Analysis of Power Flexibility Control with Business Model Implementation and Application in Agricultural Sector

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Abstract

Recent times have seen a huge rise in Renewable Energy generation, especially for electricity production. However, since some of these sources are intermittent in nature, an important work-around to overcome this is to control and manage flexible loads from various sectors through effective demand response programs. Demand response in the residential, industrial and transport sector have been studied in literature. However, one of the sectors which has not yet been addressed for load matching and controlling despite a huge existing potential, is the agricultural sector. The present work explores power flexibility characterisation in the irrigation sector in Portugal.

The model developed optimises the irrigation power consumption by minimising the cost while simultaneously ensuring the watering level is always within the farmer-defined allowable flexibility limits and desirable levels for the crops. It is confirmed that the final daily watering is sensitive to the maximum and minimum limits as well as the start day of the program depending on the electricity supplier tariff and schedule chosen. In the test case run for 5 weeks, an additional cost of €160 is found when the objective function is minimised for a 1km^2 field such that the watering is close to the desired crop water level as opposed to the case where only the cost is strictly minimised. The code works based on inputs from farmers. A potential business case for integration of this model with electricity suppliers is discussed, both qualitatively and quantitatively.

Introduction

The huge increase in Renewable Energy (RE) generation has been instrumental in causing the share of gross electricity consumption in Europe from RE sources in 2016 to be more than a quarter (29.65%) and has since only been increasing [1].

One huge problem with this increase, arises from the fact that some RE sources are intermittent in nature. Moreover, the connected loads or appliances that are flexible in nature are not controlled effectively.

One important solution for this is the deployment of storage technologies. However, storage systems often tend to be expensive and have finite capacities. Another important work-around to overcome the intermittency problem of RE installations is to control and manage flexible loads from various sectors through effective Demand Response (DR) programs. With the current advent of the Internet of Things (IOT), the accessibility of DR programs is increasing as a source of effective load management in various sectors. DR systems can often be incorporated through the installation of smart meters. Lack of an effective management system, either through controlling flexible loads or Distributed Energy Sources (DERs) generally causes various problems in the grid such as wastage or shortage of energy.

DR in the residential and industrial sector have been studied in literature. However, one of the sectors which has not yet been addressed for load matching and controlling is the agricultural sector. Agriculture is a production-oriented sector and has become increasingly mechanised with farmers having large amounts of power loads for irrigation, crop drying, operation of mechanised equipment etc. [2]. At the same time, this sector has a vast potential since the related loads are flexible (to a large extent), which leaves a lot of scope for optimisation of their power usage.

State of the art

The importance of power flexibility has been understood in the present-day scenario and there has been a lot of research performed in order to come up with effective demand response programs by trying to characterise this flexibility (mainly focussing on the residential and industrial sectors). Residential power users can offer a range of data based on their daily usage habits [3] which can help power aggregators control their load effectively. Studies in scheduling household appliance usage in association with the markets have also been undertaken [4]. Modelling household flexibility and integration of renewable energy sources together with valuation of the flexibility is another area which has been explored [5].

Industrial power customers are often the bearers of large equipment loads. Similarly, commercial and non-residential buildings also have very high building power loads. The proper use of operative demand response systems can lead to huge power savings in these sectors [6]. Identifying and utilising the flexibilities in buildings have also been performed [7] [8].

In order to understand the concept of power flexibility better, some studies on household demand response programs [9] [4] as well as flexibility characterisation for conventional thermostatically controllable loads [10], were examined. Some quantitative studies in flexibility measurement and flexibility markets were investigated, [11] [12] [13].

Reviewing the flexibility that is provided by a variety of sectors (other than the irrigation sector), facilitated in allowing for a comparison and identification of points of similarity or differences.

The main point of similarity between these sectors and the irrigation sector is that in both cases, the user-desired conditions affect the flexibility that can be imparted by the application. In the case of the loads of the irrigation sector, this is defined by the farmer in terms of the quantity of water that is allowable in the soil (depending on the type of crop grown). This translates to the use of the irrigation system in order to water the field with a required amount of water each day.

In general some crops need to be irrigated at specific times of the day. This could even depend on weather conditions. However in the present thesis it is assumed that there is no hourly time constraint for irrigation. This makes the flexibility less localised to specific hours and more spread out which increases its value for DR.

It is assumed that the crops can be irrigated at any time during the day and can follow the least cost tariffs of available power. A detailed understanding and study of the existing consumer usage and timings has not been performed.

Irrigation sector

According to [14], the total area equipped for irrigation globally, in 2012 was over 324 million hectares. Out of this, 85% (or 275 million hectares) is irrigated. The irrigation area worldwide has increased steadily over the years as demand for food has also increased. The total irrigated area in Portugal in 2014 was around 552 thousand hectares [15]. This included areas for full and partial control irrigation, spate or flood irrigation as well as for lowland areas and pastures. It is pretty clear that there is an immense market for smart irrigation in Portugal, some of which is already being tapped by Trigger Systems through their pilot projects.

There are various types of irrigation systems which are either simple or complex and automated or manually controlled. Some of the types of irrigation are surface, localised, drip, sprinkler, central pivot, lateral mover and sub-irrigation [16].

Every crop in its life cycle is characterised by phenological phases. Each crop has an desirable level of water required to be present in the soil which varies with the phenological phase it is currently in. Plants also have certain limits of maximum and minimum allowable water levels in the soil. These are the flexibility limits of the crop.

Value addition with power consumption

Given the context of the irrigation sector and available smart programs that are automating the operation of the irrigation equipment, the next step for value addition is to optimise the farmer's electricity usage for irrigation while simultaneously staying within the flexibility limits of the crops' requirement. Since this flexible electricity usage has potential to be used in DR programs or by utilities to balance out power needs there is another potential for value addition to the existing IOT platform. The following two value propositions have been identified and explored in varying levels of detail through this work:

1. **Optimisation of farmers load usage by characterising flexibility**: A model is built to achieve the irrigation needs of the farmer within the flexibility requirements of the crops (while staying close to the desired level). It has been optimised such that the electricity cost is minimised. This ensures that power is used only as necessary and especially helps automate the irrigation process for cases where a farmer has bi-hourly or tri-hourly tariffs.
2. **Flexibility provision for electricity suppliers**: Based on the cost optimisation model, a possible market fit for integration with a DSO is discussed.

Power consumption optimisation model

The aim of the model developed is to determine the watering schedule after minimising the cost of the electricity needed for irrigation together with maintaining the desired plant water level in the soil. The following steps are performed to develop this model:

1. **Defining the CVX objective function:** two terms are minimized in the solver;

the cost function:

The cost of electricity for the farmer is minimised. Based on the tariffs and schedule of the electricity used by the farmer, the cost function is defined by summing up the electricity usage by hour and the daily electricity cost (as specified by the electricity supplier).

the closeness to the desired soil water level

Another function is defined which calculates the water level every day and returns an effective cost value which reduces the difference between the water level for the day and the desired level of water for the day. The value returned by the function defines the closeness of the daily actual water level to the daily desired water level

An empirical coefficient α is used in this term. The value of this coefficient has been fixed based on running the program and observing the behaviour of this function. It ensures that the soil water throughout the number of days that the program runs, stays closest to the desired value on all days. A quadratic function has been used because at times the water level at the end of the day could be higher or lower than the ideal level to be maintained.

2. **Defining the variable of the CVX function**: it is the fraction of each hour for which the irrigation equipment is switched on.
3. **Defining the constraints:** the constraints ensure that the soil minimum and maximum flexibility limits are respected.
4. **Defining the cost function:** this is done depending on the electricity supplier. The schedule could be simple, bi-hourly or tri-hourly. The pricing scheme is such that consumers pay a price per day (€/day), as well as a price per kWh consumed (€/kWh) depending on the hour of the day.
5. **Defining the inputs to the CVX function**: the following input parameters are defined:
    - Area of the land to be irrigated (km^2)
    - Initial water level in the soil (mm)
    - Maximum allowable soil water (mm/day)
    - Minimum allowable soil water (mm/day)
    - Desired soil water (mm/day)
    - Daily water lost (mm/day)
    - Power rating of irrigation equipment (kW)

Results

Input parameters for test case:

The input cost is defined using the following parameters:

- Electricity Supplier: EDP
- Schedule: Tri-hourly electricity tariff, Weekly schedule (summer)
- Potencia: 3.45 kVA

The cost input values for the test cases are shown in Table 1 [17].

Table 1: Cost inputs

Term	Value
Cost per day (€/day)	0.2297
Off-peak cost (€/kWh)	0.0942
Medium cost (€/kWh)	0.1715
Peak cost (€/kWh)	0.2942

The schedule is shown in Figure 1.

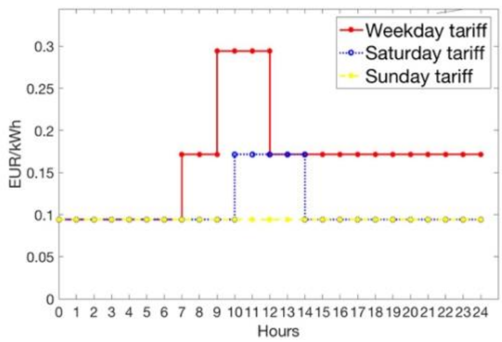

Figure 1: Cost schedule

The crop inputs are shown in Table 2.

Table 2: Crop input parameters

Input parameter	Value
Crop	Potato
Initial water in the soil (mm)	0.5
Land area (km^2)	1
K_C index	0.75

The location input chosen is Mafra in Portugal.

The following are the results:

1. **Influence of alpha** (α): When the program is run for 5 weeks (35 days) the results can be seen in Figure 2 and Figure 3 for alpha values of 0 and 1 respectively.
   It can be seen that in the case where $\alpha = 0$, only the cost is optimised. Therefore at the end of every week (Saturday and Sunday), the maximum watering is performed such that the minimum tariff hours are utilised effectively even for the coming weeks. The total cost for the period in this case is €1203.

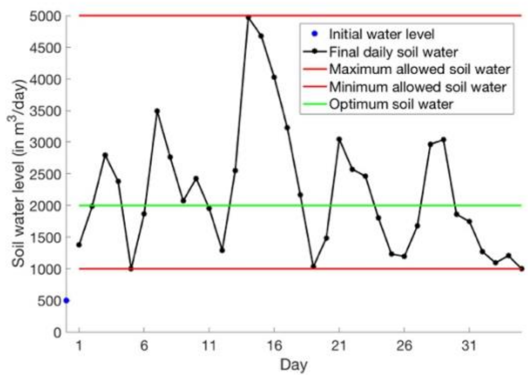

Figure 2: Daily water level for 35 days with alpha = 0

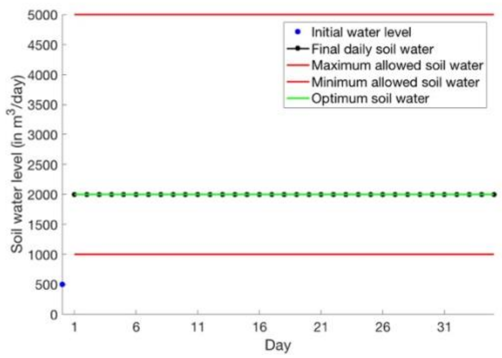

Figure 3: Daily water level for 35 days with alpha = 1

However, when $\alpha = 1$, the optimisation is done while simultaneously making sure the value of watering every day is always closest to the desired level. In this case, as expected, the cost is higher, €1360, since there is an added condition. The farmer can decide if this ~€160 difference is worth allowing the crops to be in a 'semi-stressed' state and achieving potentially lower comparable yields in order to save money. It must be noted that the crops never go into a totally stressed state as the maximum and minimum daily limits for the crop (as specified by the farmer) are always respected.

2. **Sensitivity with maximum allowable soil water:** the sensitivity can be seen in Figure 4 and Figure 5.

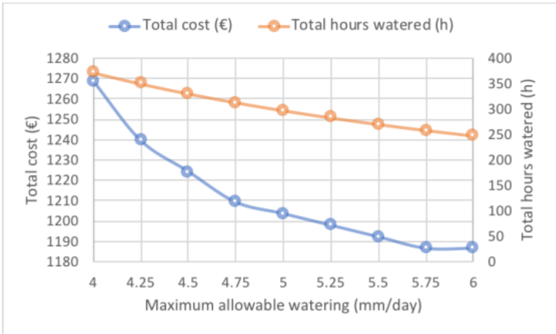

Figure 4: Sensitivity with maximum allowable water with alpha = 0

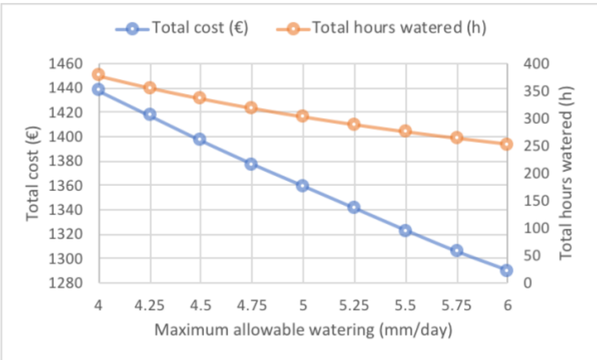

Figure 5: Sensitivity with maximum allowable water with alpha = 1

It can be seen that the total cost and the watering hours decrease with increase in the maximum allowable watering. This is observed because the pumping capacity increases to take into account the potential higher amount of water which can be pumped in order to ensure that a higher value for the maximum allowable limit can be accommodated. Since the pumping capacity is increased, the hours in which the irrigation can be achieved decreases.

If an alpha value of 1 is used, then the trend observed is also the same but the slope of the linear variation is different. The total cost as well as the hours watered are higher in this case as expected.

3. **Sensitivity with minimum allowable soil water:** the sensitivity can be seen in Figure 6 and Figure 7.

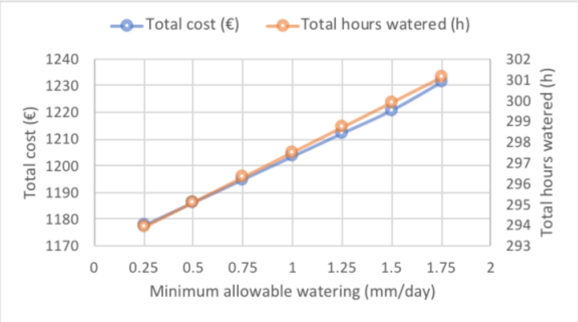

Figure 6: Sensitivity with minimum allowable water for alpha 0

As the minimum allowable level increases, the plant becomes more demanding which increases the hours of watering necessary to keep it in a non-stressed state. This directly results in an increase in total cost.

In the case with alpha = 1, the total cost and hours watered do not vary because at all times the water level is close to the desirable water limit.

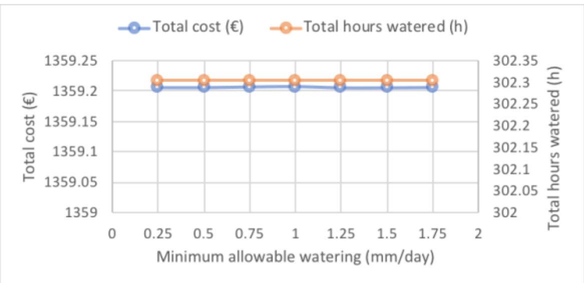

Figure 7: Sensitivity with minimum allowable water for alpha 1

4. **Sensitivity with different start dates of simulation:** it was observed that the watering trends differ if the simulation is started on a Monday (Figure 2) as opposed to a Saturday or Sunday (Figure 8). This is expected as the tariff scheme is weekly and depends on which day of the week the program starts.

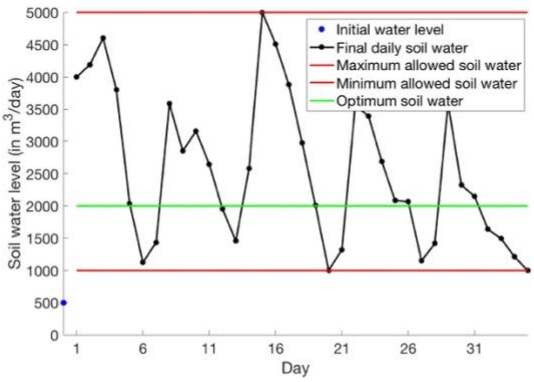

Figure 8: Daily water level for 35 days with alpha = 0 with Sunday start

Integration of model with electricity suppliers

While looking for the applications of this model to add business value to existing systems, the electricity market was studied.

The markets studied include the wholesale market (capacity, day-ahead, intra-day and ancillary market) and the retail market.

On considering the markets mentioned, the best fit for incorporation of power flexibility is the intra-day or ancillary market since the farmers' flexibility can be used to make real-time changes in power supplies.

A qualitative business model was developed highlighting the following:

The *customer segments* are as follows:

- flexible load consumers such as any actor in the agricultural industry (mainly farmers who want to manage irrigation loads or power used during crop drying and other processes). This also includes power consumers like municipalities that have large lawns to be watered.

- electricity retailers/distributors who need to manage power in the real-time and ancillary markets

These customer segments also define the *key partners* of the business.

The *value proposition* of this business is the following:

- Flexible load users make cost savings as the time of usage is controlled according to the least cost hours and user-defined flexibility limits. For example, the irrigation needs are flexible and defined by the maximum and minimum water allowable during specific stages in the crop growth.
- On the side of the electric supplier or distributor, the main value proportions are in relation to the ancillary market for better load forecasting, congestion management and frequency control by being able to harness this flexibility (by sending more power to a line if allowable or curbing power to a line during peak periods). The retail market also has the added value proposition of using this flexibility to reduce costs related to real time shifting of loads (which is invariably more expensive as they are done last minute).

One *customer channel* is to integrate control devices with the farmer's load, through an installation process, in order to monitor and control their load. This will also include customer care and support to follow up with them in the occurrence of any fault in the control. Another channel will involve marketing the device to potential farmers as well as to suppliers/distributors.

The *customer relationships* are formed through the application interface with both the farmer (to get the farmer's inputs on the flexibility as explained in Section **Error! Reference source not found.**) and suppliers.

The *revenue streams* could be through selling the control devices to the farmers as well as selling the flexibility of the farmers to suppliers or distributors.

The *key resources* to facilitate the business will involve the necessity to manufacture control devices as well as to develop the application interfaces with the farmer as well as with the suppliers or distributors. The existence of an IOT platform to facilitate this smart system is also necessary.

The *key activities* to be executed are monitoring and control of the power from the farmer as well as communicating with the farmer through the app interface and communicating with the supplier in order to manage the flexibility.

The *cost structure* will involve that incurred for the manufacture of the control devices as well as to build the interface of the app with the farmer and supplier. It will also involve developing an IOT platform.

To make a quantitative analysis of the business case, the power needs of the farmers are estimated in three locations in Portugal

The energy requirements in the three regions were estimated as shown in Table 3.

Table 3: Energy requirements from 3 locations

Location	Location1	Location2	Location3
Agricultural land estimation (km^2)	12	45	18
Power required for irrigation (kW)	166	622	249
Total irrigation electrical energy required per year (kWh/y)	1451852	5444444	2177778
Flexible energy per year (kWh/y)	87111	326667	130667

Based on the total annual irrigation electrical energy required as well as an estimation of the flexible energy available and existing tariff, a pricing scheme can be made.

Conclusion

Through this thesis, power flexibility in the irrigation sector is explored and the model developed helps to optimise the cost of power consumption by using the inherent flexibility in watering different crops.

It is found that the value of alpha is important in determining the desired level of watering to fix how much 'stress' is imparted to the growing crops. It is also seen that as the maximum allowable flexibility is increased, the hours watered and costs are reduced. The hours watered and costs are visibly dependent on the area of irrigation.

Future works:

Going forward, the following limitations in the present model can be addressed and included:

- the ramping power while switching on and off the pumps during the hours of use can be added
- time resolution of the cost can be reduced to 15 or 30 minute resolutions
- weather models can be incorporated
- integration of model with local RE production of farmers.

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