapts daily to its environment due to climate variability. ET helps quantifies “how much water is needed”.

Rational irrigation scheduling also requires irrigation managers and irrigators to know when to start irrigation, not just the amount of water used by the crop since the last irrigation or rainfall event. A number of tools can refine irrigation scheduling by identifying when irrigation should start. Devices include temperature sensors to measure the actual ET at a specific field, soil moisture sensors to measure how much water is left in a particular soil profile, and pressure chambers to measure the water potential in a leaf or a stem.

This reports reviews the different irrigation scheduling techniques in the context of California. Crop water needs during spring and summer months are mainly fulfilled by irrigation due to typical Mediterranean weather conditions, characterized by hot and dry spring/summer seasons and rainfall primarily concentrated during fall and winter months. The report summarizes rational irrigation based on (1) ET, (2) ET augmented with soil moisture monitoring (ET-SMM).

Plant-based measurements are more labor intensive and can also be destructive such as taking a leaf in a pressure chamber. They will be used primarily in the project to verify that the crops are not over stressed by reducing water application based on rational scheduling. It will be the responsibility of the growers to share the data with the collaborators of the project.

Rational irrigation scheduling is not meant to replace the experience that growers have accumulated over the years. It is invaluable because each field is different. They have their own “sensors” with their eyes, ears and fingers. However, it provides a systematic and objective approach to improve the efficient use of water in irrigated agriculture while limiting the risk of undesired effects on a crop by consistently monitoring the field.

2. ET-based irrigation scheduling

Accurate estimation of crop water use is necessary to determine the amount of irrigation water to apply to crop fields throughout the crop season. Quantifying the crop evapotranspiration (ET) since the last irrigation or rainfall event represents the basic information needed by growers to implement a rational irrigation schedule.

Irrigation scheduling entails the following steps:

1. Observe water use frequently;
2. Start irrigation to compensate for water used for ET, and other losses due to inefficiencies in the irrigation system
3. The duration is based on the target amount of water and the application rate;
4. Predict the next irrigation based on ET forecasts or actual ET measurements.

2.1 Evaporation and transpiration

Evapotranspiration is the loss of water to the atmosphere through the combined processes of water evaporation from the soil and plant surfaces (E) and transpiration through the plant tissues (T). Both processes occur simultaneously and are difficult to separate (Allen *et al.*, 1998).

For well-watered crops under optimal agronomic conditions, the crop evapotranspiration (ET_c) occurs at its "potential" rate and can be estimated through the Equation 1:

$$ET_C = K_C \times ET_O \qquad [1]$$

where K_C is the crop coefficient (dimensionless) and ET_0 is the evapotranspirative demand by the atmosphere, or reference evapotranspiration (inches or mm per day).

2.1.1 Reference Evapotranspiration (ET_0)

Reference evapotranspiration represents the amount of water lost from a reference surface, either grass (ET_0) or alfalfa (ET_r), when water is not limited. It depends upon different factors:

- Weather parameters: net radiation, air temperature, wind speed and relative humidity

- Plant factors: root depth, canopy density, canopy height, and growth stage.

Different methods and equations have been developed to estimate the ET_0 on the basis of different variables (Hargreaves et al. 1985; Snyder and Pruitt, 1985; Jensen et al., 1990; Allen et al., 1994, 1998). The FAO-56 Penman-Monteith equation is the most widely-used and recommended method for estimating reference ET.

2.1.2 Crop Coefficients (K_c)

Crop coefficients (Kc) are adjustment factors relating the ET of a specific crop with that of the reference crop (ET_0) under the same micro-climatic conditions.

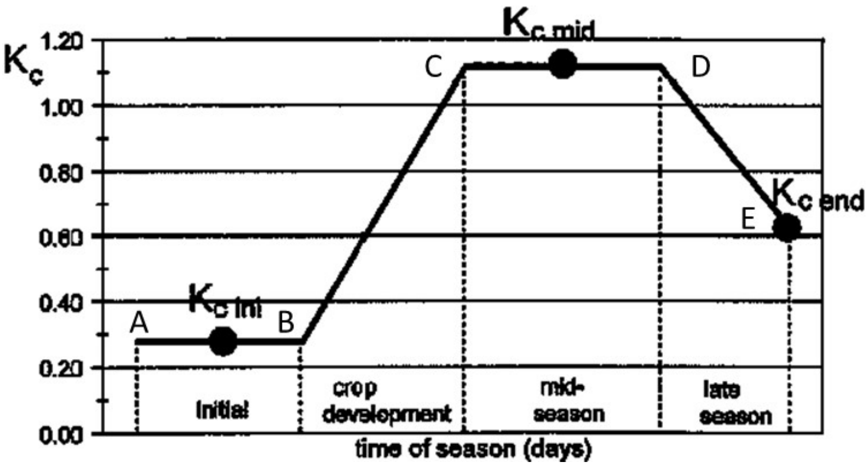
For annual crops, Allen *et al.* (1998) defined K_c values for four crop stages, i.e. initial, crop development, and mid-season and late season stages. Table 1 reports K_c values commonly used in California for scheduling irrigation for processing tomatoes, alfalfa, pistachios and almonds, according to Snyder et al. (2016) and Ferguson et al. (2005).

Table 1: Crop coefficients (Kc) for processing tomatoes, alfalfa, almonds and pistachios

Crop coefficients	Processing Tomatoes1)	Alfalfa1)	Almonds1)	Pistachios2)
Kc B	0.33	1	0.55	0.54
Kc C	1.1	1	1.15	1.14
Kc D	1.1	1	1.15	1.40
Kc E	0.65	1	0.65	0.60

1) Snyder *et al. (2016)*
2) Ferguson *et al.* (2005)

Figure 1. Constructed crop coefficient curve for different stages of development of a plant



Source: Allen et al. (1998)

2.2 Crop evapotranspiration

Measuring actual crop evapotranspiration is not easy and can be quite expensive, as it requires specific devices to accurately measure various physical microclimatic and crop parameters.

The selection of a particular device or a service should be based on evaluating its advantages and disadvantages in term of cost, installation, ease of use, data access, and maintenance needs.

2.2.1 California Irrigation Management Information System (CIMIS)

Alternatively, crop evapotranspiration can be estimated considering weather-derived values of ET_0 and crop coefficients at user-selected time steps throughout the duration of the crop season. ET_0 can be obtained from the California Irrigation Management Information System (CIMIS), whereas the crop coefficients are available from several published sources.

The CIMIS was developed in 1982 and currently manages a network of over 145 weather stations throughout California. The network is operated by the California Department of Water Resources (DWR). Station data include measured parameters such as solar radiation, air temperature, soil temperature, relative humidity, wind speed, and wind direction, as well as derived parameters such as vapor pressure and dew point temperature. The hourly weather data is used to calculate hourly reference ET. CIMIS uses the Penman-Monteith equation modified by Pruitt and Doorenbos (1977) (http://wwwcimis.water.ca.gov/Resources.aspx). Hourly references ET are added up over 24-hour time step to estimate daily ET_0.

Daily crop evapotranspiration (ET_C) can be estimated using equation 1, where daily ET_0 is obtained from the nearest CIMIS station or from Spatial CIMIS, and the K_c values can be taken from different published sources as those indicated in Table 1.

> For the project we selected Spatial CIMIS (http://wwwcimis.water.ca.gov/SpatialData.aspx). The CIMIS staff have recently improved the spatially accuracy of ET_o estimates. Spatial CIMIS incorporates solar radiation data from the Geostationary Operational Environmental Satellite (GOES). Relative humidity, air temperature, and wind speed data which are also required for the ET estimates are estimated by triangulating from stations closest to the location of a field.

2.2.2 Actual evaporation from the residual of energy balance method.

Actual crop evapotranspiration under field conditions can be obtained from the residual of energy balance method by measuring specific micro-climatic and crop-related parameters. The simplified surface energy balance can be written as shown in Equation 2 below:

$$\mathrm{Rn} = \mathrm{G} + \mathrm{H} + \mathrm{LE} \qquad [2]$$

where Rn is the net radiation (Wm^{-2}), G is the soil heat flux (Wm^{-2}), H is the sensible heat flux (Wm^{-2}) and LE (Wm^{-2}) is the latent heat flux.

LE can be calculated from the residual between Rn, G and H as shown in Equation 3:

$$\mathrm{LE} = \mathrm{Rn} - \mathrm{G} - \mathrm{H} \qquad [3]$$

Latent heat flux density is then divided by the latent heat of evaporation (λ) to obtain the mass flux density of water vapor (Equation 4), which can be finally converted to hourly and daily ET.

$$ETa = \frac{LE}{\lambda}$$

[4]

This approach requires accurate measurement of the main energy balance components. Analytical procedures have been developed to estimate the actual crop ET by means of lysimeters, the Eddy Covariance method (Moore, 1986; Gharsallah *et al.*, 2013), and the Surface Renewal method (Paw *et al.*, 1995, Snyder *et al.*, 1996; Castellvi, 2004; Shapland *et al.*, 2012a, 2012b).

In addition, other methods are available to estimate some parameters of the surface energy balance using remote sensing techniques, such as SEBAL (Bastiaanssen *et al.*, 1998), S-SEBI (Roerink *et al.*, 2000), and METRIC (Allen *et al.*, 2007).

For this project, the actual evapotranspiration of each crop, processing tomatoes, alfalfa, almonds and pistachios will be estimated using Tule ET stations (https://tuletechnologies.com/). These devices estimate the actual crop ET over the fields by the surface renewal method, measuring the sensible heat flux (H) over the crop canopy and using satellite-based estimation of net radiation (Rn).

2.2 Irrigation water requirements

Crop ET represents the water used (evapotranspired) from a cropped surface in a given period of time. The following section describes the calculation of net and gross irrigation water requirements, accounting for some extra water to apply to compensate for irrigation inefficiencies and losses.

2.2.1 Net irrigation water requirement (I_n)

The crop water needs can be calculated from the soil-water balance in the root zone using Equation 5 presented below:

$$I_n = ET_C - P - G_w - \Delta SW + RO + D_p \qquad [5]$$

where I_n is the net irrigation (inches or mm), ET_c is the crop evapotranspiration (inches or mm), P is the total precipitation (inches or mm), G_W is the capillary rise of water (inches or mm), ΔSW is the change in soil water storage in the crop root zone (inches or mm), RO is the surface runoff (inches or mm) and D_p is the deep percolation from the root zone.

Effective precipitation (P_e) is the fraction of rainfall that infiltrates and stores in the soil, and can be available to the crop. The definition of P_e by USDA Soil Conservation Service (1967) does not include surface runoff or percolation below the crop root zone. As such, the real-time effective precipitation can be estimated using the Equation 6 (USDA, 1967):

$$P_e = P - RO - D_p \qquad [6]$$

where P_e is the effective precipitation or precipitation infiltrated and stored in the soil root zone and available to plants (inches or mm).

The maximum effective precipitation cannot exceed the amount of water depleted from the soil root zone (soil water depletion) relative to the soil water content at field capacity. If the calculated effective precipitation is larger than depleted water, the soil water depletion should be used rather than the effective precipitation value. For a short time after a rain, the upward flow from the groundwater is very small and can be neglected while estimating effective precipitation (USDA, 1967).

In some regions of California where groundwater aquifers are deep and there is no shallow watertable, the capillary rise of water can be neglected. In such cases, the Equation 5 can be simplified to derive the Equation 7, which defines the net irrigation requirement as the difference between the crop evapotranspiration and effective rainfall (Brouwer & Heibloem, 1986).

$$I_n = ET_C - P_e \tag{7}$$

Calculations of net irrigation water requirement require the real-time reference evapotranspiration provided by CIMIS or other ET sensors, and the estimation of effective precipitation to define the total amount of water depleted from the soil root zone since the last irrigation or rainfall event has occurred.

2.2.2 Maximum net irrigation depth

The maximum net irrigation depth to apply during an irrigation event depends on the available soil water holding capacity (AWC), the depth of the root zone (Z_r) and the Management Allowable Depletion (MAD). AWC is the amount of water that can be held in a unit of soil volume, and is estimated as the difference between the soil water content at field capacity and that at permanent wilting point which, in turn, depends on soil texture, organic matter content, bulk density and eventual soil stratification. MAD is the soil water content at which plant stress occurs. To prevent plant stress, a recommended threshold value of MAD as percent of AWC in the root zone is used to manage the irrigation. Then, the maximum net irrigation depth (inches or mm) can be calculated using the Equation 8:

$$I_{max} = AWC * Z_r * \frac{MAD}{100} \tag{8}$$

where AWC is expressed in inches of water per foot of soil, or mm of water per m of soil, MAD in percent of AWC, and Z_r in feet or m.

2.2.3 Gross irrigation depth (I_g)

The gross irrigation depth can be calculated accounting for water losses due to irrigation inefficiencies, which can be all included in a term called water application efficiency, as shown in Equation 9.

$$I_g = \frac{I_n}{AE} \tag{9}$$

where I_g is the gross irrigation requirement (inches or mm) and AE represents the application efficiency (Table 2).

Table 2: Application Efficiency in California

Irrigation method/system	Average AE (%)
Hand move/solid-set sprinklers	70
Continuous-move sprinklers	80
Under-tree sprinklers	80
Drip Irrigation	85
Micro-Sprinkler	80
Furrow irrigation	75
Border irrigation	80

Source: Hanson et al., 1995

The net and gross irrigation depths can be then converted into volume (gallons) or irrigation duration (hr). The volume of water to apply during an irrigation event can be calculated by Equation 10:

$$V_W = I_g \cdot A \qquad [10]$$

where V_w is the total volume of water to apply and A is the irrigated acreage.

The time-duration necessary to apply the gross irrigation depth for microirrigation systems depends on the system capacity and can be calculated by the equation 11 (Morris *et al*., 2011):

$$I_T = \frac{I_g \cdot L_S}{q \cdot 11.55} \qquad [11]$$

where I_T is the irrigation time needed (hours), L_S is the lateral spacing (inches) and q is the flow rate of laterals (gpm/100 ft).

In surface irrigation systems, the time required to apply the gross irrigation depth is determined by:

$$I_T = \frac{I_g \cdot A}{Q} \qquad [12]$$

where Q (cfs) is the available water supply.

3 Soil Moisture Monitoring

A soil moisture monitoring system can be used alone or in combination with the other irrigation scheduling methods to improve irrigation management practices.

Soil moisture monitoring allows keeping track of what is happening in the soil root zone with regard to a) how much water infiltrates during an irrigation or rainfall; b) how much water is depleted (up-taken by plants) between irrigations; and c) maintaining adequate soil water conditions. Overall, monitoring soil moisture status enables to match irrigation applications with the actual crop water use (ET) with the aim of targeting optimal soil water conditions for plants growth and production.

Soil moisture based irrigation scheduling entails the following steps:

1. Observe soil moisture frequently;
2. Start irrigation at specific levels of soil moisture (allowable depletion, allowable matric potential or tension);
3. Stop irrigation when soil moisture reaches target levels;
4. Predict the next irrigation based on the measured soil moisture depletion rate.

3.1 Irrigation based on ET and Soil Moisture Monitoring (ET-SMM)

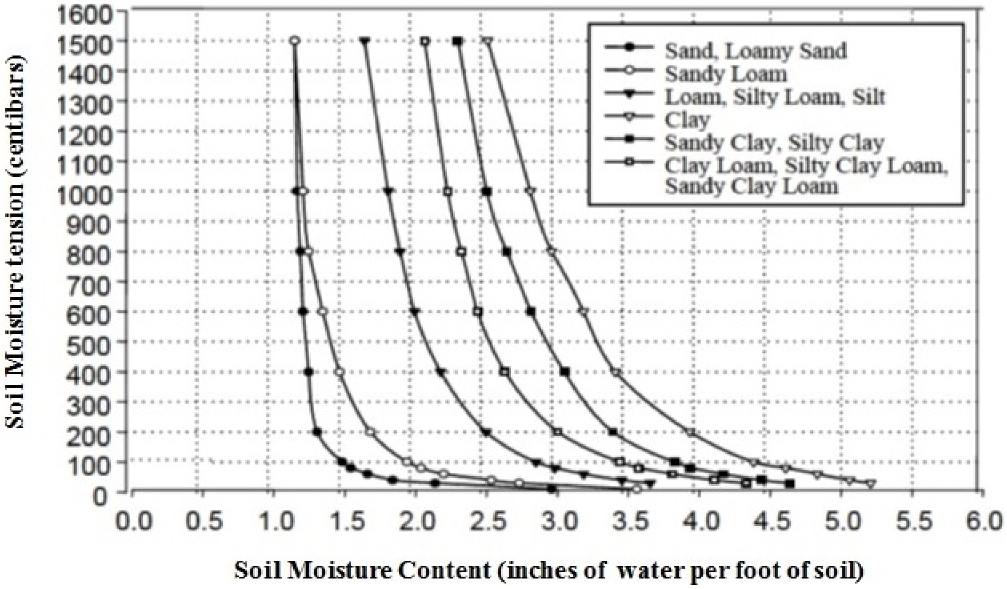
When used in combination with crop ET, monitoring soil water status enables to trigger irrigation before water deficit conditions occur in the root zone and also to prevent excess water, whereas crop ET can provide information on the amount of irrigation water to apply. In addition, soil moisture monitoring can provide feedback information on soil water status to make sure irrigation events are managed adequately in terms of irrigation timing, frequency and duration to prevent the occurrence of both water deficit and excess.

A soil moisture monitoring system consist of sensors that reveal the current soil water status in the root zone during and between irrigation events and can provide answers to these key questions (Hanson *et al.*, 2007):

- When should irrigation take place?
- What is the water uptake pattern of the roots?
- Did enough water infiltrate the soil?
- Is too much water being applied?
- What was the depth reached by the irrigation water?

Soil moisture can be measured in terms of soil water content and tension. Soil moisture content tells how much water is available per unit of soil and is expressed in percent (% of weight or % of volume) or inches of water per foot of soil. The soil moisture tension tells how strongly water is held by soil particles, meaning that the higher the tension, the drier the soil and the more difficult is for plants to extract water. The two types of measurement can be related through the development of soil-specific water retention curves, such as those shown in Figure 1 below.

Figure 2. Soil water retention curves for different soil textures



Source: Ley et al. (1996)

3.2 Types of soil moisture sensors

Some sensors measure soil water content while others measure soil water tension. In reality all sensors measure soil properties or parameters that are related to soil moisture content or tension through a specific calibration. As such, soil moisture sensors are categorized into two major groups differing for the measured parameters:

- Sensors measuring soil water content: Neutron probes, Time Domain Transmissivity (TDT), Capacitance, Time and Frequency Domain Reflectometry sensor (TDR, FDR) and Amplitude Domain Reflectometry (ADR).
- Sensors measuring soil moisture tension: Tensiometers and Granular Matrix sensors

The selection of a particular device should be based on evaluating the advantages of a sensor advantages and disadvantages in term of cost, installation, ease of use, data access, and maintenance needs. Examples of sensors measuring tension: Irrometer and Hortau. Examples of sensors measuring water content: Observant with Sentek probes, Irrometer. Some vendors provide the sensors as a service so growers do not have to maintain them (e.g., Hortau).

For the project we selected tensiometers from Irrometer (http://www.irrometer.com/). Three watermark sensors will be installed at different depths in the ground to monitor soil moisture. Soil moisture is measured by a column of water in a porous container (probe) that enters in balance with the moisture in the soil surrounding it. The soil-water balance provides a measurement of the tension between the soil and the plant. The unit is kilo Pascal (kPa).

In common irrigation practice, the recommended values of soil moisture tension and content at which irrigation should occur are based on 50% of AWC and are shown for the different soil textures in the Table 2 and 3 (reported below).

Table 3. Recommended values of soil moisture tension at which irrigation should occur for the different soil textures

Soil Type	Soil Moisture Tension (centibars)
Sand or Loamy Sand	40-50
Sandy Loam	50-70
Loam	60-90
Clay Loam or Clay	90-120

Table 4. Recommended values of soil moisture content at which irrigation should occur for the different soil textures

Soil Type	Available Water (in/ft)	Allowable Depletion (in/ft)	Available Water in 4ft Root Zone (in)	Allowable Depletion in 4 ft Root Zone (in)
Coarse Sand	0.5	0.25	2.0	1.0
Loamy Sand	1.0	0.50	4.0	2.0
Sand Loam	1.5	0.75	6.0	3.0
Fine Sandy Loam	2.0	1.00	8.0	4.0
Clay Loam	2.2	1.10	8.8	4.4
Clay	2.3	1.15	9.2	4.6
Organic Clay Loams	4.0	2.00	16.0	8.0

Additional information on soil moisture measurements can be obtained from the UC ANR publication "Monitoring soil moisture for irrigation water management", available at http://anrcatalog.ucanr.edu/Details.aspx?itemNo=21635.

4 Plant Water-Based Measurements

Plant water-based measurement is another approach used to verify proper irrigation scheduling. It is the closest to traditional irrigation practices because it requires onsite inspection rather than remote sensing. Water status in plant tissues directly affects metabolic and physiologic processes. Plant water status provides information about how water moves through the soil-plant system and about atmospheric evaporative demand.

Numerous methods have been developed to measure or monitor parameters directly or indirectly related to plant water status (Hsiao, 1990). Some of them are listed below:

- Plant water potential
- Relative water content
- Hydraulic press
- Organ dimensions
- Stomatal opening
- Canopy temperature
- Xylem cavitation
- Expansive growth of leaves or stems

The choice of a specific measurement method depends on the plant's relative sensitivity to water deficit and on the particular purpose of the measurement (Hsiao, 1973). The most common parameters measured in the field are plant water potential and canopy temperature.

The plant water potential (ψ) is critical for water transport between soil, plant and atmosphere. Thermocouple psychrometry, hydrometry, Shardokow dye method or pressure chamber (Scholander *et al.*, 1965) are used to measure plant water potential. However, pressure chamber is the most common and robust method used on the field. Midday stem water potential (SWP) was proposed as accurate and reliable approach to determinate water stress in prunes (McCutchan and Shackel, 1992). Shackel *et al.* (1997 and 2000) developed plant water potential models for different crops, such as almond, walnut and grapes. Reference values of plant water potential, which depends on soil and weather conditions, can be defined for these crops in different areas of California. Additional information on irrigation scheduling using stem water potential can be found at http://informatics.plantsciences.ucdavis.edu/Brooke_Jacobs/index.php.

Canopy temperature is another method used to assess the plant water status indirectly. Water deficit is shown when canopy temperature significantly increases above air temperature as a result of stomata closure. Stress degree day (SDD) is an indicator that represents the summation of canopy-air temperature difference over time (Jackson *et al.* 1977). SDD is also frequently used for irrigation scheduling.

Measurements of plant water status can be used to provide a "safety net" when ET-based or SMM-based irrigation scheduling is implemented. Plant water-based monitoring helps to determine when irrigation is needed ("too much stress"). However, it does not say how much needed is required and its accuracy can vary depending on the who makes the measurement (e.g., pressure chambers). In addition, plant measurement techniques are different for each crop.

5 Implementation of irrigation scheduling techniques

Rational irrigation scheduling for processing tomato, alfalfa, almond and pistachio will be based on the combination of the different techniques described above. The exact strategy (amount of water applied to the field) will depend on historical data from the field (energy, water, and yield). The goal is to achieve an improvement of 20% in water use efficiency.

We describe below an irrigation schedule to minimize excess or deficit irrigation. Partial ET irrigation is covered in another document because partial irrigation scheduling is more specific to a type of crop in order to avoid undesired effects (loss of yield, degradation in quality, etc.).

Our goal is to simplify the information necessary to tune irrigation scheduling by automating the calculation and boiling down the information to a duration ("how many hours should I run the pump?"). We review here the two main scheduling techniques.

5.1 Irrigation based on ET

5.1.1 Sources of ET data

Daily crop water requirements will be estimated by the nearest ET station. Public stations are available from CIMIS. We also selected for this project Tule stations because they provide actual ET data for a spefici field. We will support those two cases and the grower will select the source of ET data depending on the budget and the capabilities at a specifc farm:

1. We will provide the potential ET (ETc) from the Spatial CIMIS and accepted crop coefficients. The crop coefficients can be imrpoved by knowing the planting date and estimating the canopy coverage.
2. In the case a Tule station is installed, we will collect the actual ET (ETa) for the field. This can significantly improve the irrigation schedule because the amount of ET is measured onsite rather than estimated from weather stations and remote sensing. However, the Tule station needs to be maintained.

5.1.2 Scheduling based on ET

Irrigation scheduling can be implemented in software by following the following steps:

1. Identify the application rate of the irrigation system (inches per hour or gallons per minute).
2. Calculate the irrigation depth from the amount of ET since the last irrigation event (or rainfall)
    a. Download ET data (from Tule or Spatial CIMIS).
    b. Calculate effective precipitation (P_e).
    c. Calculate the net irrigation requirement (I_n).
    d. Calculate the gross irrigation requirement (I_g).
3. Calculate the duration of the irrigation event
    a. Quantify the total volume of water to apply (V_w)
    b. Convert to the necessary irrigation duration (I_T) by using the most recent application rate

5.2 Irrigation based on ET and SMM

5.1.1 Sources of SMM data

In this project we opted for the tension approach because it is easier to calibrate. There are several vendors and we selected Irrometer with watermak sensors.

5.1.2 Scheduling based on ET and SMM

The irrigation schedule can be optimized by monitoring the soil moisture:

1 Identify the application rate of the system (inches per hour or gallons per minute)
2 Select the most appropriate soil moisture sensors and install before crop transplanting.
3 Optimize the location of the soil sensors according to soil map and recent observation of the field to mitigate variability across the field.
4 Identify the typical frequency of irrigation events in a week based on the soil moisture depletion rate and the capacity of the irrigation system.
5 Select the source(s) of soil moisture data.
6 Start irrigation at target levels of soil moisture (allowable depletion such as 50% of AWC).
7 Calculate the irrigation depth (inches) – same method as ET
8 Calculate the duration of the irrigation event
    a. Quantify the total volume of water to apply (V_w)
    b. Convert to the necessary irrigation duration (I_T)

5.3 Examples

5.3.1 for processing tomato

In this example we implement irrigation scheduling based on a combination of ET from a Tule station and soil moisture monitoring from an Irrometer station.

Plant water status will also be checked weekly by measuring the difference between canopy and air temperature. We will also measure the canopy by taking images weekly.

2.3.2 Example for almonds.

In this example, irrigation of an almond orchard is scheduled on the basis of crop ET from Spatial CIMIS. Plant water status will be checked weekly by the grower. The farming crew will measure SWP using a pressure chamber (http://fruitsandnuts.ucdavis.edu/pressure_chamber_operation/).

We will also check the vigor of the orchard, and the evolution of the canopy using monthly aerial images taken with visible and infra-red cameras.

GLOSSARY

Term	**Definition**
UC ANR	University of California, Division of Agriculture and Natural Reources
ADR	Amplitude Domain Reflectometry
AWC	Available Water Holding Capacity
CIMIS	California Irrigation Management Information System
ET	Evapotranspiration
FDR	Frequency Domain Reflectometry
MAD	Maximum Allowable Depletion
SDD	Stress Degree Day
SWP	Stem Water Potential
TAW	Total Available Water
TDR	Time Domain Reflectometry
TDT	Time Domain Transmissivity
UCD	University of California, Davis
USDA	United States Department of Agriculture

REFERENCES

Allen, R.G., Smith, M., Perrier, A. and Pereira, L.S. 1994. An update for the calculation of reference evapotranspiration. ICID Bull. Vol. 43, No. 2, 1-34

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper n. 56. FAO, Rome, Italy, 300 pp.

Allen, R., Tasumi, M., and Trezza, R. (2007). "Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model." J. Irrig. Drain Eng., 133(4), 380–394.

Bastiaanssen, W., Noordman, E., Pelgrum, H., Davids, G., Thoreson, B., and Allen, R. (2005)."SEBAL Model with Remotely Sensed Data to Improve Water-Resources Management under Actual Field Conditions." J. Irrig. Drain Eng., 131(1), 85–93.

Brouwer, C., and Heibloem, M. 1986. Irrigation water management: irrigation water needs. Training manual, 3.

Castellvi, F., 2004. Combining surface renewal analysis and similarity theory: a new approach for estimating sensible heat flux. Water Resour. Res. 40 (5).

Ferguson, L., Beede, R. H., Freeman, M. W., Haviland, D. R., Holtz, B. A., and Kallsen, C. E. 2005. Pistachio Production Manual. Fruit and Nut Research and Information Center, 4th ed. University of California, Davis, CA.

Hanson, B., Bowers, W., Davidoff, B., 1995. Field performance of microirrigation systems. In: Microirrigation for a Changing World, Proceedings of Fifth International Microirrigation Congress, April 2–6, 1995. American Society of Agricultural Engineers, Orlando, FL, pp. 769–774

Hanson, B. Orloff, S., and Sanden, B. 2007. Monitoring soil moisture for irrigation water management (Vol. 21635). UCANR Publications.

Hargreaves, G. L., Hargreaves, G. H., and Riley, J. P. 1985. Agricultural benefits for Senegal River basin. Journal of Irrigation and Drainage Engineering, 111(2), 113-124.

Hsiao, T. C. 1973. Plant responses to water stress. Annual Review of Plant Physiology 24, 519-570.

Hsiao, T. C. 1990. Measurements of plant water status. Agronomy, (30), 243-279.

Jackson, R.D., Reginato, R.J. and Idso, S.B. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Resour. Res. 13: 651-656

Jensen, M. E., Burman, R. D., and Allen, R. G. 1990. Evapotranspiration and irrigation water requirements. ASCE.

Ley, T., Stevens, R.G., Topielec, R.R., Neibling, W.H. 1996. Soil Water Monitoring and Measurement. Washington State University Cooperative Extension; the Oregon State

University Extension Service; and the University of Idaho Cooperative Esctension System. Pacific Northwest Extension Publication 475.

McCutchan, H. and Shackel K.A. 1992. Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). Journal of the American Society for Horticcultural Research, 117, 606-611

Moore, C.J., 1986. Frequency response corrections for eddy correlation systems. Boundary-Layer Meteorol. 37, 17–35.

Morris, M. and Schwankl, L. 2011. The California Microirrigation Pocket Guide. System Management & Maintenance. California USDA-Natural Resources Conservation Service and The University of California cooperation Extension Irrigation Program.

Paw U, K.T., Qiu, J., Su, H.B., Watanabe, T., and Brunet, Y., 1995. Surface renewal analysis: a new method to obtain scalar fluxes without velocity data. Agric. For. Meteorol. 74, 119-137

Pruitt, W.O., Doorenbos, J., 1977. Empirical calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data? In: Proceedings of the International Round Table Conference on "Evapotranspiration", International Commission on Irrigation and Drainage, Budapest, Hungary, 20 pp

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E. 2009. AquaCrop the FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agronomy Journal, 101(3), 438-447.

Roerink, G.J., Su, Z., Menenti, M., 2000. S-SEBI: a simple remote sensing algorithm to estimate the surface energy balance. Phys. Chem. Earth Part B 25 (2), 147–157.

Scholander, P.F., Hammel, H.T., Hemmingsen E.A. and Bradstreet, E. D. 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. Proc. Natl. Acad. Sci. U.S.A. 52:119-125

Shackel, K.A., H. Ahmadi,W. Biasi, R. Buchner, D. Goldhamer, S. Gurusinghe, J. Hasey, D. Kester, B. Krueger, B. Lampinen, G. McGourty, W. Micke, E. Mitcham, B. Olson, K. Pelletrau, H. Philips, D. Ramos, L. Schwankl, S. Sibbett, R. Snyder, S. Southwick, M. Stevenson, M. Thorpe, S. Weinbaum, and J. Yeager. 1997. Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnology 7:23–29.

Shackel, K., B. Lampinen, S. Sibbett, and W. Olson. 2000. The relation of midday stem water potential to the growth and physiology of fruit trees under water limited conditions. Acta Hort. 537:425–430.

Shapland, T.M., McElrone, A.J., Snyder, R.L., and Paw U, K.T., 2012a. Structure function analysis of two-scale scalar ramps. Part I: theory and modeling. Boundary-layer Meteorology, 145(1), 5–25.

Shapland, T.M., McElrone, A.J., Snyder, R.L., and Paw U, K.T., 2012b. Structure function analysis of two-scale scalar ramps. Part II: ramp characteristics and surface renewal flux estimation. Boundary-layer Meteorology, 145 (1), 27–44.

Snyder, R. and Pruitt, W.O. 1985. Estimating Reference Evapotranspiration with Hourly Data. VII-I-VII-3. Snyder, R., D. W. Henderso, W.O., Pruitt and A. Dong (eds.). Calif. Irrig, Magmt. Systems Final Rep., Univ. Calif. Davis.

Snyder, R.L., Spano, D., and Paw U, K.T., 1996. Surface renewal analysis for sensible and latent heat flux density. Bound. Layer Meteorol. 77, 249–266.

Snyder, R.L. Orang, M., Bali, K. Eching, S. and Zaccaria, D. 2016. BISm. Basic Irrigation Scheduling.

World Water Assessment Programme 2009 The United Nations World Water Development Report 3: Water in a Changing World (Paris, London: UNESCO Publishing, Earthscan). USDA 1967 Irrigation Water Requirements Tech. Release no. 21 (Washington, DC: United States Department of Agriculture Soil Conservation Service (USDA-SCS))

Energy Research and Development Division
Product

PARTIAL IRRIGATION SCHEDULING
Appendix D

Prepared for: California Energy Commission
Prepared by: PowWow Energy

APRIL 2016
EPC-14-081

PREPARED BY:

Primary Author(s):
Teresa Carrillo-Cobo, UC Davis
Daniele Zaccaria, UC Davis
Kate Scow, UC Davis

PowWow Energy
425 Broadway
Redwood City, CA 94063
Phone: 415-658-7125
http://www.PowWowEnergy.com

Contract Number: EPC-14-081

Prepared for:

California Energy Commission

Leah Mohney
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the University of California for providing useful information for the development of this report.

ABSTRACT

This document describes the principles and applications of partial irrigation for the different crops considered in the present project.

Almond, pistachio, processing tomato and alfalfa have different sensitivity and tolerance to water stress, as a result of specific physiologic features, responses and adaptation mechanisms.

Crop water use is also known as evapotranspiration and abbreviated ET, which is typically expressed as depth of water per unit time (inches per day or month, mm per day or month, etc.) ET measures the combined effects of water evaporation from soil and canopy surface and transpiration through the crop canopy.

In the present report, we will use the term *potential crop evapotranspiration* or ET_c to indicate the evapotranspiration from a disease-free crop growing in large agricultural fields under non-restricting soil and soil water conditions and under adequate fertility. In other words, ET_c refers to the water evapotranspiration from a crop that has no reduction in transpiration due to shortage of soil water. The term *actual crop evapotranspiration* or ET_a refers instead to the actual evapotranspiration from a crop in its site-specific conditions, which can happen to be different from those defining the potential crop evapotranspiration, causing limitation of soil water and fertility, thus restricting the vegetative growth and production, and generating lower crop evapotranspiration than ET_c.

The impact of water limitations on crop growth and production depends on the severity of water stress, the duration of crop exposure and the growth stage when stress occurs. A partial irrigation strategy can be defined on the basis of Deficit Irrigation Levels (DIL), which refer to water applications as percentages of ET_c at different periods during the crop cycle. In general, partial irrigation results in the actual crop evapotranspiration or ET_a being lower than the potential crop evapotranspiration or ET_c, which may also cause a reduction in crop yield.

In tree crops, the yield reduction resulting from water deficit usually occurs during the current season when soil water limitations happen (or partial irrigation is conducted) due to decrease in leaf water potential and partial closure of stomata. In other terms, tree crops have a carry-forward mechanism dragging the effects of water limitations from one year on the few subsequent crop seasons. Partial Irrigation can also be referred to as Deficit Irrigation (DI), and may bring some positive effects in terms of improved quality of crop production.

Carrillo-Cobo, Teresa; Zaccaria, Daniele; Scow, Kate (UCD). 2015. ***Partial Irrigation Scheduling.*** California Energy Commission. Publication number: CEC-500-YYYY-XXX.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. Rationale for partial irrigation strategies

In areas characterized by Mediterranean climate like California, irrigation is needed to establish and maintain the necessary available soil-moisture and nutrient conditions over time for optimal crop growth and production, while avoiding or minimizing the risk of water and nutrient limitations to plants. Different irrigation strategies can be implemented to maximize the net income for farmers on the basis of availability and cost of the different production factors and on the crop yield response to water. Adequate irrigation scheduling allows farmers and irrigators to water their crops with the proper timing, an adequate amount of irrigation water and frequency as well as to set the times to be compatible with optimal crop production, considering the relationships between soil, water, plant and atmosphere and the specific crop-yield responses to water. Generally speaking, the irrigation scheduling approach most frequently used in California aims at full satisfaction of the crop water requirements, or at full replenishment of crop water use, which usually results in maximum crop growth and yield, and stand longevity.

Partial irrigation strategies may be considered and pursued during periods of limited water supply, or to achieve specific quality targets of crop production. Regulated and Sustained Deficit Irrigation are common partial irrigation strategies with related scheduling approaches that could be used to achieve specific targets for crop production or to maximize water-use efficiency and water productivity (more crop per drop). Different crops have different sensitivities and tolerances to water deficit during their various growth and production stages. A good understanding of the crop's yield responses to water is needed to successfully implement a partial irrigation strategy. Plants respond to water stress via both molecular and physiological mechanisms, which impact the plant's photosynthetic capacity. Water stress induces reduction of leaf water potential and partial closure of stomata. This reduces CO_2 assimilation by leaves that, in turn, affect plant growth and the overall productivity. In addition, other adaptation mechanisms may also be involved, such as osmotic adjustment to increase stress tolerance.

The use of micro-irrigation methods (drip and micro-sprinkler) enables farmers to keep better control on water and nutrient applications. In other words, micro-irrigation methods are more suitable than surface and sprinkler irrigation methods to implement partial irrigation.

Several research studies have been conducted on partial irrigation strategies and their implementation in commercial field conditions. According to Fereres and Soriano (2007), managing water deficit during certain periods of the crop season could help not only in lowering the production costs but also in saving water, maintaining crop quality, as well as keeping nutrients and pesticides within the root zone for plant uptake. However, prior to implementing partial irrigation across all crops, an in-depth understanding of benefits and adverse impacts of water limitations is needed, especially on crops sensitive to water stress such as some vegetables, fruit and nut crops.

Regulated deficit irrigation or RDI has been successfully used in different crops such as maize (Kang *et al*. 2000; Farré and Faci, 2006), fruit tress (Girona *et al.* 1993; Goodwin & Boland, 2000) and grapevines (McCarthy *et al.* 2000). In these studies, crop yield was maintained and production quality was improved in some cases, while the amount of applied water was substantially reduced.

The implementation of deficit irrigation is among the recommended strategies for periods of drought. The Drought Management website (http://ucmanagedrought.ucdavis.edu/) of the University of California recommends deficit irrigation levels for various crops under drought conditions. An alternative strategy to implement during years with limited water supply would be to reduce the irrigated acreage.

The present report summarizes some recommendations for partial irrigation to implement during 2016 and 2017 in the different demonstration sites on almond, pistachio, processing tomato and alfalfa as part of the project funded by the California Energy Commission (CEC). It also focuses on optimizing irrigation applications without reducing the irrigated acreage during the crop season.

2. Partial irrigation scheduling for nut crops

In nut crops, deficit irrigation strategy must be considered in its effects on the crop yield in the current and following seasons. A poorly implemented partial irrigation strategy may generate a great risk of reducing crop production for a few years following that when water deficit occurs.

The effects of water restrictions on crop yield depend on the severity of water stress and the specific sensitivity of the growth stage to deficit. Nut crops have three main growth stages:

- Early season: this stage is sensitive to water stress. During this period the following phonologic processes occur: vegetative growth, bud break, bloom, flowering and fruit set, establishment of fruit positions and development of carbohydrate reserves for future yields. Water deficit lead to reduced canopy growth, reduction of fruiting spurs and future yield which could be cumulative in the following years if water deficit persists. In consideration of these processes and crop physiological responses, partial irrigation should be avoided during this period.

- Fruit Growth and Development: again, this a sensitive period to water stress in most nut crops, and could be broken down in a three-stage process. The first stage corresponds to fruit growing in size, the second to embryo enlarging, whereas the third stage is characterized by increase in seeds' weight. Water deficit should be avoided during the first and third stages, whereas mild water stress could occur during the second stage with significant impacts on some nut crops.

- Postharvest: this is in general the more tolerant stage to water stress in most nuts crops, with the exception of almond. However, irrigation cannot be significantly reduced, as fruiting buds usually develop during this period.

The deficit irrigation strategy should be implemented considering the specific characteristics of each nut crop. Some considerations for implementing partial irrigation strategies in almond and pistachio are presented in the following sections.

2.1 Implementation of partial irrigation in almonds

Almond is a crop moderately tolerant to water stress (Fereres and Goldhamer 1990; Torrecillas *et al*. 1996). The impact on crop yield will be based on the magnitude of water stress and the specific growth stage when stress occurs. Significant water deficits in almond trees normally show their effects during the crop season when stress occurs, and also during a few following seasons even if when full irrigation is then applied.

Different stress management strategies can be implemented depending on the severity of water supply limitations, as suggested by the University of California drought management website (http://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Almonds/):

- Strategy 1: Moderate water stress

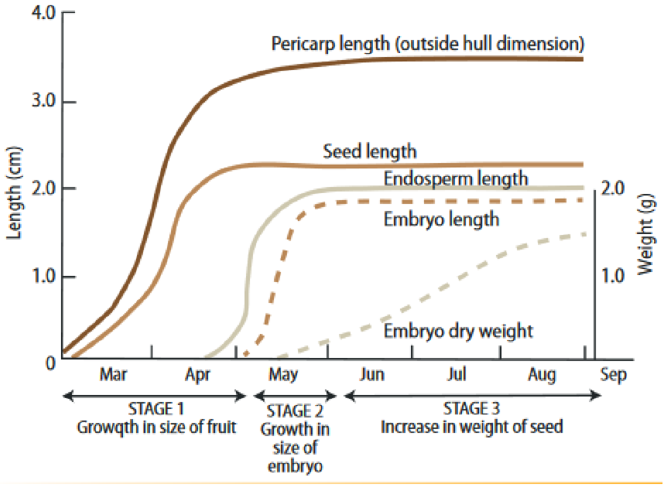
- Strategy 2: More severe water stress
- Strategy 3: “Staying Alive” Drought

Strategies 2 and 3 are options rarely used and should be avoided when possible. Severe water stress can adversely affect yield as a result of reduction of vegetative growth, and decrease of kernel size and fruit load. Following a deficit irrigation period, the normal yield is reached again after several years of full irrigation (Prichard et al. 1994). However, the best yield results are obtained when moderate water stress (Strategy 1) is applied.

The fruit and kernel development can be divided into three different stages (Figure 1):

- Stage 1. Fruit growth, seed and hull reach full size. Hull shell and integuments grow rapidly.
- Stage 2. Embryo (edible kernel) reaches full size. The fruit is subject to rapid expansion.
- Stage 3. Embryo loses moisture and dry weight increases. When hull, shell and kernel differentiation are complete, kernel begins to accumulate solids at a continuous rate until harvest.

Figure 1. Almond fruit development stages



Source: Micke, 1996

Water stress should be avoided during periods of active vegetative growth and during fruit development. Moderate water stress during the vegetative growth can reduce canopy growth and the future crop yield. This effect may not be as extensive in the year following water deficit but a prolonged water stress can have a cumulative effect in the consecutive years (Lampinen *et al*. 2007).

During the fruit growth periods (Stage 1 and stage 2), water deficit should be avoided, as it could increase nut drop and also result in smaller kernels. However, the right water stress during the stage 3 is challenging to define. Mild-to-moderate stress during the hull split period (stage 3) can have positive effects such as control of excessive vegetative growth, reduction of hull rot and improvement of the hull split. In contrast, excessive water application in this period can extend the duration of hull split period and thus delay harvest. In addition, severe stress post-hull split/pre-harvest could affect kernel quality as reported by Goldhamer and Viveros (2000) and thus should be avoided. Some studies demonstrated that moderate water stress after the onset of hull split had little or no impact on individual kernel dry weight (Torrecillas *et al.* 1989, Teviotdale *et al.* 2001, Shackel *et al.* 2004 and Goldhamer *et al.* 2006).

The post-harvest period is more sensitive to water stress than pre-harvest period. During this stage, fruit buds are developed and vulnerable to severe water stress with negative impacts on crop yield (Goldhamer & Holtz, 2009).

Doll and Shackel (2015) suggest two methods for managing deficit irrigation in almonds:

- Method 1: DI **at hull split.** In this case, deficit irrigation is applied only after kernel fill and until 90% hull split is achieved, and full irrigation is applied during all other stages. The most accurate method for scheduling irrigations is by assessing the tree water status by measuring mid-day stem water potential (SWP) with a pressure chamber along the crop season. Irrigation water is then applied when SWP reaches specific threshold values. Shackel *et al.* 2004 recommended applying water when trees reach SWP values of -14 to -18 bars. This strategy has the important benefit of reducing hull rot and improving the harvesting conditions, in terms of force and time required for shaking (Tetviotdale *et al.* 2001).
- Method 2: **Proportional DI.** Water is applied as a fixed fraction of ET_c using the ET-based irrigation scheduling method (see Chapter 2 of Rational Irrigation Report). As such, a water depth corresponding to a fraction of ET_c is applied at each irrigation event throughout the crop season

Goldhamer *et al.* (2006) studied different irrigation schedules during pre-harvest and post-harvest periods, and uniform deficit rates across the season over four years with moderate water stress (between 55 and 85 percent of ET_c). Results showed that the best strategy in terms of yield and yield components is obtained when a uniform deficit rate is applied throughout the season, relative to potential crop evapotranspiration. Yield is slightly reduced but this strategy minimizes the risk of larger yield reductions that may occur as a consequence of irrigation deficits during the most sensitive stages. In general, a moderate water stress strategy is recommended during the entire crop season, with water applications conducted at 85% of the ET_c, as shown in the example presented in Table 1.

Another approach entails scheduling irrigations based on plant water status, i.e. irrigating when the midday stem water potential measured by pressure chamber reaches pre-determined thresholds values indicating the occurrence of plant water stress.

In the context of the present project, DIL are used for weekly planning purposes, and the water status of almond trees at site 1 will be monitored using SWP measurements, thus enabling the grower to tailor the partial irrigation schedule and manage risks.

In both strategies, irrigation schedules must also account for the average application efficiency achieved by the selected irrigation system (e.g., drip). One example is described in section 5.

Table 1: Example of Deficit Irrigation Levels (DIL) for almonds using Proportional Deficit Irrigation (DI), and Hull Split Deficit Irrigation. The deficit levels are expressed as percentage of potential crop ET (ET_c).

Periods	DIL (%) for Proportional DI	DIL (%) for Hull Split DI
Mar 1-15	85	100
Mar 16-31	85	100
Apr 1-15	85	100
Apr 16-30	85	100
May 1-15	85	100
May 16-31	85	100
Jun 1-15	85	50
Jun 16-30	85	50
Jul 1-15	85	50
Jul 16-31	85	50
Aug 1-15	85	100
Aug 16-31	85	100
Sep 1-15	85	100
Sep 16-30	85	50
Oct 1-15	85	0
Oct 16-31	85	0
Nov 1-15	85	0

Source: Goldhamer *et al.* (2006)

In practice, almond growers must deal with other factors that should be considered in reducing water (Doll and Shackel, 2015). In the context of the present project, the grower selected Hull Split DI to control disease outbreak and simplify field activities before harvest. The grower will also differentiate irrigation by variety before harvest. Three or four varieties of almond trees within one field are not uncommon, and the trees are set in a particular pattern to optimize pollination. While reducing irrigation at a particular time might not stress a tree of one variety, it could have adverse effects on another variety. Proportional DI strategy may minimize this problem by applying water deficit evenly across the season.

2.2 Implementation of Partial Irrigation in pistachios

Pistachio is an extremely drought-tolerant species (Spiegel-Roy *et al.,* 1977, Goldhamer *et al* 1983). DI strategies can be followed during drought periods to save water, and in normal years to optimize water usage and reduce production costs. However, drought tolerance does not necessarily mean that pistachio trees can produce well with little water. The impacts of deficit irrigation depend on the crop growth stage when water limitations occur.

Goldhamer *et al*. (1983, 1984, 1985, 2004 and 2005) conducted research studies on deficit irrigation of pistachio in California. Results showed that deficit irrigation cannot be applied for the entire crop season and reduced water applications should be conducted only during stress-tolerant periods. Four pistachio growth stages were identified and classified based on tolerance to waters stress:

- Stage 1: boom, leaf out and shell expansion
- Stage 2: shell hardening
- Stage 3: nut filling, shell split and hull split

Water shortages should not occur during Stages 1 and 3. However, partial irrigation can be implemented during Stage 2 and during post-harvest periods, which will minimize negative impacts on fruit yield or quality. Partial irrigation scheduling in these stages can be implemented by applying a fixed fraction of ET_c using the ET-based irrigation scheduling method (see section 2 of Rational Irrigation Schedule report).

Various levels of water stress on stress-tolerant periods were evaluated. Results showed that during Stage 1, water stress slightly increases shell splitting but reduces the nut size at harvest. However, Phene *et al.* 1987 found that water applications at 50% of ET_c during Stage 2 had no effect on yield. Also, deficit irrigation during Stage 2 reduces fungal disease. The percentage of reduction relative to ET_c depends on the soil type. Shallow soils retain less water and have a smaller moisture zone, so irrigation at 50% of ET_c could be considered. In soils with deeper root zones and greater water-holding capacity irrigation could be reduced at 25% of ET_c during Stage 2, without causing significant yield impacts on yield. In orchards characterized by heterogeneous soils deficit irrigation strategies should be very carefully evaluated prior to implementation.

A sound deficit irrigation strategy can reduce water usage with only mild impacts on crop yield during the current and following crop seasons. Goldhamer (2005) recommended a conservative deficit irrigation strategy where during Stage 1 and Stage 3 the pistachio trees should be fully irrigated at ETc, whereas during Stage 2 (from mid-May to early July) water should be applied at 50% of ET_c. During the post-harvest period, irrigation can be applied at 25% of ET_c. Table 2 reports an example of the above-described conservative deficit irrigation strategy.

Table 2: Pistachio Deficit Irrigation Level (DIL) for pistachio trees. They are expressed at percentages of potential crop ET (ET_c).

Period	Growth Stage	Deficit Irrigation Level (%)
Apr 1-15	Stage 1	100
Apr 16-30		100
May 1-15		100
May 16-31	Stage 2	50
Jun 1-15		50
Jun 16-30		50
Jul 1-15	Stage 3	100
Jul 16-31		100
Aug 1-15		100
Aug 16-31		100
Sep 1-15		100
Sep 16-30	Stage 4	25
Oct 1-15		25
Oct 16-31		25
Nov 1-15		25

Source: Goldhamer (2005).

Zaccaria and Sanden (unpublished data, 2015) compared actual evapotranspiration (ET_a) of pistachio measured by the residual of energy balance method through a combination of surface renewal and eddy covariance equipment in three mature well-watered pistachio orchards in the San Joaquin Valley during 2015. The ET_a values were compared with ET_c, of mature pistachio estimated using reference evapotranspiration (ET_o) from CIMIS network and the crop coefficient (K_c) recommended by Goldhamer (2005). The comparison showed that ET_c estimated using ET_o and K_c was greater than ET_a thus highlighting the importance to evaluate the relation between ET_a and ET_c prior to defining the fraction of ET_c to be applied when following a partial irrigation schedule. The project is funded by the California Department of Food and Agriculture and the Pistachio Research Board.

Within the present project, commercial stations for estimating ET_a have been installed at site 2 in control and treatment pistachio orchards to tailor the partial irrigation schedule based on the comparison between ET_a and ET_c.

At site 1, partial irrigation schedules will be tailored on the basis of SWP measurements.

3. Partial irrigation scheduling in processing tomato

In California processing tomato fields are mainly irrigated using subsurface drip irrigation (SDI) (63%), although furrow irrigation (33%) remains in some areas (Tindula *et al.* 2013). ET-based irrigation scheduling is one of the methods commonly used to estimate the amount of water to apply with SDI systems. Under normal conditions, full irrigation is conducted throughout the entire crop season to maximize crop production. Research shows that tomatoes under SDI should be irrigated with small and frequent water applications, and that the irrigation depth and frequency depends mainly on the soil type.

DI strategy can be implemented without incurring in significant yield losses when tomato fields are irrigated with SDI systems. Tomatoes are sensitive to water stress especially during fruit set, when moderate and severe levels of water deficit can significantly reduce the yield. However, after fruit set, a reduction in irrigation can be implemented with minimal impact on crop production.

Two alternative deficit irrigation strategies are usually recommended:

- Strategy 1: full irrigation during the first part of the crop season followed by little or no irrigation for the remaining part of the season.
- Strategy 2: implementation of deficit irrigation during the entire crop season by applying a specific fraction of the water needed for achieving the maximum yield.

There is some uncertainty in predicting which deficit irrigation strategy may result in the greatest yield reduction. Strategy 2 probably reduces the yield more than Strategy 1 under similar field conditions. Also, reductions in irrigation rates during certain specific stages of the crop season (Strategy 1) can have a significant effect on fruit quality (Johnstone et al. 2005; Patane and Cosenrino, 2010; Patane *et al*., 2011 and Faveti *et al*. 2009) in term of total solids and soluble solids. However, both these strategies may result in some water savings per unit of cropped area and in some increases in water productivity

The water stress levels to be adopted depend on different aspects, but mainly on soil water holding capacity and the presence of shallow water table. Different research trials were conducted in controlled research plots and in commercial tomato fields with interesting results, which are summarized in the drought management website of the University of California (UC) (http://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Processing_Tomatoes/).

Different fractions of tomato ET_c were applied during the 60 days before harvest in processing tomatoes grown on two different soil types. The results showed that at 50% of ET_c, the yields were slightly higher than 90% of the yield from fully irrigated tomatoes grown on clay-loam soil. However, yield reductions may be greater in a sandy loam soil when less than 75% of ET_c is applied. The recommended conservative deficit irrigation strategy is illustrated in Table 3 below. Specifically, during early season irrigation events aim at fully matching the crop water requirements so that no water stress will occur during the vegetative growth stage. Irrigation cutback may start about 6 weeks before harvest, with water applications at 75% of ET_c.

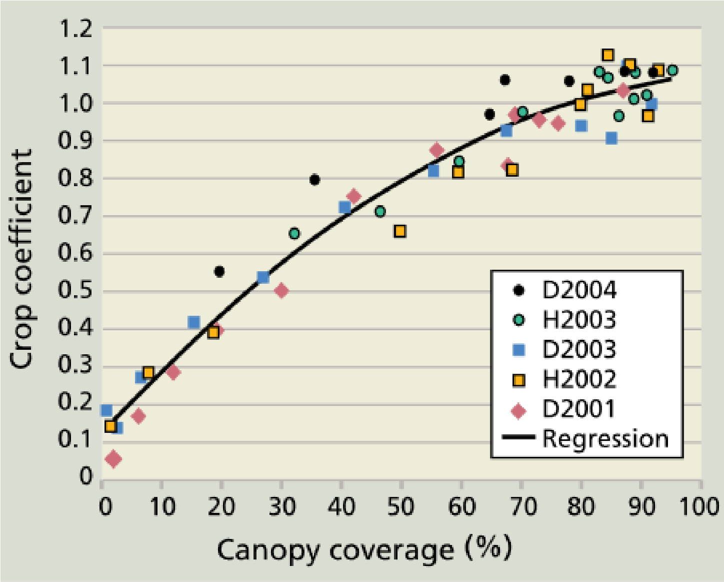
Table 3: Proposed Deficit Irrigation levels (DIL) for processing tomatoes. Levels are expressed as percentages of potential crop ET (ET_c) that correspond to fully watered tomato plants.

Period	DIL (%)
May 1-15	100
May 16-31	100
Jun 1-15	100
Jun 16-30	100
Jul 1-15	100
Jul 16-31	75
Aug 1-15	75
Aug 16-31	75

ET_c is commonly estimated by multiplying the reference evapotranspiration (ET_o) by the appropriate crop coefficient (K_c). ET_o is estimated using meteorological data and the K_c varies with the crop growth stage. Results from recent research studies (Hanson and May, 2006) showed that Kc can be estimated based on the canopy size (fractional canopy cover) (Figure 2).

However, in the context of the present project, commercial ET stations have been installed at the tomato fields (sites 3 and 4) to estimate ET_a on a daily basis based on field-specific conditions (local weather, crop management practices and other environmental factors).

Figure 2. Relation between average crop coefficient and canopy coverage.



Source: Hanson and May (2006).

4. Partial irrigation scheduling in alfalfa

Alfalfa is relatively drought tolerant and offers some degree of adaptability to water stress. DI strategies can be adopted, but the impact should be carefully evaluated. Impacts of water stress on alfalfa depend on several aspects like soil characteristic (texture, depth, salinity), weather conditions, timing and duration of water deficits, and on the crop variety. However, any DI strategy will adversely impact the alfalfa yield relative to that resulting from full irrigation.

There are two main DI strategies that can followed at the selected alfalfa fields:

- Strategy 1: Starvation Diet. DI is applied during each growth period. Two different options can be implemented: reduce the number of irrigations between cuttings (flood and sprinkler irrigation) or reduce the amount of water applied per irrigation (sprinkler or drip irrigation).
- Strategy 2: Partial-Season irrigation. During the early-season cuttings, fully irrigate the crop and then apply deficit irrigation towards the summer when the alfalfa ET demand is high.

Strategy 1 reduces the yield at each crop cycle throughout the season. However, when Strategy 2 is applied, important benefits are achieved in term of alfalfa yield and quality. The highest yields are usually obtained from the first cuttings in the spring and early summer (Orloff *et al.*, 20014). Production is reduced during the last crop cycles that can produce about 25% of the total annual production. The deep root system of alfalfa allows access to deep soil moisture and water uptake from deep soil layers, especially during the necessary dry-down periods (irrigation cutoffs) before and after the cuttings.

There are regional differences in what irrigation strategy works best for alfalfa. In the intermountain areas, a large portion of the total annual production of alfalfa (around 75%) is obtained by mid-July (Orloff *et al.*, 2014). Thus in these areas, the best partial irrigation strategy could be to irrigate until the 2nd cutting and then stop irrigations during the rest of the crop season. In contrast, studies in the Sacramento Valley showed that early summer cut-off (July) of irrigation followed by fall irrigation could save water and minimize alfalfa yield losses (Hanson *et al*. 2007).

In addition, alfalfa quality is higher in spring, which contributes to a higher market price for hay during this period. Thus it is not advisable to reduce water applications in spring since it may significantly impact yield, quality and net profit during this specific time. In summary, Strategy 2 is recommended for minimizing reductions of farmers' profit.

For the purpose of the present project, DI using starvation diet will not be applied at the selected alfalfa field (site 5) because of practical matters. The first starvation diet option, which is to reduce the number of irrigation between cuttings, could not be pragmatic since only one irrigation event per cycle is applied. In addition, applying less water during each cycle is not an option in this project because will result in low yields at each cut. Also, surface irrigation relies on water supplied by irrigation districts by gravity where water has little to no energy foot-print and thus represents the most energy efficient solution.

Water and energy saving on these fields could be achieved by optimizing surface irrigation management using Rational Irrigation Schedules based on site-specific field characteristics, soil infiltration parameters, and proper cut-off times.

5. Example of calculations for partial irrigation schedule for demonstration field (site 3).

Partial irrigation scheduling for almonds, pistachios, processing tomatoes and alfalfa will be based on the combination of ET-based irrigation scheduling and soil moisture monitoring methods. The sequence of steps to define the irrigation schedule is similar to that indicated in the report on Rational Irrigation Scheduling s (Heading 5.2.2.) with some additional considerations.

The calculation of partial irrigation scheduling for one day in a commercial field is shown in the following example:

Assume:

- Location: Davis
- Crop: Processing tomatoes
- Area: 8 acres
- Date of transplant: April 22, 2016
- Day of the year (DOI) for the calculation: July 20, 2016^{h}
- Depth of root zone 90 days after transplanting: 4 feet
- Irrigation method: SDI
- Irrigation system characteristics: Obtained from a manufaturer's catalog and onsite measurement:
    - Flow rate: 0.16 gph
    - Drip tape lateral spacing: 60 in
    - Emitter spacing: 14 in
    - Flow rate of lateral: 0.23 gpm/100 ft
    - Irrigation system application efficiency: 85 % (Table 4)

Table 4. Potential Application Efficiencies of well-designed and well-managed irrigation systems

Irrigation system	Potential EffA (%)
Sprinkler Irrigation Systems	
LEPA	80-90
Linear move	75-85
Center pivot	75-90
Traveling gun	65-75

Side-roll	65-85
Hand-move	65-85
Solid-set	70-85
Surface Irrigation Systems	
Furrow (conventional)	45-65
Furrow (surge)	55-75
Furrow (with tailwater reuse)	60-80
Basin	60-75
Precision level basin	65-80
Microirrigation Systems	
Bubbler (low head)	80-90
Microspray	85-90
Micro-point source	85-90
Micro-line source	85-90
Surface drip	85-95
Subsurface drip	> 95

Source: Adapted from Howell (2003)

- Soil characteristics: Measure or obtained from NRSC web soil survey
    - Clay loam soil type
    - Soil Water Holding Capacity: 1.2 inches of water per foot of soil
- Tension soil moisture
    - Tension: 95 centibars
- Weather data: daily rainfall from CIMIS.
    - Rainfall: 0 in
- Local management practices:
    - MAD: 50 %
- ET_a from the commercial ET station
    - 1 day since last irrigation event: 0.27 in

- Irrigation strategy: Partial irrigation. Example of deficit irrigation level is 75% of ET_c during this day (Table 3).

  Note: In this example it is assumed that the field is well watered and therefore ET_a corresponds to ET_c, thus we can apply a deficit irrigation level of 75% of ET_a.

Calculations:

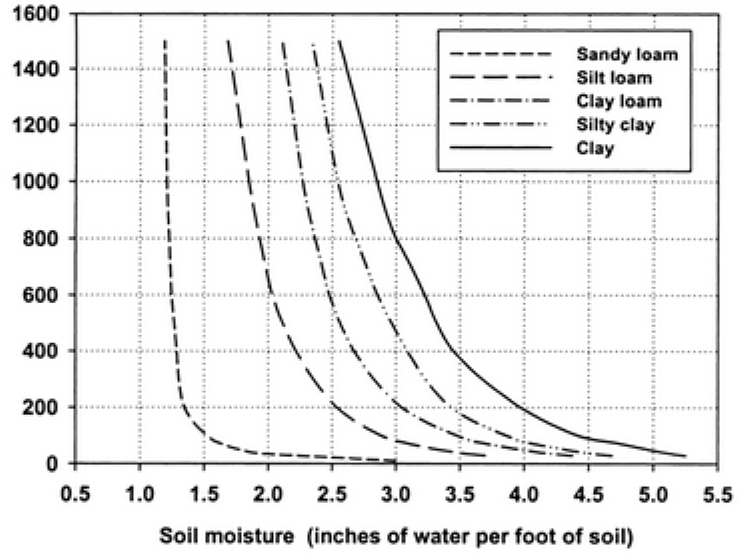
a) *When to start irrigation?*

   Soil moisture tension = 95 centibar. Start irrigation (on clay soil irrigation should start when soil moisture tension reaches 90-100 centibars, Table 5).

Table 5. Recommended values of soil moisture tension at which irrigation should occur (50% MAD)

Soil Type	**Soil Moisture Tension (centibars)**
Sand or loamy sand	40-50
Sandy loam	50-70
Loam	60-90
Clay loam or clay	90-120

Figure 3. Relationship of soil moisture tension for different soil textures



Source: Ley et al. (1996)

b) How much water to apply?

The applied water should be similar to the amount of water used by the crop since the last irrigation and or rain event.

1. Effective precipitation (Pe): 0 in

2. Net irrigation depth (I_n).

   $$I_n = ET_a - P_e$$

   I_n = (0.27 in * (0.75)) – 0 in = 0.2 in (Partial Irrigation 75%, Table 3).

   $I_n < I_{max}$

3. Gross irrigation depth $I_g = \frac{I_n}{AE}$

   I_g = 0.2 in / (0.85) = 0.24 in

4. Volume of water to apply

   $$V_W = I_g \cdot A$$

   Vw = 0.24 in * 8 ac = 1.92 ac-in

   Vw = 1.92 ac-in * 27,154 gallons/ac-in = 52,135.7 gallons

5. Irrigation Set time

   $$I_T = \frac{I_g \cdot L_s}{q \cdot 11.55}$$

   I_T = 0.24 in * 60 in / (0.23 gpm/100 feet * 11.55) = 5.42 hours.

GLOSSARY

Term	**Definition**
CEC	California Energy Commission
DI	Deficit Irrigation
DIL	Deficit Irrigation Levels
ET	Evapotranspiration
ET_0	Reference evapotranspiration
ET_a	Actual crop evapotranspiration
ET_c	Potential crop evapotranspiration
K_c	Crop coefficient
SDI	Sub-surface Drip Irrigation
UC	University of California

REFERENCES

Doll, D. and Shackel, K. 2015. Drought Management for California Almonds. Impacts of Stress on Almond Growth and Yield. Pub. 8515. UCANR Publications.

Farré, I., & Faci, J. M. 2006. Comparative response of maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench) to deficit irrigation in a Mediterranean environment. Agricultural Water Management, 83(1), 135-143.

Favati F., Lovelli S., Galgano F., Miccolis V., Di Tommaso T., Candido V. 2009. Processing tomato quality as affected by irrigation scheduling Sci. Hortic., 122 , pp. 562 ‑ 571

Fereres E., Goldhamer D.A. (1990) Deciduous fruit and nut trees. In: Stewart BA, Nielsen DR (eds) Irrigation of agricultural crops Mon.#30. American Society of Agronomy, Madison WI, pp 987–1017

Fereres, E., & Soriano, M. A. 2007. Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany, 58(2), 147-159.

Girona, J., Mata, M., Goldhamer, D. A., Johnson, R. S., & DeJong, T. M. (1993). Patterns of soil and tree water status and leaf functioning during regulated deficit irrigation scheduling in peach. Journal of the American Society for Horticultural Science, 118(5), 580-586.

Goldhamer, D.A., Beede, R., Moore, J.M., Weinberger, G. and Menezes, J., Jr. 1983. Water use requirements and physiological response to water stress in pistachio. Annual report of the California Pistachio Commission, Crop Year 1982 - 1983, pgs. 53-57.

Goldhamer, D.A., Kjelgren, R., Beede, R., Moore, J.M., Menezes, J., Jr., and Weinberger, G. 1984. Physiological response of pistachio to severe water stress. Annual report of the California Pistachio Commission, Crop Year 1983 - 1984, pgs. 44-47.

Goldhamer, D.A., Kjelgren, R., Beede, R., Williams, L., Moore, M.J., Lane, J., Weinberger, G. and J. Menezes, 1985. Water use requirements of pistachio trees and response to water stress. Annual report of the California Pistachio Commission, Crop Year 1984 - 1985, pgs. 85-92.

Goldhamer, D.A and B. H. Beede. 2004. Regulated deficit irrigation effects on yield, nut quality and water-use efficiency of mature pistachio trees. Journal of Horticultural Science & Biotechnology 79 (4) 538-545.

Goldhamer, D.A. 2005. “Irrigation Management” in University of California Pistachio Production Manual. Edited by L. Ferguson. pgs. 103-116.

Goldhamer DA, Viveros M, Salinas M. 2006. Regulated deficit irrigation in almonds: Effects of variations in applied water and stress timing on yield and yield components. Irrigation Science 24(2):101–14

Goldhamer, DA and Holtz, B. 2009. Rational Early Season Drought Planning for Almond Growers. The Pomology Post. Madera County. Vol 59, March, 2009

Goodwin, I., & Boland, A. M. 2002. Scheduling deficit irrigation of fruit trees for optimizing water use efficiency. In Deficit Irrigation Practices.

Hanson, B., Bowers, W., Davidoff, B. 1995. Field performance of microirrigation systems. In: Microirrigation for a Changing World, Proceedings of Fifth International Microirrigation Congress, April 2–6, 1995. American Society of Agricultural Engineers, Orlando, FL, pp. 769–774

Hanson, B., and May D.M. 2006. New crop coefficients developed for high-yield processing tomatoes. http://CaliforniaAgriculture.ucop.edu. April-June.

Hanson, B., Putnam, D. and Snyder, R. 2007. Deficit irrigation of alfalfa as a strategy for providing water for water-short areas. Agricultural Water Management 93, 73-80.

Howell, T.A. 2003. Irrigation efficiency. Encyclopedia of Water Science (Web pages 467–472). http://www.cprl.ars.usda.gov/pdfs/Howell-Irrig%20Efficiency-Ency%20Water%20Sci.pdf

Johnstone, P. R., Hartz, T. K., LeStrange, M., Nunez, J. J., & Miyao, E. M. 2005. Managing fruit soluble solids with late-season deficit irrigation in drip-irrigated processing tomato production. HortScience, 40(6), 1857-1861.

Kang, S., Shi, W., & Zhang, J. 2000. An improved water-use efficiency for maize grown under regulated deficit irrigation. Field Crops Research, 67(3), 207-214.

Lampinen, B., T. Dejong, s. Weinbaum, S. Metcalf, C. Negron, M. Viveros, J. Mc Ilvane, N. Ravid, and B. Baker. 2007. Spur dinamics and almond productivity. Modesto: 2007-2008 Annual Management Website (ucmanagedrought.ucdavis.edu)

Ley, T., R. G. Stevens, R.R. Topielec and W. H. Neibling. 1996. Soil water monitoring and measurement. Washington State University Cooperative Extension; the Oregon State University Extension Service; and the University of Idaho Cooperative Extension System. Pacific Northwest Extension Publication 475.

McCarthy, M. G., Loveys, B. R., Dry, P. R., & Stoll, M. 2002. Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines. In Deficit Irrigation Practices.

Orloff, S., Bali, K. and Putnam, D. 2014. Deficit irrigation of alfalfa and grasses: What are the impacts/options? Proceedings, 2014 California Alfalfa, Forage, and Grain Symposium, Long Beach, CA, 10-12 December, 2014. UC Cooperative Extension, Plant Sciences Department, University of California, Davis, CA 95616.

Patanè, C., Cosentino, S.L. 2010. Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. Agricultural Water Management, 97, pp. 131 – 138

Patanè, C., Tringali, S., & Sortino, O. 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. Scientia Horticulturae, 129(4), 590-596.

Phene, B. C., Goldhamer, D. A., Menezes, J., Beede, R., Weinberger, G. and Cervantes, Z. 1987. Response of Pistachio Trees to Three Consecutive Years of Irrigation Cut-off. In Annual Report, Crop Year 1986–1987.

Prichard, T., W. Asai, P. Verdegaal, W. Micke, and B. Teviotdale. 1994. Effects of water supply and irrigation strategies on almonds. Modesto: Almond Board of California. Comprehensive Project Report 1993–94.

Shackel, K., R. Buchner, J. Connell, J. Edstrom, A. Fulton, B. Holtz, B. Lampinen, W. Reil, and M. Viveros. 2004. Final Report: Deficit Irrigation Management During Hull Split. Modesto: Final Report to The Almond Board of California

Spiegel-Roy, P., Mazigh, D., Evenari M. 1977. Response of pistachio to low soil moisture conditions Journal American Society of Horticultural Science, 102, pp. 470–473

Tindula, G. N., Orang, M.N. and Snyder R.L. 2013. Survey of Irrigation Methods in California in 2010. J. Irrig. Drain Eng. 139 : 233-238.

Torrecillas A., Alarcon J.J., Domingo R., Planes J., Sanchez-Blanco M.J. 1996. Strategies for drought resistance in leaves of two almond cultivars. Plant Science 118:135–143

Micke, W. C. 1996. *Almond Production Manual* (Vol. 3364). UCANR Publications.

http://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Almonds/

http://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Pistachios/

http://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Processing_Tomatoes/

http://ucmanagedrought.ucdavis.edu/Agriculture/Crop_Irrigation_Strategies/Alfalfa/