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Opportunities for Electricity Demand Management in Irrigated Agriculture

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Disclaimer

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Table of Contents

List of Figures

Introduction

Integrating the agricultural sector into energy demand management incentive programs requires a decision support system for irrigation management – tools to more precisely plan and track water and energy use across the growing season. Balancing on-farm irrigation and energy needs with a dynamic electricity grid is becoming increasingly important to energy users, energy producers and California's energy infrastructure. For irrigators, this means balancing crop water demand during the season against the cost and timing of energy use.

This report will outline linkages between irrigation energy demand and the operational imperatives of the electricity grid. It discusses economic opportunities for on-farm energy conservation and electric load shifting and challenges of demand management programs, including: (i) timing of pumping energy use to take advantage of utility Time of Use (TOU) rates; and (ii) responding to Demand Response (DR) events, specifically farms with limited system capacity. This report will also present an overview of an irrigation planning and management tool designed to facilitate participation in demand management programs.

Evolution of the California Grid

California's electricity system is undergoing unprecedented change. California's current goals call for meeting 50% of the state's retail electricity sales with renewable energy by 2030 and reducing greenhouse gas (GHG) emissions to 40% below 1990 levels by 2030 (CARB, 2016). A 50% renewable electricity system in California will have a high penetration of variable solar and wind generation. Fluctuations and uncertainty of variable generation will make the operation of an already complex electricity system even more complicated. One way to offset the unpredictability of renewable resources is through DR programs, by which end users are induced to change their electric demand to match the supply. Historically, DR resources have been used to reduce the system level peaks (e.g. hot summer days). As California moves closer to its target of 50% renewables, traditional DR can provide local reliability, but more importantly faster time scale DR services (also referred to as Ancillary Services) will be more important for facilitating the intermittency of renewable generation.

With higher penetration of intermittent renewable sources, the grid needs to deal with generation variability. Intra-hour variability and short-duration ramps are one of the immediate challenges faced by a 50% renewable grid. However, other challenges arise as the California grid decarbonizes over time. Historically peak hours were defined as the hours between 12pm-6pm (PG&E, 2016). Proliferation of solar generation in California (especially rooftop solar) is forcing those peak hours to shift to later hours in the day (4pm-9pm)[1]. This is most commonly referred to as the "Duck Curve" (Figure 1), where

[1] Although there are no updates to agricultural customer TOU periods, PG&E has announced new residential and commercial TOU rates with 3pm-8pm and 4pm-9pm as new peak hours.

the increased solar generation is significantly dropping the net electricity demand during the day, which in turn results in significant ramps in the later hours (CAISO, 2016).

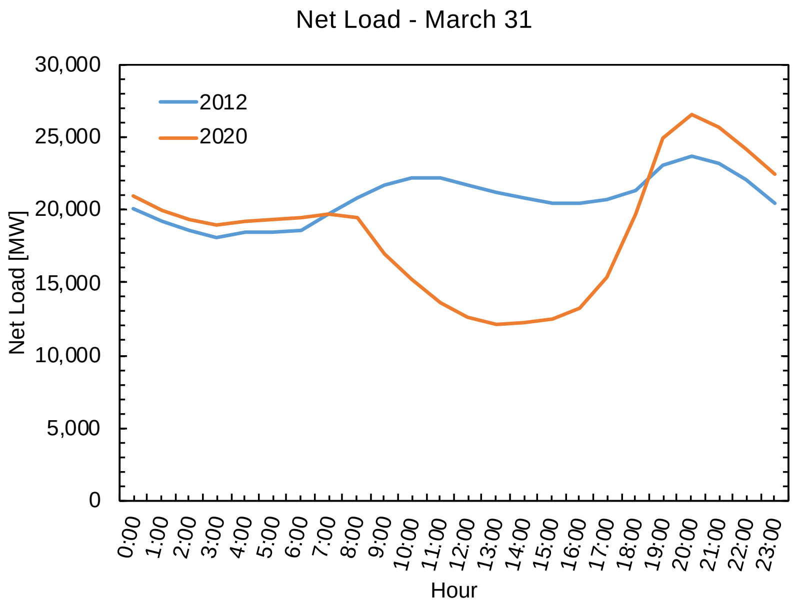

Figure 1: The duck curve shows steep ramping needs and over-generation risk (CAISO 2016)

The Duck Curve might be better explained by looking at the generation mix of California's grid under a 50% renewable portfolio standard (RPS) shown in Figure 2. In a 50% RPS scenario, thermal power plants will ramp down as solar resources come online early in the day (1). However, thermal powerplants cannot drop to zero since a minimum spinning capacity is needed for contingency as well as the evening ramp up. Therefore, in the absence of cheap energy storage, excess renewable generation must be curtailed in to maintain grid stability (2). Curtailment refers to the practice of disconnecting solar or wind generators from the grid during periods of low demand to avoid overwhelming the grid. As solar resources stop generating electricity in the evening (3), thermal power plants (mostly natural gas) need to ramp up to make up for the lost solar generation, and the evening ramp up will become more pronounced as increasing renewable (especially solar) penetration continues to drive down the net load (4).

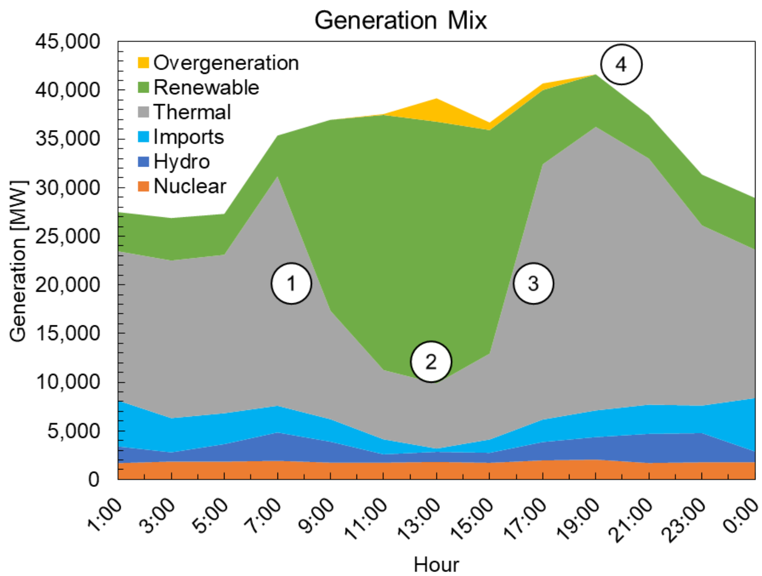

Figure 2: California grid under 50% RPS (E3 2014)

Agricultural Irrigation and the California Grid

Agricultural irrigation pumping is a significant component of California's electric demand and a resource that can provide DR services to the grid and contribute to its stability. In addition, distribution feeders that serve agricultural customers often have low diversity in their types of customer loads, and exercise of a large number of irrigation pumps on a single feeder can cause over-voltage issues (Olsen 2015). Over-voltage incidents can result in significant damages to equipment (variable frequency drives in particular) and disrupt normal operations for extended periods. Therefore, demand management of agricultural loads is not only beneficial to the grid, but it also makes farming operations more resilient.

In 2016, the peak demand of the California's electricity grid was 46 GW (CAISO 2016). In the same year, the peak demand for agricultural irrigation pumping was 1.3 GW (3% of California's total peak electricity demand) (CAISO 2016). As of 2015, California Investor Owned Utilities' (IOUs) total DR portfolio was 2.1 GW (Alstone, et al., 2016). Theoretically, 62% of the current IOU DR portfolio can be satisfied through agricultural irrigation DR alone.

Agricultural irrigation can help address several challenges highlighted in Figure 2. As shown in Figure 3, agricultural load is highly concentrated in the summer months, coincident with the peak demand of the grid as a whole. In addition, highest daily demand for agricultural irrigation occurs during hours with highest levels of evapotranspiration, which are coincident with highest levels of solar electricity generation.

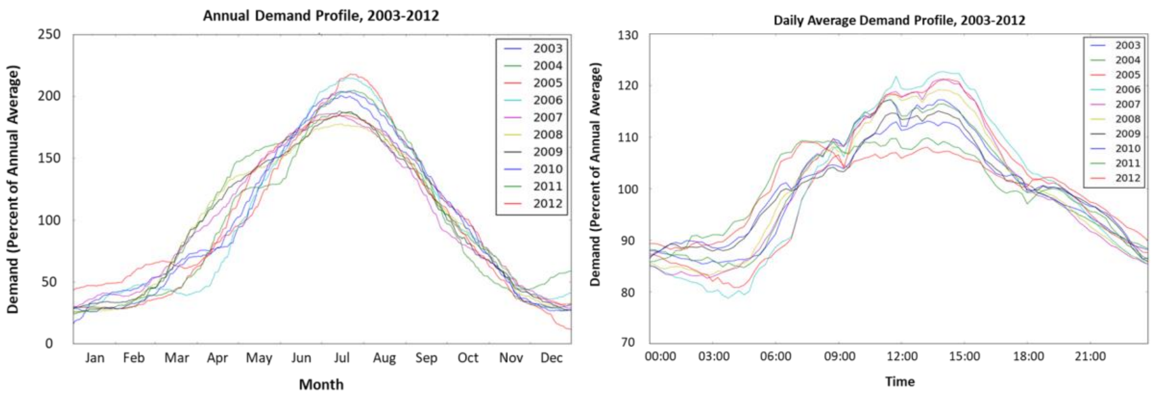

Figure 3: Estimated daily demand for a subset of PG&E agricultural customers, relative to daily average, 2003-12 (Left), and average daily demand profiles for interval meters, 2003-12 (right)

Solar curtailment, whereby solar generators are disconnected from the grid to protect the grid from being overwhelmed, occurs between the hours of 12-6 PM, hours of peak irrigation demand. A flexible and dynamic irrigation system can take excess load off the grid by over-irrigating during certain hours of the day (and less in other hours) in order to facilitate higher levels of solar integration into the grid and eliminate solar curtailment. In the absence of cost effective battery storage, irrigation pumping can be a valuable resource for balancing the electricity grid.

Current State of Agricultural Demand Response

Time of Use (TOU) pricing is a cost effective option for modifying load shapes because there are minimal, if any, site-level technology enablement costs. And while the load reduction at any given site is typically small, the breadth of participation if the rates are default or mandatory provides a substantial statewide effect. TOU can contribute substantially to overall DR potential. The impacts of TOU pricing on agricultural accounts is clearly distinguishable in average daily demand profiles of agricultural accounts recorded by Pacific Gas and Electric’s SmartMeters as shown in Figure 4. Mandatory TOU rates were introduced in 2009 and over 75 percent of firms faced their first month of mandatory TOU pricing in the summer of 2010 (Jessoe, et al., 2013). Therefore, the impact of TOU rates become apparent in years post 2010 in Figure 4. The time period highlighted in yellow, indicates the summer peak hours of 12:00PM to 6:00PM.

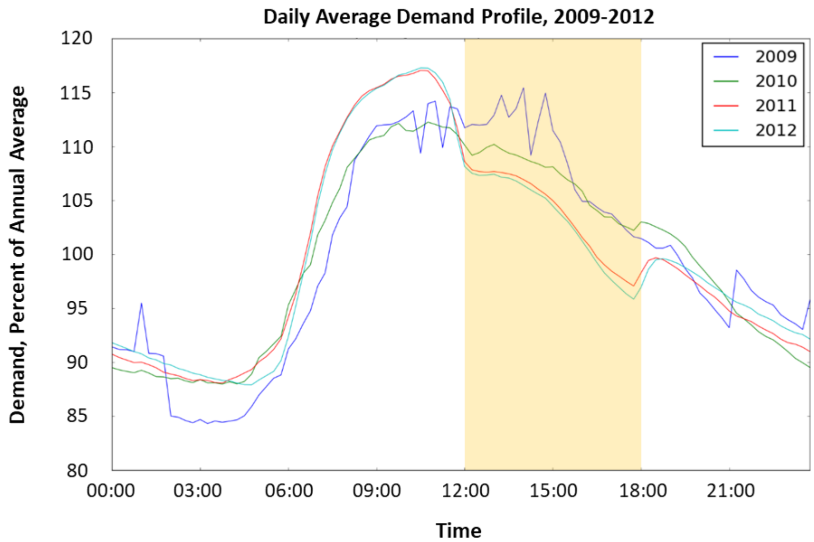

Figure 4: Average daily SmartMeters demand profiles, 2009-2012

In addition to TOU, several utilities offer various DR programs tailored toward agricultural irrigation customers with a combined load shed magnitude of 0.7 GW dating back to 2004. Although largely successful, challenges faced by agricultural DR programs include unreliable shed rates (35%-85% relative to baseline load) and low participation rates (20%) (Olsen 2015).

Most agricultural irrigation systems operate in a manual or semi-automated fashion which require long notification periods in order to participate in DR programs. This along with challenges such as lack of communications, manual controls, and farm operational limitations (irrigation capacity, water delivery schedules, and labor) has led to a low participation in DR programs by agricultural customers (Olsen 2015).

Currently agricultural irrigation pumping can only participate in traditional DR programs offered through utilities (also referred to as demand side DR). In the near future, fast responding DR services that can participate directly into the electricity markets will become more valuable (Alstone, et al., 2016). Automated DR (Auto-DR or ADR), another DR strategy in which loads are shed automatically in response to grid control signals unless the customer opts-out, allows quicker, more reliable load shedding with less effort required by grid operators and growers alike. ADR has the potential to be used for ancillary services, which are growing in importance due to the load uncertainty and variability caused by the integration of large shares of renewables (Watson et al. 2012). Such services are referred to as supply side DR. In order to provide supply side DR to the grid, loads should directly interact with the California Independent System Operator (CAISO). Besides limited pilot programs such as Demand Response Auction Mechanism (DRAM), there are currently no other mechanisms in place that allows pumping loads to directly provide supply side DR, so agricultural customers can only provide resources to the grid by enrolling in a TOU, DR, or ADR program offered by their local utility or through a third party aggregator.

Examples of TOU and DR from Cooperating Farms

The examples presented below illuminate the nature of the demand management challenges from the irrigators' perspective. This limited overview of demand management for irrigated agriculture in the San Joaquin Valley illustrates the management decisions that must be made. The following examples are based on an actual almond farm located in Turlock, California. The 92 acre farm is supplied by one groundwater pump. The farm received 38.4 inches of water, plus 4 inches of rainfall in 2017. In all the following examples, irrigation schedules are modified so that the water requirement of 38.4 inches is satisfied.

Example 1: Irrigation Scheduling with TOU Considerations

The first case involves shifting time of use for a 92 acre almond orchard with ample delivery system capacity, a readily available water supply (The ranch sits along the Delta-Mendota canal). The orchard is irrigated in three sets. Most irrigation events were 24 hours or more, so most irrigation events span three days. The actual sequence of irrigation dates and durations in 2017 is indicated by the histogram in Figure 5. The wide spacing between irrigation events indicates ample irrigation system capacity, allowing the farm to easily shift irrigation dates and durations. This represents an ideal opportunity for energy load shifting. It is simple to plan and implement, and presents a clear financial benefit. Energy rates for the farm are $0.195 per kWh for off peak hours and $0.445 per kWh for 8 peak hours daily. An alternative schedule, indicated in Figure 6, would restrict irrigations to the 16 off-peak hours each day.

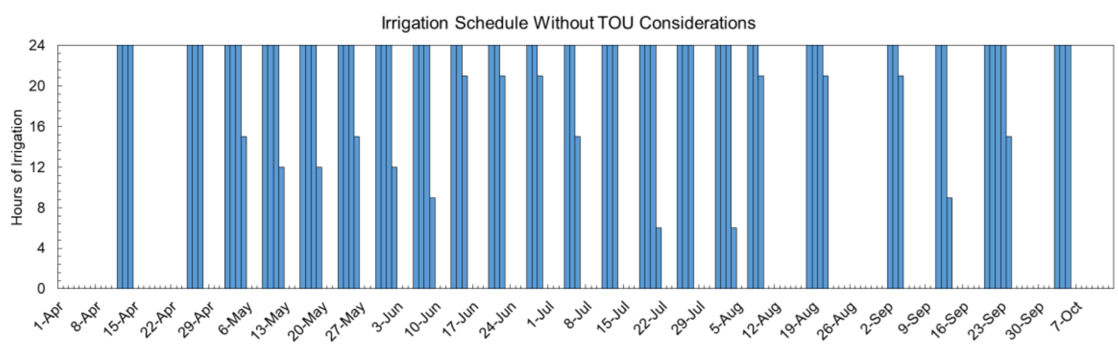

Figure 5: Actual sequence of irrigation events (without TOU)

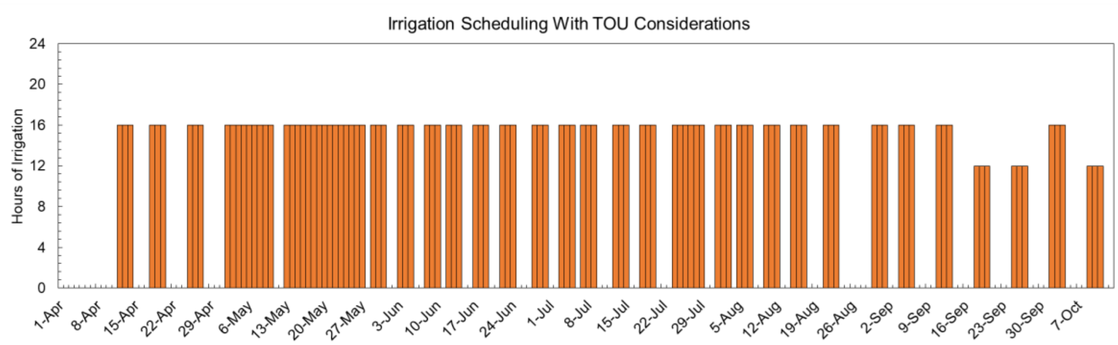

Figure 6: Alternative time of use (TOU) management

The alternative schedule would have achieved virtually the same seasonal pattern of crop water availability (total inches of water applied to the fields) as the actual schedule (Figure 5). Estimated pumping energy use in 2017 was 75 kW for 1908 hours, a total of 143 MWh. Pumping costs would then be $39,681 for the actual schedule (Figure 5) and $27,834 for the pumping strategy that considers TOU pricing (Figure 6). This simple TOU strategy would have achieved a saving of $11,847 in 2017.

Example 2: Demand Response and Limited Pumping Capacity

Capacity Bidding Program (CBP) and Base Interruptible Program (BIP) are examples of two DR incentive programs offered by Pacific Gas and Electric Company (PG&E) that are most suited for agricultural customers. The incentive program stipulates that interruptions will last no more than four hours, with no more than one interruption per day and no more than ten per month. In this example, we illustrate how the participation of the same farm as "Example 1" in a program similar to BIP[2] will impact its normal operation. If the farm were also following the TOU schedule as illustrated in Figure 6, it will be operating close to maximum pumping capacity. The analysis begins with the irrigation schedule based on 16 hour sets presented in the previous example (same schedule as in Figure 6). A modified schedule with occasional interruptions generated at random times is overlaid on the TOU management-schedule (Figure 7, with lighter bars indicating DR event days). DR event days are illustrated with lighter bars. Irrigation events on DR event days do not exceed 12 hours to indicate a 4 hour interruption per event. If an interruption is called when no pumping was planned it is indicated as a negative four-hour bar. On those days when no pumping was planned additional pumping for 8 to 12 hours can be inserted to compensate for preceding interruptions.

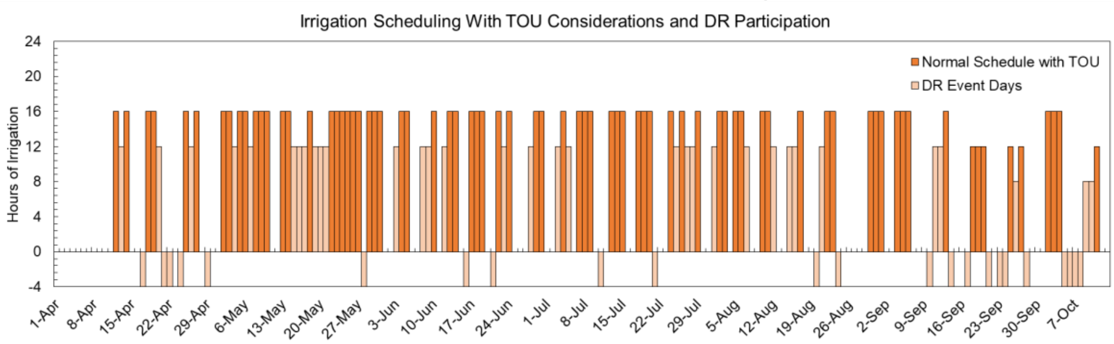

Figure 7: Combining TOU and DR management

It appears from Figure 7 that the irrigator could compensate for most interruptions shown by shifting irrigation dates by a day or two. The same total volume of water was applied in both Figure 6 and Figure 7. Estimated impacts of such limited delays on crop production should be minimal (as will be discussed in the following example).
This example can also illustrate an important constraint common to DR programs, which is that a farm shall only be compensated for DR participation in months when they would normally be using a significant percentage of pumping capacity. For example, the

[2] BIP was selected for this example due to its simple compensation rate. CBP incentive calculations are more complicated with capacity payments varying by month and notification period.

requirement might stipulate that the pump(s) enrolled in a DR program must operate at least 70% of the time. In this case the seasonal pumping with TOU considerations (not pumping during the 6 peak hours every day) from May through August would exceed the 70% level. If the financial incentive for participating in the DR program were ~$8 per kW per month (PG&E 2018) and the farm qualifies for four months, the payout would be an additional $2400 per year. However it is important to note that enrollment and successful participation in such a DR program could entail capital investment for remote system control and variable speed pumping, which are not considered here.

Example 3: ET, Deficit Irrigation and the Yield Impacts of Interruptions

Evapotranspiration[3] (ET) is a widely used irrigation parameter for estimating crop yields and for estimating yield impacts when irrigation is limited (deficit irrigation or regulated deficit irrigation). Depending on the crop, some degree of deficit irrigation may actually increase farm profits by reducing costs of water, energy and other inputs, and by increasing management flexibility. With some crops deficit irrigation can also improve crop quality if carefully applied at specific growth stages. Modeling of ET and the impacts of ET deficits during the season is, therefore, a central issue for DR management.

Figure 8 shows a schedule for another orchard in which a similar TOU strategy as the first example (Figure 6) was developed for a maximum of 15 off-peak hours per day. However, in this case the irrigation capacity could not meet scheduled crop water demands on six days in late July and August, indicated by red bars, each representing 15 hours of additional pumping needed to maintain the intended soil moisture pattern. The cumulative irrigation deficit during that interval would be 6% of intended seasonal water use. Scheduling of additional irrigations to compensate for the 6% deficit would involve significant rescheduling of water application to the field. And the farm orchard will not have an opportunity to catch up with lost irrigation until late August. Additional irrigations in late August will not mitigate the impacts to the crop of a month long period of stress from mid-July to mid-August. Because that deficit is concentrated in a one month interval and roughly coincides with the onset of harvest, effects on yields could be even more severe.

[3] Evapotranspiration (ET) is a combined measure of crop water use (transpiration) and water lost to the atmosphere through evaporation. ET is directly correlated with plant growth and yield. Up to a certain growth stage, any amount of water a crop is able to transpire is transformed into plant material. As the crop approaches full ET (100% ET), the water available to the crop is less useful. Beyond full ET replacement (110% or 120% ET), there is more water in the soil that the crop can use and the excess water saturates the soils, causing hypoxic conditions that can create yield losses (Allen et. al. 1998).

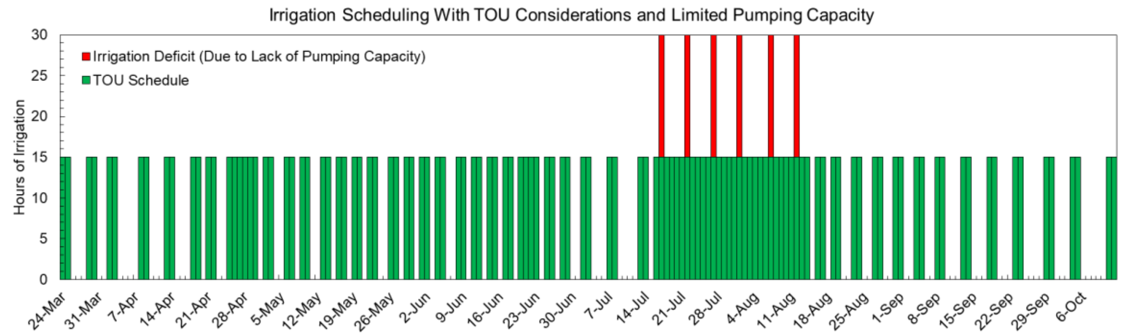

Figure 8: Deficits caused by pumping interruptions

The consequences of such periods of stress will depend on the complex relationships between irrigation timing and amounts, crop water availability, and crop response to available water. The ability of a crop to recover from a delayed or missed irrigation will depend on the stage of growth, the reserves of water in the soil, atmospheric conditions and the physiology of the crop. Operating with crop stress as part of an irrigation strategy requires an advanced irrigation management model to estimate the effects of reduced crop water availability on the cumulative daily ET. Currently such advanced irrigation management models are not commercially available.

Example 4: Conjunctive Management of Multiple Fields

Figure 9 illustrates the greater complexity involved in conjunctive management of multiple fields. Conjunctive management refers to coordinated irrigation of various fields within a farm using the same water source and water delivery infrastructure. Figure 9 shows pumping demand for four fields on another cooperating farm in 2017, each represented with a different color. The stacked bars represent hours of pumping in each of the four fields.

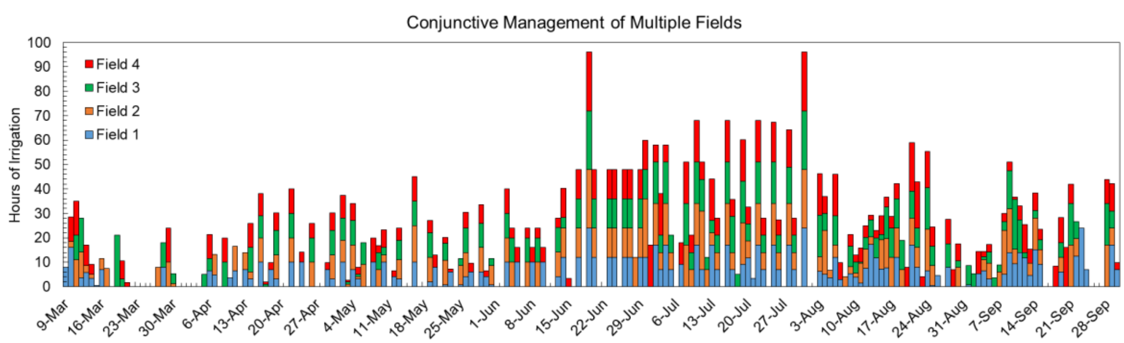

Figure 9: Conjunctive management of four fields

The highly irregular pattern indicates this farm could reduce peak demands substantially by shifting most irrigation dates by a day or two. Figure 10 represents an alternative irrigation schedule for the same four fields after shifting some irrigation dates.

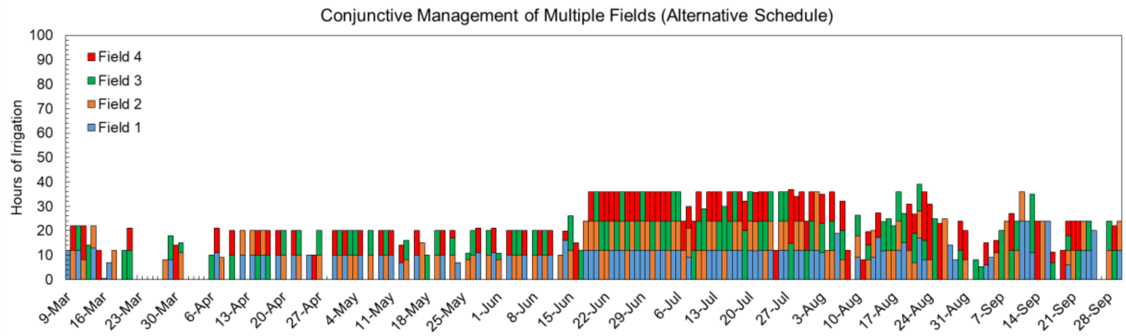

Figure 10: Conjunctive management of four fields (Alternative Schedule)

However, such re-scheduling can be complicated by the need to re-allocate limited water among different and competing applications, such as different crops, differences in field characteristics (e.g. soil parameters) and differences in irrigation system characteristics in the different fields.

Management in this case is further complicated by the fact that about 20 groundwater pumps and 100 valves are used to irrigate those four fields. Without complete automation, such re-scheduling can result in several hours of labor spent on manually adjusting valves and turning irrigation pumps on and off.

A Decision Support System to Facilitate Demand Management

As indicated in the previous sections, irrigation planning to accommodate TOU and DR strategies will need to anticipate occasions of high crop water demand weeks or months ahead of time, especially when allocating water among multiple fields that share a common water supply. If optimal water use involves some degree of deficit irrigation, the planner will need to assess the possible yield impacts incurred by delaying, reducing or eliminating some irrigations. This requires being able to estimate in advance and across the whole season the impact and value of each irrigation and how each irrigation will translate into crop available water at full or partial ET, particularly at critical growth stages. This requires sophisticated modeling of the relationships between the crop, the soils, the atmosphere and the irrigation system, combined with site specific measurements and the irrigator's management goals.

Meeting these challenges requires accurately modeling the disposition and fate of applied water and modeling crop response to available soil moisture not just daily, but looking forward over extended periods of time. Seasonal irrigation strategies and schedules need to be easily and quickly updated to match weather variations, the availability of water, disease problems and other factors that evolve during the season. And planning needs to account for farm-specific constraints due to contractual arrangements, operating practices, risk tolerance and other factors that differ from one farm to another.

The most effective irrigation management technologies in the market today focus on monitoring daily and weekly estimated ET conditions to provide a limited water balance calculation. A water balance model calculates how much water is applied against ET estimates of how much water is used by the crop. While accurate on a weekly basis, these conventional methods of scientific irrigation scheduling do not provide adequate forecasting and accurate forward-looking schedules for the management challenges presented by deficit irrigation.

Growers need to conduct long range planning and management of irrigation strategies, including deficit irrigation, to deal with these complex management challenges (Hillyer et al, 2015). Researchers at Oregon State University have developed an irrigation management tool for planning, targeting and tracking the application of ET)[4] (screenshot shown in Figure 11). It uses a comprehensive and sophisticated modeling of the disposition and fate of applied water in order to accurately project crop water availability into the future. The tool supports five phases of irrigation management:

1. **Planning seasonal water use:** Consulting with the farm manager is an essential first step to account for the manager's prior experience, tolerance for risk or uncertainty, contractual arrangements, incidence of disease or pests and other ancillary factors that influence irrigation management. Researchers and extension leaders are also consulted to identify the best seasonal pattern of water use based on local field circumstances. In this step the irrigation strategy shown as a blue line in Figure 11 is generated.
2. **Seasonal scheduling:** Generating a full season irrigation plan, with anticipated dates and set times for all irrigation events to implement the intended seasonal pattern of water use. Gray bars in Figure 11 represent planned future irrigation events.
3. **Dynamic scheduling:** Tracking measured (illustrated as colored dots in Figure 11) and estimated soil moisture (illustrated as the blue line in Figure 11) and updating the irrigation plan continuously to account for actual seasonal weather, changing farm objectives or other changing circumstances.
4. **Recalibration:** Using incoming field data to check the accuracy of the analysis and recalibrate model parameters.
5. **Yield modeling:** In some applications water use and crop yield data have been combined to calibrate a farm-specific crop yield model for estimating yield deficits (see Example 3).

[4] http://oiso.bioe.orst.edu/RealtimeIrrigationSchedule/index.aspx

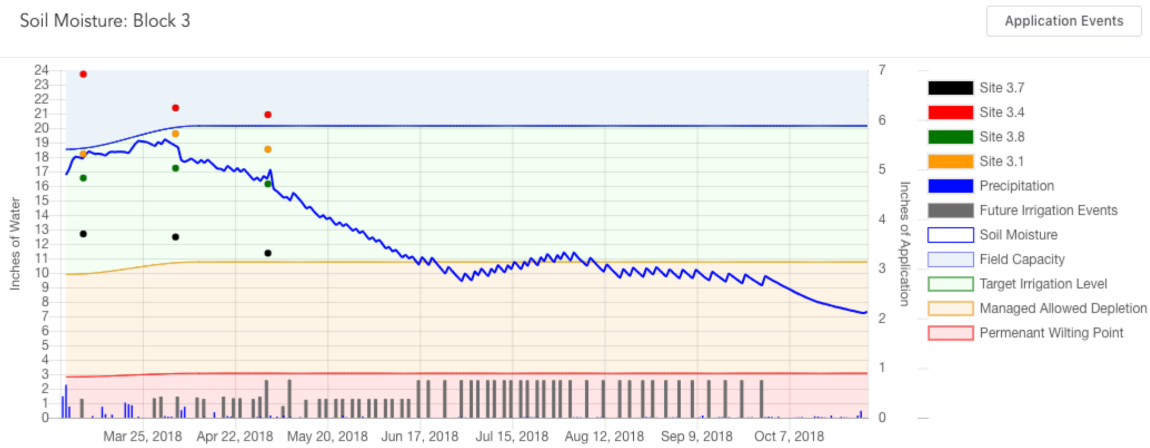

Figure 11: Screenshot of the irrigation management tool for a modeled farm

Next Steps

Existing decision support systems used by growers do not incorporate energy and demand in their management strategies. Researchers at Oregon State University, Lawrence Berkeley National Laboratory, and Irrigation for the Future are collaborating on development of a decision support system that can facilitate load control automation, increased DR program participation and customer cost optimization under available electricity tariff structures.

In order to do so, researchers need to develop an approach for anticipating DR event days using historical DR events, system load, and temperature data. The output from this analysis will complement the original site-specific irrigation schedule, and avoids irrigation sets from being scheduled on days with a high probability of DR. If an interruption in a planned irrigation schedule renders the original schedule infeasible, as illustrated in Example 3, the algorithm will generate alternative new schedules, reject schedules that violate operational constraints, evaluate the outcomes of feasible schedules in terms of a specified objective function, and repeat this sequence in a systematic search for *the* best schedule.

The final decision support system will provide irrigators a way to more accurately evaluate their opportunities to work with energy markets with less risk and greater transparency. This also gives energy providers and the grid a way to more accurately evaluate and predict which irrigators within their portfolios can participate in DR events as grid demands spike.

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