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

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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June 2018

Acknowledgements

I am grateful to InnoEnergy for giving me the opportunity to do my thesis in collaboration with Trigger Systems.

I thank Francisco Manso and Sara Gonçalves, founder and co-founder of Trigger Systems respectively, for giving me the idea for this thesis as well as their patience and extensive discussion in helping me find direction when I was lost. I thank Francisco for agreeing to be my supervisor from the company and giving me a lot of flexibility. My association with the company and colleagues especially Francisco, Sara, Miguel Bordalo, Thomas Gaudich and Samuel Balula has been truly helpful and has taught me a lot.

I am grateful to Professor Duarte Sousa for being my supervisor at IST and providing me with timely guidance, encouragement as well as a lot of freedom to go about the thesis.

I thank all my close friends for their support. Special gratitude to Krishnamohan for moral support and coding advice, Miguel Hernandez for long discussions and help with debugging the code, Leon, Siddharth and Luigi for conversations about power flexibility and research guidance. Also big thanks to my family for providing me with counsel throughout this thesis and always, together with humour and some solid life lessons.

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.

Key words: power flexibility, irrigation, demand response, business case, agriculture

Resumo

Nos últimos tempos é notório o crescimento da utilização das energias renováveis, especialmente para a produção de eletricidade. Contudo, e uma vez que estas fontes são intermitentes, é imprescindível arranjar uma solução que passe por controlar e gerir as cargas provenientes dos vários setores, através de programas eficazes de resposta para a procura. O sector industrial, residencial, e dos transportes, já foram estudados pela comunidade. No entanto, o sector agrícola com um enorme potencial, ainda se encontra por explorar. Este trabalho visa analisar a caracterização da flexibilidade de potência energética consumida por sistemas de rega instalados em Portugal.

O modelo desenvolvido otimiza o consumo de energia durante a operação de rega, calendarizando a operação de rega em períodos com menor custo energético. O algoritmo baseia-se na minimização de custos e garante as necessidades hídricas das culturas exploradas se encontram sempre dentro dos limites flexíveis definidos pelo agricultor. Confirmou-se que a decisão de rega é influenciada pelos níveis hídricos definidos, pela data de começo do programa e pela tarifa de eletricidade e horário escolhido. No caso de teste, observa-se um custo adicional de 160 € quando a função é minimizada de modo a que os níveis de água se encontrem próximo do desejável para as culturas, ao invés do caso onde apenas é minimizado o custo. Este código funciona baseando-se nos requisitos do agricultor.

Por último, é descrito, quantitativamente e qualitativamente, um potencial caso de estudo para a integração deste modelo com os fornecedores de energia.

Palavras chave: potência flexibilidade, irrigação, resposta à procura, caso de estudo, agricultura

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Symbol	**Description**	**Units**
α	empirical coefficient related to weight of desirable water level characterisation	-
ET_o	reference evapotranspiration per day	mm/day
ET_C	crop evapotranspiration per day	mm/day
g	acceleration due to gravity	m/s^2
h	height of the underground tank for pumping	m
K_C	index for crop evapotranspiration	-
η_e	Electrical efficiency of motor	(0 to 1)
η_m	Mechanical efficiency of pump	(0 to 1)
P_p	pumping power	kW
$\dot{V}$	volumetric flow rate	l/s

List of acronyms

Acronym	**Description**
BRP	Balance Responsible Party
DER	Distributed Energy Resource
DR	Demand Response
DSO	Distribution System Operator
EE	Energy Efficiency
EV	Electric Vehicles
EWH	Electrical Water Heaters
IOT	Internet of Things
RE	Renewable Energy
TSO	Transmission System Operator

1 Introduction

1.1 Background

Recent times have seen a huge rise in Renewable Energy (RE) generation, especially for electricity production. In Europe (EU), the share of gross electricity generation from RE sources in 2016 was 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. The resource might be available when the demand for it is not present while during peak demand times, there might be no resource available to supply to it due to weather and other meteorological conditions. 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 to store the energy when it is produced during times of availability and use it when there is demand for it. 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. However, DR programs and smart meters are not yet widely installed and used in most countries. In this context, there is a huge potential to make energy savings in various sectors by effectively managing power usage with resource availability. Lack of an effective management system, either through controlling flexible loads or Distributed Energy Resources (DERs) generally causes various problems, the main ones being the following:

1. **Wastage of energy:** Power companies need to be able to forecast the amount of power needed to supply to demand which operatively affects power generation. Any kind of over-estimation of power demand leads to wastage of energy.
2. **Shortage of energy:** On the other hand, if the prediction of the energy demand is not accurate, for example, if on a particular day the demand is higher than the production, there is a shortage of energy, which is also not desirable.

This results in an imbalance in the grid as well as poor predictability of the power demand by electricity producers resulting in energy and monetary losses. There are various sectors in which strategies can be adopted to build a case for the creation of effective DR processes to address the above problems.

Another common option for utilities is to create a pricing scheme with varying tariffs for different time periods. This curtails peak loads to some extent as people try to switch off their appliances during peak tariff timings to avoid paying high electricity bills to their electricity supplier.

Demand Response 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 DR application potential since the related loads are flexible to a large extent, which leaves a lot of scope for optimisation of their power usage.

1.2 Problem statement of thesis

The present thesis explores power flexibility in the agricultural sector, specifically in the irrigation process. In order to exploit the power flexibility of the farmers in the irrigation process, the objective of the present work is mainly to develop a program that will automate the farmers irrigation electricity usage to correspond to the least cost hours according to the tariff chosen. Subsequently this power flexibility is quantified and valued through a simple business model to be sold to electricity suppliers or distributors.

The thesis has been carried out in collaboration with **Trigger Systems**, an eco-innovative start-up that manufactures smart systems for sustainable irrigation. The company’s approach towards automated irrigation is through the use of virtual sensors (through mathematical modelling) as opposed to physical probes (used in traditional automation).

The work done through this thesis can be added to the existing IOT platform (through an app interface to receive user inputs) to create business value for Trigger Systems through the farmers as well as electricity suppliers or distributors. Portugal is selected as a case study for the results of the model, due to the availability of irrigation data.

1.3 Structure of the thesis

The thesis looks into aspects of power flexibility in the irrigation sector, electricity markets and its application.

Firstly a literature survey is conducted on methods for quantifying flexibility and DR in various sectors which provides an idea on its potential use in the agricultural sector. This is followed by an overview of the irrigation sector in Portugal as well the types of irrigation and irrigation cycles. Subsequently the program for power consumption optimisation is described in detail and the results of test cases and sensitivity analyses are examined.

Further, in an attempt to integrate the model with electricity suppliers or distributors, the electricity market is briefly examined to consider where a business model could appropriately match this power flexibility. A qualitative and brief quantitative description of the business model is made followed by concluding remarks and possible future work.

2 Power flexibility and Demand response

2.1 Definitions

Power flexibility broadly represents the availability of a load for being controlled (modified by switching on or off) at a particular time during the operation of the power system while remaining within the comfort usage limits defined by the user of the appliance [3]. Power flexibility is dependent on the controllable load parameters (depending on the type of appliance) as well as the consumer's habits of active load utilisation patterns and regular use depending on comfort levels (for example the temperature set point of an electric water heater) predefined by the user.

The available power flexibility is exploited by DR programs which aim to optimise the energy usage of appliances either to minimise the costs of electricity or to match the resource availability. This is done with some adjustments to the utilisation pattern of the consumer. Demand response (DR) is defined by the Federal Energy Regulatory Commission as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [4].

2.2 State of the art

The importance of power flexibility is widely understood in the present-day scenario and there has been a lot of research undertaken in order to come up with effective DR programs by trying to characterise this flexibility (mainly focussing on the residential and industrial sectors). Studying the existing literature in already developed fields was helpful while looking to apply these to the irrigation sector. Residential power users can offer a range of data based on their daily usage habits which can be examined. Based on a study carried out by Almeida et al. (2011), the demand trends of 12 representative EU countries were monitored. This is augmented by a lifestyle study in order to understand what kind of loads formed the main fraction of the overall household power demand [5]. Apart from providing valuable inputs for designing flexibility management programs, this study also facilitated outlining policy recommendations for promoting behavioural changes for market transformation of power needs.

This kind of information can also benefit power aggregators control their load effectively as a two-way communication system between the Distribution System Operator (DSO) and the household (through a smart meter). Therefore, DR, with its many advantages, plays an important role in achieving many goals such as peak shaving, load balancing, frequency regulation and maintaining the stability of the voltage [6]. Often there are monetary incentives that are used to ensure changing usage behaviours of consumers and many times these pricing schemes are a combination of the hourly electricity spot price as well as the tariff schedule depending on the time of the day. Pilot studies have also been conducted to focus on the DR from household customers using smart metering and load control. For example, in a pilot study conducted in Norway by Sæle et al. (2011), it was found that there is an existing DR potential for Electrical Water Heaters (EWH) of 1 kWh/h. It was estimated that this aggregated potential of over 50% of Norway's households corresponds to 4.2% of the peak load in Norway [7]. It is also clear from studies of this manner that the implication of load reduction in peak timings has a repercussion on the day-ahead market bids provided by various electricity suppliers. These analyses often affect the business models associated with the changes made.

Such a study was conducted on scheduling household appliance usage in association with the day-ahead market pricing [8]. Through this work, a comprehensive home energy management system structure was developed taking into account the usage of all types of controllable loads (thermostatically controllable loads like air conditioners and EWHs as well as non-thermostatically controllable loads) including Electric Vehicles (EVs). Modelling household flexibility and integration of RE sources together with a valuation of the flexibility is another area which has been researched [9]. Scheduling models like these to model the stochastic matching of demand and supply are also important in DR programs.

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 DR systems can lead to huge power savings in these sectors as depicted through [10] and [11]. Identification and utilisation of the flexibilities in buildings has also been researched. Bode et al. (2017) studied how to recognise and use the potential for modifying the usage of building energy systems so as to tap into their flexibility [12]. Moreover, in buildings, a major part of the load could be due to systems that convert power to heat such as heat pumps. Finck et al. (2018) studied the aspect of providing optimal control for these power demands due to building storage systems to achieve DR in a building [13].

Even in the transport sector, available power flexibility through the users of EVs has been explored by various research groups. This is because depending on their state, EVs can act as loads (drawing energy from the grid), suppliers (providing energy to the grid) or energy storage devices. The use of smart meters can allow utilities to have access to the charging times and rates of various customers and this can be used to build a management system. The various DR programs and customer classifications have been made with specific stress on integration of EVs with smart grids as well as the introduction of customer indices to estimate the acceptance of customers towards proposed DR programs [14] [15]. As recent as about a decade ago, DR and Energy Efficiency (EE) have been promoted in Portugal and a study has been carried out which explains this experience for two years from the Portuguese point of view [16].

In order to better understand the concept of power flexibility better, some studies on household DR programs [17] [8] as well as flexibility characterisation for conventional thermostatically controllable loads [3], were examined. Further, some quantitative studies in flexibility measurement [18] and flexibility markets [19] were reviewed. Various business models for flexible demand for power were also investigated [20], [21] [22].

The irrigation sector, as mentioned earlier, has a lot of flexible loads. The modernisation of irrigation equipment and systems provide for potential not only in increasing water productivity, system reliability and reduction of operation costs [23] but also to integrate power savings and DR programs. The main study focus on making technological innovations in irrigation management has been connected to increasing agricultural productivity [24]. Irrigation strategies are reinvented based on catering to the needs of the growing population as well as ensuring food security and studies have documented these changes and the advances made [25].

Studying the flexibility that is provided by a variety of sectors thus helped in allowing for a comparison and identification of similarities and differences which are explained in the following section.

2.3 Comparison of other sectors with irrigation sector

Based on the literature described in the previous section, a comparison could be drawn between other sectors (household, industrial or vehicle flexibility) and the irrigation sector.

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 to water the field with a required amount of water each day. Depending on the crop, irrigation equipment and rate of flow, there is a relation between the millimetres (mm) of water content in the soil and the hours for which the equipment is switched on. In some cases, a relation is also provided between the hours of watering and the increase in the mm of water content in the soil and can be found in manuals of companies manufacturing the irrigation systems [26]. Another issue is that the minimum, maximum and desired levels of water are defined irrespective of the electrical equipment used by the farmer.

In the other sectors with flexible loads, the user-desired conditions define the power taken up by the equipment such as the temperature set points of fridges or EWHs which in turn, define how much flexibility is available for the device.

In general some crops need to be irrigated at specific times of the day. This could even depend on weather conditions. For example, in some cases, in order to avoid excess evaporation of water, crops could be watered in the evenings and early hours of the morning. However in the present thesis it is assumed that there is no hourly time constraint for irrigation. 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 daily maximum and minimum limit of soil moisture is allowable for avoiding damage to the plants. This makes the flexibility less localised to specific hours and more spread out. This is opposed to the case with thermostatically controlled loads like EWHs or ACs which need to be used by consumers at specific hours of the day.

The pattern of usage is important for other sectors (eg. EWH is used in morning for shower and a fridge is used throughout the day), but, it is not very strict for the irrigation sector (except for some crops and during extreme seasons). Therefore, a detailed study of the existing consumer usage and timings has not be performed. It is assumed that since the management of irrigation power usage is in the best interest of the farmer, he will accept the proposition without hesitation since monetary benefits are also ensured through potential DR programs.

3 Irrigation sector

According to [27], the total area equipped for irrigation globally, in 2012 was over 324 million hectares. Out of this, 85% or 275 million hectares are irrigated. The irrigated 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 [28]. This included areas for full and partial control irrigation, spate or flood irrigation as well as lowland areas and pastures. It is clearly evident 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.

3.1 Types of irrigation and measurement

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 [29]. Other types include pop-up irrigation, use of riser and mist pipes as well as canon sprinklers [30]. Some common irrigation systems are shown in Figure 1 [31], [32], [33], [34] , Figure 2 [35] and Figure 3 [30].

Figure 1: Types of irrigation systems - 1

Figure 2: Central pivot irrigation

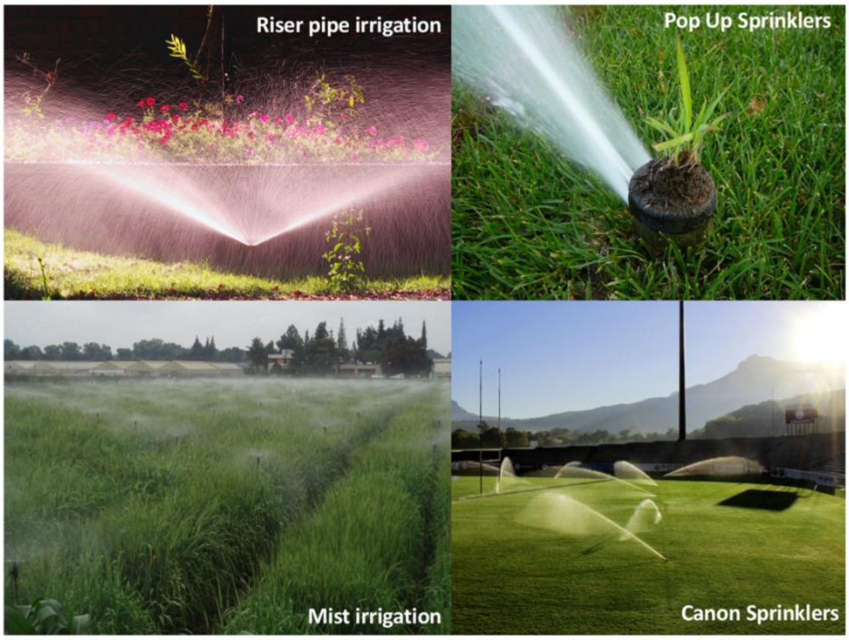


Figure 3: Types of irrigation systems - 2

In all these types of irrigation, the soil absorbs the water provided to it, which is measured in mm of water content per unit area or volume (mm/m^2 or mm/m^3). This quantity can be measured using probes which are sensor devices that are placed in the soil which measure the water content and are read at specific times [36].

These sensors can be used to measure the quantity of water in a profile of soil and the amount of irrigation necessary to achieve a specific desired amount of water in the soil. These probes could either be used to make quick readings or set up to obtain long-term measurements.

3.2 Irrigation cycle and requirements

Every crop in its life cycle is characterised by phenological phases. Phenology is defined as the “the study of the timing of recurring biological events in the animal and plant world, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species” [37]. These phases are related to the growth cycle of the plant and in terms of irrigation requirements, each crop has different needs in each phenological phase. Some examples of phenological phases of plants are the unfolding of the plant leaves, flowering of plants in spring, ripening of fruit and colour changing and leaf fall in autumn [38]. Phenological phases also affect the evapotranspiration of plants.

The process of evapotranspiration is the combined effect of two distinct processes through which water is lost not only through the surface of the soil (through evaporation) but also through the crop (through transpiration). Some of the factors that affect evaporation of soil water are the degree of plant canopy shading and amount of water in the soil. On the other hand, the factors that affect crop transpiration are solar radiation, temperature and humidity of air as well as wind currents [39].

Therefore, each crop has a desirable level of water required to be present in the soil which varies with the phenological phase it is currently in. Similar to the ideal level of water, plants also have certain maximum and minimum allowable water levels in the soil. These are the flexibility limits of the crop. If the water in the soil falls outside these flexibility limits, then the crop is harmed and does not grow well. In these times it is known to be in a state of ‘stress’ (outside its comfort zone). Therefore, at all times, the irrigated levels should remain within the flexibility limits and as close to the desirable water level as possible.

For any given crop, there are two most common methods of achieving the required irrigation amount in a field. They are explained as follows:

1. **Full glass method of irrigation**: In this type of irrigation, the soil is irrigated to its maximum content (depending on the flexibility of the crop being grown) and is replenished every time the water level comes down from this maximum allowable water content. It is called full glass because in the context of the analogy (with the glass being the farmer’s field and the capacity of the glass being the maximum limit of irrigation), the water level is always maintained at the maximum allowable limit in this case. In other words, the ‘glass is always full’.
2. **Empty glass method of irrigation**: On the other hand, in this type of irrigation, initially, the soil is irrigated to the minimum limit of water content (depending on the necessity of the crop

being grown) and is only replenished (with the required extra amount) once the water level falls below the minimum allowable limit for the crop. It is called empty glass because the analogical 'glass is always empty' in this scheme.

As explained earlier, the amount of water absorbed by the plants everyday varies according to various factors including the weather conditions (evaporation of soil water depending on atmospheric humidity and wind conditions as well as transpiration of the crop). The full and empty glass methods of irrigation are both practical in their own way depending on the farmer's needs and methodologies. There is no one best method. Empty glass method of irrigation results in lower costs but this might not always be desirable for the smooth growth of the crop. If the yield of the crop is preferred over the cost, then full glass can be used in order to make sure the soil water is always abundant and at the maximum allowable limit for the crop. A trade-off between the two methods can be used since the plant is not in a stressed state in either of the methods.

3.3 Automated irrigation

The measurement of the allowable water in both cases of full and empty glass irrigation is done using sensors or probes. In most cases, the farmer has to manually switch on and off the irrigation system based on the readings on the probes. With the advent of the IOT, models, programs and controllers are being built to automate the irrigation process so that the sensors are read and signals automatically control the operation of the irrigation system based on the flexibility limits of the plants and the desired level of water that they should have. These innovative smart irrigation methods help save a lot of water and therefore reduce costs for the farmer. The subsequent inclusion of weather models makes this even more helpful by tracking the wind speeds and precipitation.

3.4 Value addition with power considerations

Given the context of the irrigation sector and available smart programs (through companies like Trigger Systems) that are automating the operation of the irrigation equipment, the next step for value addition is to add a layer of intelligence to the existing IOT framework 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:

- **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), 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.
- **Flexibility provision for electricity suppliers and distributors**: Based on the cost optimisation model, a possible market fit for integration with a DSO is discussed.

4 Power consumption optimisation for farmer

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 model is explained through the following steps:

1. Defining the CVX objective function
2. Defining the decision variable in the CVX optimisation
3. Defining the CVX constraints
4. Defining the electricity cost function
5. Defining parameters and input functions to the CVX solver
6. Plotting the results and calculation of total cost.

4.1 Defining the CVX objective function

In this section, the two terms which are minimised by the solver are described. The sum of these two terms defines the objective function which is minimised based on the constraints described in the next section.

4.1.1 Operation cost minimisation

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).

4.1.2 Ideal water level cost function

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.

The final objective function is given as follows:

$$Objective\ function\ = Operation\ cost\ function\ + Difference\ from\ ideal \tag{1}$$

4.2 Defining the variable of the CVX optimisation

The variable of the optimiser program is chosen as the fraction of each hour for which the irrigation equipment is switched on. It thus follows that the sum of the daily fractions (over all 24 hours for each day) provides the total hours for which the equipment is used for the chosen day.

4.3 Defining the CVX model constraints

The main constraint is that the water at the end of the day should be within the maximum and minimum allowable daily limit of soil water. For this, the water at the end of each day is defined. It must be noted that the initial soil water and daily water lost (through evapotranspiration) is taken into account in order to get the true value of water at the end of each day.

Once this is done, the constraint on the water at the end of each day is made to ensure this value remains between the maximum and minimum limits.

4.4 Defining the cost function

There are five major electricity suppliers in Portugal [40]. They are:

1. EDP Comerical
2. Union Fenosa
3. Endesa
4. Galp and
5. Iberdrola

Among these suppliers, EDP Comercial has the maximum market share (~90%). There are usually three modes or schedules of providing electricity: simple, bi-hourly and 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. The consolidated available information of all these suppliers for Portugal is compiled in Appendix 10.1. This information not only consists of the simple, bi-hourly and tri-hourly schedules but also the prices per day and per kWh of each of the suppliers as presently available.

In order to define the cost function, the hourly cost per kWh for 24 hours and all the days included in the program. By default the program is set to run for five weeks (with a tri-hourly schedule and weekly cycle: with same tariffs from Monday through Friday (weekdays) and a different tariff each for Saturday and Sunday (weekends).

4.5 Defining the parameters and inputs for the CVX function

To minimise the objective function of the program, the amount of water in the soil before starting the irrigation program (initial soil water) is measured. The desired water level as well as the maximum and minimum allowable water per day for the current phenological phase is also used. The rating of the equipment used by the irrigation system of the farmer is considered to determine how much power is used. The area of the field is another important parameter that the farmer has to input because it is based on this area and the allowable water limit (mm/day) that the total required volume of water per hour is computed. This value in turn allows for the computation of the power needs for the hour.

Therefore, for the CVX optimiser, the following input parameters are defined:

- Area of the land to be irrigated
- Initial water level in the soil
- Maximum allowable soil water
- Minimum allowable soil water
- Desired soil water
- Daily water lost
- Power rating of irrigation equipment

5 Results and discussion of optimisation model

To test the model and observe trends, the model is run for five weeks to see the effect of various parameters on the final soil water and cost of electricity for the farmer.

The cost is defined using the following parameters:

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

Table 1 shows the electricity cost inputs [41].

Table 1: Electricity 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

To keep the hourly time resolution of the program, it is assumed that the peak power is from 9-12. Table 2 shows the input tariff schedule used in running the program.

Table 2: Input tariff schedule

Season	Timings	Monday - Friday (hours)	Saturday (hours)	Sunday (hours)
Summer	Off - peak	0-7	0-9, 14-20, 22-24	0-24
	Medium	7-9, 12-24	9-14, 20-22	-
	Peak	9-12	-	-

The input cost function is shown in Figure 4.

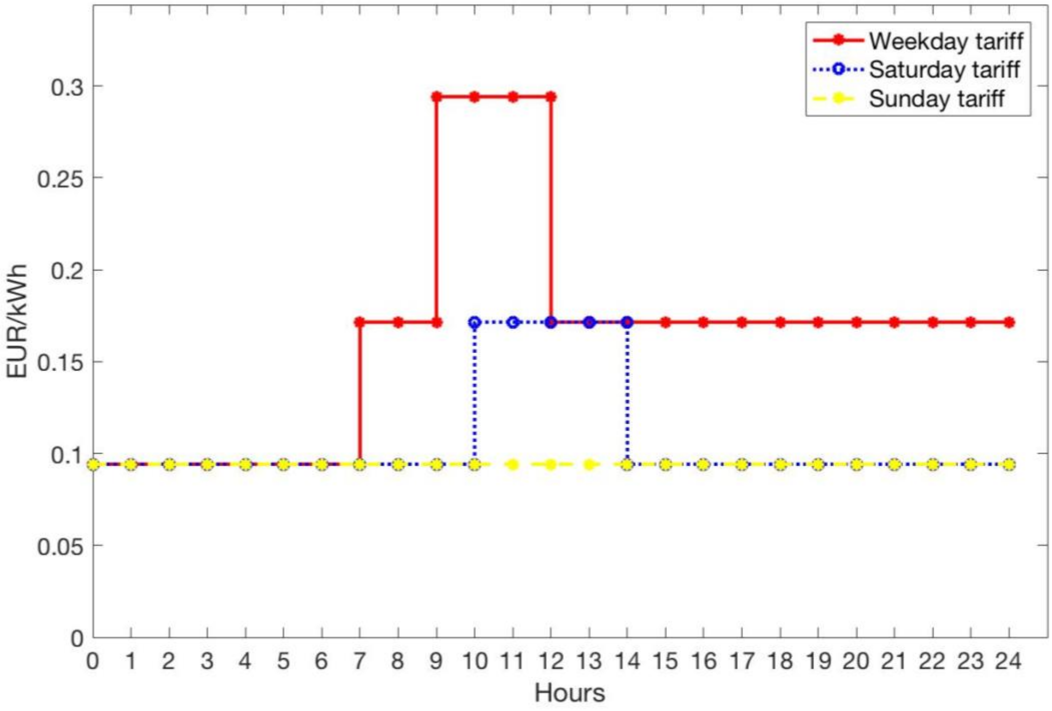


Figure 4: Electricity tariff for the week (in summer)

The agricultural land area is chosen as 1 km^2 for the reference case.

For the purpose of analysis the Potato crop is chosen with the input parameters shown in Table 3.

Table 3: Crop input parameters

Parameter	Value
Initial water in the soil (mm)	0.5
$\boldsymbol{K_C}$ index	0.75

The K_C index value in Table 3 is assumed to correspond to the medium growth phase of the crop [39]. The maximum, minimum and ideal allowable soil water are generally proprietary information of farmers (and varies from one to the other). In the test case, values for these inputs are taken based on discussions with agronomists from the company and are approximations (since they depend on a lot of factors).

The location chosen is Mafra in Portugal. The daily water lost is calculated depending on the location and the specific day (taking into account weather conditions). It is calculated using a tool developed by Trigger Systems [42].

The actual crop evapotranspiration, ET_c in mm/day is calculated using the following equation:

$$ET_c = K_c \cdot ET_o \tag{2}$$

where

ET_o: reference evapotranspiration (in mm/day)

K_c: crop factor

As mentioned, the rating of the equipment used by the irrigation system of the farmer determines the amount of power used.

The pumping power, P_p, in kW is then calculated as follows:

$$P_p = \frac{h \, \dot{V} \, g}{\eta_e \, \eta_m \cdot 1000} \tag{3}$$

where

h is the height of the underground tank for pumping (in m); taken as 50 m

$\dot{V}$ is the volumetric flow rate for the day in (litre/s)

g is the acceleration due to gravity, (in m/s^2)

η_e is the electrical efficiency of the motor and

η_m is the mechanical efficiency of the pump

5.1 Influence of alpha

As mentioned in Section 4.1.2, alpha (α) is an important parameter in the optimisation program.

Its importance is demonstrated by changing values of α and running the code.

When the value of alpha is 0, it is expected that the objective function is optimised strictly with respect to the cost of electricity. If the program is run for a week, this makes certain that the final water in the soil at the end of every day is closest to the minimum allowable water level (to minimise the cost while simultaneously ensuring that the plant does not go into a state of stress). The result of this run is shown in Figure 5.

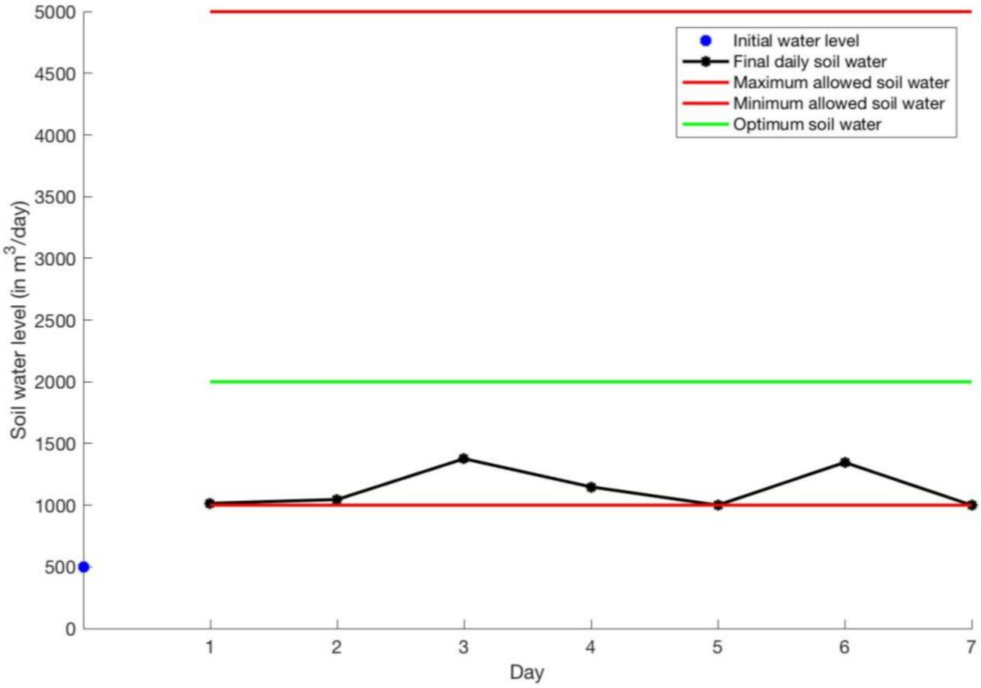


Figure 5: Daily soil water level for α = 0

The corresponding fraction of each hour for which watering is done as well as the tariff pattern is shown in Figure 6. It can be easily noted that watering is done only in the off peak hours and not during the peak periods.

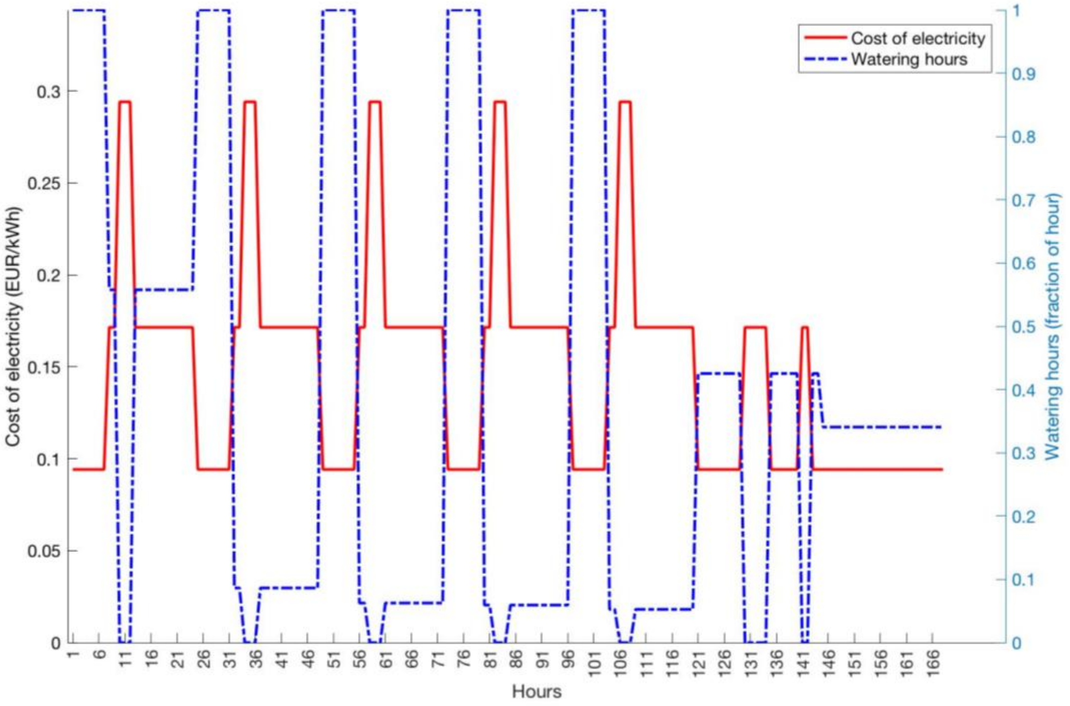


Figure 6: Electricity tariff and watering per day for α = 0

The fraction of the hour for each day of the week which is watered is seen in Figure 7.

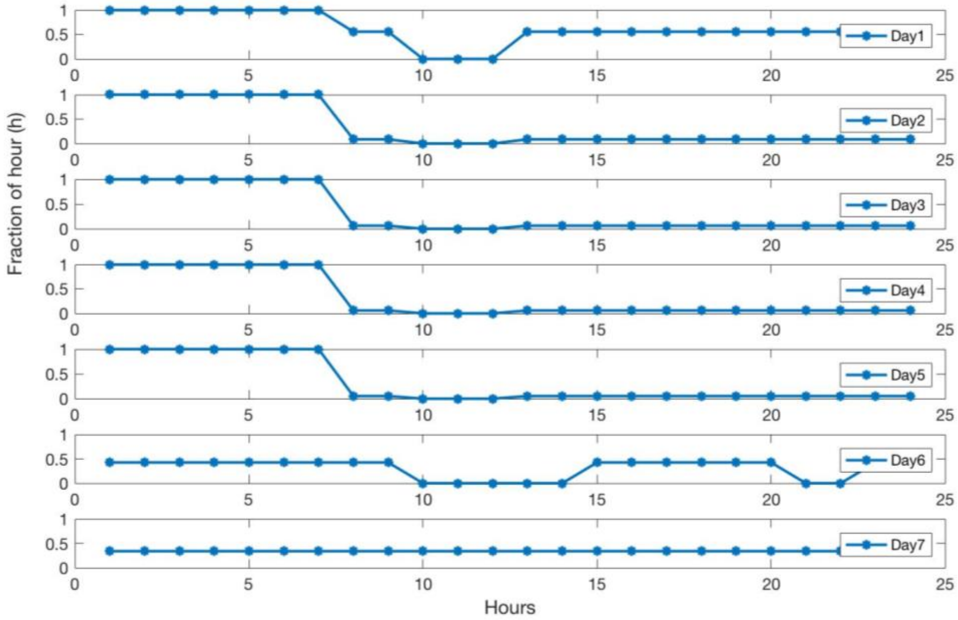


Figure 7: Weekly watering per day for α = 0

On the other hand, if the value of α is increased, then the value of the final water level is at the desired level as expected. This can be seen in Figure 8. The watering done to ensure this is shown in Figure 9.

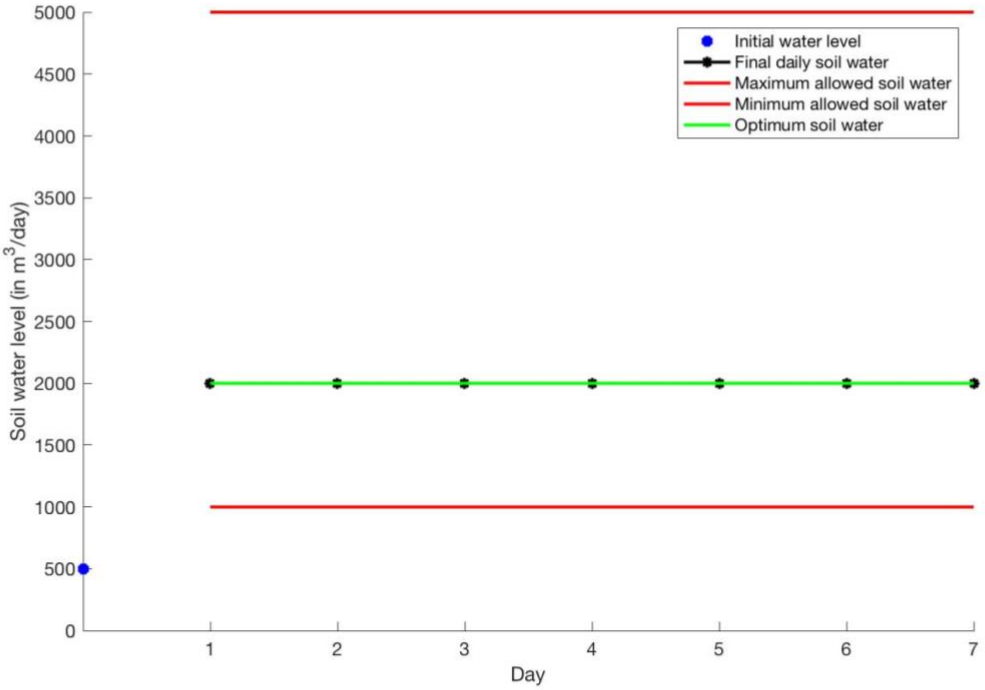


Figure 8: Daily soil water level for α = 1

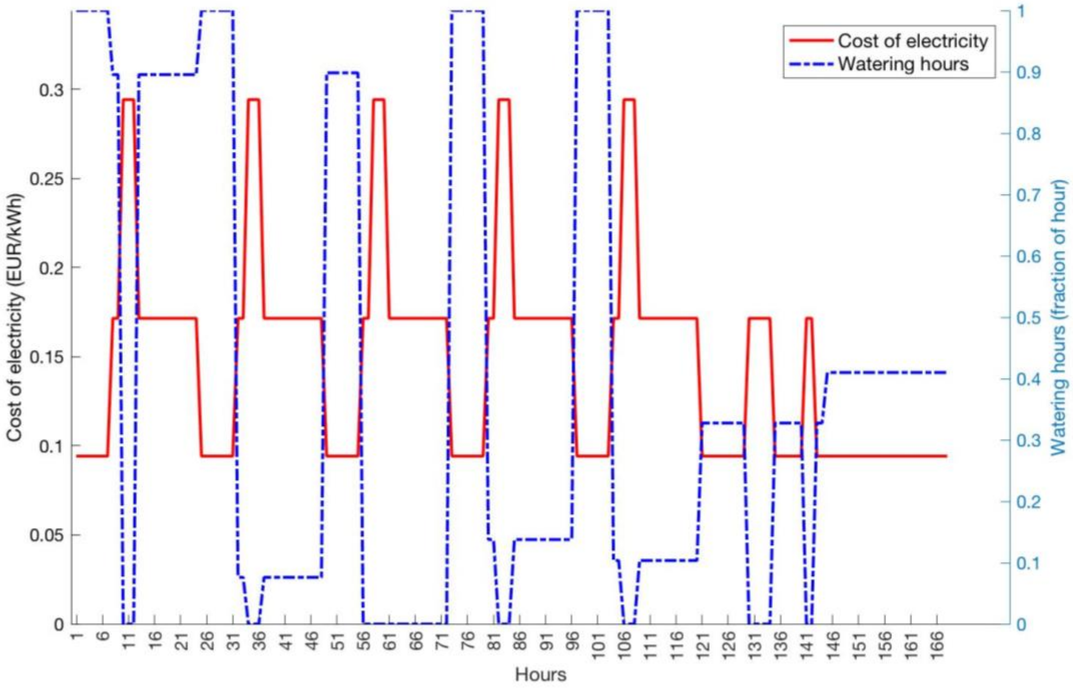


Figure 9: Cost of electricity and watering per day for α = 1

The fraction of the hour for each day of the week which is watered is seen in Figure 10.

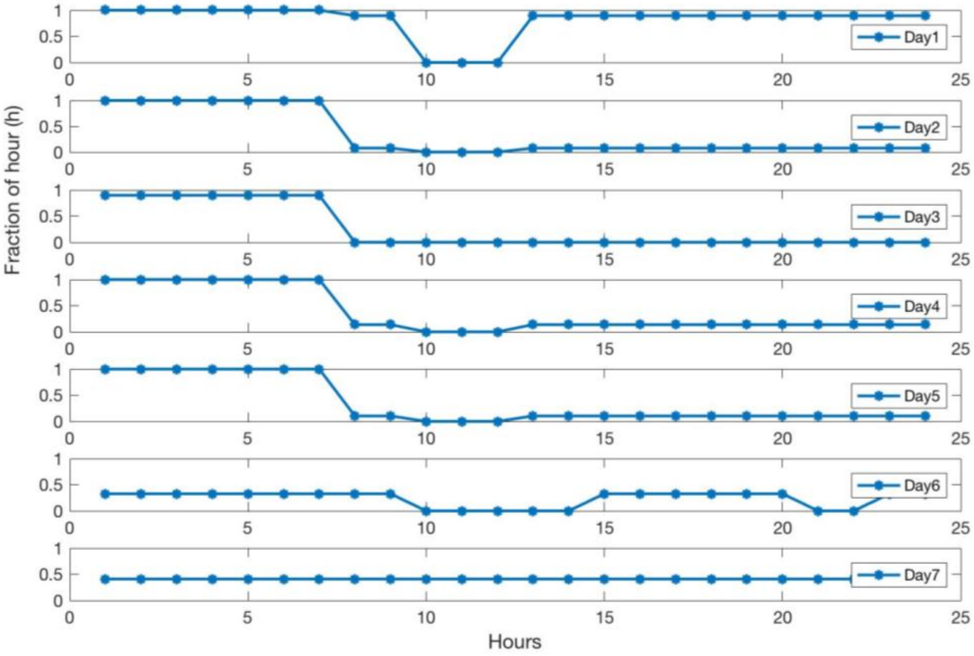


Figure 10: Weekly watering per day for α = 1

The same program is run for a default period 35 days (5 weeks) and the results and trends are observed in Figure 11 to Figure 14.

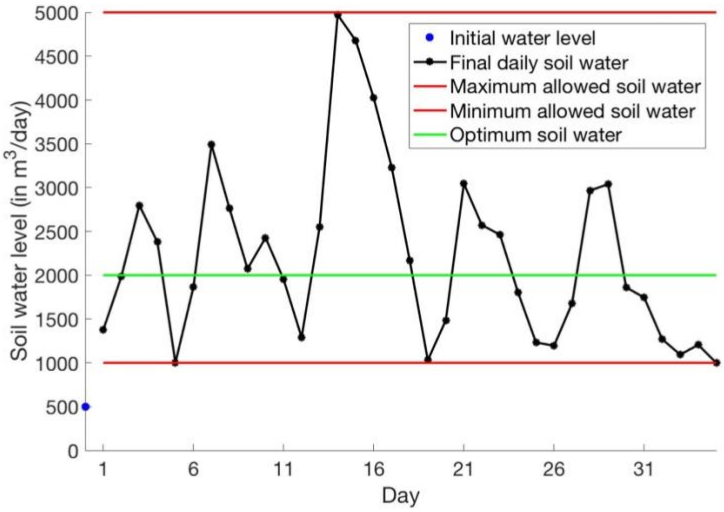


Figure 11: Daily water level for 35 days with α = 0

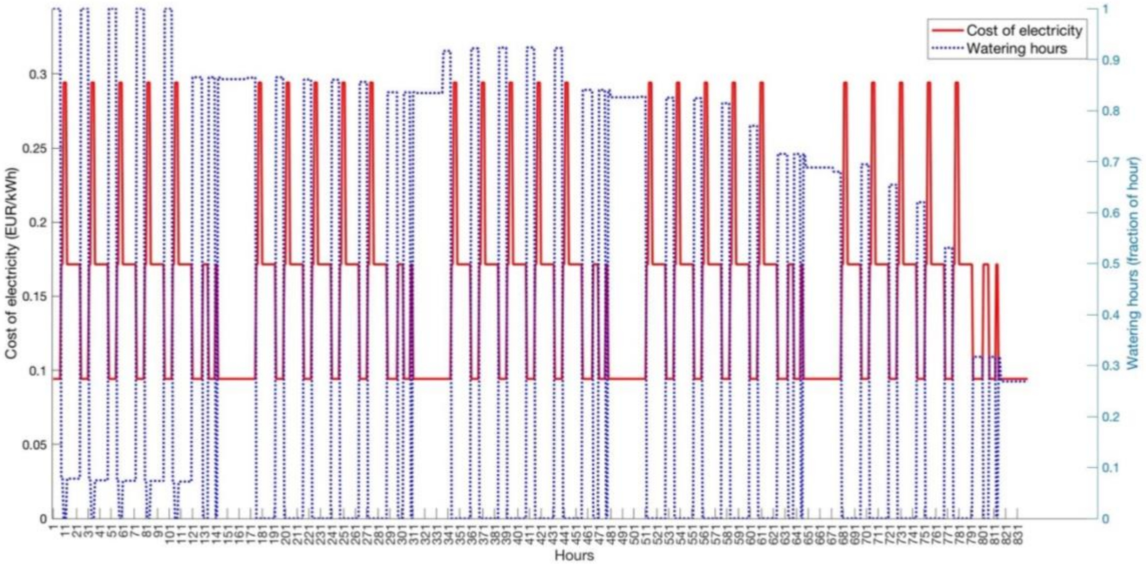


Figure 12: Electricity tariff and watering with α = 0

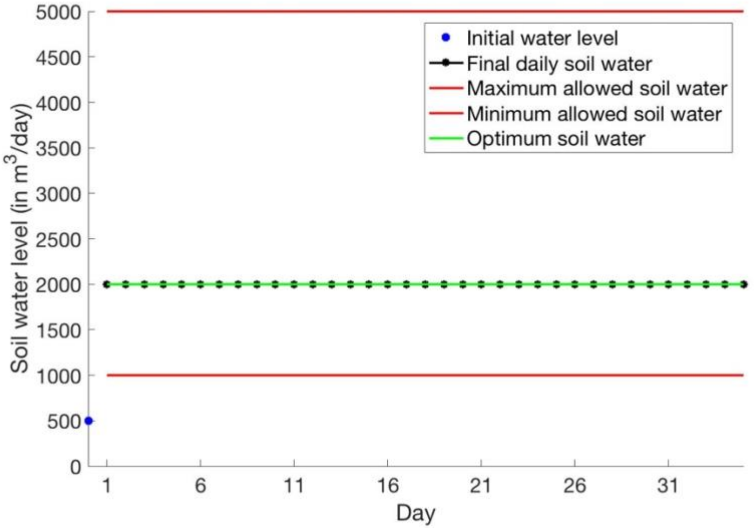


Figure 13: Daily water level for 35 days with α = 1

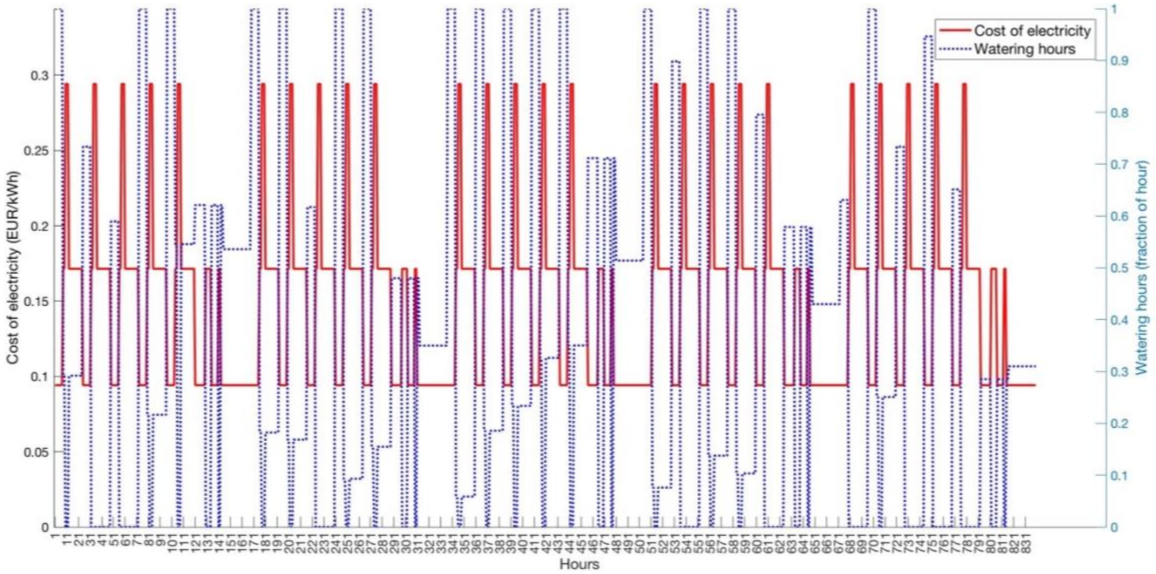


Figure 14: Electricity tariff and watering with α = 1

The total cost for the period in the case where $\alpha = 0$ is €1203. However, when $\alpha = 1$ (Figure 13 and Figure 14), then 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 constraint.

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 so as to save money. It must be noted that the crops never go into a totally stressed state as the maximum and minimum daily flexibility limits for the crop (as specified by the farmer) are always respected.

5.2 Sensitivity analyses

In this section, the sensitivity of the daily soil water levels and cost with respect to the maximum, minimum levels of allowable soil water are examined. Apart from this, the variation with the irrigated land area of the farmer and changes arising due to the variation in the start day of the simulation is investigated.

5.2.1 With maximum allowable soil water

In this section, the sensitivity of the water levels with changing maximum allowable limits is checked to see if any trend is observed.

Figure 15 shows the cost and watering hours variation with changes to the maximum allowable limit.

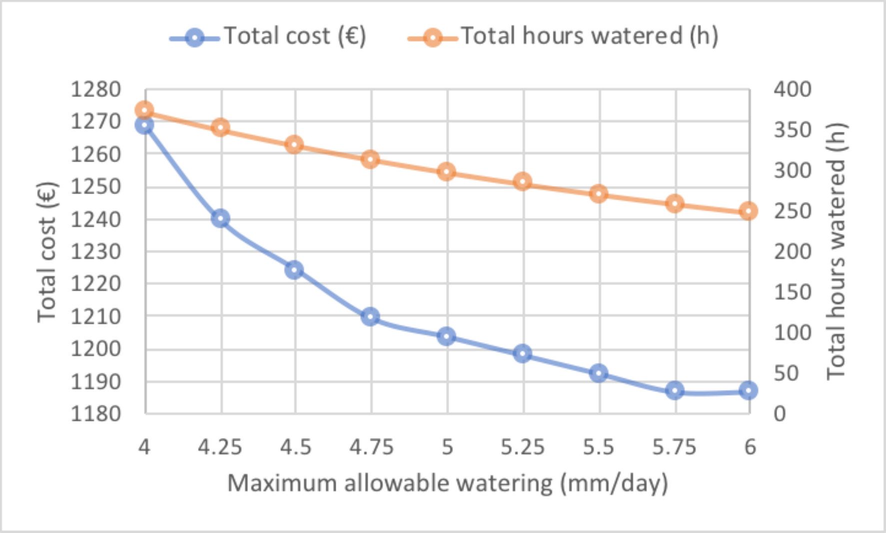


Figure 15: Sensitivity with maximum allowable water with α = 0

It is seen that the total cost and the watering hours decrease with increase in the maximum allowable watering. This is observed because the pumping power increases to take into account the potentially higher amount of water that can be pumped in order to ensure that a higher value for the maximum allowable limit is accommodated. Since the pumping power is increased, the hours in which the irrigation can be achieved decreases. This is observed with an alpha value of 0.

If an alpha value of 1 is used, then the trend observed (seen in Figure 16) is also the same but the slope of the variation is different. The total cost as well as the hours watered are higher in this case as expected.

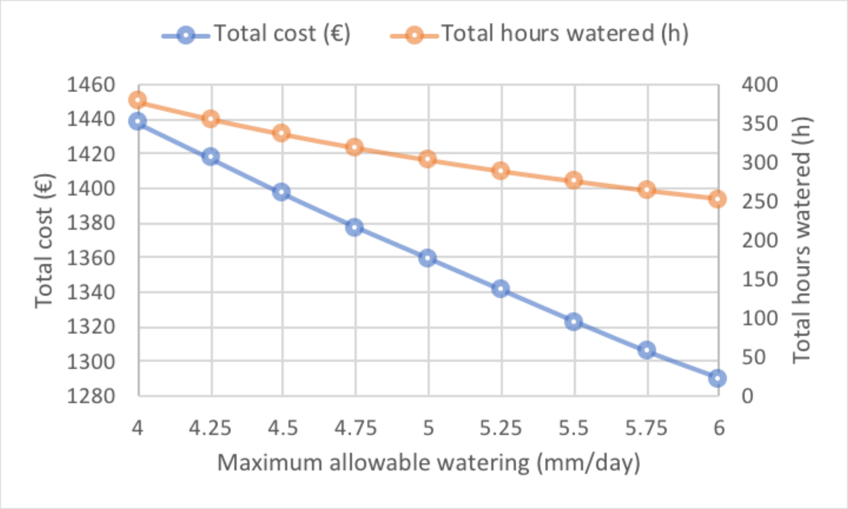


Figure 16: Sensitivity with maximum allowable water with α = 1

5.2.2 With minimum allowable soil water

Figure 17 shows the sensitivity of the total cost and hours watered with the minimum allowable watering limit for alpha = 0. This trend is expected since as the minimum allowable level increases, the plant becomes more demanding in terms of its lowest allowable water limits. This directly results in an increase in total cost. This is observed from Figure 17.

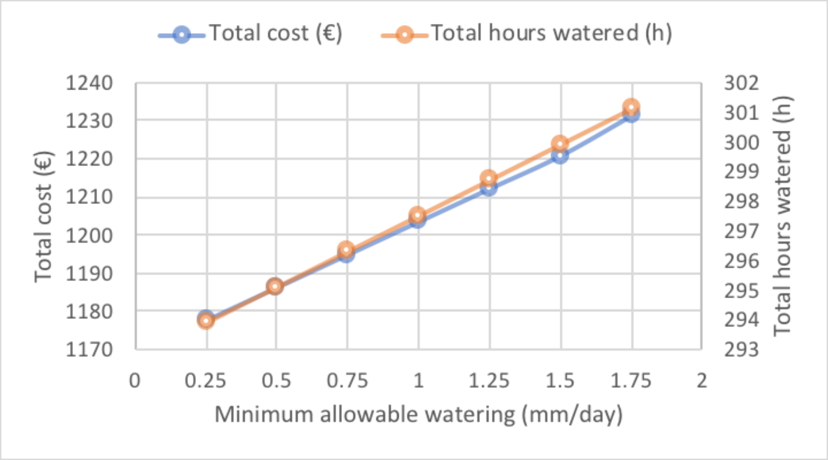


Figure 17: Sensitivity with minimum allowable water for α = 0

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 and therefore this does not contribute to much of a change. This can be seen in Figure 18.

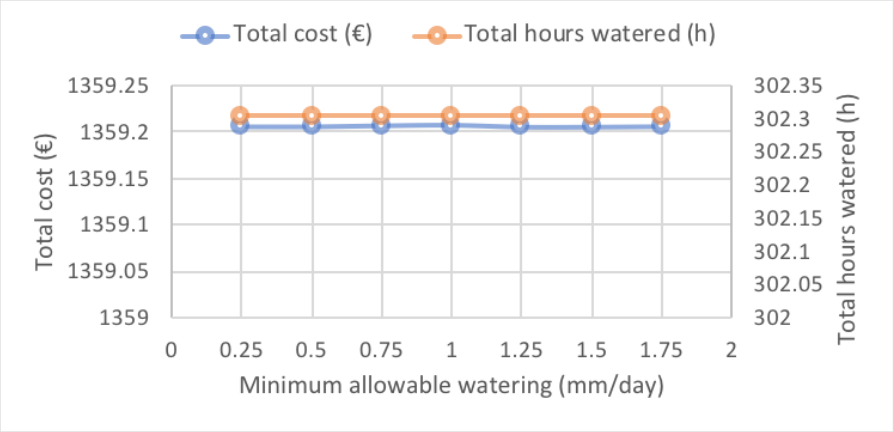


Figure 18: Sensitivity with minimum allowable water for $\alpha = 1$

5.2.3 With irrigated land area

The sensitivity of the total cost for the farmer as land area increases in a simulation of 35 days is depicted in Figure 19. As can be observed, this is carried out for alpha values of 0 and 1 and the cost of the irrigation for alpha = 1 is higher.

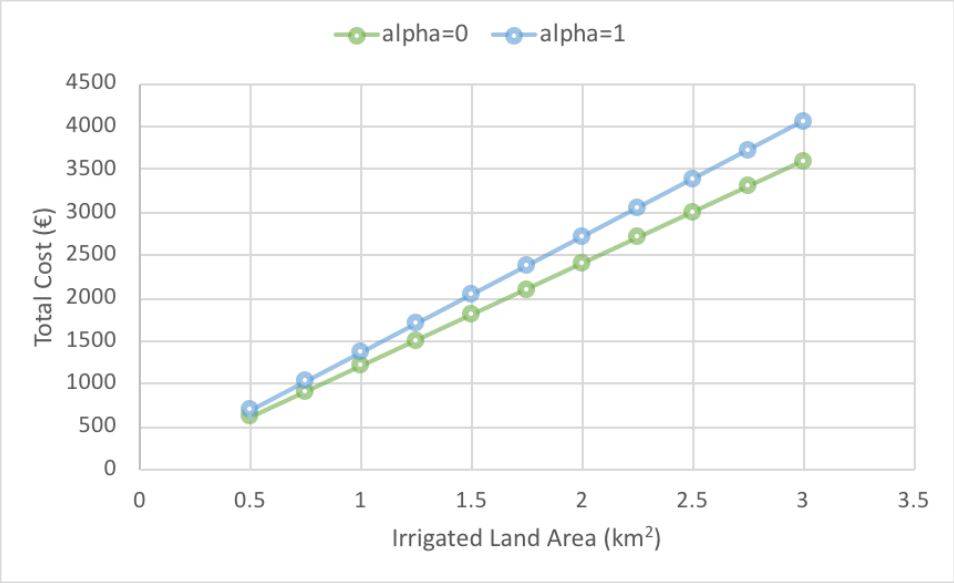
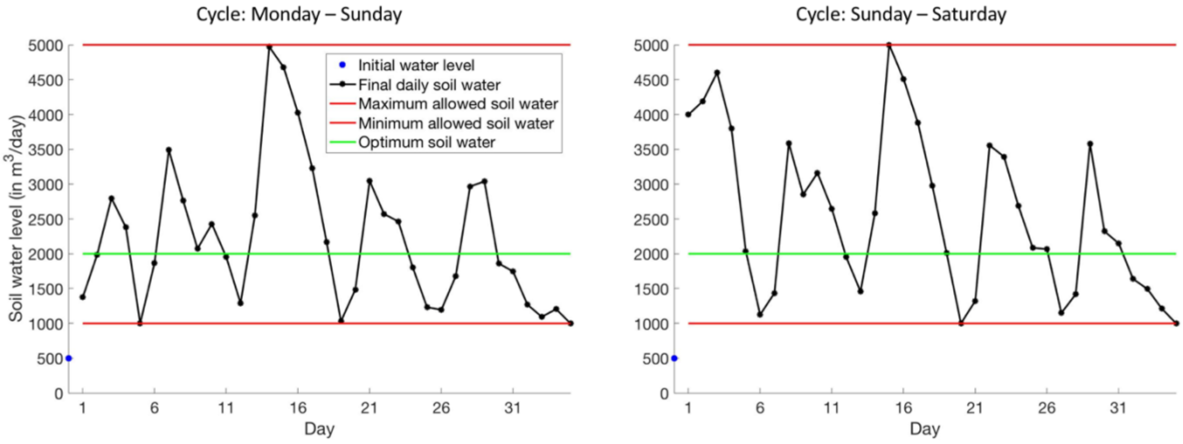


Figure 19: Sensitivity of total cost with irrigated land area

The trend observed is linear because the fraction of the hours for which watering is done remains the same with every run. The only changing parameter in each simulation is the combined rated power of the pumps. This result is also intuitive since the number of pumps (and thereby their combined rated capacity) increases as the irrigation field area increases.

5.2.4 With different start dates of simulation

As demonstrated in Section 5.1, it is seen that the program only has meaning when run over long periods of time (> 1 week). Keeping this in mind, another point to be noted is that the trends of the daily water level are also affected depending on the start day of the simulation. It differs if the simulation is started on a Monday (or any weekday) as opposed to a Saturday or Sunday. This can be seen in Figure 20, which compares the instances when the program is started on Monday (following the weekly tariff cycle from Monday - Sunday) as opposed to when it is started on Sunday (following the weekly tariff cycle from Sunday-Saturday) with alpha 0.


Cycle: Monday – Sunday

Cycle: Sunday – Saturday

Figure 20: Comparison of watering for different program start days for $\alpha = 0$

In both situations, the total hours watered are the same. However the cost in the case of the Monday start is slightly higher (€ 1205) than the Sunday start (€ 1190) since the program is trying to stay within the allowable water limits (starting from initial water of 0.5 mm which is lower than the minimum level). In one case it is able to use the lower tariffs of Sunday right away in comparison with the other case.

6 Potential for integration with electricity suppliers or distributors

While looking for the applications of this model to add business value to existing systems, the electricity market was studied. In this chapter, the possible integration of the optimised code with electricity suppliers or distributors is discussed.

6.1 Overview of electricity markets

To initially understand where the possible integration of the developed code could fit into the business side of electricity suppliers, a brief examination of electricity markets is conducted. The electricity system is shown in Figure 21 [43], consisting of the electricity generator, Transmission System Operator (TSO), DSO and the final electricity consumer (who could also be a prosumer). Based on these actors, the electricity market is broadly divided into the wholesale and retail market.

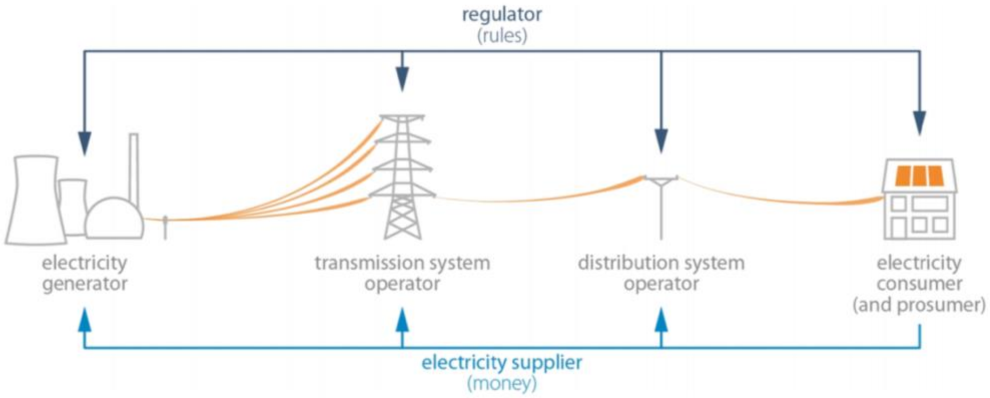


Figure 21: Schematic of the electricity system

6.1.1 Wholesale market

The actors in the wholesale electricity market usually are the generators, electricity suppliers and large industrial consumers [44]. The transactions occurring on this market can be long term or short term.

- *Capacity market*: these markets are usually bound by long term contracts, which are made between generators and large industrial power users. They could be yearly (up to 20 years) or weekly contracts. They are sometimes also referred to as forward or future markets.
- *Day ahead market*: this market is made for the following day on the preceding day where bids are placed on capacity for every hour. Following this, the demand and supply curves determine the equilibrium market price and all the electricity supply players who bid with values higher than the market price end up buying the power from the generators. The result of the auction is such that only the most efficient

generating stations provide power and only the highest bidders can buy the power offered by them.

- *Intra-day market*: this market involves the trade of electricity 15 minutes before the delivery time during specific periods of the day. The prices are higher in this case since it is last minute consumption.
- *Ancillary market*: this market consists of frequency control, voltage regulation and congestion management and is usually done by the TSO in close association with the DSO.

The intra-day and ancillary markets also consist of secondary actors who are either third party power aggregators or Balance Responsible Parties (BRPs). They have control over certain loads through DR programs managing aggregated loads.

6.1.2 Retail market

The retail electricity market operates between electricity supply companies and final consumers. Portugal, as mentioned earlier, has five main electricity suppliers: EDP Comercial, Endesa, Galp, Iberdrola and Union Fenosa [40]. Each company has a competitive pricing scheme to attract more customers and generally offer tariffs based on simple, bi-hourly and tri-hourly schedules as already discussed.

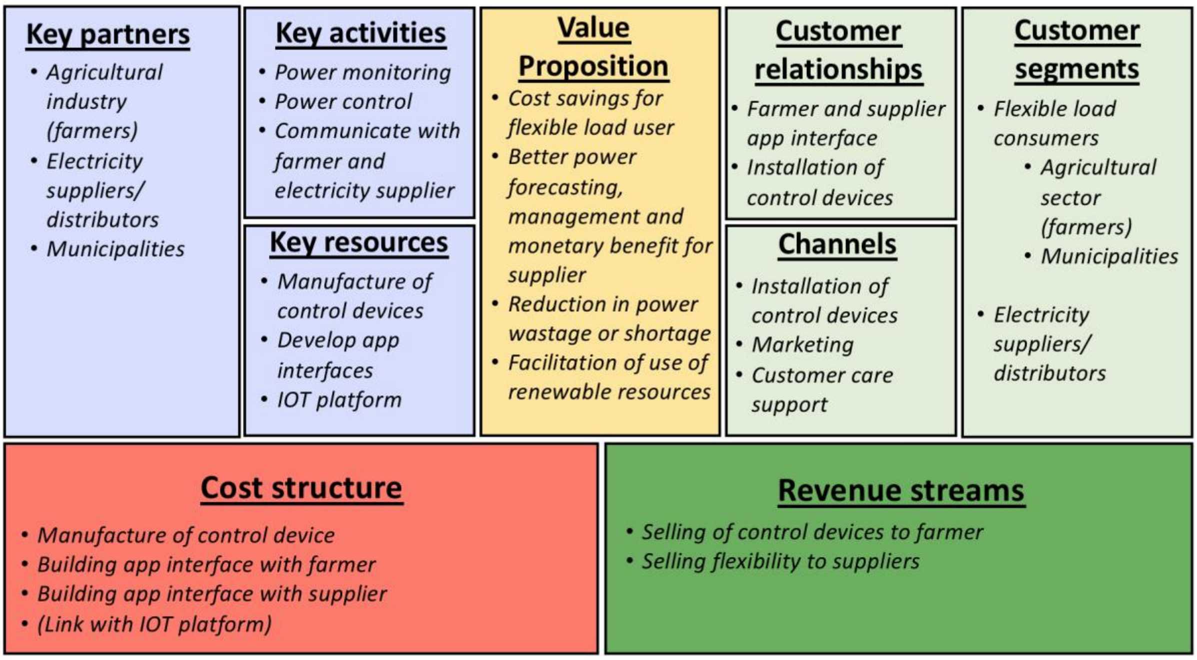
On considering the markets mentioned, the best fit for incorporation of power flexibility is the intra-day or ancillary market since the farmers' flexibility can be used to make real-time changes in power supplies.

7 Business model

To make a viable business proposition for the final model to be developed, in the present chapter the qualitative aspects of the business model canvas as well as a potential quantitative estimation of the pricing scheme is discussed.

7.1 Qualitative analysis

The generic business model canvas for the proposed business case is shown in Figure 22.



Key partners
- *Agricultural industry (farmers)*
- *Electricity suppliers/ distributors*
- *Municipalities*

Key activities
- *Power monitoring*
- *Power control*
- *Communicate with farmer and electricity supplier*

Key resources
- *Manufacture of control devices*
- *Develop app interfaces*
- *IOT platform*

Value Proposition
- *Cost savings for flexible load user*
- *Better power forecasting, management and monetary benefit for supplier*
- *Reduction in power wastage or shortage*
- *Facilitation of use of renewable resources*

Customer relationships
- *Farmer and supplier app interface*
- *Installation of control devices*

Channels
- *Installation of control devices*
- *Marketing*
- *Customer care support*

Customer segments
- *Flexible load consumers*
  - *Agricultural sector (farmers)*
  - *Municipalities*
- *Electricity suppliers/ distributors*

Cost structure
- *Manufacture of control device*
- *Building app interface with farmer*
- *Building app interface with supplier*
- *(Link with IOT platform)*

Revenue streams
- *Selling of control devices to farmer*
- *Selling flexibility to suppliers*

Figure 22: Business model canvas

The **customer segments** are twofold:

- 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) 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.

7.2 Quantitative analysis

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

The agricultural land was estimated and the approximate irrigation needs were determined.

The agricultural land was estimated from Google Earth by observing the pattern of the terrain and measuring and calculating the approximate area that would require irrigation (agricultural lands).

Approximately, the amount of agricultural land estimated in Location 1 is 12km^2, in Location 2 around 45 km^2 and in Location 3 around 18 km^2.

The assumptions made in the power estimation are shown in Table 4.

Table 4: Assumptions for power requirement estimation

Parameter	Assumed value
Annual culture irrigation	600 mm/year
Head (height of underground tank for pumping)	50 m
Motor efficiency	75%
Pump efficiency	90%

Using the above parameters, the pumping power, P_p in $Watts$ is calculated.

The result of the overall electrical energy requirement estimation is shown in Table 5.

Table 5: Power and energy estimation from farmer

Location	Reference	Location 1	Location 2	Location 3
Agricultural land estimation (km^2)	1	12	45	18
Power (kW)	14	166	622	249
Total irrigation electrical energy per year (kWh/y)	120988	1451852	5444444	2177778

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.

8 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 'semi-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 and are found to increase when the minimum allowable soil water is increased.

The code developed for this model has also been extended to optimise the cost of charging of EVs based on the distance to be travelled on the following day and specifications of the vehicle charger and power requirements. Therefore the model is demonstrated to be replicable and extendable to other sectors with appropriate modifications.

8.1 Future work

Going forward, there is potential for augmentation of the present model to make it more comprehensive and useful by adding extra analyses. The following tasks can be performed to take forward the present work and increase its practical value:

1. Integration of the model with the farmers that have RE generation and adding weather models
2. Extension of the model to also aggregate flexibility from other sectors and integrate with the electricity providers.
3. Considering the ramping power while switching on and off the pumps during the hours of use
4. Reducing time resolutions to 15 or 30 minute intervals.

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10 Appendix

This chapter contains the compiled information of the electricity suppliers.

10.1 List of electricity suppliers in Portugal

This appendix contains the details of all the electricity suppliers:

As shown in the text the simple, bi-hourly and tri-hourly schedules are shown from Table 6 to Table 10.

Table 6: Simple scheme

Season	Mon-Fri (hours)
Summer and winter	0-24

Table 7: Bi-hourly weekly schedule

Season	Timings	Monday - Friday (hours)	Saturday (hours)	Sunday (hours)
Summer	Off - peak	0-7	0-9, 14-20, 22-24	0-24
	Peak	7-24	9-14, 20-22	-
Winter	Off - peak	0-7	0-9:30, 13-18:30, 22-24	0-24
	Peak	7-24	9:30-13, 18:30-22	-

Table 8: Bi-hourly daily cycle

Season	Timings	Monday - Sunday (hours)
Summer and winter	Off - peak	0-8, 22-24
	Peak	8-22

Table 9: Tri-hourly weekly schedule

Season	Timings	Monday - Friday (hours)	Saturday (hours)	Sunday (hours)
Summer	Off - peak	0-7	0-9, 14-20, 22-24	0-24
	Medium	7-9:15, 12:15-24	9-14, 20-22	-
	Peak	9.15-12.15	-	-
Winter	Off - peak	0-7	0-9:30, 13-18:30, 22-24	0-24
	Medium	7-9:30, 12-18:30, 21-24	9:30-13, 18:30-22	-
	Peak	9:30-12, 18:30-21	-	-

Table 10: Tri-hourly daily cycle

Season	Timings	Monday - Sunday (hours)
Summer	Off - peak	0-8, 22-24
	Medium	8-10:30, 13-19:30, 21-22
	Peak	10:30-13, 19:30-21
Winter	Off - peak	0-8, 22-24
	Medium	8-9, 10:30-18, 20:30-22
	Peak	9-10:30, 18-20:30

The following are the tariff rates for the respective electricity suppliers:

10.1.1 EDP

Table 11 to Table 13 list the tariffs for the schedules of EDP [41].

Table 11: EDP tariff for simple schedule

EDP- simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
1.15	0.1175	0.1595
2.3	0.1675	0.1598
3.45	0.2182	0.1569
4.6	0.2762	0.1605

EDP- simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
5.75	0.3297	0.1617
6.9	0.3794	0.1619
10.35	0.5321	0.162
13.8	0.6925	0.1633
17.25	0.8522	0.1642
20.7	1.0156	0.1649

Table 12: EDP tariff for bi-hourly schedule

EDP- bi-hourly			
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)	
		Peak (Fora de Vazio)	Off-peak (Vazio)
1.15	-	-	-
2.3	-	-	-
3.45	0.2281	0.2027	0.0968
4.6	0.2806	0.2028	0.0969
5.75	0.3321	0.2029	0.0969
6.9	0.3835	0.2028	0.0969
10.35	0.5337	0.2028	0.0969
13.8	0.6902	0.203	0.0971
17.25	0.8486	0.2034	0.0975
20.7	1.0137	0.2033	0.0974

Table 13: EDP tariff for tri-hourly schedule

EDP- tri-hourly				
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)		
		Peak (Ponta)	Medium (Cheias)	Off-peak (Vazio)
1.15	-	-	-	-
2.3	-	-	-	-
3.45	0.2297	0.2942	0.1715	0.0942

EDP- tri-hourly				
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)		
		Peak (Ponta)	Medium (Cheias)	Off-peak (Vazio)
4.6	0.2816	0.2942	0.1715	0.0942
5.75	0.3336	0.2942	0.1715	0.0942
6.9	0.3857	0.2942	0.1715	0.0942
10.35	0.5357	0.2942	0.1715	0.0942
13.8	0.6928	0.2942	0.1715	0.0942
17.25	0.8584	0.2941	0.1714	0.0941
20.7	1.0242	0.2941	0.1714	0.0941
27.6	1.3282	0.3119	0.1494	0.0757
34.5	1.6373	0.3118	0.1493	0.0756
41.4	1.9552	0.3119	0.1494	0.0757

10.1.2 Endesa

Table 14 and Table 15 show the tariff for the schedules of Endesa as a power supplier. This supplier does not provide power with tri-hourly schedule and sometimes are only provided to heavy industrial customers [45].

Table 14: Endesa tariff for simple schedule

Endesa- simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
1.15	-	-
2.3	-	-
3.45	0.1683	0.1564
4.6	0.2212	0.1564
5.75	0.2718	0.1564
6.9	0.3217	0.1564
10.35	0.4741	0.1564
13.8	0.6292	0.1564
17.25	0.7842	0.1564
20.7	0.9355	0.1564

Table 15: Endesa tariff for bi-hourly schedule

Endesa- bi-hourly			
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)	
		Peak (Fora de Vazio)	Off-peak (Vazio)
1.15	-	-	-
2.3	-	-	-
3.45	0.1683	0.1897	0.0954
4.6	0.2212	0.1897	0.0954
5.75	0.2718	0.1897	0.0954
6.9	0.3217	0.1897	0.0954
10.35	0.4741	0.1897	0.0954
13.8	0.6292	0.1897	0.0954
17.25	0.7842	0.1897	0.0954
20.7	0.9355	0.1897	0.0954

10.1.3 Galp

Table 16 and Table 17 show the tariff for the schedules of Galp as a power supplier. Galp does not provide power with tri-hourly schedule and sometimes are only provided to heavy industrial customers [46].

Table 16: Galp tariff for simple schedule

Galp - simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
1.15	0.1565	0.1608
2.3	0.2065	0.1608
3.45	0.222	0.1608
4.6	0.281	0.1608
5.75	0.3512	0.1608
6.9	0.4221	0.1608
10.35	0.6316	0.1608
13.8	0.8348	0.1608

Galp - simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
17.25	1.0382	0.1608
20.7	1.2419	0.1608

Table 17: Galp tariff for bi-hourly schedule

Galp- bi-hourly			
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)	
		Peak (Fora de Vazio)	Off-peak (Vazio)
1.15	-	-	-
2.3	-	-	-
3.45	0.1683	0.1897	0.0954
4.6	0.2212	0.1897	0.0954
5.75	0.2718	0.1897	0.0954
6.9	0.3217	0.1897	0.0954
10.35	0.4741	0.1897	0.0954
13.8	0.6292	0.1897	0.0954
17.25	0.7842	0.1897	0.0954
20.7	0.9355	0.1897	0.0954

10.1.4 Iberdrola

Table 18 and Table 19 show the tariff for the schedules of Iberdrola as a power supplier. It does not have a bi-hourly schedule scheme [47].

Table 18: Iberdrola tariff for simple schedule

Iberdrola- simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
1.15	0.1565	0.1608
2.3	0.2065	0.1608
3.45	0.222	0.1608
4.6	0.281	0.1608
5.75	0.3512	0.1608

Iberdrola- simple		
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
6.9	0.4221	0.1608
10.35	0.6316	0.1608
13.8	0.8348	0.1608
17.25	1.0382	0.1608
20.7	1.2419	0.1608

Table 19: Iberdrola tariff for tri-hourly schedule

Iberdrola- tri-hourly				
Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)		
		Peak (Ponta)	Medium (Cheias)	Off-peak (Vazio)
27.6	1.4089	0.3065	0.1524	0.0845
34.5	1.756	0.3065	0.1524	0.0845
41.4	2.103	0.3065	0.1524	0.0845

10.1.5 Union Fenosa

Table 20 to Table 22 show the tariff for the schedules of Union Fenosa as a power supplier [48].

Table 20: Union Fenosa tariff for simple schedule

Union Fenosa- simple			
Annual consumption (MWh/year)	Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)
	1.15	0.0849	0.1576
	2.3	0.1346	0.1612
	3.45	0.1844	0.1626
	4.6	0.2341	0.1628
	5.75	0.2838	0.1631
< 10 MWh	6.9	0.3314	0.1636
	10.35	0.4827	0.1652
	13.8	0.6318	0.1638
	17.25	0.781	0.164

	20.7	0.9274	0.1643
> 10 MWh	6.9	0.29983	0.1645
	10.35	0.4475	0.1652
	13.8	0.5966	0.1652
	17.25	0.7458	0.1652
	20.7	0.8949	0.1652

Table 21: Union Fenosa tariff for bi-hourly schedule

Union Fenosa- bi-hourly				
Annual consumption (MWh/year)	Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)	
			Peak (Fora de Vazio)	Off-peak (Vazio)
	1.15	-	-	-
	2.3	-	-	-
	3.45	0.1844	0.2055	0.1001
	4.6	0.2341	0.2053	0.0999
	5.75	0.2838	0.2052	0.0998
< 10 MWh	6.9	0.3194	0.2058	0.1004
	10.35	0.4686	0.2053	0.0999
	13.8	0.6177	0.2054	0.1
	17.25	0.7669	0.2054	0.1001
	20.7	0.916	0.2055	0.1002
> 10 MWh	6.9	0.29983	0.2065	0.1011
	10.35	0.4475	0.2059	0.1005
	13.8	0.5966	0.2059	0.1005
	17.25	0.7458	0.2059	0.1005
	20.7	0.8949	0.2059	0.1005

Table 22: Union Fenosa tariff for tri-hourly schedule

Union Fenosa- tri-hourly					
Annual consumption (MWh/year)	Contracted power (kVA)	Price per day (€/day)	Price per kWh (€/kWh)		
			Peak (Ponta)	Medium (Cheias)	Off-peak (Vazio)
	1.15	-	-	-	-
	2.3	-	-	-	-
	3.45	0.1844	0.27978	0.1732	0.0956
	4.6	0.2341	0.3023	0.1777	0.1001
	5.75	0.2838	0.3023	0.1777	0.1001
< 10 MWh	6.9	0.3334	0.3019	0.1773	0.0997
	10.35	0.4827	0.3016	0.177	0.0994
	13.8	0.6318	0.3016	0.177	0.0994
	17.25	0.781	0.3018	0.1772	0.0996
	20.7	0.9301	0.3021	0.1775	0.0999
	27.6	0.12284	0.305	0.1487	0.0794
	34.5	1.5267	0.3051	0.1488	0.0795
	41.4	1.8251	0.3052	0.1489	0.0796
> 10 MWh	6.9	0.29983	0.3032	0.1786	0.101
	10.35	0.4475	0.3026	0.178	0.1004
	13.8	0.5966	0.3026	0.178	0.1004
	17.25	0.7458	0.3026	0.178	0.1004
	20.7	0.8949	0.3026	0.178	0.1004
	27.6	1.1932	0.3055	0.1492	0.0799
	34.5	1.4915	0.3055	0.1492	0.0799
	41.4	1.7898	0.3055	0.1492	0.0799

Depending on the electricity supplier chosen by the farmer in the input user interface tab of the app, the cost function and schedule is modified in order to make the usage optimisation.