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Water-Energy-Food nexus approach for sustainable innovation: application In agrivoltaics for desalination in a dry rural environment

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Water-Energy-Food Nexus Approach For Sustainable Innovation: Application In Agrivoltaics For Desalination In A Dry Rural Environment

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Abstract

Nowadays, the world is facing many issues regarding the well-being of humans and the environment. Many causes may be related to this problem, such as energy production based on fossil fuels, water scarcity in some areas of the world along with the unbalanced allocation of global fresh water, food insecurity in arid regions, etc. More specifically, agriculture fields in arid areas not only need much more water than other regions, but also the accessibility to fresh water is much more limited. Apart from this, a lot of energy in the form of renewables can be obtained in these areas, but these usually correspond to poor areas of the world where tis extraction is much more difficult. The chosen case study corresponds to an area called Chtouka-Ait Baha, Morocco, where a desalination plant was built recently to provide water to many different agricultural fields and greenhouses, apart from the water extracted from other water sources. Nowadays, this area suffers from severe food and water scarcity, with the projection of losing access to groundwater in the future due to reckless extraction. In order to tackle all of these issues at once, any sustainable solution for water use and energy security should be implemented addressing every aspect of the Water-Energy-Food nexus. The idea is to install photovoltaic panels above the crops to power the desalination plant and reduce the irrigation requirements. A framework is developed to be able to analyse the different features of the area and the nexus between them, and another software called MicroGridsPy serves as the decision taker in the implementation stage. As for the results obtained, a reduction in irrigation of around 20% is achieved, while powering with electricity all the assets of the region occupying a moderately low amount of area compared with the total area of study.

Key words: agrivoltaics; desalination plant; wef nexus (water-energy-food nexus); framework; photovoltaic panels; irrigation; greenhouses

Al giorno d'oggi, il mondo sta affrontando molti problemi riguardanti il benessere umano e l'ambiente. Molte cause possono essere legate a questo problema, come la produzione di energia basata sui combustibili fossili, la scarsità d'acqua in alcune aree del mondo insieme all'allocazione sbilanciata delle risorse idriche globali, l'insicurezza alimentare nelle regioni aride, ecc. Più specificamente, i campi agricoli nelle aree aride non solo necessitano di molta più acqua rispetto ad altre regioni, ma anche l'accessibilità all'acqua dolce è molto più limitata. Oltre a questo, molta energia sotto forma di fonti rinnovabili può essere ottenuta in queste aree, ma queste di solito corrispondono a zone povere del mondo dove questa estrazione è molto più difficile. Il caso di studio scelto corrisponde a un'area chiamata Chtouka-Ait Baha, in Marocco, dove è stato recentemente costruito un impianto di desalinizzazione per fornire acqua a molti campi agricoli e serre diversi, oltre all'acqua estratta da altre fonti idriche. Al giorno d'oggi, questa area soffre di grave scarsità di cibo e acqua, con la previsione di perdere l'accesso alle falde acquifere in futuro a causa dell'estrazione sconsiderata. Per affrontare tutti questi problemi contemporaneamente, qualsiasi soluzione sostenibile per l'uso dell'acqua e la sicurezza energetica dovrebbe essere implementata affrontando ogni aspetto del nesso Acqua-Energia-Cibo. L'idea è di installare pannelli fotovoltaici sopra i campi per alimentare l'impianto di desalinizzazione e ridurre i requisiti di irrigazione. Viene sviluppato un framework per poter analizzare le diverse caratteristiche dell'area e il nesso tra di esse, e un altro software chiamato MicroGridsPy funge da decisore nella fase di implementazione. Per quanto riguarda i risultati ottenuti, si ottiene una riduzione dell'irrigazione di circa il 20%, alimentando con elettricità tutte le risorse della regione occupando una quantità moderatamente bassa di area rispetto all'area totale di studio.

Parole chiave: agrivoltaico; impianto di desalinizzazione; nesso acqua-energia-cibo (nesso wef); framework; pannelli fotovoltaici; irrigazione; serre

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Introduction

Current situation on climate change is critical, as several impacts on well-being of humans have been noticed, not only in the form of extreme weather events, such as heatwaves, storms or floods, but also illnesses and diseases. Regarding low-income countries, these areas are the most affected by climate change, as death rate due to extreme weather events has been fifteen times higher than in less vulnerable countries, even though their contribution to global emissions could be considered negligible, as stated by the WHO [1]. Moreover, according to WHO database, six hundred million people get foodborne illnesses every year and 2 billion people lack access to safe drinking water, besides the fact that children under the age of five account for 30% of foodborne deaths. Climate stressors increase waterborne and foodborne disease risks, especially in vulnerable areas, affecting food availability, quality and diversity. All these consequences are related to three main areas: pollution, water scarcity and food insecurity.

Pollution refers to any human waste released to any mean of nature. It has recently increased by 66% due to many different factors like industrialisation, urbanisation, fossil fuels, etc, causing over nine million deaths each year [2]. As for air pollution, the most dangerous form of pollution, it represents around seven million deaths each year and its main contributor is particulate matter, which are defined as small particles of matter with a diameter less than 2.5 micrometres [3]. The smaller the particle is, the easier it is to enter our respiratory system and cause severe damage to our health. The main sources that emit these kind of particles are related to human activities, such as industrial machines, power generation stations, vehicles, etc [4].

This issue is related to the term energy transition, which is based on two main aspects [5]. The first one refers to optimization of current energy systems, trying to reach new frontiers for the efficiency of new technologies, but also to create new frameworks that can represent the connections among policy formulation, growth of energy infrastructure, market dynamics, environmental consequences, and supply reliability. And the second aspect refers to the task of effectively managing the environmental and social costs, risks, and benefits of this transition in a sustainable manner, in order to quit using fossil fuels which not only pollute the environment but will also run out eventually.

The most challenging issue for energy transition is managing the variability in the outputs for some renewable energy sources, as these are very dependent on natural events such as wind gusts, sun hours or river flows. In order to be able to provide energy at any demand hour, this energy must be stored to be released when needed. Most common natural energy sources can be stored relatively easy, such as potential energy for water can be obtained by storing the mass of water in a high place, or heat energy by using isolation walls for the recipient used for storage, but the most common and commercial form of energy, which refers to electricity, cannot be so easily stored as the technology of batteries among other type of storages do not currently allow to storage big amounts of electricity [6].

More specifically, the different electricity storage technologies are divided into four different work principles, these being electrical, mechanical, thermal and chemical [6], [7]. In *Figure 1*, it is shown the main technologies for each category and their time scale, specifying the amount of time needed to charge and discharge

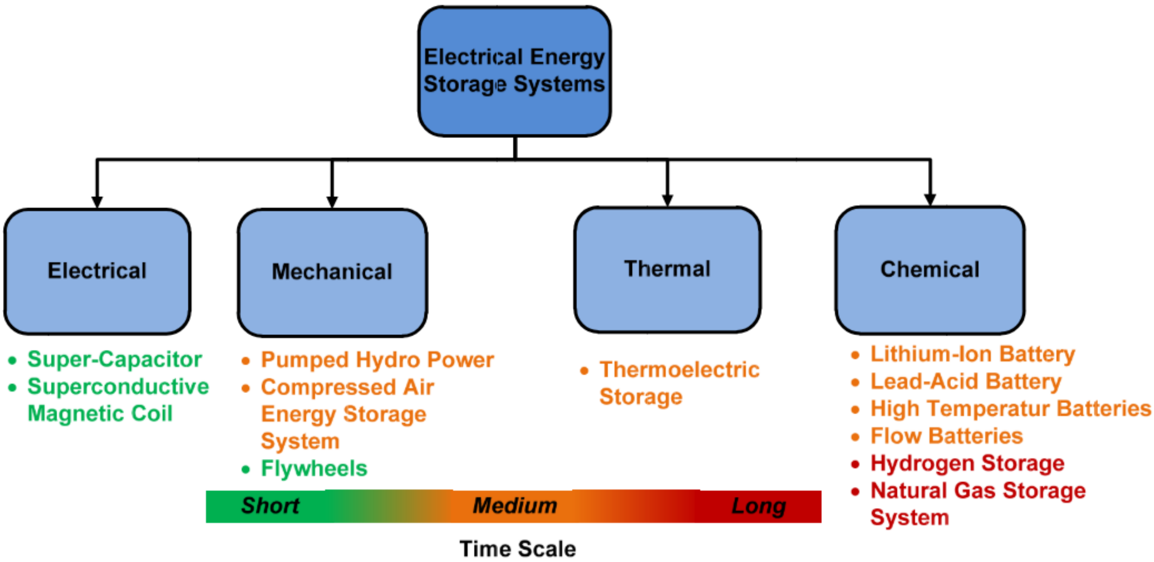

Figure 1 - Classification of Energy Storage Technologies

Another relevant issue concerning human's wellbeing is water scarcity, leading to a severe threat to food security, human health and natural ecosystems [8]. This problem is mainly noticed in arid regions, where most of the population is concentrated and every source of freshwater is either far away or scarce, while the majority of freshwater is found in areas with very low density of population [9]. Just to give a bare estimation of the global distribution of water, 68.9% of freshwater comes from glaciers, while the remaining 30.8% corresponds to groundwater and the final share of 0.3% belongs to freshwater coming from lakes and river, that is to say, surface water [10]. This uneven distribution of freshwater, alongside with an exponential rise in population and a decline in water availability, greatly affect not just water usage and withdrawal rates, but also global security. A decrease in withdrawal levels leads to higher water scarcity, resulting in heightened security tensions.

This can be easily seen in current conflicts over water, being the conflict between Egypt and Ethiopia one of the most relevant, arguing over the control of Nile river. Egypt has held power over the Nile for many years. Nevertheless, Ethiopia recently built a large dam to produce hydroelectric power. Ethiopia asserts that the dam will have no impact on the flow of the Nile downstream, but Egypt does not share the same opinion, believing that the dam will negatively affect the availability of such an important resource as water is [11]. Moreover, according to the Pacific Institute and the list of water conflict chronology that they have created and keep creating to this day, there have been 543 conflict over water since 2020 [12].

Another closely related matter is the decline in chemical quality of water post usage. Nations like Pakistan, China, India, Argentina, Sudan, and countries in central Asia with large populations are impacted by the wastewater produced post-usage. If the treated wastewater cannot be recycled, it will flow into the remaining water sources and impact the chemical composition of freshwater, consequently affecting its usability [9]. Moreover, about half of the wastewater produced by humans is released into rivers or oceans without being treated, polluting the few sources of freshwater available for humanity [13].

Apart from this, salinity plays a crucial role in the chemical quality of water. Not only the presence of dissolved salts and ions in water can create challenges for humans as they impact its chemical properties, but also it can affect agriculture [9]. When the water taken out for crops goes beyond the root area and combines with groundwater, it elevates the water table and brings salt to the surface of the earth. When the water evaporates from the mixture, it results in leaving the salt in the soil, leading to soil salinity that reduces agricultural productivity and causes food insecurity.

Desalination is regarded as one of the most efficient methods for expanding water supply. However, it is crucial to understand that, in order to tackle this issue, a diverse strategy must be implemented, taking into account centralized management, education, advancements in water collection and harvesting technologies, irrigation, farming methods, distribution systems, leak prevention, recycling of wastewater, etc [13].

Finally, one main consequence of the instability generated by these issues is food insecurity. It is defined as the inability to reach the minimum intake of calories needed by a person in a single day [3]. This issue was already very severe in certain parts of the world, such as Sub-Saharan Africa and Southern Asia, as shown in *Figure 2*, but the pandemic and the wars between Ukraine and Russia, and between Palestine and Israel has only aggravated the situation. *Figure 2* also shows the incredibly high rates of undernourished individuals in some areas of the world, while in North America or Europe this rate is below 2.5%, showing the disparity between developed countries and developing countries, as the world's average is 9.2% nowadays.

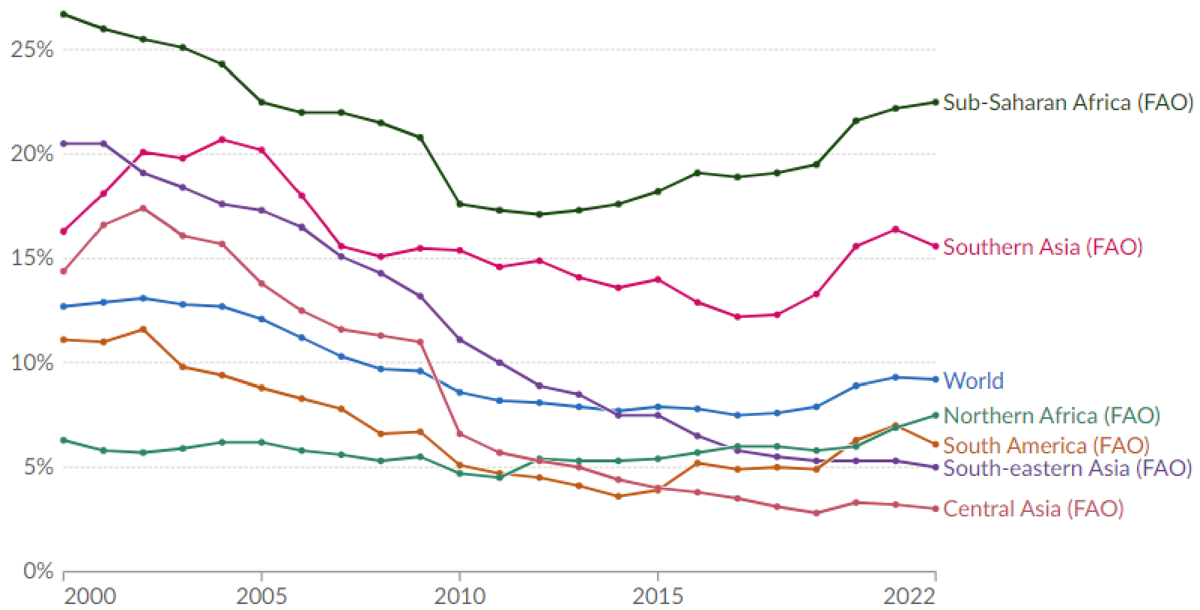

Figure 2 - Share of the population that is undernourished (2022, Our World in Data)

Moreover, according to FAO [14], almost six hundred million individuals are expected to suffer from chronic hunger in 2030, showcasing the significant hurdle in reaching the SDG goal of ending hunger. This is approximately one hundred and nineteen million higher than a situation without the pandemic or the war in Ukraine or Palestine, and about twenty-three million more than if the war in Ukraine had not taken place. It is anticipated that Asia will experience the most advancements, while Latin America and the Caribbean are not expected to see any progress. In Africa, hunger is predicted to greatly escalate by 2030.

Another relevant indicator of food insecurity, and more specifically malnutrition, is the share of children who are stunted [15]. Stunting occurs when a child's height is considerably below the normal range for their age, caused by inadequate nutrition and/or frequent infections. *Figure 3* shows the current status of this indicator, showing that the areas previously mentioned also show high values for this indicator, while areas with low values in the share of undernourished individuals present exceptionally low values or no data, stating that this issue is not relevant in those countries.

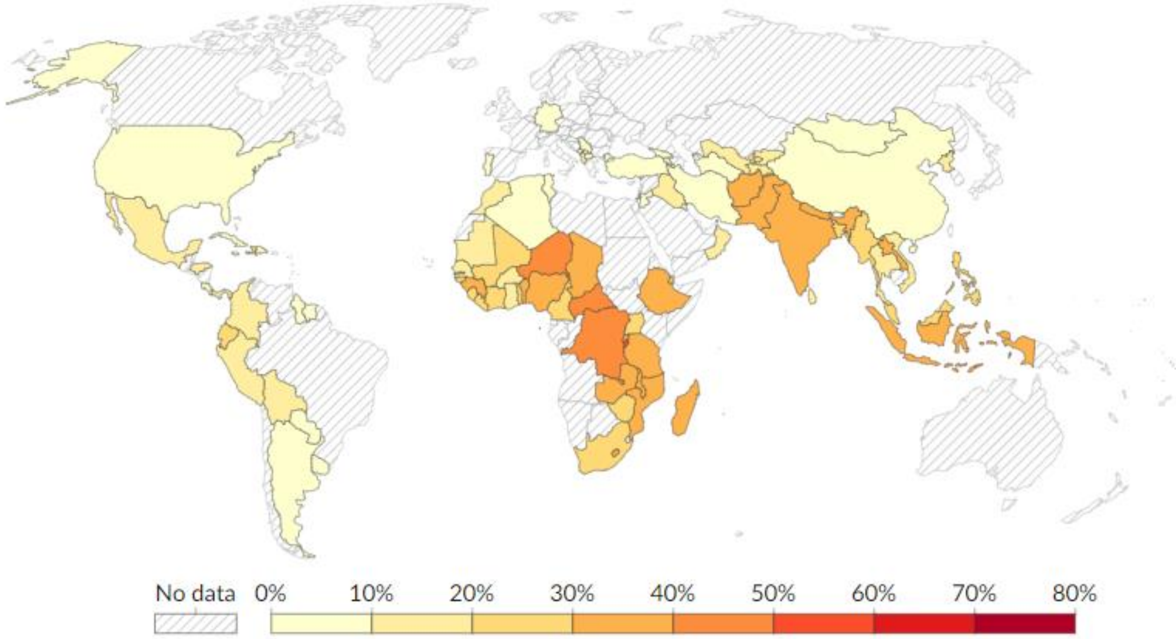

Figure 3 - Share of children who are stunted (2021, Our World In Data)

Regarding the sector of agriculture, inflation on food price is higher than 5% in half of the world, leading to a lack of food availability and access for many families around the world [16]. Besides, as a consequence of the war between Ukraine and Russia, many countries have put in place restrictions, not only on the export of food, but also on fertilizers and insecticides trading.

All of these issues can be considered by implementing a Water-Energy-Food nexus approach, which focuses on recognizing trade-offs and synergies among water, energy, and food systems, integrating social and environmental impacts, and direct the development of policies that span across sectors [17], [18], [19].

As a summary, many problems are threatening the Earth and its life on it, mainly due to human activities, so it is our responsibility to think on ways to not only stop this trend, but also to reverse the situation into a recovery path so that future generations can enjoy a fruitful life.

Finally, with this study, the following Sustainable Development Goals will be covered: SDG number 1, No Poverty; SDG number 2, Zero Hunger; SDG number 3, Good Health and Well-Being; SDG number 6, Clean Water and Sanitation; SDG number 7, Affordable and Clean Energy; SDG number 11, Sustainable Cities and Communities; and SDG number 13, Climate Action [20].

State of the Art

In the next section, named Methodology, the relationships between the different technologies and assets to be taken into account will be explored, showing what is needed to be able to integrate all of these technologies together, apart from the technical pathways to make this happen for a specific area that meets the requirements.

For this current section, each of the technologies will be explained from an engineering point of view, deepening in its characteristics, its requirements and its products. The features to be explained are desalination plant and agrivoltaics.

Desalination Plant

As commented earlier, desalination is widely regarded as a vital source of fresh water. Nevertheless, one of the biggest obstacles to its widespread use is its high cost. The whole process requires around 75.2 TWh per year, which represents around 0,4% of global electricity, used to power the water pumps and the treatment processes [21]. Energy required by desalination plants can be divided into four sections: the pumping system, which refers to the water intake; the pre-treatment processes, which refer to the filtering of raw water to eliminate solid elements and using chemicals to decrease salt buildup and corrosion within the desalination system; the desalination processes, in order to remove salt from saltwater to obtain fresh water; and the post-treatment processes, which involves the correction of pH [22], [23], as shown in *Figure 4*. As for the pumping system, it depends on distance, flow rate and friction, and as for the three treatment processes, these depend on quality of water fed into the system, treatment technology employed and plant capacity [24].

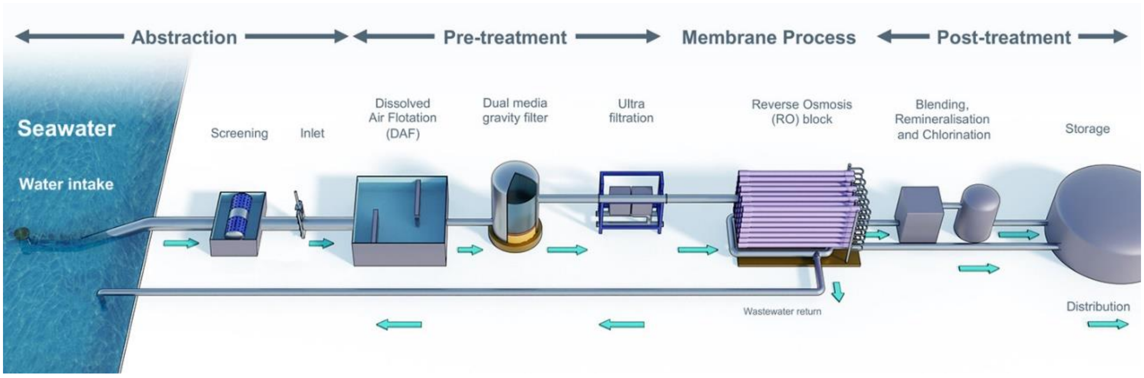

Figure 4 - Processes of a desalination plant (rotork.com)

Desalination techniques have relied either on mechanically driven membrane processes like reverse osmosis (RO) or on thermal distillation techniques like multi-stage flash (MSF) and multi-effect distillation (MED) [25], [26], [27]. These technologies correspond to the 93.2% of the total desalination plants, with reverse osmosis corresponding to the 68.7% [22]. For their high importance above other kind of technologies, these processes will be explored more in detail, with a special emphasis on reverse osmosis.

Multi-effect distillation (MED) consists on several heat recovery exchangers set in line in order to re-use the output heat from the previous heat exchanger, as well as a final condenser, as shown in *Figure 5*. Pipes transport the vapor from the initial chamber to the following one and, as the pressure in the second chamber is less than that in the first one, the boiling point is also lower. This allows for the condensation of vapor in the first chamber and simultaneous vapor production in the second chamber by channelling the vapor through pipes. This procedure is carried out in the following chambers in a similar manner, utilizing the steam produced in the preceding flash chamber to create additional vapor at reduced pressure. In the ultimate chamber, the vapor is condensed within the condenser, which is chilled by the saltwater. The salty water generated in earlier compartments is typically moved into the following compartments to enhance the removal of additional fresh water, due to the reduced pressure within them [22].

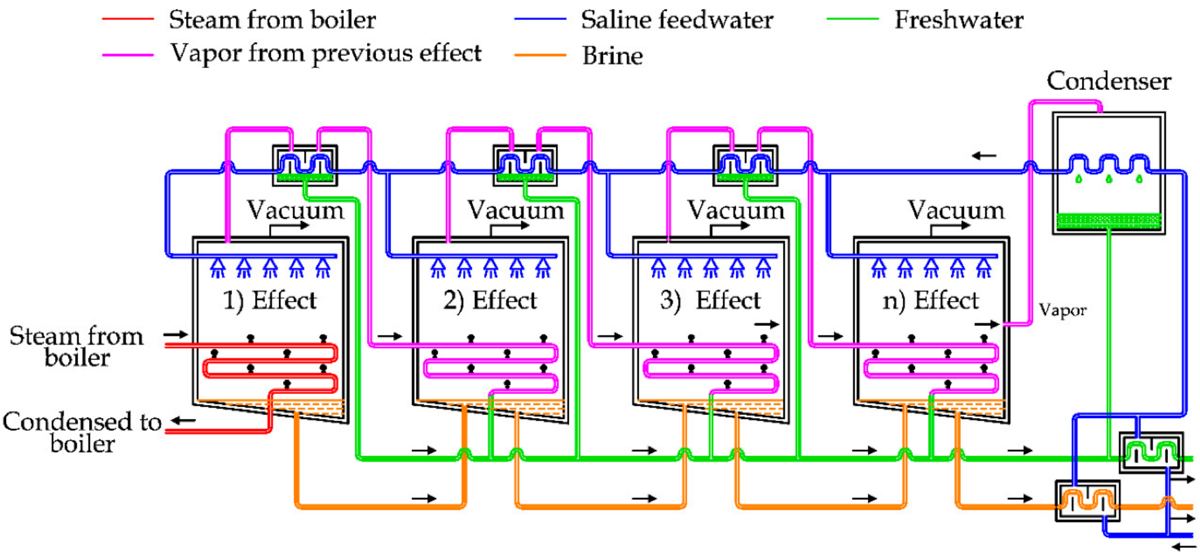

Figure 5 - Multi-Effect Distillation (MED) desalination unit

MED is especially impacted by the issue of scaling on the pipes when compared to other desalination technologies that rely on heat. From the 1980s onwards, numerous research studies have been conducted on MED, exploring ways to lower temperatures in order to address scaling problems and pipe corrosion. Nevertheless, MED is currently used in the food sector for extracting juice from sugarcane and obtaining salts from seawater as well [22].

As for Multi-Stages Flash (MSF) desalination plants, they share some similarities with Multi-Effect Distillation (MED) desalination plants, as a heat supply is needed and they take advantage of the reduction in pressure in order to create vapor. As seen in *Figure 6*, the main difference is that freshwater is obtained directly in the heat exchangers inside the flash stages, and not in separate chambers. This makes MSF plants much easier to perform maintenance operations on removing the scaling, as saltwater only flows through one line of pipes, and not two as in MED desalination plants [22]. For clarification, scaling consists on the crystallization of a concentration of salts into the walls of the pipes due to the excess on the solubility limit of the concentration [28].

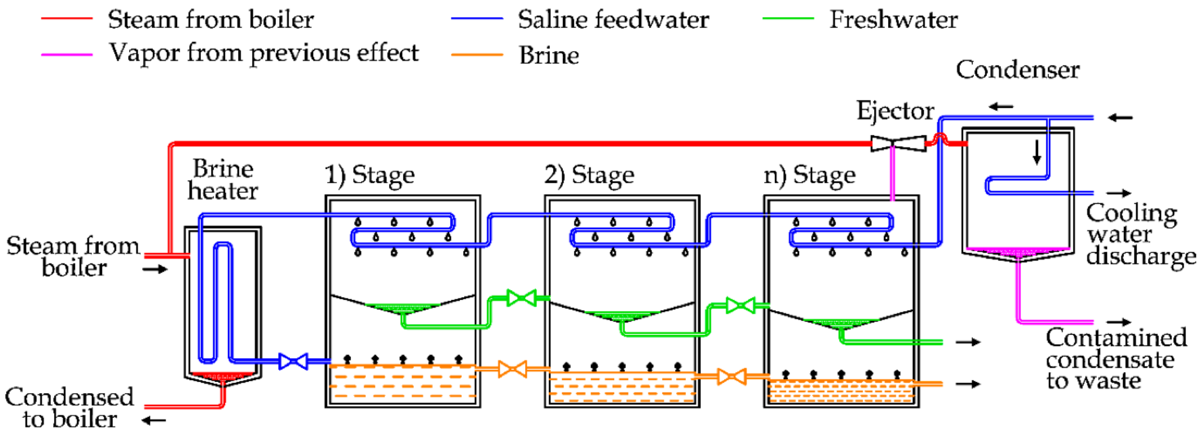

Figure 6 - Multi-Stage Flash (MSF) desalination unit

Finally, referring to reverse osmosis (RO) desalination plants, they are one of the most energy-efficient methods to obtain freshwater from saltwater [29], especially compared to the other two commented methods above. This technology is becoming increasingly popular due to their ease of use, compactness, low chemical usage, low energy consumption, and the development of improved membrane materials. This technology consists on a RO membrane that filters the supplied seawater in order to remove salt. As we are dealing with membranes, the removal of suspended and dissolved solids in the pre-treatment processes is key, to make sure that the membrane is never blocked by any unwanted residues [28].

Apart from the different existing technologies to obtain freshwater from seawater, some other issues need to be accounted for, being one of them the powering of these plants. As commented earlier, desalination plants consume a vast amount of energy, currently supplied mainly from fossil fuels and non-renewable sources of energy, polluting the environment in the form of greenhouse gases emissions. Moreover, other polluting outputs are obtained from this process, such as brine, chemicals added during pre-treatment, by products obtained from the chemical reactions taking place in the pre-treatment processes, etc [30].

For these many reasons, it is necessary to power desalination plants with renewable energy sources, in order to decrease the greenhouse gases emissions as much as possible. Solar, wind, geothermal, wave, and tidal energy, in addition to hydropower and biomass energy, are the primary sources of renewable energy. Hydropower and biomass energy are not compatible with desalination technology as they rely on water resources that may be lacking in countries with water scarcity. Furthermore, solar energy is the most suitable renewable energy source to combine with desalination technology as it can generate the necessary heat and electricity for all desalination processes, regardless the technology employed [31].

Nevertheless, several factors impact the selection of a renewable energy source for a desalination plant, including the plant's size, location, feed pressure, feed water characteristics and projected cost of the water product. The primary obstacles to the implementation of renewable energy are the low levels of intensity and intermittence of various renewable energy sources [32]. For this reason, a hybrid perspective with a high penetration of renewables is the preferred strategy nowadays, in order to have backup energy for those moments when renewables cannot provide energy to the system, even though a residual amount of greenhouse gases emissions would be thrown to the environment.

Finally, after considering how to obtain freshwater from saltwater and its challenges, what that water will be used for is a key aspect of this whole process, being the main two purposes irrigation water for agriculture and drinking water to meet domestic and industry demands. In more detail, roughly 69% of the world's usable water resources are utilized for irrigation, with the rising demand for water leading to a higher number of desalination plants being constructed for agricultural irrigation only [33].

To obtain an average cost of desalinated water, it is necessary to consider three key aspects: the technology to be used for desalination, the quality of the feed water to be desalinated and the required quality of the product water. As for feed water, this totally depends on the area where the desalination plant is located, although brackish water should be avoided as it produces soil salinization. As for product water, this depends on climate, soil, water management, but mostly on which crops are cultivated near the desalination plant. For this reason, if a desalination plant is being designed to create freshwater for irrigation or mostly for irrigation purposes, a more flexible and adaptive strategy can be taken in order to reduce costs as much as possible [34].

Agrivoltaics

An agrivoltaics system consists on installing photovoltaic panels above an agriculture field to take advantage of the land occupied by the crop, as shown in *Figure 7*, so that the PV panels do not consume more land, while providing some benefits to agriculture, being one of them the reduction of water demand for irrigation as the water requirement from a crop is related to the solar radiation reaching the ground [35]. That is why agrivoltaics suppose an opportunity to take advantage of the space taken by the PV panels, as the world land availability is decreasing over time, to produce crops which can be used for many different purposes. By implementing these two different assets, agriculture and photovoltaic energy, the food-energy nexus is enhanced by improving the efficiency of the PV panels, which produce renewable and non-polluting energy, while producing crops meant to be consumed or sold.

Figure 7 - Example of an installed agrivoltaics system (Dezeen.com)

One of the negative aspects of the implementation of these two practices together is the reduction of the crop yield in most of the cases, as less solar radiation reaches the ground. Nevertheless, this impact could even be positive if the place being considered has an excess of solar radiation depending on some other factor, following the equation [36], [37]:

$$\left(1 - \frac{Y_a}{Y_{mp}}\right) = k_y(1 - \frac{ET_a}{ET_m})$$

Where Y_a represents the actual yield (ton/ha) found in the area, while Y_{mp} represents the expected value for yield (ton/ha) if there were optimal conditions of water provided to the crop, solar radiation reaching the ground and soil in terms of nutrients and salinity. On the other side of the equation, ET_a represents the actual evapotranspiration, that is to say, the volume of water available for the crop; ET_m represents the crop water requirement from the crop, that is to say, the water that the crop would need if optimal conditions were present; and k_y is called the yield response factor, which represents the reduction in evapotranspiration on yield losses and it is a characteristic parameter of each crop [37].

The k_y values differ depending on the crop and they change throughout the growing season based on growth stages with the following meanings:

If k_y is higher than 1: crop yield decreases significantly when water is limited, leading to higher reductions in production due to stress.

If k_y is lower than 1: crop shows higher tolerance to water shortage, and partially bounces back from stress, resulting in yield reductions that are less than expected with lower water availability.

If k_y is equal to 1: the decrease in yield is directly proportional to the decrease in water consumption.

Another negative aspect about this technology is that governments have constrained its development due to the excessive soil consumption, the landscape impact and the food competition that agrivoltaics would generate, as not only food would be produced, but energy as well. Nowadays, most agrivoltaics systems are related to energy saving strategies or to increase farmers' income [38]. In the end, the successful implementation of agrivoltaics systems depends on farmers' acceptance.

One of the main determinants of PV solar cells performance and cost is the efficiency of the semiconductor. Despite its high cost, crystalline silicon has a high efficiency of 16–18% for monocrystalline silicon and 15–17% for polycrystalline silicon. Despite being cheaper than crystalline silicon solar cells, organic solar cells are less stable and efficient [39]. By using sun-tracking devices and reflective surfaces to concentrate solar radiation, solar cells can produce more electricity [40]. Moreover, recent studies [35] have shown that vegetation increases the efficiency of PV solar cells due to the decrease in air temperature underneath the PV solar cell in a way that serves as a cooling method. This happens mainly due to the greater balance of latent heat energy exchange from plant transpiration in comparison to sensible heat exchange from radiation from bare soil, which would be the common installation method.

Methodology

The general idea of this study is to decarbonize an area with croplands surrounding a desalination plant by creating an autonomous environment where photovoltaic panels power the different assets of the area, desalination plant provides water for irrigation and consumption and agrivoltaics reduce the irrigation needed. As for the yield, it would probably decrease, although it could be prevented by using fertilizers and other kind of techniques, as well as it depends on what type of crop is, as seen in the sub-section Agrivoltaics. Photovoltaic panels would also benefit from having crops underneath, as their evapotranspiration would cool the PV systems and increase their efficiency.

This concept can be adapted to many different case studies. However, there are some suitable characteristics that would make the chosen case study a perfect one to be applied the methodology that will be explained.

The first and most important characteristic is the existence of a freshwater production plant, that being a desalination plant, a wastewater treatment plant, or any kind of plant that would extract all the residues present in the water treated. The most suited one is a desalination plant taking water from a sea or an ocean, as the water requirements from the crops will be remarkably high and large amounts of water are needed in order to meet those demands.

The second characteristic is the presence of croplands nearby the desalination plant, in order to be able to use that water for irrigation while covering the crops with the photovoltaic panels, which will power the desalination plant and reduce water requirements from the crops. If the crops are too far away from the desalination plant, the cost of water and electricity transportation would be remarkably high and the losses from the pipes and cables due to friction would decrease substantially the efficiency of the whole system, but the methodology could be applied anyways, as efficiencies are taken into account at all stages.

In the end, any similar case study that meets some of these two characteristics is suitable for implementing this methodology.

As for the methodology itself, this first step consists on a specific and thorough analysis of the area, also known as data gathering, in which many different parameters are obtained and studied, in order to get a general understanding of the case study selected. These parameters obtained may vary from case study to case study, but the most important ones would be historical weather data of the location, water produced by the different sources in the area, energy required in the area, crop parameters as surface occupied by each of them, planting and harvesting dates, yields, and many more parameters that will be later described and assessed, and finally data on food access and food availability in the region. After this process, some of these data would be used to calculate very relevant information such as volume of irrigation needed (m^3/year), expected production (ton/y), amount of food needed to be sold locally in order to meet daily intake of calories per person, percentage of salary that each household would need to invest into buying the necessary food for their daily life, among others.

This data will be presented in a new framework developed in this thesis in order to take into account which data would be needed so that results would automatically be obtained. This framework was developed on Excel in order to facilitate its use and will be presented and explained in the sub-section Framework.

The second step would be to use some of the previously gathered data as inputs of an open-source model developed by the Department of Energy of Polytechnic University of Milan, using the software Python, called MicroGridsPy. This model was first created to satisfy demands from household by means of a minigrid system, but it will be used in this project to model the capacity to be installed in order to power the different assets in the area. Even though it was not the intention It was developed for, it can perfectly be used as the equations would be the same. This programme will be further explained in the sub-section MicroGridsPy.

From this starting point, the first thing to accomplish is to focus on a case study that fulfils the requirements described earlier. For that matter, the chosen case study is the desalination plant in Chtouka Ait-Baha, Morocco. This case study will be used in order to explain the methodology followed and, even though each particular case study is unique in terms of assets, requirements and issues to be accounted for, both the framework and the model employed can be easily applied to a different case study.

SECTION A

Area Analysis

The chosen desalination plant is in the basin of Chtouka Ait Baha, located in the province of Souss-Massa, which is found in the central part of Morocco, as shown in *Figure 8*. The desalination plant provides water for both the greenhouses located right next to it and to the city of Agadir, serving as a source of irrigation water and drinking water [41], [42].

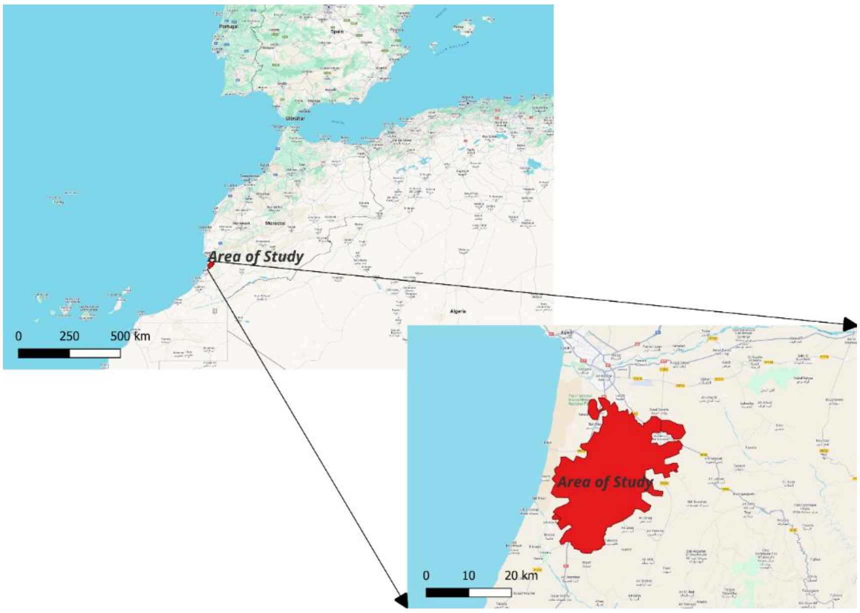

Figure 8 - Location of area of study

This region is pioneer in the field of partnerships in the form of exports, as 8.5% of the region's surface is dedicated to agriculture, from which the majority of it is sold externally [43]. For the whole region of Souss-Massa, the most cultivated crops are citrus fruits, date palms, fruit trees, olive trees, argan trees, saffron and vegetable crops, but as for the basin of Chtouka Ait-Baha, the most important crop is tomatoes, with the remaining crops not being cultivated in the same proportion as in other areas inside Souss-Massa [44].

As for the different assets in this area, the most important geographic points to take into account are represented in *Figure 9 and 10* [41], [45].

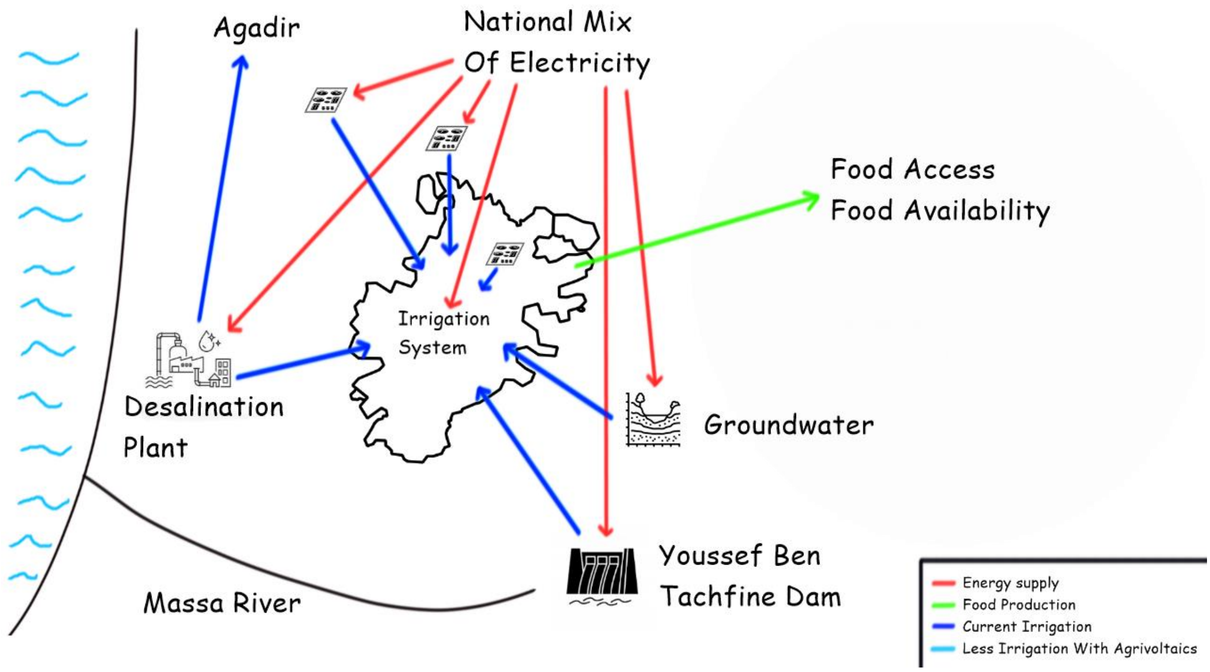

Figure 9 – Current Assets of the Area

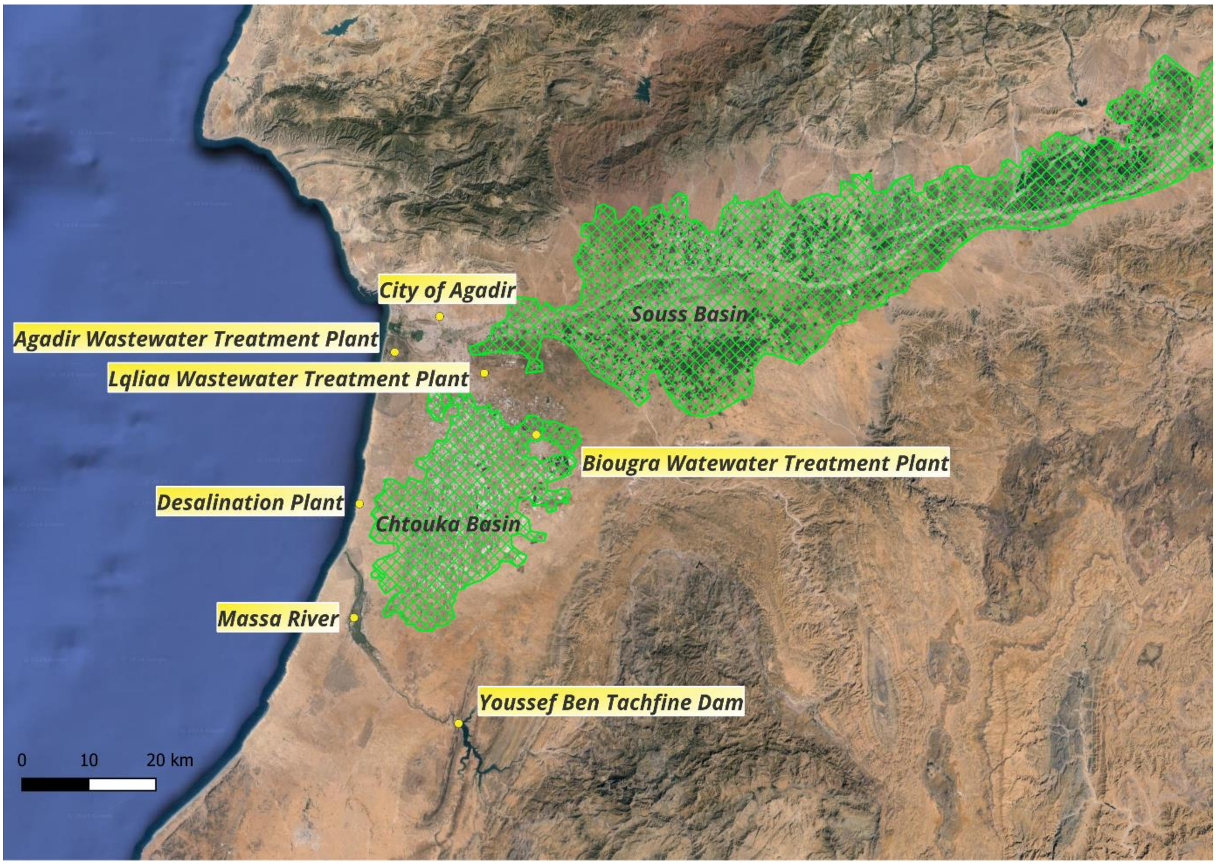

Figure 10 - Most important assets in the region

Figure 9 shows the different inputs and outputs to the area of study from each of the most relevant assets. After the implementation of the photovoltaic panels, the new inputs, outputs and assets will be represented.

The area that will be studied in this project is the Chtouka basin, being made up of both greenhouses and open cropfields, besides that this surface also coincides with the Chtouka aquifer, which will be a major supplier of water to the region [46].

It is also worth highlighting the Souss basin, which contains the Souss aquifer, as it is the other major cultivated area of Souss-Massa. Nevertheless, this area will not be taken into account for the study, although it could be considered in further studies of this region [47], [48].

As for the different assets surrounding the Chtouka basin, the desalination plant is the main focus. It was built by the end of 2019 and it includes the desalination plant itself, with two water intakes with two pipelines, a pumping station, all the machinery for the reverse osmosis process, a reservoir for the desalinated water and another pipeline for the disposal of brine; the facilities for the transport and distribution of irrigation water, which includes three pump stations and the distribution pipelines; and the supply of electricity, including the transmission lines to power the whole desalination plant and its processes [49]. It currently has a capacity of 275,000 m^3, which is divided into half between the city of Agadir and the basin full of greenhouses and open cropfields, but it is scheduled to be upgraded to an expanded desalination plant, doubling the current capacity [41], [50]. However, there are many different important features to take into account apart from the desalination plant.

One of them is the Youssef Ben Tachfine Dam, which provides water to the region through a canal and it also requires a pumping system to increase the piezometric height of the flow. The remaining water that is not pumped into the basin follows the river Massa to the Atlantic Ocean, irrigating as well some open cropfields situated right next to the river, which are meant to supply food to the city of Massa, situated next to the river as well [51], [52].

In addition, there are also some wastewater treatment plant situated in the area that filter the residual water coming from the cities of Agadir and Biougra, which can be later used as irrigation water for the same area. In total, there are twelve wastewater treatment plants situated in the province of Souss-Massa, but only the three plants marked in *Figure 10* will be taken into consideration, as they are the only ones providing water to the area of study [41].

Furthermore, another important asset in the region is the groundwater taken from the Chtouka aquifer through a series of pumps to extract it from the ground. In the recent years, the extraction of water from this source has been performed without any restrictions on its use, making the aquifer depth to decrease exponentially, as the withdraw of water from the Chtouka aquifer has increased almost 7 times the amount from 2007 to 2020 [47], [48]. This will lead to a decrease in the depth level of the Chtouka aquifer from 84 m in 2020 to 101 m in 2050, causing the irruption of seawater into the groundwater, contaminating it with salt and making it not suitable for irrigation [41], [53].

Finally, to understand the distribution of the crops is key, because even though it has been commented that the majority of the crops cultivated in the area are tomatoes among other crops, it is important to acknowledge in which proportion these crops are distributed in the area between greenhouses and open cropfields, as the implementation of the agrivoltaics system would not affect in the same way to either of them.

As seen in *Figure 11*, more than half of the area is covered by greenhouses, while open cropfields and market gardening suppose only a fraction of the total surface dedicated to crops [41], [46], [54]. In the section discussion, what implications this will have along with the results of the area cover by photovoltaic panels obtained in the section of implementation will be explored.

As for the irrigation system, the assumption of drip irrigation in the Chtouka basin and surface irrigation in the Massa river will be made and, as the focus will be on the Chtouka basin, the irrigation studied will only be drip irrigation [45].

Finally, it is worth mentioning the share of electricity supplied in the area. This comes from butane-driven pumps (20%), solar photovoltaic energy (10%) and from the national grid of Morocco (70%), being this last one greatly dependant on coal (54%), natural gas (19%) and oil (9%). For this reason, a decarbonisation of this region is a priority, as Morocco aims at reaching 52 % of renewable electricity by 2030 [41]. However, this will be difficult to achieve mainly due to the covid pandemic, the war between Russia and Ukraine and the war between Palestine and Israel, as global economy has been negatively affected by these events, among others [55]. For these many reasons, this project will make the area independence from the national grid based on photovoltaic energy.

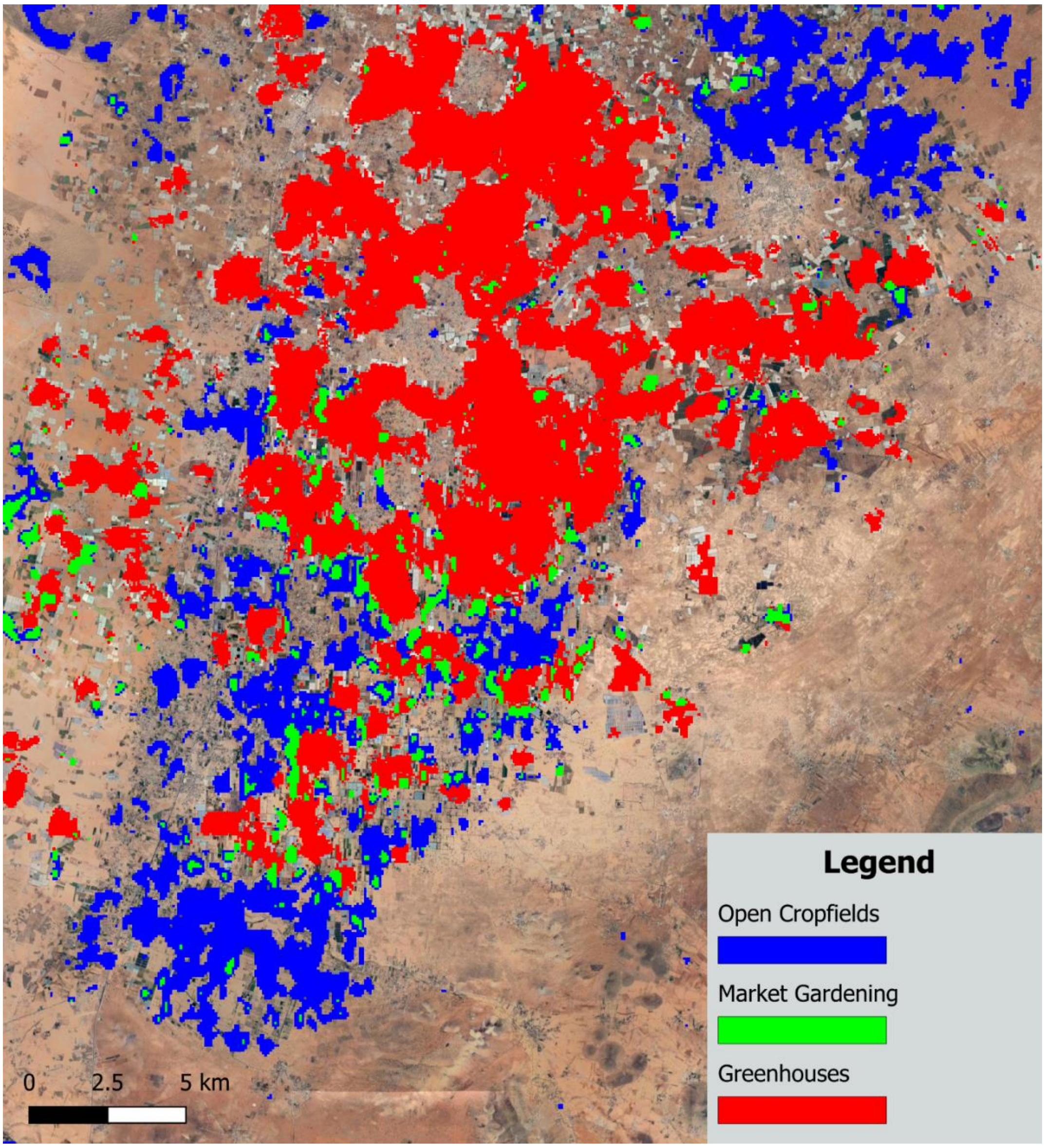

Figure 11 - Crops differentiation between greenhouses, market gardening and open cropfields

Nevertheless, even though the majority of the crops are cultivated under greenhouses, these do not always show the same structure, some being more professional and some others being simpler, as shown in the following figures [56], [57], [58].

Figure 12 – Example of a Proper Greenhouse

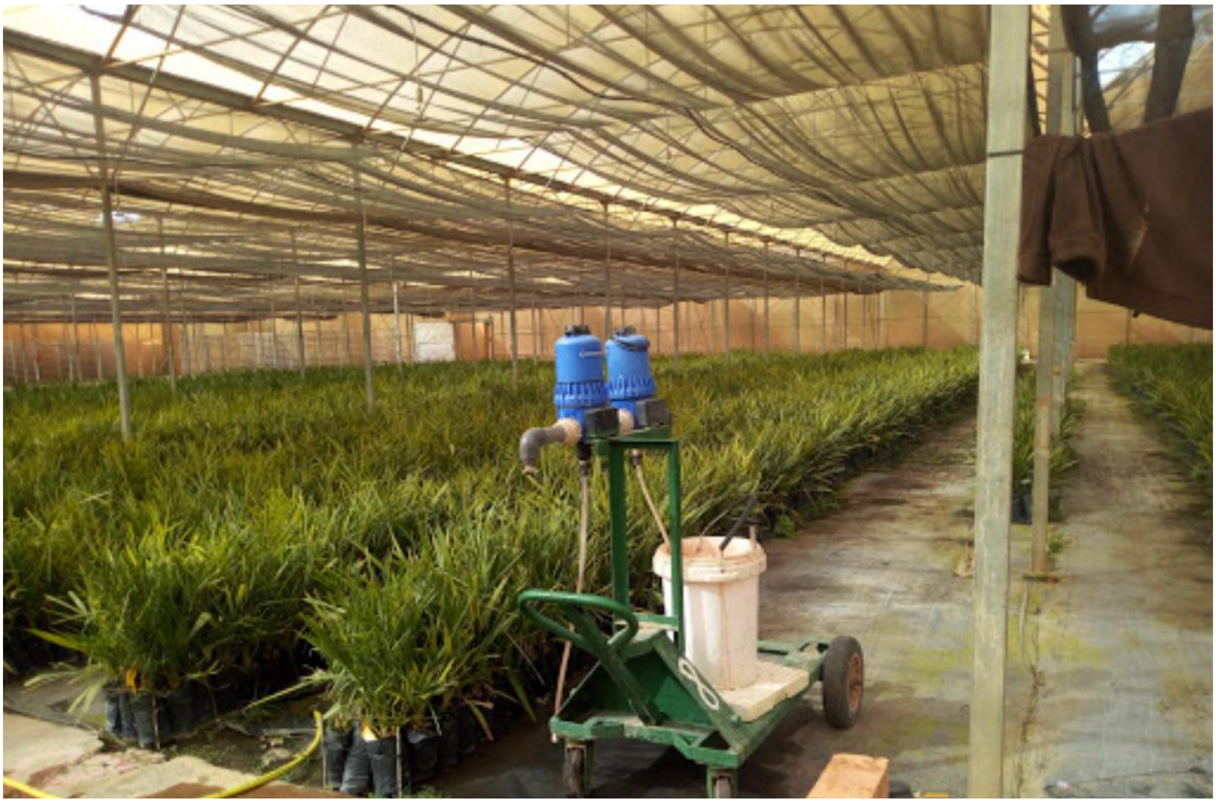

Figure 13 – Example of an Average Greenhouse

Figure 14 – Example of a Bad Greenhouse

It is clear that not every greenhouse can be tackled in the same way, as they do not always share the same design. In the section of Implementation, a solution for each of these greenhouses will be presented.

Now that a general idea of the area with all its assets has been presented, all the inputs taken into account in the analysis of the area will be commented.

Input Data for Area Analysis

In this section, most of the data used later were obtained through literature. However, some of them had to be calculated through simple relations or by using models in order to get all the data needed to fully understand the region. In the following sub-sections, the different procedures to obtain the data are addressed.

Energy Requirements

This refers to the energy needed in Gigawatts hour to produce or obtain from a source of water the whole amount of water used in the basin for one year. There can be two different methods in order to calculate this data.

The first option and most common one is to directly find the value from literature. In this case, there would not be anything to be done to the value, as it would be what we desire.

The second option is to find the specific energy requirements of the technology used in the process assessed, that being pumping stations, filtering processes, etc. This data is measured in Kilowatts hour per cubic meter, being the energy needed to produce one cubic meter of potable water. In this case, data on water extracted from each source of water per year would be needed in order to calculate the energy requirements of each source of water.

For this project, as water extracted from each water source is also needed, specific energy requirements were selected as the inputs and, even if the data found was energy requirement, the specific energy requirement would be computed with the extracted water just dividing the first value by the second one in order to introduce all the data in the same order of magnitude.

The input data obtained for this project are [41], [59], [60].

	Specific energy requirements (kWh/m^3)
Desalination Plant	3.655
Groundwater Pumps	0.625
Dam Pumps	0.333
Wastewater Plant	0.45

Table 1 – Specific Energy Requirements

There is still one remaining asset that must be considered in the energy requirements section, and that is the energy consumed by the irrigation system, being in this case a drip irrigation system. For this part, the irrigation requirements will be used as inputs in order to calculate the value of energy consumed. Therefore, irrigation requirements will be computed first and then the energy requirement from the drip irrigation system.

Irrigation Requirements

For the calculation of the irrigation requirements, these can be obtained directly from literature, but these data depend on many different factors that may significantly vary the values obtained. For this reason, a model developed in R by Nikolas Galli and the Department of Civil and Environmental Engineering will be used in order to get the desired data from a series of inputs such as weather data, crop parameters, or soil characteristics.

The input data needed to use the model are the planting and harvesting day of each crop; soil characteristics in the form of field capacity, wilting point, non-effective rainfall fraction and maximum infiltration rate; climate data for ten years; elevation of the area; and some crop parameters.

As for the planting and harvesting days, the input data can be checked in *Table 2* [61].

	Planting day	Harvesting day	Total days
Tomato Greenhouse First Harvest	2	181	179
Tomato Greenhouse Second Harvest	274	151	240
Pepper Greenhouse	91	273	182
Banana Greenhouse First Year	60	120	423
Banana Greenhouse Second Year	32	59	390
Tomato	91	304	213
Pepper	274	151	240
Potato	305	151	209
Green peas	60	243	183
Sweet corn	274	90	179
Alfalfa	60	120	60
Green beans	213	365	152
Strawberries	60	304	244
Blueberries	60	304	244
Blackberries	60	304	244
Raspberries	60	304	244
Citrus	2	31	392
Zucchini	91	243	152
Cucumbers	152	90	213
Eggplants	274	212	179
Sweet Melons	335	365	240
Peaches	60	334	274

Table 2 – Planting and Harvesting Day

For the soil characteristics, the soils present in the area are sandy loam and silty loam, so the characteristics of loam will be considered to perform the study, obtaining the following input data in *Table 3* [62], [63], [64], [65].

Field Capacity (mm/m)	260
Wilting Point (mm/m)	90
Non-Effective Rainfall Fraction	0.05
Maximum Infiltration Rate (mm/h)	15

Table 3 – Soil Characteristics

As for the climate data, it was obtained from Visual Crossing [66] for the weather station of Agadir, as it includes all the relevant data necessary for the model. The data obtained from this webpage are maximum temperature, minimum temperature, mean temperature, dew point, feels like, precipitation, precipitation chance, precipitation cover, precipitation type, snow, snow depth, wind speed, wind gust, wind direction, visibility, cloud cover, relative humidity, sea level pressure, solar radiation, solar energy, UV index, severe risk, sunrise time, sunset time, moon phase, a weather icon, short text about the weather, description of the weather for the day and list of weather stations sources.

Apart from this, the elevation in the area varies depending on where the focus is, as the west is closer to the ocean so it has a lower elevation and the east part is higher. Then, by calculating the mean of several points in the area, the elevation calculated is 90 m, which also correspond to the central part of the area [67].

Finally, the crop parameters needed for the model are shown in *Table 4* [61], [68].

Crop name	Kc ini	Kc mid	Kc end	Kcb ini	Kcb mid	Kcb end	Initial stage (%)	Dev. Stage (%)	Mid. Stage (%)	Late stage (%)	Root (m)	Depletion (m)
Tomato Greenhouse First Harvest	60	120	80	15	115	70	22	30	30	18	0.7	0.4
Tomato Greenhouse Second Harvest	60	120	80	15	115	70	19	25	39	17	0.7	0.4
Pepper Greenhouse	60	115	90	15	110	80	21	29	33	17	0.5	0.3
Banana Greenhouse First Year	50	110	100	15	105	90	31	23	31	15	0.5	0.35
Banana Greenhouse Second Year	100	120	110	60	110	105	33	16	49	2	0.5	0.35
Tomato	60	115	80	15	110	70	21	28	31	20	1.5	0.4
Pepper	60	105	90	15	100	80	14	19	52	15	1	0.3
Potato	50	115	75	15	110	65	21	25	29	25	0.6	0.35
Green peas	50	115	110	15	110	105	20	30	35	15	1	0.35
Sweet corn	30	115	105	15	110	100	20	30	40	10	1.2	0.5
Alfalfa	40	120	115	30	115	110	17	33	33	17	2	0.55
Green beans	50	105	90	15	100	80	20	33	33	14	0.7	0.45
Strawberries	40	85	75	30	80	70	10	24	37	29	0.3	0.2
Blueberries	40	85	75	30	80	70	10	24	37	29	0.3	0.2
Blackberries	40	85	75	30	80	70	10	24	37	29	0.3	0.2
Raspberries	40	85	75	30	80	70	10	24	37	29	0.3	0.2
Citrus	65	60	65	60	55	60	16	25	33	26	1.5	0.5
Zucchini	50	95	75	15	90	70	25	35	25	15	1	0.5
Cucumbers	60	100	75	15	95	70	19	29	38	14	1.2	0.5
Eggplants	60	105	90	15	100	80	23	31	31	15	1.2	0.45
Sweet Melons	50	105	75	15	100	70	19	28	41	12	1.5	0.4
Peaches	55	90	65	45	85	60	8	26	44	22	2	0.5

Table 4 – Crop Parameters

It is worth noting that the different stages do not refer to the total days that the crop is being cultivated, but the proportion of each stage in percentages, that is to say, the sum of the 4 stages must sum up to one hundred.

The final thing to take into account is the difference in the inputs between normal conditions and agrivoltaic conditions. According to literature [35], [38], [39], [69], the implementation of agrivoltaics imply that the sun reaching the ground would be reduced by 30%, which means that if solar radiation values from climate data are multiplied by 0.7, agrivoltaic conditions could be simulated and the new irrigation requirements under these conditions would be obtained.

Once all the input data have been collected and inserted in the model, it takes those values and computes the water balance in the soil through different equations. The first step taken by the model is to calculate the reference evapotranspiration with the FAO Penman-Monteith method [68]:

$$ET_o = \frac{0.408 * \Delta * (R_n - G) + \gamma * \frac{900}{T + 273} * u_2 * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * u_2)}$$

Where ET_o is the reference evapotranspiration (mm/day), R_n is the net radiation at the crop surface (MJ/(m^2+day)), G is the soil heat flux density (MJ/(m^2+day)), T is the mean daily air temperature at 2 meters height (ºC), u_2 is the wind speed at 2 meters height (m/s), and Δ is the slope vapour pressure curve (kPa/ºC), which can be calculated as [68]:

$$\Delta = \frac{4098 * (0.6108 * \exp\left(\frac{17.27 * T}{T + 237.3}\right))}{(T + 237.3)^2}$$

Apart from this, γ is the psychometric constant (kPa/ºC), which can be calculated as [68]:

$$\gamma = 0.000665 * 101.3 * (\frac{293 - 0.0065 * z}{293})^{5.26}$$

Where z is the elevation above sea level (m).

Finally, e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), and $(e_s - e_a)$ is the saturation vapour pressure deficit (kPa), which can be calculated as [68]:

$$e_s = 0.6108 * \frac{(\exp\left(\frac{17.27 * T_{max}}{T_{max} + 237.3}\right) + \exp\left(\frac{17.27 * T_{min}}{T_{min} + 237.3}\right))}{2}$$

While e_a is calculated from the weather data values as $\frac{e_{max}+e_{min}}{2}$.

The second step taken in the model is to calculate the Kc values from the different Kc values obtained from literature for each stage of the crop growth.

After that, the crop evapotranspiration is calculated as:

$$ET_c = K_c * ET_o$$

From this point, how to calculate the irrigation requirement of each crop depends on the irrigation system adopted, being for this case a drip irrigation system. For this final calculation, the assumption of starting the study period when soil has reached the maximum available depletion (MAD) was made, that is to say, $\theta(0) = MAD$. The equation used to calculate this value for irrigation for each time step “i” is:

$$Irrigation(i) = \max\left(0, ET_c - (\theta(i) - MAD)\right)$$

After this, $\theta(i)$ would be recomputed for the next step as:

$$\theta(i+1) = \theta(i) + Precipitation(i) - ET_a(i) + Irrigation(i) - Percolation(i) - Runoff(i)$$

Where $ET_a(i)$ is the actual evapotranspiration at each time step “i”, which is calculated as:

$$ET_a = \min(ET_c, \theta(i) - MAD)$$

After running the model for each crop twice, under normal conditions and under agrivoltaic conditions, the results obtained are the following.

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
Tomato Greenhouse	975.12	975.12
Pepper Greenhouse	531.87	531.87
Banana Greenhouse	1001.75	1001.75
Tomato	725.03	579.32
Pepper	662.80	535.11
Potato	525.17	427.26
Green peas	639.32	508.68
Sweet corn	386.27	312.66
Alfalfa	171.85	131.36
Green beans	378.14	310.36
Strawberries	670.87	541.78
Blueberries	670.87	541.78
Blackberries	670.87	541.78
Raspberries	670.87	541.78
Citrus	707.90	565.62
Zucchini	440.10	346.65
Cucumbers	581.16	467.98
Eggplants	400.98	325.39
Sweet melons	666.75	528.66
Peaches	739.33	589.26

Table 5 – Irrigation Requirements

In the appendix, a more detailed description of the results obtained from the model for “Tomato Greenhouse” is given.

From *Table 6* it is clear that by preventing some solar radiation from reaching the ground, the irrigation needed by a crop decreases regardless of what crop it is, especially in this case study, as there is so much solar radiation, especially in Summer, that there is an excess of solar radiation, ending up being harmful for the crops.

Finally, the last point to be highlighted from this table is the assumption that greenhouses simulate a similar condition, even though the microclimate generated under Photovoltaic panels is not the same as the one created by greenhouses. Nevertheless, they both prevent all solar radiation from reaching the ground, so the assumption is properly applicated in this case.

From here, now that the values for irrigation requirements have been calculated, it is possible to calculate the energy required by the drip irrigation system.

Yield and Area of Each Crop

In this section, the most optimal outcome is to obtain both the yield and area occupied by each crop from literature from reliable sources of information. However, not always all the information needed is available for the researcher. For that reason, another data can be used in order to obtain the other two input data needed, that being the production of each crop. Summing up, yield can be obtained from area and production and area can be obtained from yield and production.

Apart from this, what consequences do agrivoltaics have over yield is still under research, but thanks to previous studies, it is possible to estimate how much percentage of initial yield under normal conditions is kept under agrivoltaic conditions.

By using the commented methodology, the values for yields and areas of each crop can be checked in *Table 6* [45], [59], [65], [70], [71], [72], [73], [74], [75], [76].

	Yield (ton/ha)	Area (ha)	Percentage of yield under agrivoltaic conditions compared to yield under normal conditions (%)
Tomato Greenhouse	160	6415	86
Pepper Greenhouse	80	1609	86
Banana Greenhouse	60	366.6	83
Tomato	80	8.93	86
Pepper	40	806	86
Potato	60	1320	83
Green peas	8	806	86
Sweet corn	80	806	76
Alfalfa	100	1000	86
Green beans	30	107.5	84
Strawberries	40	403	86
Blueberries	17.5	134.33	83
Blackberries	12.5	134.33	83
Raspberries	12.5	134.33	83
Citrus	10	786	82
Zucchini	35	107.5	86
Cucumbers	25	107.5	86
Eggplants	26.9	107.5	86
Sweet melons	25	241	86
Peaches	35	107.5	83

Table 6 – Yield and Area of Each Crop

Drip Irrigation Energy Requirements

The irrigation system is not a source of water in order to obtain the water extracted from it, and from there to obtain the energy requirement through the specific energy requirement associated to the technology used in the irrigation. Nevertheless, it is an essential system in agriculture and the energy consumed by it must be computed as well, although following a different process than for water sources.

For this reason, the energy requirement from the drip irrigation system will be calculated from the daily flow meant for irrigation, calculated from the irrigation requirements and the area occupied by each crop, losses from the system in meters and the efficiency of the irrigation system.

For this case, the irrigation requirements and the area of each crop have been calculated above. As for the efficiency of the irrigation system, by dealing with a drip irrigation system, this value will be set to 0.56.

Finally, respect to the losses of the system, there are four differentiated losses to be taken into account. The first one are the losses due to the transportation of water from the source to the location where it will be used for irrigation, setting this value to 5.9 m.

Secondly, the operation losses can be set to a value of 14 m. Thirdly, the losses due to the height that the irrigation system has to raise the water forces to compute the irrigation twice, as this value varies between surface water and groundwater. As for surface water, this value is 2.5 m, and as for ground water, this value is 84 m, as commented in the section Area Analysis. Lastly, the losses due to the drawdown cone can be computed through the Cooper-Jacob's formula [77], [78]:

$$s = \frac{Q}{4 * \pi * T} * \left[-0.5772 - \ln \frac{r^2 * S}{4 * T * t} \right]$$

Being s the drawdown (m), Q the daily flow (m^3/day), T the transmissivity (m^2/day), r the radial distance (m), S the storativity and t the pumping time (days).

In order to be able to compute the energy twice, the volume of irrigation will be divided in the following proportion: 60% for the desalination plant and the dam, and 40% for the groundwater. In 2030, when the desalination plant will be upgraded, this proportion will change to 65% for the desalination plant and the dam and 35% for the groundwater.

After computing this methodology twice, the results obtained are 9.45 GJ for the irrigation water coming from the desalination plant and the dam and 26.73 GJ for the irrigation water coming from groundwater, summing up to a total value of 36.18 GJ.

Remaining Inputs Obtained Directly From Literature

These data are obtained directly from data, but they are not less important than any of the other input data described earlier.

The first data to be mentioned are the efficiencies of the transportation of water from the different sources, set to 0.9, and the efficiency of the irrigation system, set to 0.95 as it is a drip irrigation system [79].

The rest of the data refer to the current situation on the economic and social situation in the area. The chosen indicators to be taken into account as input data are shown in *Table 7* [59], [60], [80], [81].

Average annual income per household (DH/y)	207,800.00
Total households in the area of study	405,684.00
Currency conversion (DH to €)	0.091557
Total population of the region	1,900,567.08

Table 7 – Economic and Social Information of the Region of Chtouka Ait-Baha

There are also some economic parameters related to the crops that must be considered in order to acknowledge which crops are the most requested ones from population and which of them are the most expensive ones. The chosen indicators are the production cost of obtaining one kilogram of that crop and the market cost of each crop per kilogram. These data are shown in Table 8 [70].

	Production cost (DH/kg)	Market price (DH/kg)	Food supply per person (kg/cap/y)
Tomato Greenhouse	1.83	9.85	16.34
Pepper Greenhouse	2.29	16.255	0.13
Banana Greenhouse	3.5	9.81	8.96
Tomato	1.83	9.85	16.34
Pepper	2.29	16.255	0.13
Potato	1.75	8.305	36.35
Green peas	3.99	61.605	0.44
Sweet corn	0.76	19.645	20.51
Alfalfa	0.46	63.8	0
Green beans	3.99	14.865	0.11
Strawberries	1.5	19.72	2.16
Blueberries	1.5	53.875	2.16
Blackberries	1.5	53.875	2.16
Raspberries	1.5	53.875	2.16
Citrus	1.81	16.07	0.32
Zucchini	2.78	10.175	10.3
Cucumbers	3.99	6.205	10.3
Eggplants	2.78	30.19	10.3
Sweet melons	3.99	9.8	2.16
Peaches	2.78	34.665	2.16

Table 8 – Economic and Social Information of the Crops in the Region of Chtouka Ait-Baha

Finally, the crops studied in this project correspond to the crops present in the area of study. However, there are many important crops and food for the daily intake of a person that is not cultivated in the area but population needs it anyways, so it is crucial to make a list with the most relevant ones to give much more context of the situation.

Regarding this case study, a good list with important crops not cultivated in the region of Chtouka Ait-Baha is rice, wheat, barley, maize, sugar, pulses, nuts, soyabean oil, onions, oranges, apples, grapes, among others.

Framework

Inputs of the Framework

This refers to an Excel file where inserting the inputs mentioned above, some interesting and relevant results would be automatically obtained.

As for the inputs just described, the input data sheet of this Excel file would look like in *Figure 15*.

	Maximum available water to be extracted (m^3/y)	Percentage of water to be extracted	System efficiency (transportation)	Specific energy requirements (kWh/m^3)
Desalination Plant	82,125,000.00	55.55%	0.9	3.655
Groundwater	89,999,875.00	100.00%	0.9	0.625
Canal From Dam	84,000,000.00	100.00%	0.9	0.333
River Near Massa	36,833,975.00	0.00%	0.9	0
Wastewater Plants	28,172,890.00	50.00%	0.9	0.45

Average annual income per household (DH/y)	207,800
Total households in the area of study	405,684
Currency conversion (DH to €)	0.0915570
Total population of the region	1,900,567.08

Irrigation system energy requirements (GWh/y)	36.18
Efficiency of the irrigation system	0.95

	Irrigation requirements WITHOUT agrivoltaics (mm/y)	Irrigation requirements WITH agrivoltaics (mm/y)	Yield WITHOUT agrivoltaics (ton/ha)	Percentage of yield under agrivoltaic conditions compared to yield under normal conditions (%)	Area (ha)	Production cost (DH/kg)	Market price (DH/kg)	Food supply per person (kg/cap/y)	Relevant crops needed by popupulation not taken into account in the study
Tomato Greenhouse	975.12	975.12	160	86%	6415	1.83	9.85	16.34	Rice
Pepper Greenhouse	531.87	531.87	80	86%	1609	2.29	16.255	0.13	Wheat
Banana Greenhouse	1,001.75	1,001.75	60	83%	366.6	3.5	9.81	8.96	Barley
Tomato	725.03	579.32	80	86%	8.93	1.83	9.85	16.34	Maize
Pepper	662.80	535.11	40	86%	806	2.29	16.255	0.13	Sugar
Potato	525.17	427.26	60	83%	1320	1.75	8.305	36.35	Pulses
Green peas	639.32	508.68	8	86%	806	3.99	61.605	0.44	Nuts
Sweet corn	386.27	312.66	80	76%	806	0.76	19.645	20.51	Soyabean Oil
Alfalfa	171.85	131.36	100	86%	1000	0.46	63.8	0	Onions
Green beans	378.14	310.35	30	84%	107.5	3.99	14.865	0.11	Oranges
Strawberries	670.87	541.78	40	86%	403	1.5	19.72	2.16	Apples
Blueberries	670.87	541.78	17.5	83%	134.33	1.5	53.875	2.16	Grapes
Blackberries	670.87	541.78	12.5	83%	134.33	1.5	53.875	2.16	
Raspberries	670.87	541.78	12.5	83%	134.33	1.5	53.875	2.16	
Citrus	707.90	565.62	10	82%	786	1.81	16.07	0.32	
Zuchhini	440.10	346.65	35	86%	107.5	2.78	10.175	10.3	
Cucumbers	581.16	467.98	25	86%	107.5	3.99	6.205	10.3	
Eggplants	400.98	325.39	26.9	86%	107.5	2.78	30.19	10.3	
Sweet melons	666.75	528.66	25	86%	241	3.99	9.8	2.16	
Peaches	739.33	589.26	35	83%	107.5	2.78	34.665	2.16	

Figure 15 – Input Data Sheet

This input data sheet is adjusted to this case study in particular, but it can also be adjusted to a different case study which demands other indicators to be studied or if the data found about that case study is scarce or different. As a summary, this can serve as a reference point for new projects trying to implement a similar methodology, but always adapting it to the singularities of each study.

Another important asset is that this data sheet lets the user change the amount of water extracted from each source of water to reduce the water withdrawn from critical sources of water like groundwater, as previously explained, in order to relieve the stress over a certain source.

Once all the inputs have been inserted, the following output data sheet would be obtained, as shown in *Figure 16*.

From here, there are many conclusions that can be taken from the results obtained in this Excel sheet.

Outputs of the Framework

	Water used for irrigation (m^3/y)		Energy requirements (GWh/y)		
Desalination Plant	41,058,393.75		150.07	Is it enough to irrigate the basin?	YES
Groundwater	80,999,887.50		50.62	Would it be enough if there were agrivoltaics?	YES
Canal From Dam	75,600,000.00		25.17		
River Near Massa	-		-		
Wastewater Plants	12,677,800.50		5.71		
Irrigation System (Drip)	-		38.08		
Total irrigation provided (m^3/y)	210,336,081.75	Total energy required (GWh/y)	269.66		

	Expected volume of irrigation WITHOUT agrivoltaics (m^3/y)	Expected volume of irrigation WITH agrivoltaics (m^3/y)	Irrigation decrease (%)	Expected production WITHOUT agrivoltaics (ton/y)	Expected production WITH agrivoltaics (ton/y)	Production decrease (%)	Relevant crops needed by poppulation not taken into account in the study
Tomato Greenhouse	65,846,328.65	65,846,328.65	0.00%	882,704.00	882,704.00	0.00%	Rice
Pepper Greenhouse	9,008,251.11	9,008,251.11	0.00%	110,699.20	110,699.20	0.00%	Wheat
Banana Greenhouse	3,865,703.53	3,865,703.53	0.00%	18,256.68	18,256.68	0.00%	Barley
Tomato	68,149.58	54,453.32	20.10%	714.37	614.35	14.00%	Maize
Pepper	5,623,304.43	4,539,975.38	19.26%	32,240.00	27,726.40	14.00%	Sugar
Potato	7,297,046.23	5,936,673.46	18.64%	79,200.00	65,736.00	17.00%	Pulses
Green peas	5,424,166.38	4,315,729.51	20.44%	6,448.00	5,545.28	14.00%	Nuts
Sweet corn	3,277,209.26	2,652,691.43	19.06%	64,480.00	49,004.80	24.00%	Soyabean Oil
Alfalfa	1,808,939.89	1,382,693.72	23.56%	100,000.00	86,000.00	14.00%	Onions
Green beans	427,895.06	351,191.16	17.93%	3,225.00	2,709.00	16.00%	Oranges
Strawberries	2,845,917.68	2,298,292.78	19.24%	16,120.00	13,863.20	14.00%	Apples
Blueberries	948,639.23	766,097.59	19.24%	2,350.83	1,951.19	17.00%	Grapes
Blackberries	948,639.23	766,097.59	19.24%	1,679.17	1,393.71	17.00%	
Raspberries	948,639.23	766,097.59	19.24%	1,679.17	1,393.71	17.00%	
Citrus	5,856,934.56	4,679,737.61	20.10%	7,860.00	6,445.20	18.00%	
Zuchhini	498,011.93	392,256.47	21.24%	3,762.50	3,235.75	14.00%	
Cucumbers	657,626.66	529,555.71	19.47%	2,687.50	2,311.25	14.00%	
Eggplants	453,737.93	368,199.29	18.85%	2,891.75	2,486.91	14.00%	
Sweet melons	1,691,429.74	1,341,116.91	20.71%	6,025.00	5,181.50	14.00%	
Peaches	836,614.31	666,794.92	20.30%	3,762.50	3,122.88	17.00%	
Total	118,333,184.63	110,527,937.75		1,346,785.66	1,290,381.00		
							Total anual income in the region of study (€/y)
							7,718,359,035.51

	Production cost WITHOUT agrivoltaics (€/y)	Production cost WITH agrivoltaics(€/y)	Market cost WITHOUT agrivoltaics (€/y)	Market cost WITH agrivoltaics (€/y)	Amount to be sold locally to meet the food demands WITHOUT agrivoltaics (%)	Amount to be sold locally to meet the food demands WITH agrivoltaics (%)	Is it enough to not import from aborad?	And is it enough to not import from aborad if agrivoltaics was installed?	Amount of income invested to buy the crops needed (%)*
Tomato Greenhouse	147,896,446.13	147,896,446.13	796,054,641.76	796,054,641.76	3.52%	3.52%	YES	YES	0.36256571%
Pepper Greenhouse	23,209,806.44	23,209,806.44	164,749,084.57	164,749,084.57	0.17%	0.18%	YES	YES	0.00368955%
Banana Greenhouse	5,850,343.98	5,850,343.98	16,397,678.41	16,397,678.41	93.28%	93.28%	YES	YES	0.19816493%
Tomato	119,691.55	102,934.73	644,241.39	554,047.59	3.52%	3.52%	YES	YES	0.00029342%
Pepper	6,759,616.69	5,813,270.35	47,981,471.29	41,264,065.31	0.17%	0.18%	YES	YES	0.00107454%
Potato	12,689,800.20	10,532,534.17	60,222,166.09	49,984,397.86	87.23%	105.10%	YES	NO	0.68060296%
Green peas	2,355,534.55	2,025,759.71	36,369,099.22	31,277,425.33	12.97%	15.08%	YES	YES	0.06111086%
Sweet corn	4,486,732.47	3,409,916.68	115,976,130.85	88,141,859.44	60.45%	79.54%	YES	YES	0.90837981%
Alfalfa	4,211,622.00	3,621,994.92	584,133,660.00	502,354,947.60	0.00%	0.00%	YES	YES	0.00000000%
Green beans	1,178,132.59	989,631.37	4,389,208.25	3,686,934.93	6.48%	7.72%	YES	YES	0.00368644%
Strawberries	2,213,848.26	1,903,909.50	29,104,725.12	25,030,063.61	25.44%	29.58%	YES	YES	0.09591963%
Blueberries	322,852.87	267,967.88	11,595,798.96	9,624,513.14	174.43%	210.15%	NO	NO	0.26205223%
Blackberries	230,609.19	191,405.63	8,282,713.54	6,874,652.24	244.20%	294.21%	NO	NO	0.26205223%
Raspberries	230,609.19	191,405.63	8,282,713.54	6,874,652.24	244.20%	294.21%	NO	NO	0.26205223%
Citrus	1,302,544.82	1,068,086.75	11,564,582.98	9,482,958.04	7.74%	9.44%	YES	YES	0.01159353%
Zuchhini	957,663.33	823,590.46	3,505,116.69	3,014,400.35	520.71%	605.48%	NO	NO	0.23646815%
Cucumbers	981,777.16	844,328.35	1,526,798.81	1,313,046.98	728.99%	847.67%	NO	NO	0.14420490%
Eggplants	736,032.67	632,988.10	7,993,103.03	6,874,068.61	677.50%	787.79%	NO	NO	0.70161901%
Sweet melons	2,201,007.39	1,892,866.36	5,405,983.07	4,649,145.44	68.06%	79.14%	YES	YES	0.04766797%
Peaches	957,663.33	794,860.56	11,941,510.56	9,911,453.77	108.98%	131.30%	NO	NO	0.16861328%
Total	218,892,334.81	212,064,047.72	1,926,120,428.12	1,778,114,037.19					4.41%

Figure 16 – Output Data Sheet

Firstly, the energy requirements from each of the sources are calculated and summed up to obtain the total energy requirement in the area. They are calculated from multiplying the water used for irrigation by the specific energy requirements of each asset, as this is measured in kWh/m^3 of water. This information will be used later in the design and implementation of the photovoltaic panels area.

Secondly, the total volume of irrigation provided from each of the sources is calculated by multiplying the maximum available water to be extracted, the system efficiency due to transportation losses and the percentage of water to be extracted, as by modifying this value different strategies of water extraction can be assessed. Then, it is summed up to obtain a total volume of irrigation provided in the area, just like with the energy requirements. In parallel, the volume of water required to be irrigated to each crop is computed both for normal conditions and for agrivoltaic conditions, to later being summed up to obtain the total volume required to be irrigated in the area. This is calculated by multiplying the irrigation requirements obtained from the model in mm/y by the area to obtain the volume of water needed for irrigation in m^3.

Apart from this, there are two different check boxes at the top right corner of the Excel sheet that tells whether it is enough water extracted from the sources to irrigate the area based on the irrigation requirements, both for normal conditions and agrivoltaic conditions. These boxes are automatized to display a “YES” in a green cell if there is enough water to irrigate the basin and a “NO” in a red cell if there is not enough water to irrigate the basin. This was achieved with a simple conditional formula checking if the irrigation provided was bigger than the irrigation needed, and the colouring of the cells was achieved with conditional formatting, depending on which word appeared in the cell.

Thanks to the feature of the input data sheet where it allows to say how much water from each source will be extracted for irrigation, different studies can be performed in order to obtain the optimal setting between the different sources. This also helps to understand how the expansion of the desalination plant will in 2030 affect the water situation in the area and how much can the other sources of water be reduced to make sure that all the crops are receiving the water they need. Taking this even further, many experiments could be performed simulating the available water in the studied resources following estimations on how much water there will be available in the future.

In order to properly show how this works, two experiments will be conducted with different amounts of water extracted from some of the sources of water.

The first experiment was performed with 70% of extracted water from the maximum water to be extracted from the dam and 10% of extracted water from groundwater, as shown in *Figures 17 and 18*.

	Maximum available water to be extracted (m^3/y)	Percentage of water to be extracted	System efficiency (transportation)
Desalination Plant	82,125,000.00	55.55%	0.9
Groundwater	89,999,875.00	10.00%	0.9
Canal From Dam	84,000,000.00	70.00%	0.9
River Near Massa	36,833,975.00	0.00%	0.9
Wastewater Plants	28,172,890.00	50.00%	0.9

Figure 17 – Input Data Sheet Experiment 1

	Water used for irrigation (m^3/y)		Energy requirements (GWh/y)	
Desalination Plant	41,058,393.75		150.07	
Groundwater	8,099,988.75		5.06	
Canal From Dam	52,920,000.00		17.62	
River Near Massa	-		-	
Wastewater Plants	12,677,800.50		5.71	
Irrigation System (Drip)	-		38.08	
Total irrigation provided (m^3/y)	114,756,183.00	Total energy required (GWh/y)	216.54	

Is it enough to irrigate the basin?	NO
Would it be enough if there were agrivoltaics?	YES

	Expected volume of irrigation WITHOUT agrivoltaics (m^3/y)	Expected volume of irrigation WITH agrivoltaics (m^3/y)	Irrigation decrease (%)	Expected production WITHOUT agrivoltaics (ton/y)	Expected production WITH agrivoltaics (ton/y)	Production decrease (%)
Tomato Greenhouse	65,846,328.65	65,846,328.65	0.00%	882,704.00	882,704.00	0.00%
Pepper Greenhouse	9,008,251.11	9,008,251.11	0.00%	110,699.20	110,699.20	0.00%
Banana Greenhouse	3,865,703.53	3,865,703.53	0.00%	18,256.68	18,256.68	0.00%
Tomato	68,149.58	54,453.32	20.10%	714.37	614.35	14.00%
Pepper	5,623,304.43	4,539,975.38	19.26%	32,240.00	27,726.40	14.00%
Potato	7,297,046.23	5,936,673.46	18.64%	79,200.00	65,736.00	17.00%
Green peas	5,424,166.38	4,315,729.51	20.44%	6,448.00	5,545.28	14.00%
Sweet corn	3,277,209.26	2,652,691.43	19.06%	64,480.00	49,004.80	24.00%
Alfalfa	1,808,939.89	1,382,693.72	23.56%	100,000.00	86,000.00	14.00%
Green beans	427,895.06	351,191.16	17.93%	3,225.00	2,709.00	16.00%
Strawberries	2,845,917.68	2,298,292.78	19.24%	16,120.00	13,863.20	14.00%
Blueberries	948,639.23	766,097.59	19.24%	2,350.83	1,951.19	17.00%
Blackberries	948,639.23	766,097.59	19.24%	1,679.17	1,393.71	17.00%
Raspberries	948,639.23	766,097.59	19.24%	1,679.17	1,393.71	17.00%
Citrus	5,856,934.56	4,679,737.61	20.10%	7,860.00	6,445.20	18.00%
Zuchhini	498,011.93	392,256.47	21.24%	3,762.50	3,235.75	14.00%
Cucumbers	657,626.66	529,555.71	19.47%	2,687.50	2,311.25	14.00%
Eggplants	453,737.93	368,199.29	18.85%	2,891.75	2,486.91	14.00%
Sweet melons	1,691,429.74	1,341,116.91	20.71%	6,025.00	5,181.50	14.00%
Peaches	836,614.31	666,794.92	20.30%	3,762.50	3,122.88	17.00%
Total	118,333,184.63	110,527,937.75		1,346,785.66	1,290,381.00	

Figure 18 – Output Data Sheet Experiment 1

For the second experiment conducted, there will not be any water extracted from groundwater, maintaining the other sources of water constant, as shown in *Figures 19 and 20*.

	Maximum available water to be extracted (m^3/y)	Percentage of water to be extracted	System efficiency (transportation)
Desalination Plant	82,125,000.00	55.55%	0.9
Groundwater	89,999,875.00	0.00%	0.9
Canal From Dam	84,000,000.00	70.00%	0.9
River Near Massa	36,833,975.00	0.00%	0.9
Wastewater Plants	28,172,890.00	50.00%	0.9

Figure 19 – Input Data Sheet Experiment 2

	Water used for irrigation (m^3/y)		Energy requirements (GWh/y)		
Desalination Plant	41,058,393.75		150.07	Is it enough to irrigate the basin?	NO
Groundwater	-		-	Would it be enough if there were agrivoltaics?	NO
Canal From Dam	52,920,000.00		17.62		
River Near Massa	-		-		
Wastewater Plants	12,677,800.50		5.71		
Irrigation System (Drip)	-		38.08		
Total irrigation provided (m^3/y)	106,656,194.25	Total energy required (GWh/y)	211.48		

	Expected volume of irrigation WITHOUT agrivoltaics (m^3/y)	Expected volume of irrigation WITH agrivoltaics (m^3/y)	Irrigation decrease (%)	Expected production WITHOUT agrivoltaics (ton/y)	Expected production WITH agrivoltaics (ton/y)	Production decrease (%)
Tomato Greenhouse	65,846,328.65	65,846,328.65	0.00%	882,704.00	882,704.00	0.00%
Pepper Greenhouse	9,008,251.11	9,008,251.11	0.00%	110,699.20	110,699.20	0.00%
Banana Greenhouse	3,865,703.53	3,865,703.53	0.00%	18,256.68	18,256.68	0.00%
Tomato	68,149.58	54,453.32	20.10%	714.37	614.35	14.00%
Pepper	5,623,304.43	4,539,975.38	19.26%	32,240.00	27,726.40	14.00%
Potato	7,297,046.23	5,936,673.46	18.64%	79,200.00	65,736.00	17.00%
Green peas	5,424,166.38	4,315,729.51	20.44%	6,448.00	5,545.28	14.00%
Sweet corn	3,277,209.26	2,652,691.43	19.06%	64,480.00	49,004.80	24.00%
Alfalfa	1,808,939.89	1,382,693.72	23.56%	100,000.00	86,000.00	14.00%
Green beans	427,895.06	351,191.16	17.93%	3,225.00	2,709.00	16.00%
Strawberries	2,845,917.68	2,298,292.78	19.24%	16,120.00	13,863.20	14.00%
Blueberries	948,639.23	766,097.59	19.24%	2,350.83	1,951.19	17.00%
Blackberries	948,639.23	766,097.59	19.24%	1,679.17	1,393.71	17.00%
Raspberries	948,639.23	766,097.59	19.24%	1,679.17	1,393.71	17.00%
Citrus	5,856,934.56	4,679,737.61	20.10%	7,860.00	6,445.20	18.00%
Zuchhini	498,011.93	392,256.47	21.24%	3,762.50	3,235.75	14.00%
Cucumbers	657,626.66	529,555.71	19.47%	2,687.50	2,311.25	14.00%
Eggplants	453,737.93	368,199.29	18.85%	2,891.75	2,486.91	14.00%
Sweet melons	1,691,429.74	1,341,116.91	20.71%	6,025.00	5,181.50	14.00%
Peaches	836,614.31	666,794.92	20.30%	3,762.50	3,122.88	17.00%
Total	118,333,184.63	110,527,937.75		1,346,785.66	1,290,381.00	

Figure 20 – Output Data Sheet Experiment 2

Moreover, the expected production both in normal and agrivoltaic conditions is calculated by multiplying the yield by the area, matching the reduction in expected production with the reduction in yield obtained from literature.

After having calculated the values of expected production for each crop, it is possible to compute total production cost and market cost for each crop. After this, the amount of crop to be sold locally to meet the food demands would be computed with the production and market cost per tonne and, if this value is above 100%, then it would be mandatory to import that crop in order to meet food demands. In order to easily visualize this, there are check boxes indicating with a "YES" in a green cell if there is enough local crop to meet the food demands of that crop and a "NO" if it is necessary to import. These check boxes work in the same way as the ones mentioned above.

It is worth noting that the check boxes between normal conditions and agrivoltaic conditions could not match, as there is less food produced under agrivoltaic conditions, so the amount of crop to be sold locally to meet the food demands would be higher.

Finally, the amount of total income from population of the region invested to buy the crops needed would be computed, giving a good reference on how comfortable society lives in that region. For this case study, the total value obtained is 4.41% of the total income, which, at first, could not seem much, but, if it is taken into account that many other important crops are not being cultivated in the area (as stated earlier), this makes that number higher than expected.

In order to properly visualize all this information, there is an extra Excel sheet called graphs, where the most important information is represented in different graphs.

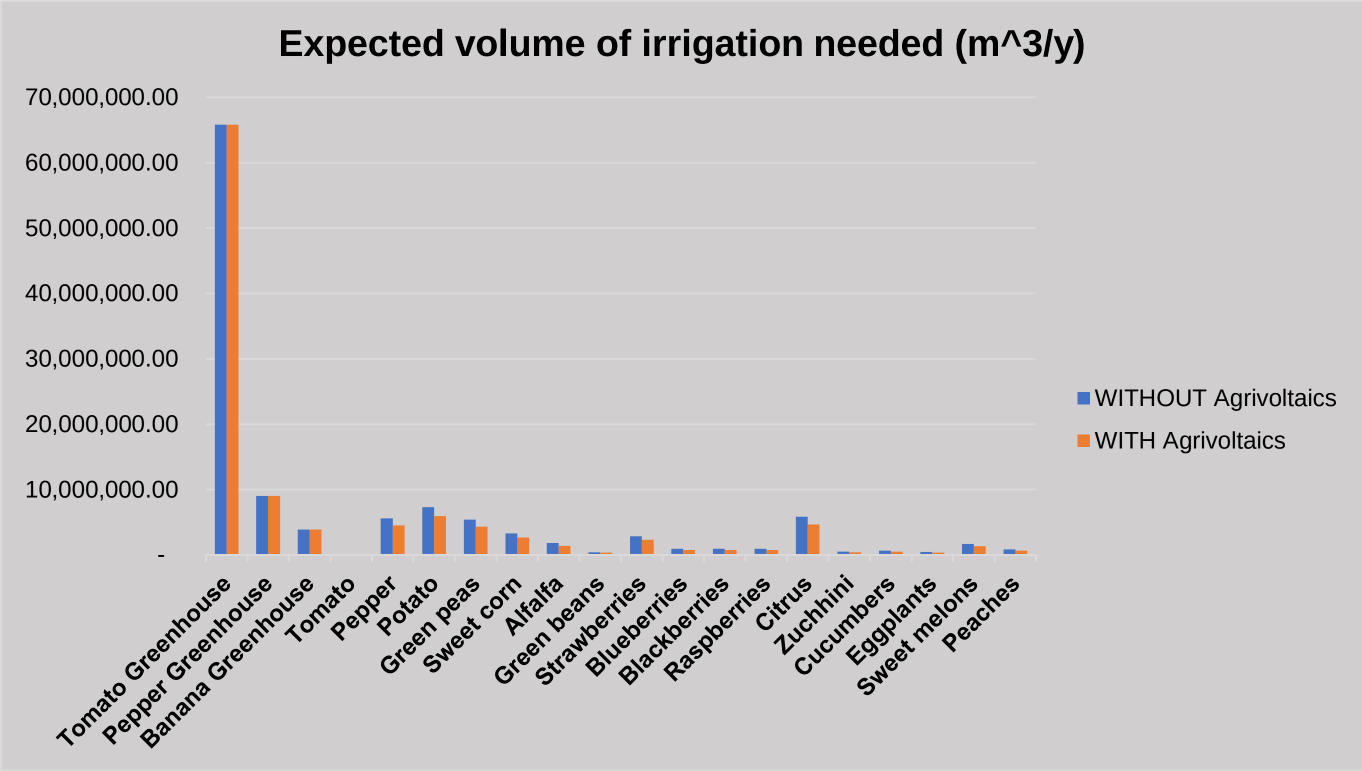

Figure 22 – Expected Volume of Irrigation Needed

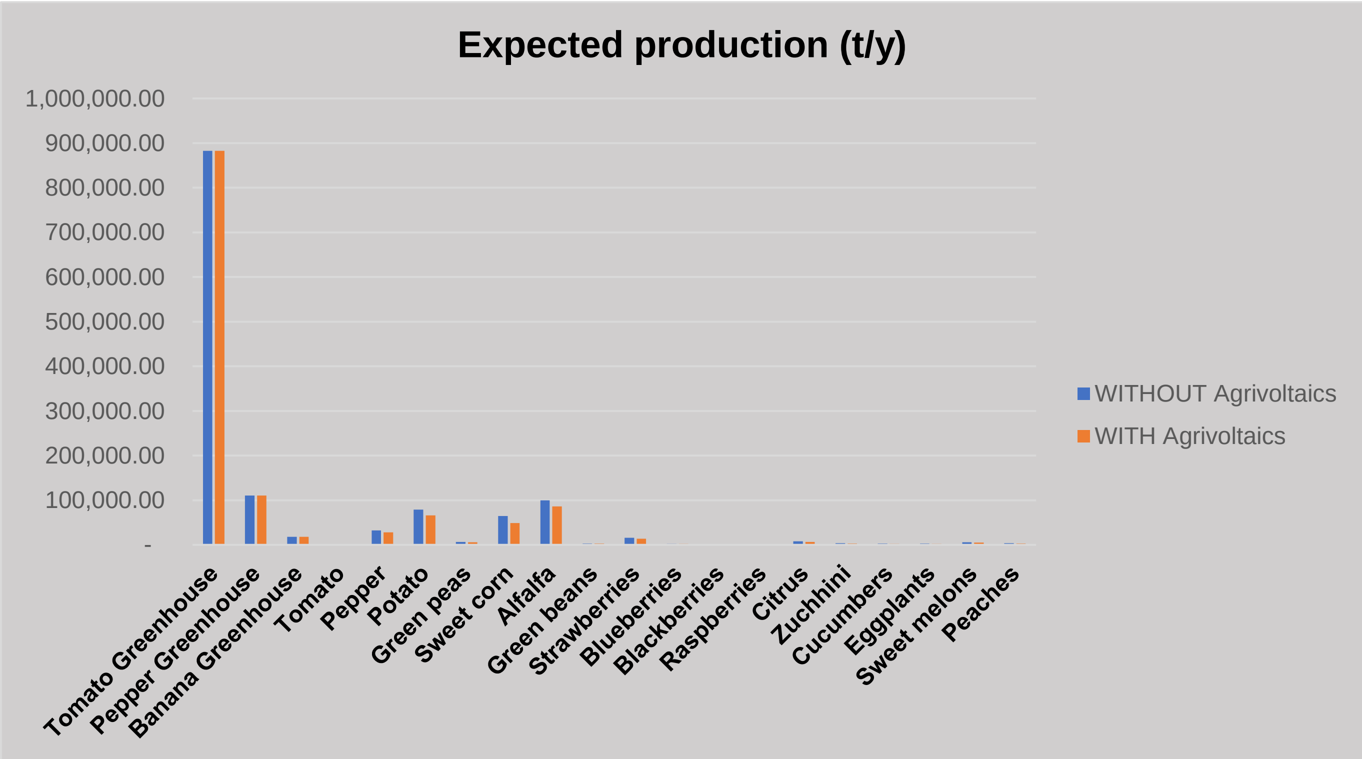

Figure 21 – Expected Production

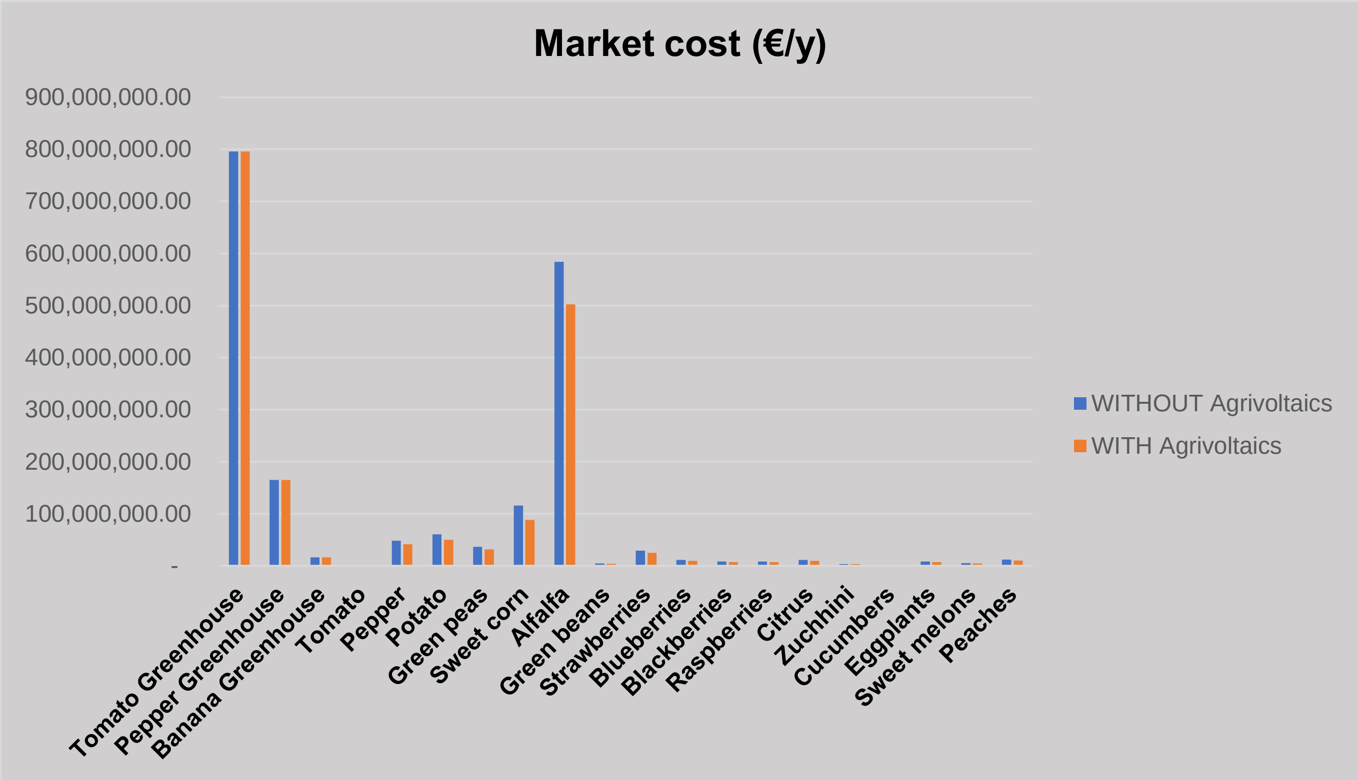

Figure 24 – Market Cost

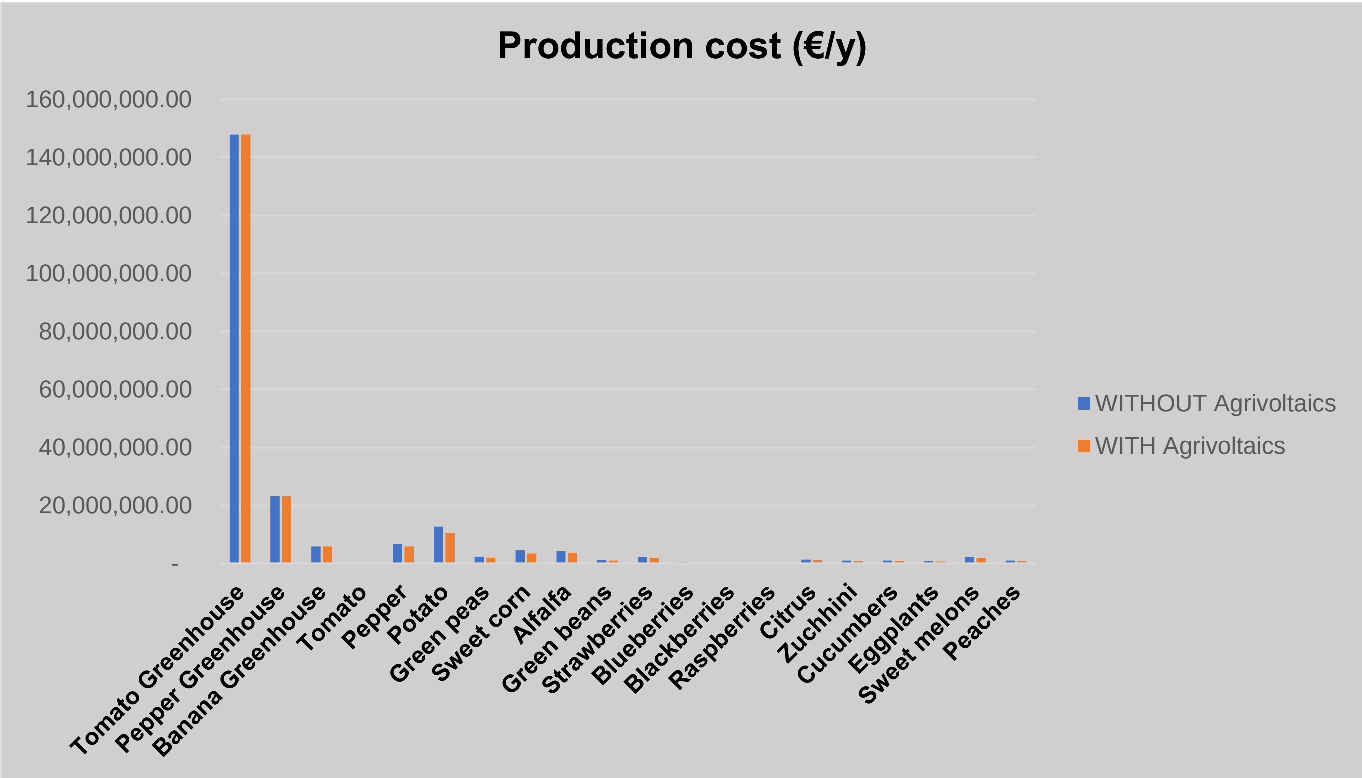

Figure 23 – Production Cost

SECTION B

Implementation of Photovoltaic Infrastructure

After having understood the main singularities of the region, it is time to implement the infrastructure of photovoltaic panels to be installed in the region, in order to power the different assets in the area with renewable energy and to make agrivoltaics happen.

To make this a reality, a model called MicroGridsPy will be used not only to compute how much area will be occupied by the photovoltaic panels, but also to obtain the total cost that this project would suppose.

MicroGridsPy

MicroGridsPy [82] is an open-source model developed in Python [83] and using the external solver Gurobi [84] to obtain the desired results, meant to get the most optimal design of a minigrid to power a village or a residential area. It was developed by the department of energy of Politecnico di Milano and, even though it was created to model a minigrid, it can be used for many other purposes as long as the input data are inserted correctly, as the equations to calculate the necessary capacity to be installed in the area and the parameterization of the photovoltaic panels to be installed would also apply to power industrial machinery.

This model differentiates two types of inputs. Energy inputs refer to the resource assessment in terms of weather data, which in this case correspond to the solar radiation associated with the area of study; and to the load assessment, as the demand should be variable between day and night.

The other input corresponds to the technological characterization, which refer to the parameterization of the different technologies taken into account in the model, being in this case photovoltaic panels, batteries and diesel genset generators.

Besides this inputs, project parameters must also be inserted, in order to set boundaries to the model so that the solver Gurobi can reach an optimal solution to the problem.

Once all these inputs have been inserted into the model, there is only left to run it and wait for the results. What this model does to obtain those results is a net present cost-oriented optimization to determine the optimal combination between the installed capacity of photovoltaic panels, batteries and diesel generators. In summary, it obtains the lowest nest present cost (NPC) for the lifetime of the project within the constraints of the system.

These constraints refer to the different equations that solve the problem, making it a linear programming problem, by using all the input data that will be described for the technological parameterization part [85], [86], [87].

After finding the most optimal solution for the problem minimizing the NPC, the results obtained from the model are the sizing of the project, the dispatch during the lifetime of the project and all the costs associated to it.

Input Data for Implementation

Many different runs with different inputs will be performed in order to find the most optimal configuration for the project. In order to do so, the varying factors will be three photovoltaic panels with different nominal powers of 440W, 490W and 540W and its associated costs, demand loads varying the share of energy needed between day and night, stating that during day more energy will be needed than during night, and imposed renewable penetration in the project, in terms of photovoltaic panels and batteries.

Firstly, as for the resource assessment, these data will be obtained from renewables.ninja [88], by setting the capacity that the panels are able to generate, getting three different series of solar radiation for each of the studied photovoltaic panels, as shown in *Figures 25, 26 and 27*.

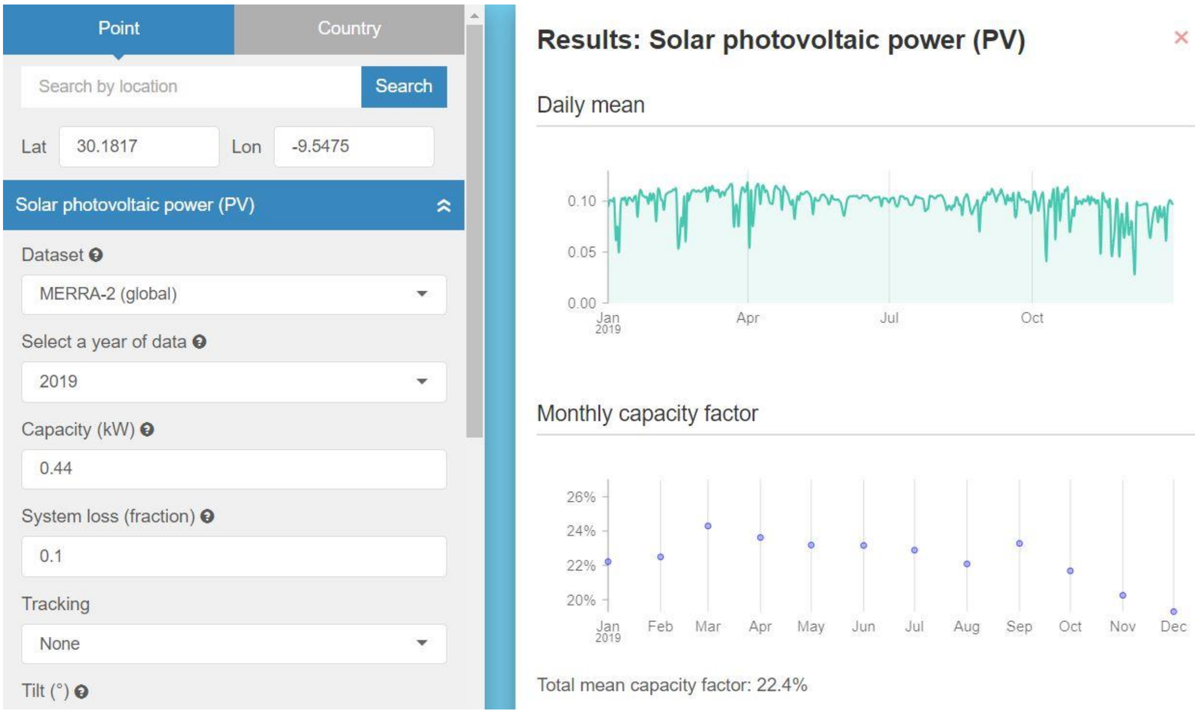

Figure 25 – Solar Radiation Time Series for 440W

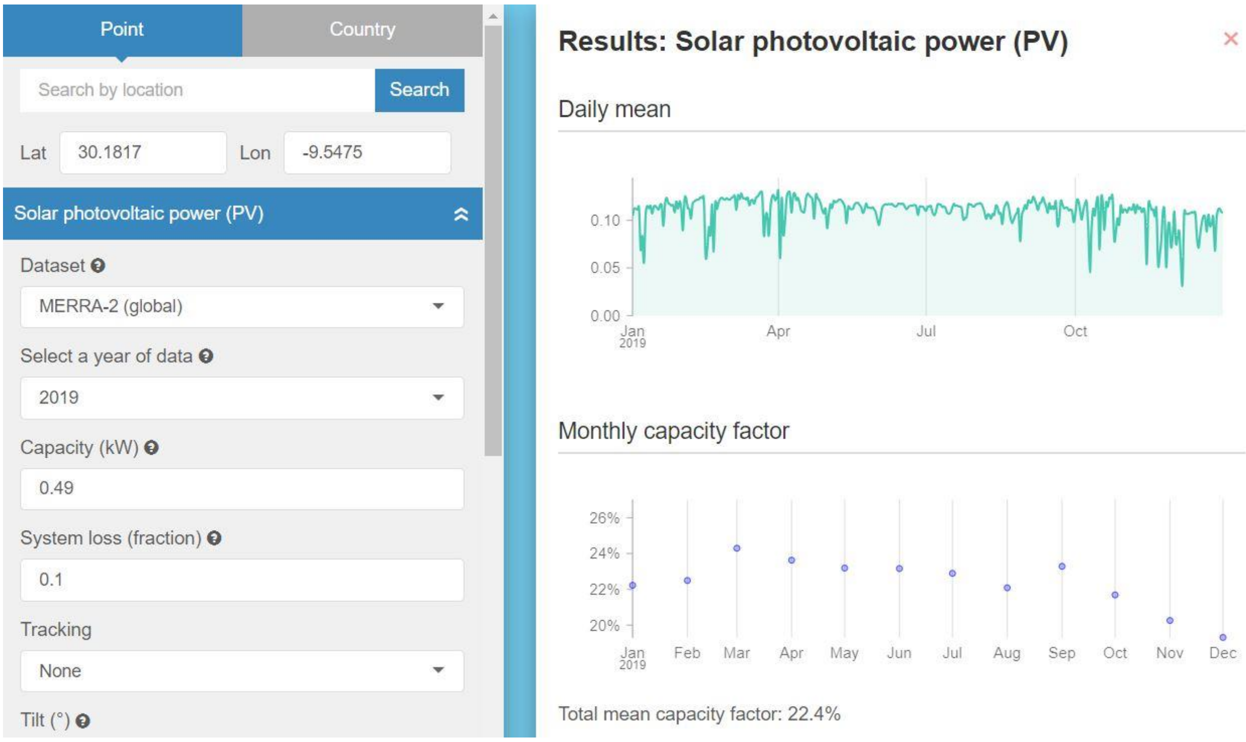

Figure 26 – Solar Radiation Time Series for 490W

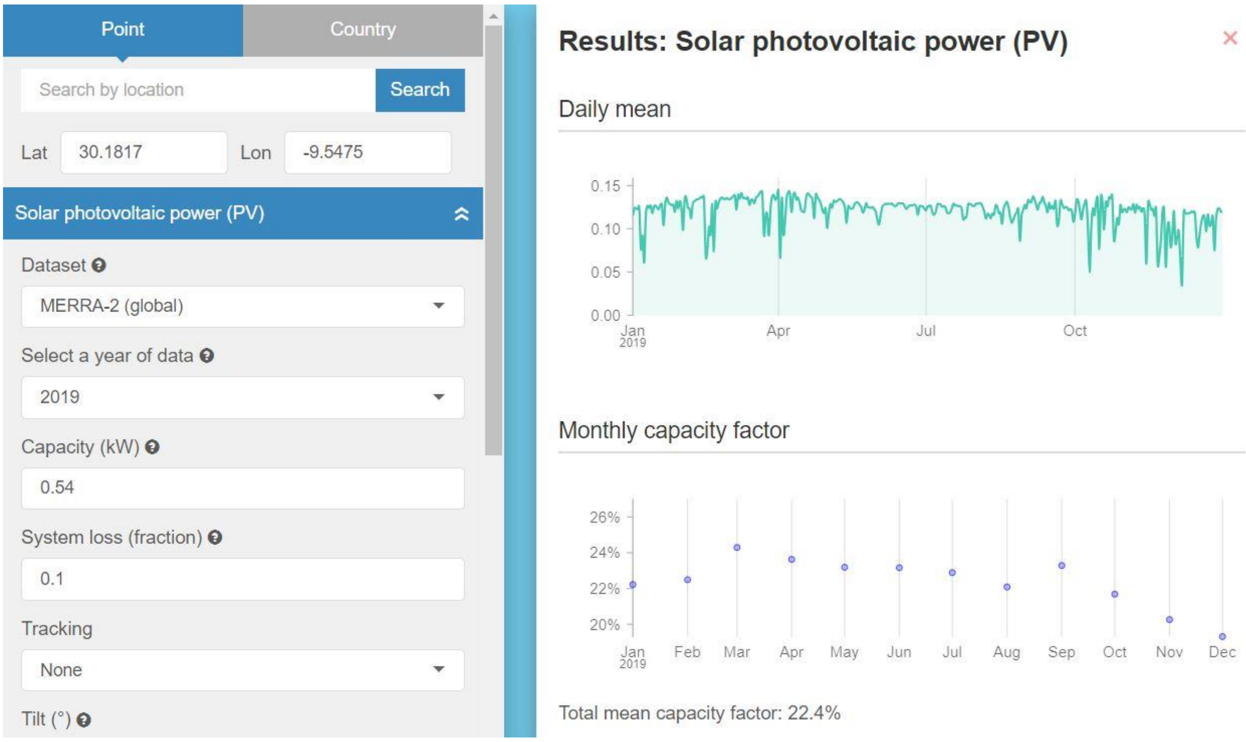

Figure 27 – Solar Radiation Time Series for 540W

Secondly, the demand series will be obtained from the input data for Area Analysis regarding the energy requirements obtained for each asset of the region. In order to be as realistic as possible, different time series will be created modifying the share between day and night of each asset.

As for the drip irrigation system, the groundwater pumping stations and the pumping station from the dam, these will only be running during the day proportionally to the solar radiation got during each day stating that these assets will only be active for when irrigation is taking place, that is to say, during daytime.

As for the wastewater treatment plants and the desalination plant, these will be active also during the night, as they not only provide water for irrigation but also for domestic and industrial use. Different proportions can be taken in order to create a time series, these being a proportional share between day and night, double the energy demands during day than night (relation 1-2), triple the energy demands during day than night (relation 1-3), etc. This greater share of energy during daytime would reduce the amount of tanks to storage water as the biggest water demands happen during daytime, both domestic and industrial uses but also for irrigation purposes.

It is important to remind that the desalination plant would be affected by an expansion in 2030, rising the water that can be produced almost double, making the energy requirements increase almost double as well. This will affect the time series from 2030, as the first five years (from 2025 to 2029, both included) one time series would be active, and the following five years (from 2030 to 2034, both included) another time series with the updated energy requirements would be active.

By summing up the value obtained in each series for each hour for one year, the final series is obtained, which will be inserted into the model as the demand requirements of the area.

And finally, the last inputs to be inserted are the technical parameters obtained from catalogues and literature and the constraints of the project itself, setting the start and duration time of the project.

As for the project parameters, the selected ones are shown in *Table 9*.

Starting date	01/01/2025 00:00:00
Duration (years)	10
Time step (hours)	1

Table 9 – Project Parameters

Regarding the technological parameters, these are separated depending on which technology they refer to. Starting from the photovoltaic panels, the chosen ones to be studied are shown in *Table 10* [89].

Hyundai HG 440W Black PERC	**Nominal Power (W)**	440
	Efficiency (%)	20.70
	Dimensions (mm)	1899 x 1096 x 30
	Area occupied (ha/panel)	0.00114668
	Price [USD]	101
	Specific Investment Cost [USD/W]	0.788326364
	Lifetime (years)	25

Trina 490W mono PERC	Nominal Power (W)	490
	Efficiency (%)	20.50
	Dimensions (mm)	2176 x 1098 x 35
	Area occupied (ha/panel)	0.00131394
	Price [USD]	147
	Specific Investment Cost [USD/W]	0.809272653
	Lifetime (years)	25

Canadian Solar HiKu6 Mono PERC 540W	Nominal Power (W)	540
	Efficiency (%)	21.40
	Dimensions (mm)	2261 x 1134 x 35
	Area Occupied (ha/panel)	0.00136527
	Price [USD]	193.55
	Specific Investment Cost [USD/W]	0.82744
	Lifetime (years)	25

Table 10 – Photovoltaic Panels Parameters

For the calculation of the area occupied, this was calculated as the multiplication of the length of the panel times the width of the panel plus the distance left between photovoltaic array's rows. The length and width of the panel can be checked from the parameter Dimensions, but the distance between each array of panels must be computed separately.

In order to do so, the following formula obtained from empirical methods will be used [90]:

$$D = l\cos\beta + d = l\,(\cos\beta + \frac{\sin\beta}{\tan(61° - \emptyset)})$$

Where D is the distance between arrays (m), l is the height of the panel (2 m), Ø is the latitude ($30°$) and β is the optimal tilt angle ($36.6°$, obtained from literature [91])

By computing the formula with the values just shown, the result obtained is 4.94 m of distance between each array, which must be summed to the width of the panel in order to calculate the area occupied by the panels.

Apart from this, it is also needed to insert in the model the specific investment cost of the technology used, in this case agrivoltaics. This value equals 0.01 USD/W [92].

Another important device related to photovoltaic panels in the inverter. The chosen brand is shown in *Table 11* [93].

Solar inverter Victron Phoenix 48/800 48V 700W	Price [USD]	220.17
	Efficiency (%)	94

Table 11 – Solar Inverter Parameters

Moreover, data associated to the battery used in this project is shown in *Table 12* [92], [94], [95]. This battery was selected among others because of its good thermal stability, long cycle life, great power capability and its low costs. One important clarification is that battery specific investment cost refers to the battery itself and the battery specific electronic investment cost refers to only the non-replaceable parts of the battery bank such as the anode, cathode, electrolyte, separator, among other materials.

Lithium iron phosphate batteries (LFP)	Battery Specific Investment Cost [USD/Wh]	0.578
	Battery Specific Electronic Investment Cost [USD/Wh]	0.278
	Battery Discharge Battery Efficiency [%]	92
	Battery Charge Battery Efficiency [%]	92
	Battery Depth of Discharge [%]	90
	Maximum Battery Discharge Time [h]	4
	Maximum Battery Charge Time [h]	4
	Battery Cycles	2500
	Battery Initial State Of Charge (SOC) [%]	0.7
	Battery Specific OM Cost [USD/W]	0.03

Table 12 – Battery Parameters

Finally, the last technology to be commented is the diesel genset generator, with its parameters represented in *Table 13* [92], [96], [97], [98], [99], [100].

Generator Efficiency [%]	0.3022
Generator Specific Investment Cost [USD/W]	0.4518958
Generator Lifetime [Years]	20
GEN unit CO2 emission [kgCO2/kW]	0
Fuel Specific Cost [USD/L]	1.4
Fuel LHV [Wh/L]	10000
FUEL unit CO2 emission [kgCO2/L]	2.7
Generator Specific OM Cost [USD/W]	0.05

Table 13 – Diesel Genset Generator Parameters

Results

After describing all the inputs to insert into the model, many different runs with different settings will be performed in order to find the most optimal setting to be implemented in the area.

The first calculations will be made with the total energy requirement inputs obtained in the input data for area analysis without using the model itself, simply dividing the total energy requirement by the efficiency of each photovoltaic panel in order to obtain the capacity to be installed, to later divide by the nominal power of the panel to obtain the number of panels to instal, to finally calculate the total area in hectares by multiplying by the area occupied by each panel. To clarify how the model MicroGridsPy works, the capacity to be installed obtained from the model takes into account the efficiency of the photovoltaic panels, so there is no need to divide between the efficiency.

For this, two different settings will be presented. The first one will take into account all the assets to be powered with electricity and the second one will only take into account the desalination plant and the drip irrigation system, as shown in *Table 14*.

		Area (ha)
All assets	**For 440W**	520.50
	For 490W	540.79
	For 540W	488.44
		Area (ha)
Desalination and drip irrigation	**For 440W**	390.37
	For 490W	405.59
	For 540W	366.33

Table 14 – Area Needed for Photovoltaic Panels from Mean Values of Energy Requirements

These values will serve as a reference to know if the model is providing reliable results and make sure that the software is being used properly.

From here, seven different experiments were conducted to better understand the behaviour of the system, varying the penetration of renewables, the assets to take into account, and the share of energy between day and night, in order to be able to study the results. For each variation, the model was run and different results on total capacity to be installed were obtained. The mentioned settings are the following:

1st. To ensure 90% penetration of renewables, while powering all the assets in the region and dividing the energy demand of the desalination plant and the wastewater treatment plants during day and night in the same proportion. It is worth remembering that the groundwater pump stations, the dam pump station and the drip irrigation system only demand energy during the day as their only purpose is to irrigate and irrigation would only be produced during daytime, proportionally to the solar radiation achieved each day.

2nd. To ensure 90% penetration of renewables, while powering all the assets in the region and dividing the energy demand of the desalination plant and the wastewater treatment plants only during daytime.

3rd. To ensure 90% penetration of renewables, while powering all the assets in the region and dividing the energy demand of the desalination plant and the wastewater treatment plants following a relation 1-2, that is to say, to demand double the energy during day than during night.

4th. To ensure 90% penetration of renewables, while powering all the assets in the region and dividing the energy demand of the desalination plant and the wastewater treatment plants following a relation 1-3, that is to say, to demand triple the energy during day than during night.

5th. To ensure 90% penetration of renewables, while powering only the desalination plant and the drip irrigation system and dividing the energy demand of the desalination plant during day and night in the same proportion.

6th. To ensure 100% penetration of renewables, while powering all the assets in the region and dividing the energy demand of the desalination plant and the wastewater treatment plants during day and night in the same proportion.

7th. To ensure 100% penetration of renewables, while powering only the desalination plant and the drip irrigation system and dividing the energy demand of the desalination plant during day and night in the same proportion.

The results obtained can be checked in the following figures.

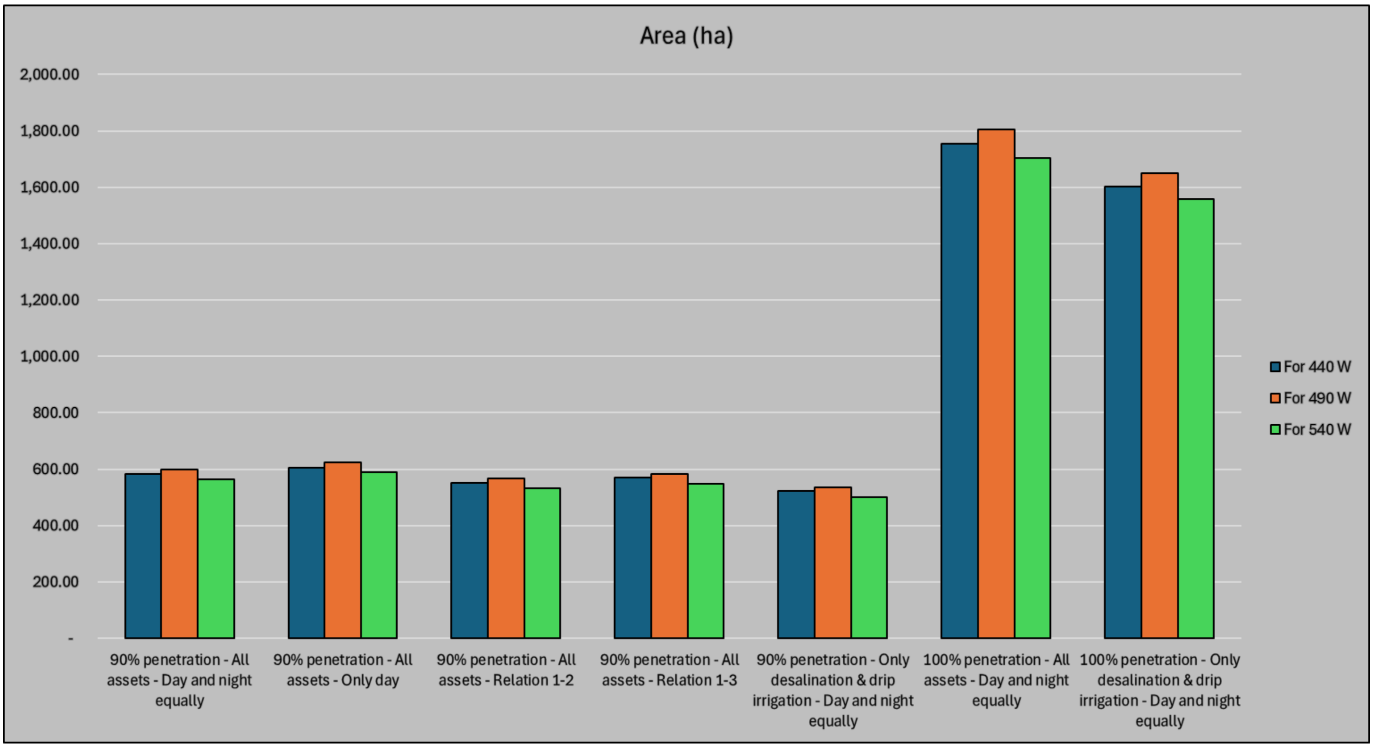

Figure 29 – Total Area to Be Used for Implementation of Photovoltaic Panels 1st Set of Runs

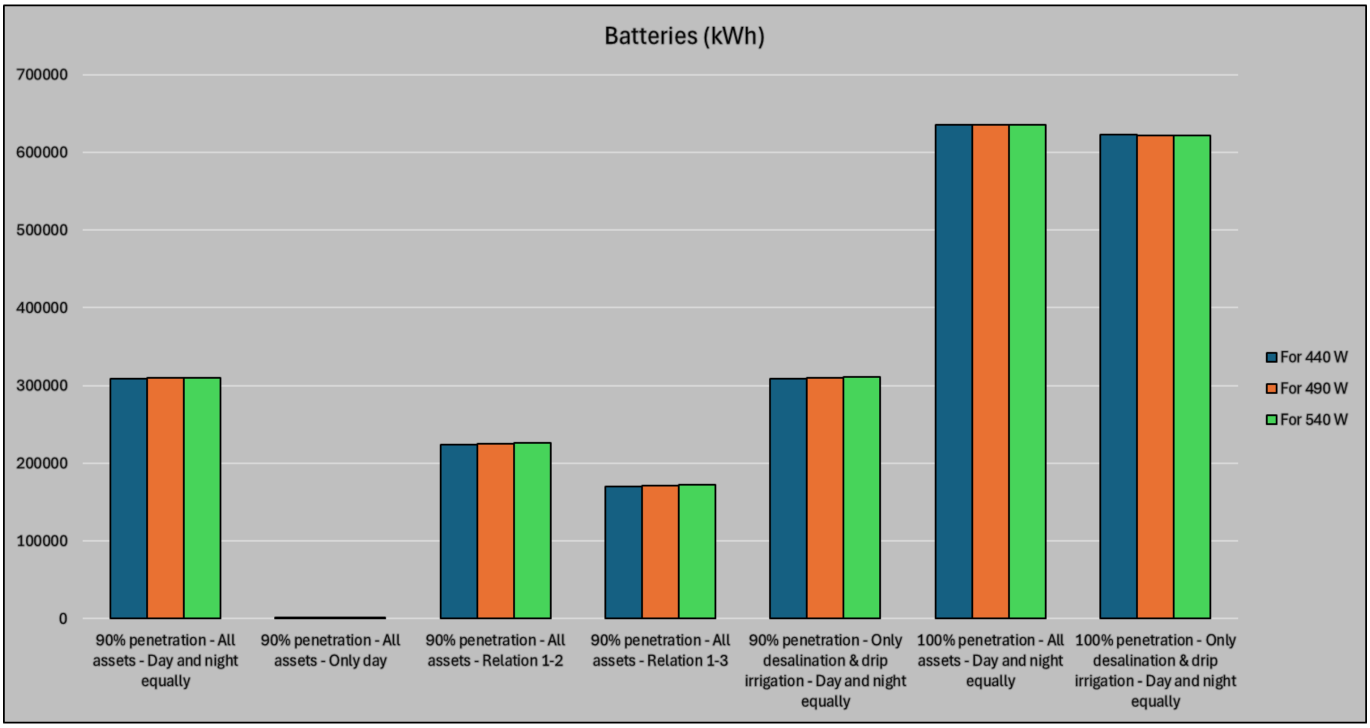

Figure 28 – Total Batteries to be Used 1st Set of Runs

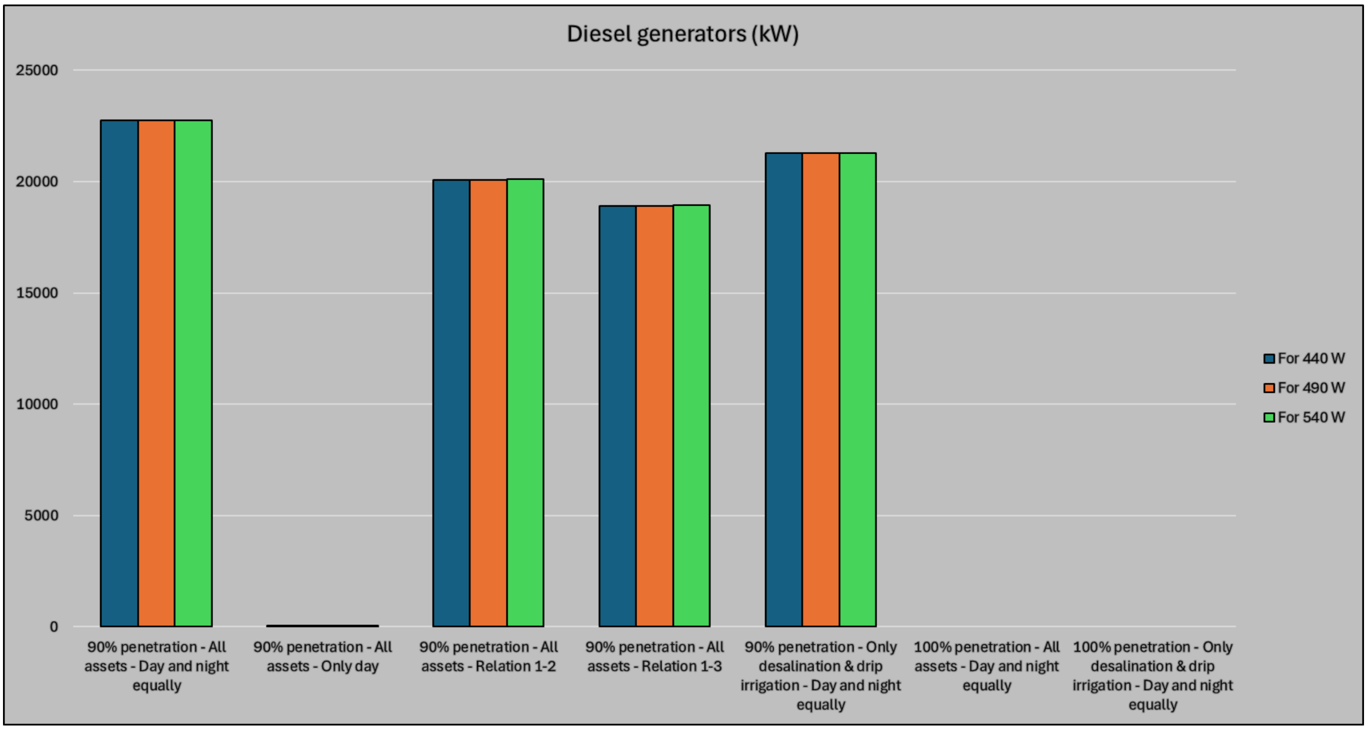

Figure 31 – Total Diesel Generators to be Used 1st Set of Runs

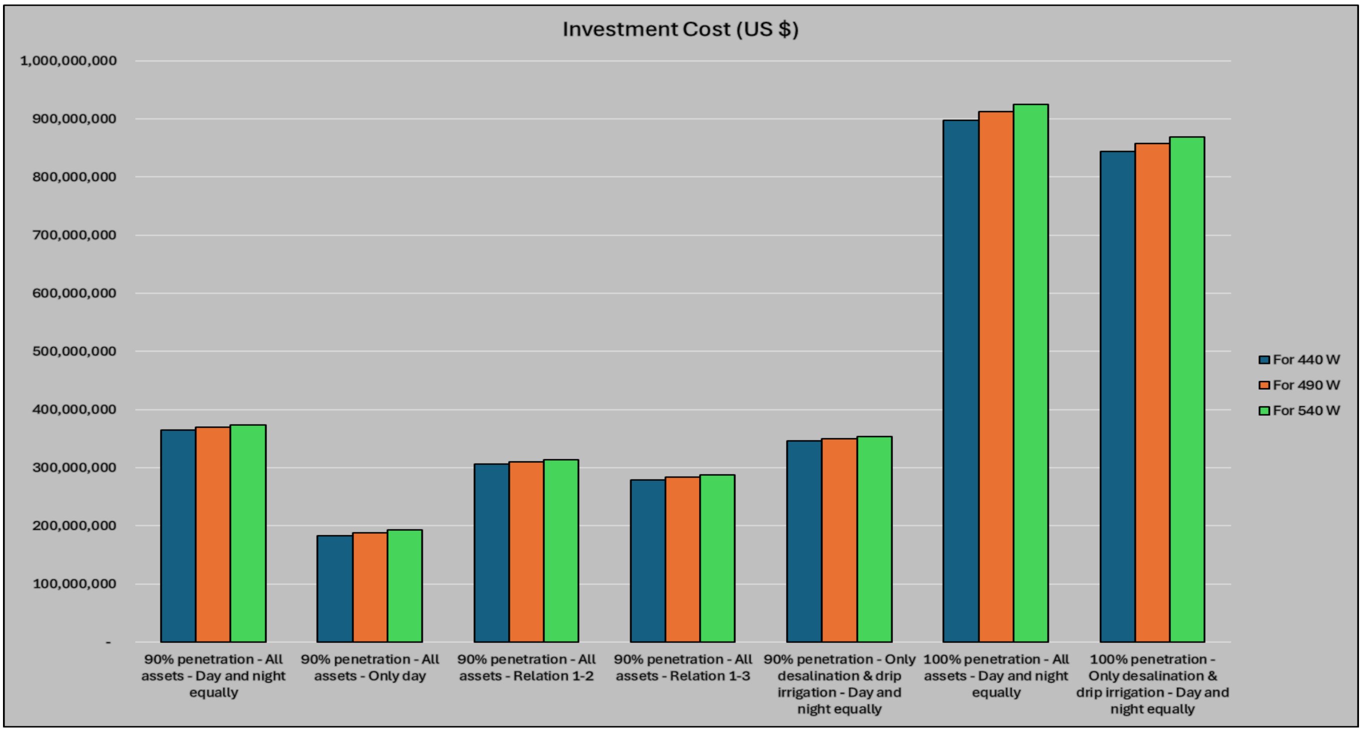

Figure 30 – Total Investment Cost 1st Set of Runs

After the analysis of these four graphs, it is noticeable the immense raise in investment needed to achieve a 100% penetration of renewables, as well as the area and batteries needed being much greater than when ensuring 90% penetration of renewables, making this option not suitable for the project.

As for the amount of assets to power, the investment cost, the amount of diesel generators and the area needed is slightly lower than powering all the assets of the area. Nevertheless, it is a minimal reduction, so all the assets of the area of study will be powered.

Regarding the share of energy demand between day and night, the best option would be powering all the different assets only during daytime, taking advantage of sun hours and avoiding using both batteries and diesel generators. However, these values where not consistent when running the model several times, minimally changing the results obtained, making them untrustworthy. As for the rest of the settings, it is clear that the more energy is demanded during daytime, the less area, batteries, diesel generators and investment cost would be needed.

Finally, the comparison between the three studied photovoltaic panels, the one with a nominal power of 490W is clearly providing worse results than the other two in terms of area needed, maintaining the other variables very similar between each panel. Moreover, the 540W panel is the most expensive and the one that requires the most batteries and diesel generators, although it needs much less area than the other two options. Considering how much less area it is needed to meet the demands and the minimal increase in investment cost, batteries and diesel generators, the chosen photovoltaic panel is the 540W panel.

Before stating the new settings to be run in the model, it is worth highlighting that the reference values obtained with mean values of energy requirements are close to 500 hectares in the case of powering all the assets and 400 hectares in the case of powering only the desalination plant and wastewater treatment plants, while when running the model, the values obtained are close to 600 and 500 hectares respectively. This raise in the area needed by the photovoltaic panels is due to the fact that the reference values were obtained with average values of energy requirements and the software MicroGridsPy calculates the capacity to be installed from peak energy demands. Therefore, the values obtained both from mean energy requirements and from the software make sense.

Now, after having understood better the system and having chosen the 540W panel and to power all the assets of the region, fifteen new settings were run in the model. These new settings could be divided into three different cases, the first one with 90% penetration of renewables, the second one with 93% and the third one with 95%. Within each of these penetration of renewables values, five different runs will be performed, varying in each of them the share in energy demand between day and night, trying the following relations: 1-3, 1-4, 1-5, 1-7 and 1-10.

The results obtained can be checked in the following figures.

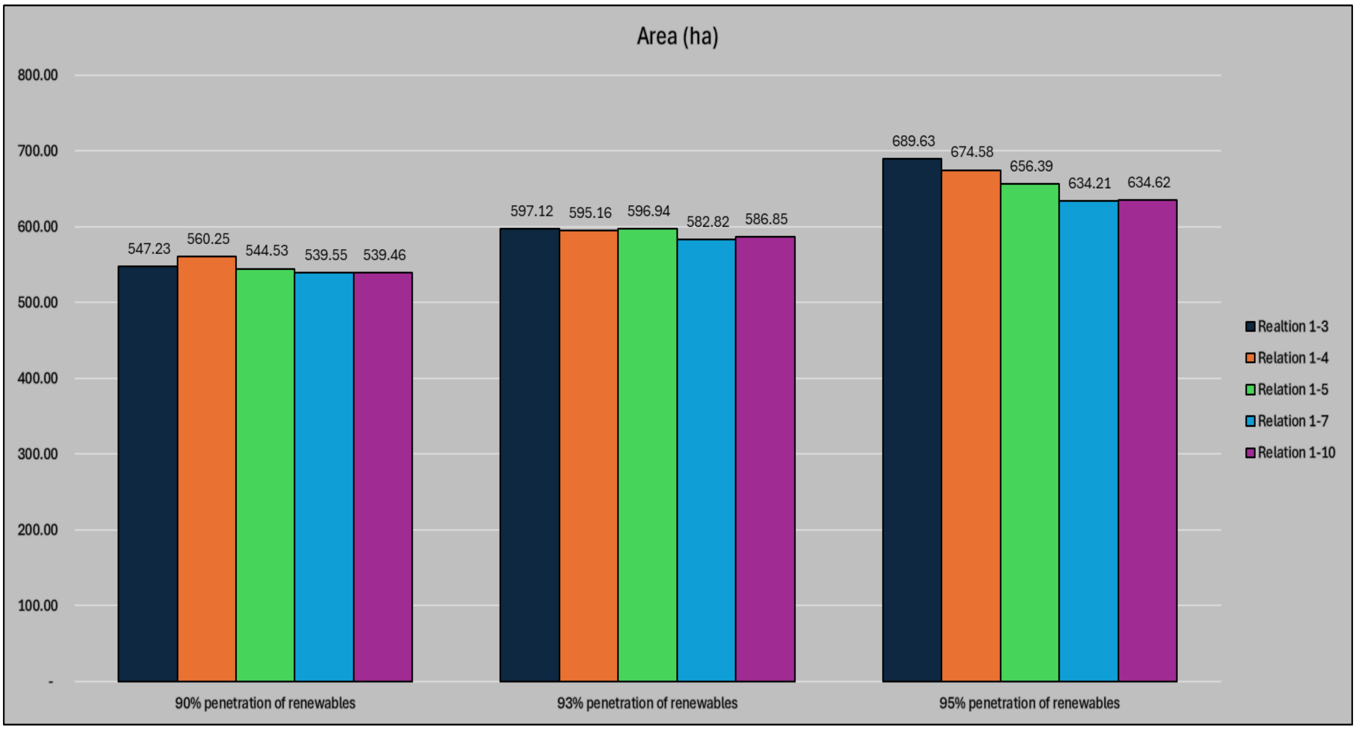

Figure 33 – Total Area to Be Used for Implementation of Photovoltaic Panels 2nd Set of Runs

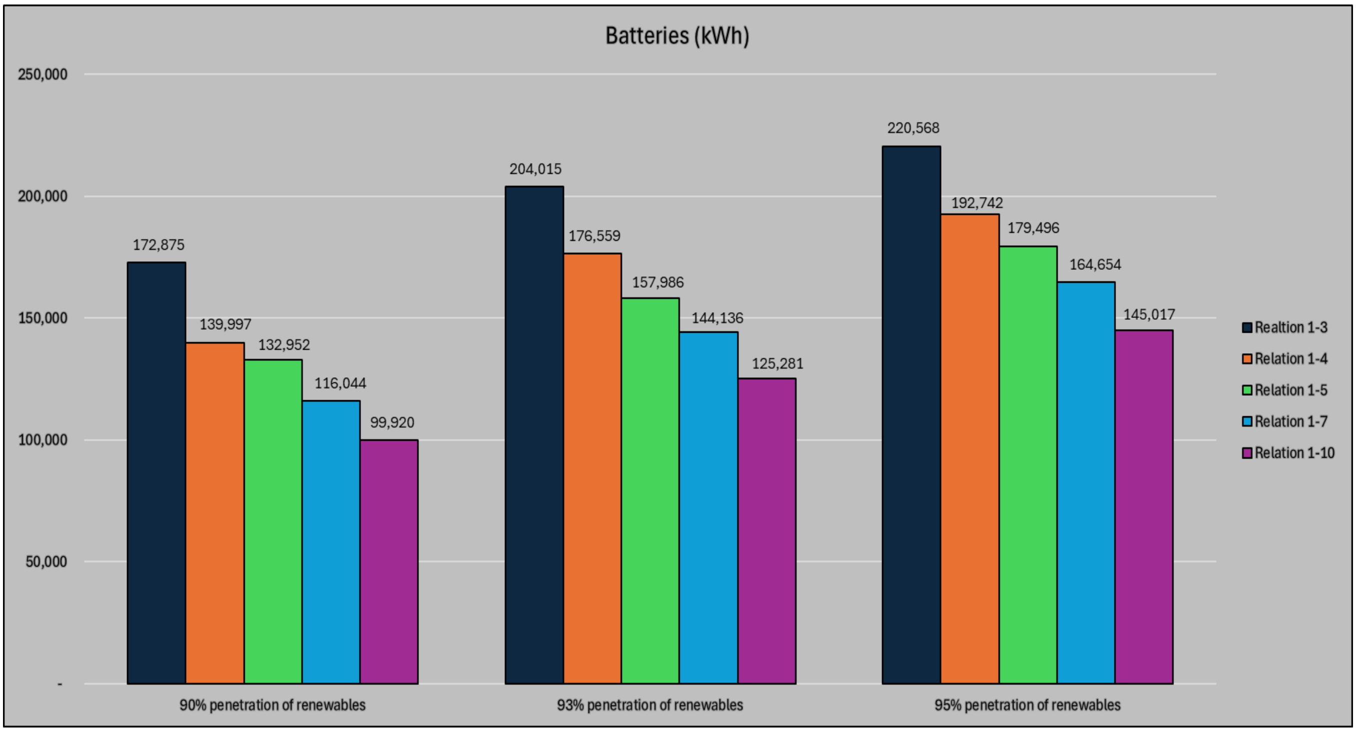

Figure 32 – Total Batteries to be Used 2nd Set of Runs

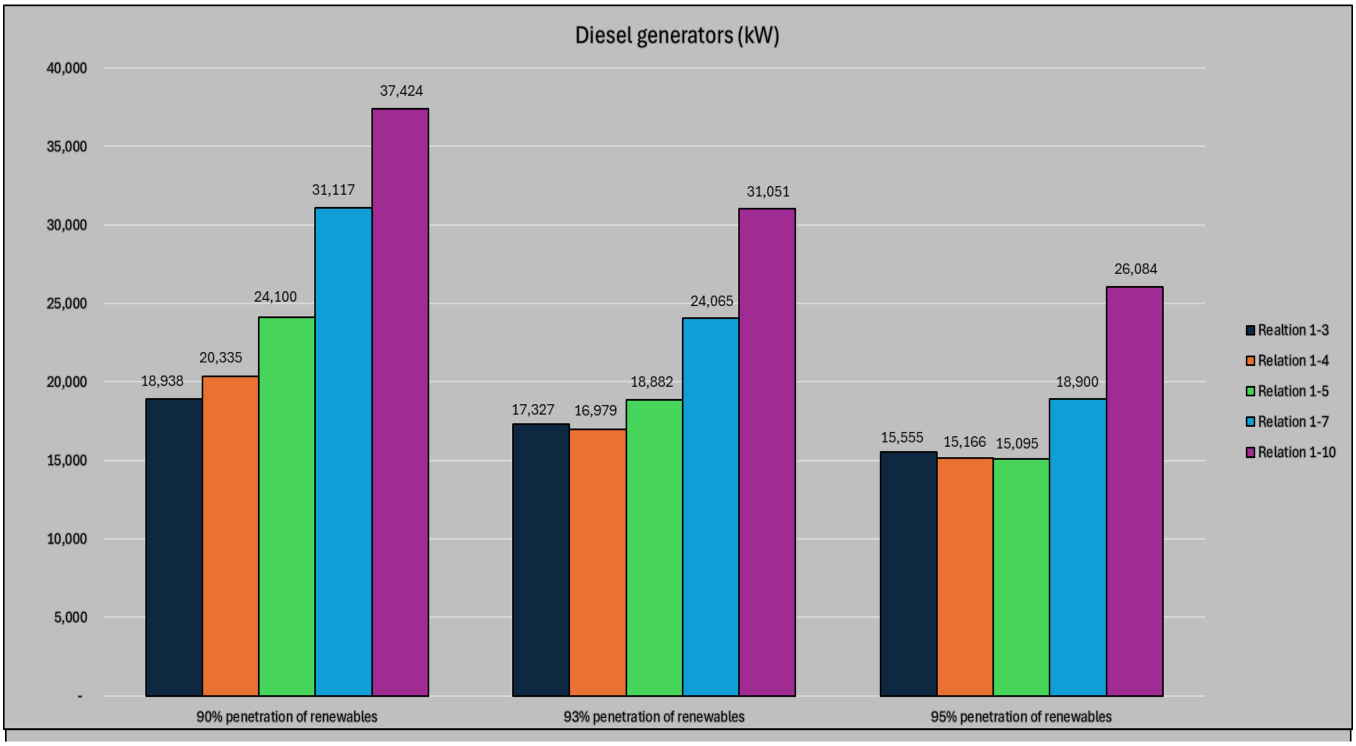

Figure 34 – Total Diesel Generators to be Used 2nd Set of Runs

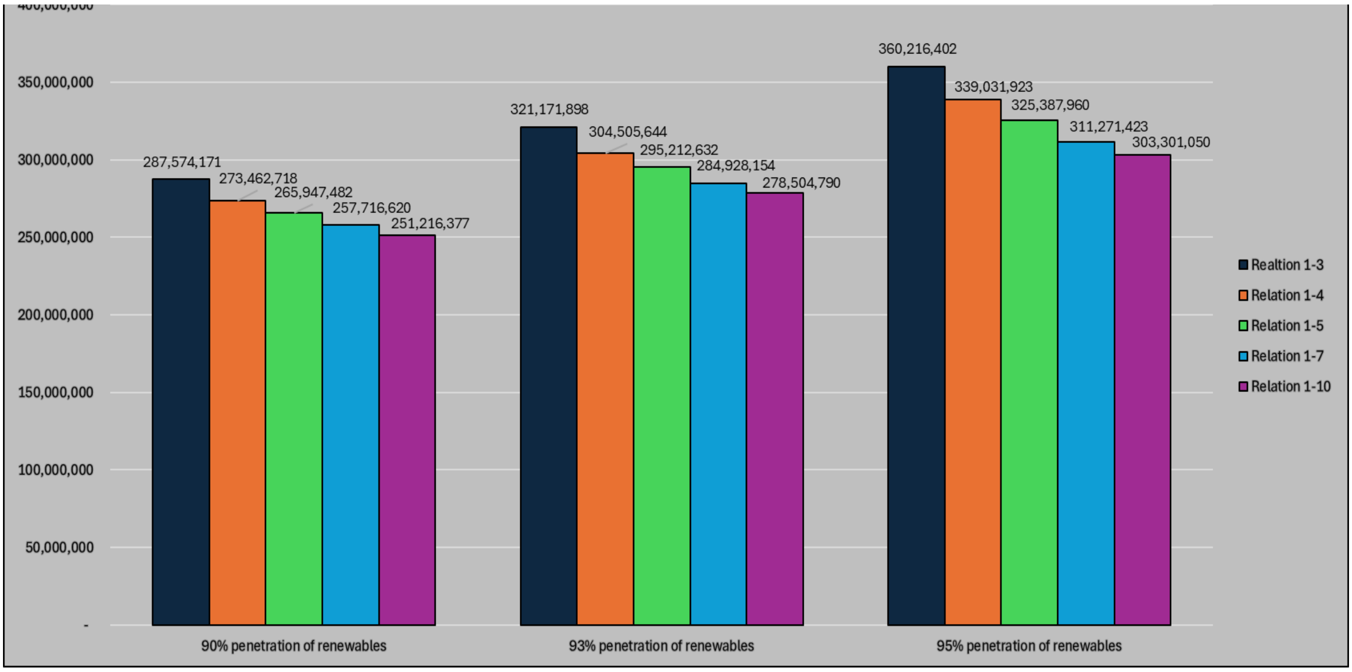

Figure 35 – Total Investment Cost 2nd Set of Runs

The main goal is to minimize all the variables, butt with a special emphasis on diesel generators, in order to reduce pollution as much as possible, and investment cost. However, investment cost decreases proportionally, and diesel generators increase exponentially from a certain point, so it is preferred to minimize diesel generators.

Following those guidelines, the chosen settings are a 93% penetration of renewables with a relation of 1-4 between night and day, and a 95% penetration of renewables with a relation 1-5 between night and day.

The exact results of these two settings are shown in *Table 15*.

	Installed capacity (W)	Number of panels	Area (ha)	Batteries (kWh)	Diesel (kW)	Investment Cost ($)
93% penetration - Relation 1-4	235,402,640.00	435,930.81	**595.16**	**176,559.39**	16,979.03	**304,505,644.00**
95% penetration - Relation 1-5	259,617,670.00	480,773.46	656.39	179,496.02	**15,094.67**	325,387,960.00
% of increase			9.33%	1.64%	-11.10%	6.42%

Table 15 – Final Results from MicroGridsPy

Finally, the chosen setting is the relation 1-5 between day and night and a 95% of penetration of renewables for its much lower pollution in the form of diesel generators, even though the area, batteries and investment cost would be higher.

From MicroGridsPy, it is also obtained different graphs in different dates showing the system energy dispatch and load demand for each of the chosen dates. For this case, the chosen dates are "01/01/2025 00:00:00", "01/01/2027 00:00:00", "01/01/2030 00:00:00" and "01/01/2033 00:00:00".

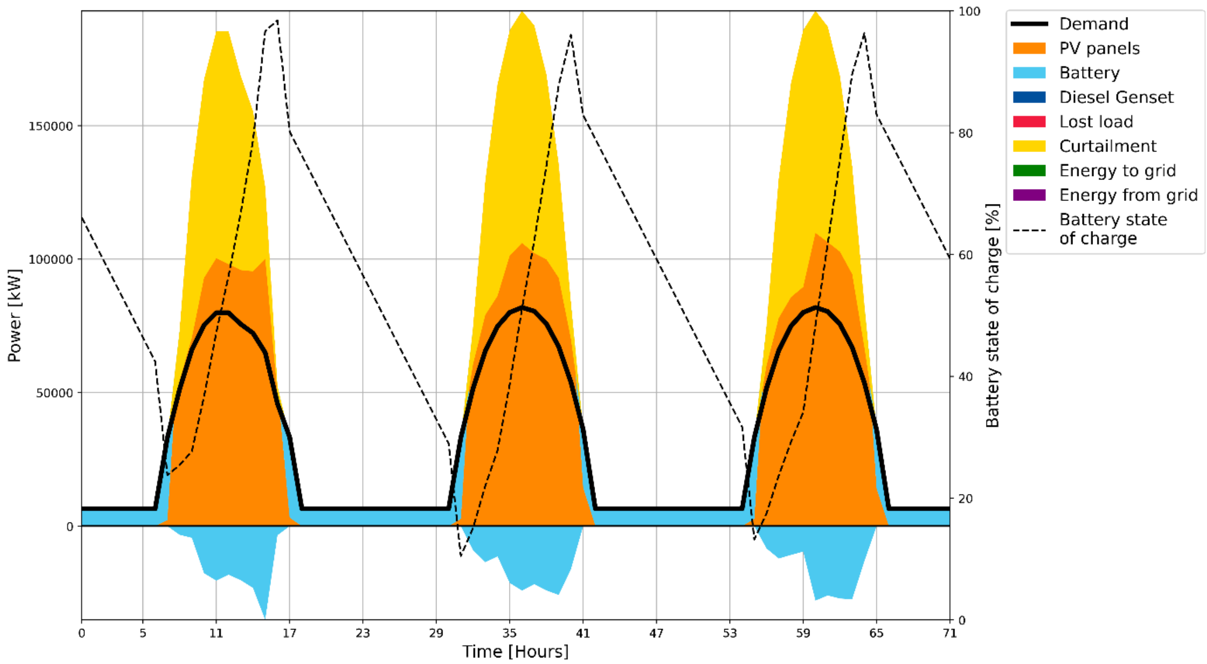

Figure 36 – Dispatch Strategy for "01/01/2025 00:00:00"

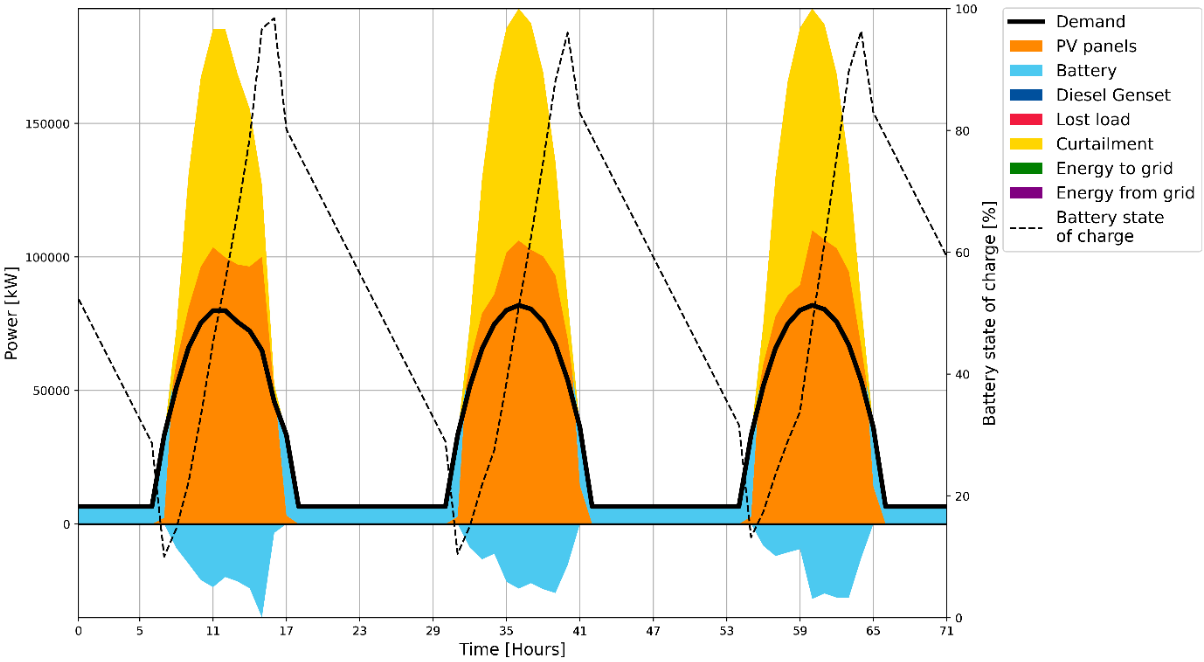

Figure 37 – Dispatch Strategy for "01/01/2027 00:00:00"

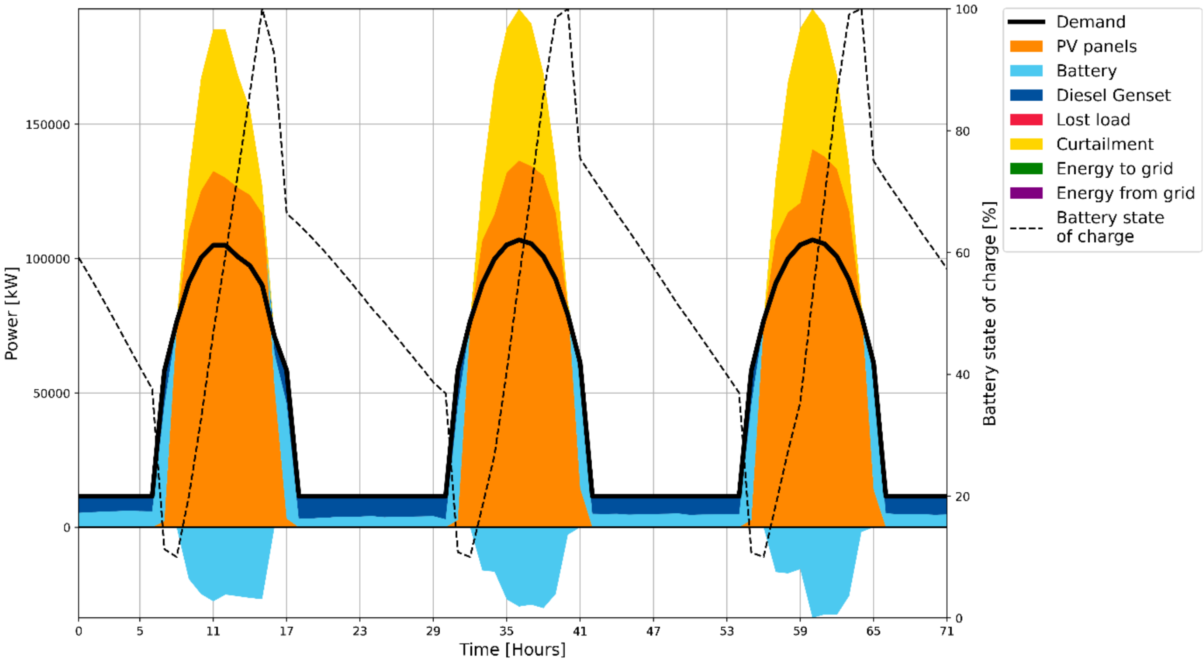

Figure 38 – Dispatch Strategy for "01/01/2030 00:00:00"

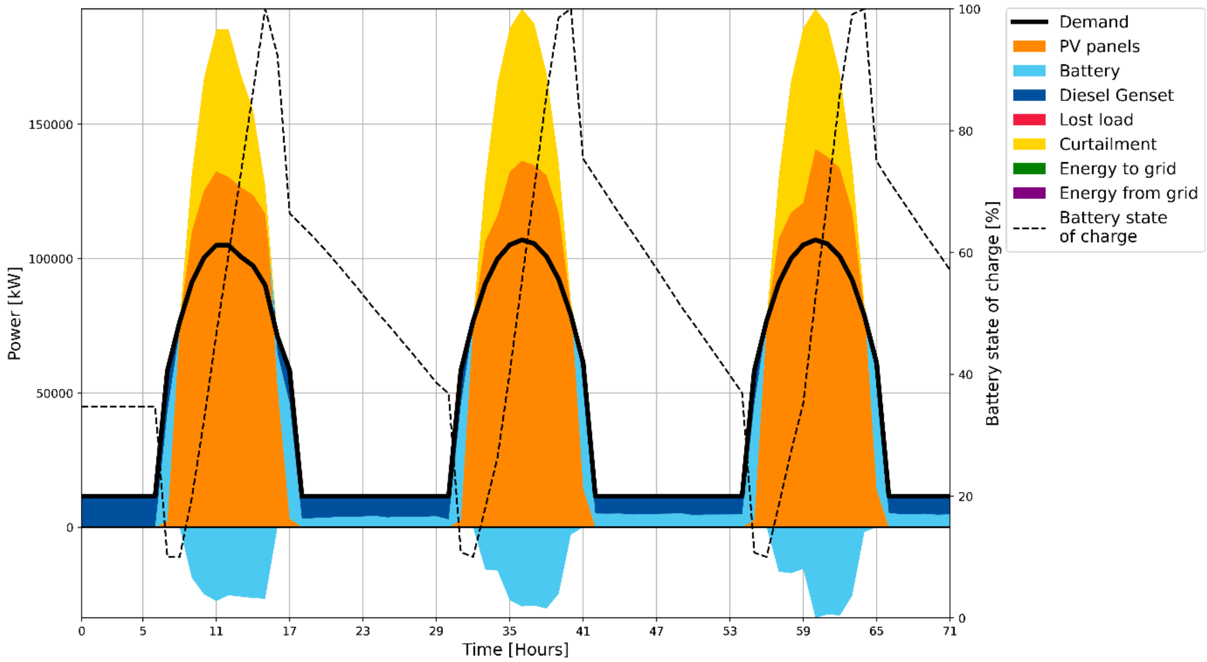

Figure 39 – Dispatch Strategy for "01/01/2033 00:00:00"

The most remarkable characteristic of these plots is the introduction of the diesel generators from 2030, coinciding with the expansion on the capacity of the desalination plant and therefore, the increase in energy demands. In this situation, the photovoltaic panels and batteries installed in 2025 would not be enough to power all the assets in the region and a backup system as the diesel generators would be needed.

In the end, to maintain the 95% penetration of renewables imposed as a constraint of the problem, the model calculated the first five years with a penetration of 99.88% and the following five years with a penetration of 90.58%.

Another output obtained from the software is the CO2 emissions that this project would produce during its ten year of lifetime, being this value 224,989.52 tonnes.

And finally, the area covered by the photovoltaic panels would equal 656.39 hectares, which, comparing with the area of study, would look like the map shown in *Figure 40*.

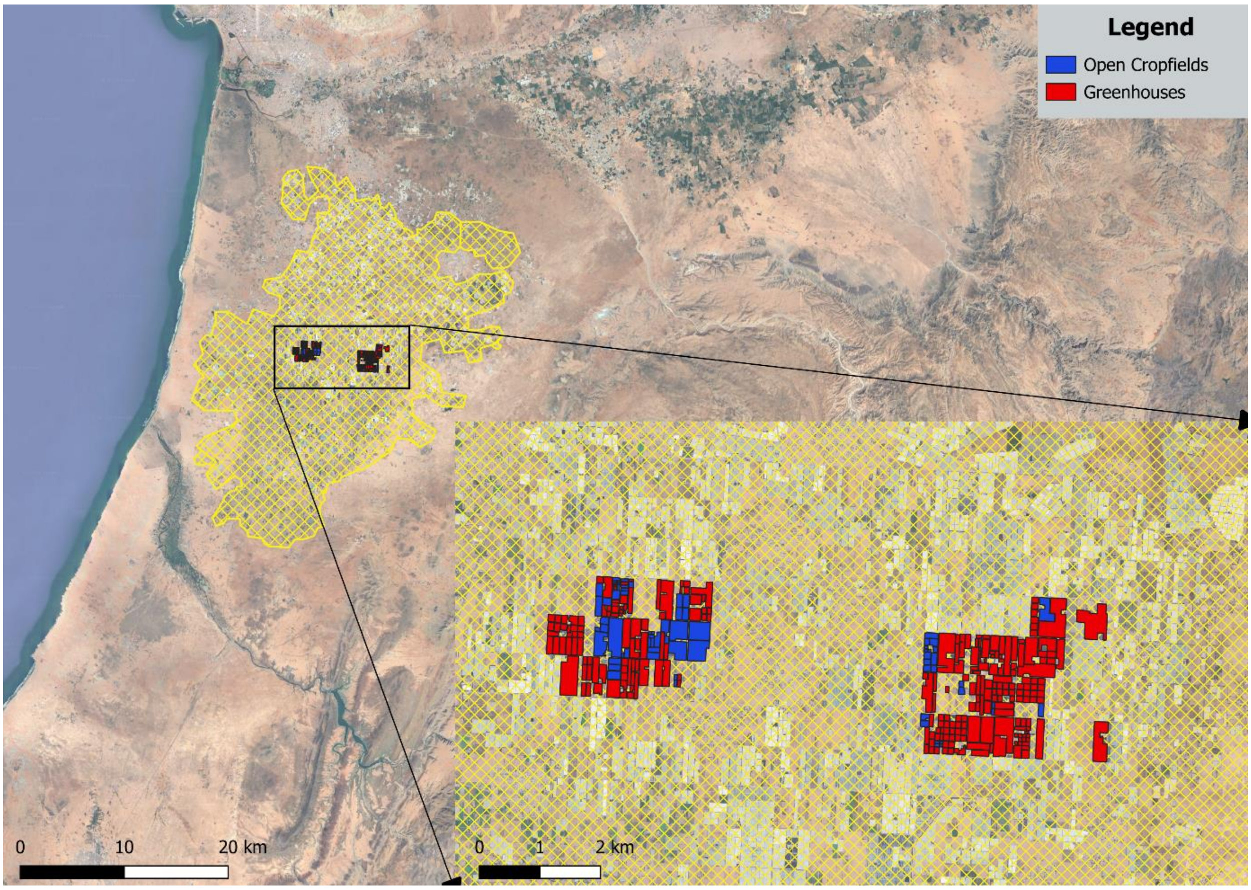

Figure 40 – Area to be Covered by the Photovoltaic Panels Comparing it to the Total Area of Study

Even though the area required by the photovoltaic panels is greater than many other similar projects, the amount of energy to be provided to the different assets of the region forces to plan a project of these dimensions.

Once the area has been chosen to be covered by photovoltaics panels, both greenhouses and open cropfields, the very last step is to make a feasible strategy on how to implement the physical structure that a photovoltaic panel suppose and how to adapt the existing structure to agrivoltaics. As for the open cropfields, these do not have to adapt in any way to the implementation of the photovoltaic panels, although the conditions under these would be modified as well as the expected water requirements and crop production, as described earlier. However, in the case of greenhouses, it depends on what kind of greenhouse is found in each slot of cropland in the area of study.

As stated in the Area Analysis, there are two different type of greenhouses. The first one is a proper greenhouse which creates a slightly different ecosystem inside of them, providing some benefits to the crops in order to enhance their production, and the second one refers to a dark loan set over the crops which try to cover the crops in order to prevent as much solar radiation from reaching the ground and harming the crops. This is special to this area and regions with similar climate, as the amount of solar radiation in certain hours of the day, especially in summer, surpasses the optimal solar radiation that a crop needs.

As for the dark loan set above the crops, this structure would just be replaced by the photovoltaic panels installed above them, in the same way as with the open cropfields. This would provide the necessary shading in order to reach the optimal amount of solar radiation reaching the ground. On the other hand, proper greenhouses already aim to achieve certain conditions for the crops, so this would have to be adapted into the agrivoltaic system, by using the photovoltaic panels to close the structure [101]. In order to achieve this, many different configurations have been developed, although many studies and implementations are still needed in order to fully understand the consequences and implications of this combination of technologies. Some proposed structures are represented in *Figure 41* [102].

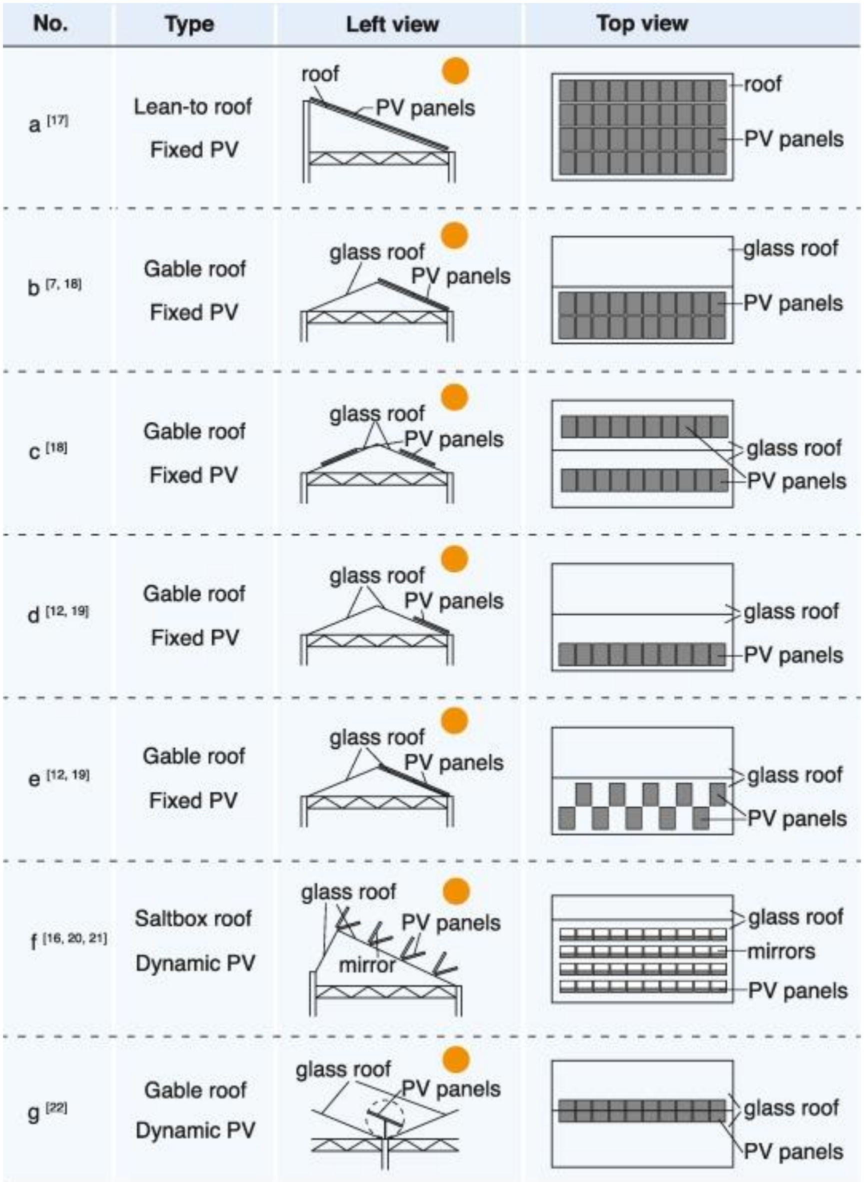

Figure 41 – Different Configurations to Combine Photovoltaic Panels and Greenhouses

Moreover, the company called Agrocare claims to have implemented black-out systems into their facilities, although no photographic evidence was found, nor in their webpage, nor in the internet [103]. Nevertheless, this new concept of greenhouses called black-out systems could suppose a good alternative in order to combine both agrivoltaics and greenhouses.

This technology is based on the concept of shorter days so that the behaviour of crops would change, leading to an increase in yield. This means that black-out curtains that do not allow light to enter the greenhouse would be primordial, in order to erase the conditions found inside the greenhouse caused by the climatic conditions in the area and impose new conditions inside the greenhouse, such as shorter days' cycles or controlling humidity and temperature [104]. This is usually achieved using LED lights or high-pressure sodium (HPS) lamps, which would provide the necessary light and heat to the crops when scheduled [105].

As a summary, the final area would look like in *Figure 42*.

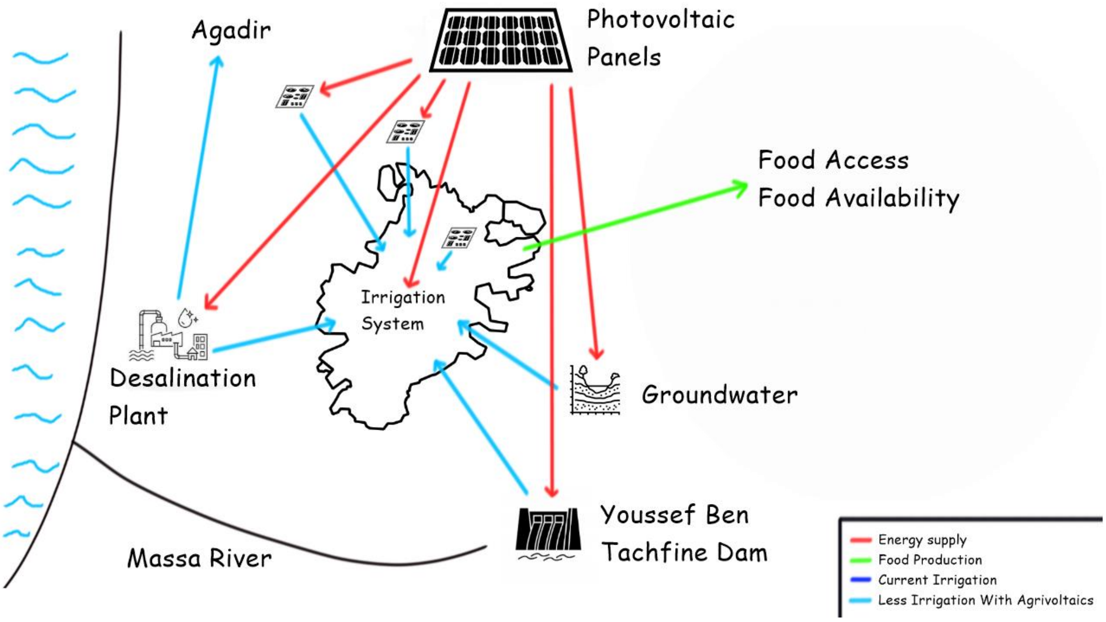

Figure 42 - Assets of the Area after Implementation

Economic Analysis

Thanks to MicroGridsPy software, the list with the different costs of the project is a result as well, resulting in *Table 16.*

Cost item	Component	Unit	Total
Weighted Net present cost	System	USD	409,328,757.00
Net present cost	System	USD	409,328,757.00
Total Investment cost	System	USD	**325,387,960.00**
Total fixed O&M cost	System	USD	34,420,035.00
Total variable O&M cost	System	USD	100,528,691.00
Salvage value	System	USD	- 51,007,930.00
Levelized Cost of Energy	System	USD/kWh	0.19
Levelized Cost of Energy scenarios	System	USD/kWh	0.19
Investment cost	PV panels	USD	214,818,044.00

	Battery bank	USD	103,748,700.00
	Diesel Genset	USD	6,821,217.00
Fixed cost	PV panels	USD	13,199,639.00
	Battery bank	USD	19,124,725.00
	Diesel Genset	USD	2,095,671.00
Lost load cost	System	USD	-
Replacement cost	Battery bank	USD	45,218,369.00
Fuel cost	Diesel	USD	55,310,322.00

Table 16 – Costs According to MicroGridsPy

The main drawback from this table is that there are some costs not taken into account in this model, such as cabling and water tanks. Each of them will be addressed and calculated separately to finally obtain a complete table with all the costs included.

The wire selected is armoured cable due to its high resistance to high temperatures. After computing the distances to be covered, as sown in *Figure 43*, and its market price, the values obtained were 97.23 kilometres in total and a cost of 35.58 DH/m, with a final cost of 316,733.00 USD [106].

Figure 43 – Cabling Representation

As a portion of water would be produced during night and most of it would not be used, water tanks to storage the excess water are needed. According to the previous calculations from the Framework and the solar radiation time series, it is possible to estimate that the total amount of water produced during night from the desalination plant and wastewater treatment plants is equal to 18,400 m^3 of water. From this position, it is recommended that at least 50% of that volume is covered by water tanks, which equals 9,200 m^3 [107].

The chosen water tank is 10.000 m^3 big, built next to the desalination plant, as it represents a much bigger water source compared to wastewater treatments plants. That stored water would be distributed across the area for industries, water supply network facilities and farmers to use this resource the following morning, before sunrise. The final price of this water tank is 39,654,332 DH, which equals to 3,994,190.52 USD [108].

After adding these two extra costs, the final investment cost of this project is 329,698,883.52 USD.

Discussion

This project has focused on three of the main current issues that the world is facing, water scarcity, lack of energy coming from renewable sources of energy in order to fight climate change, and food security.

For this matter, in order to propose an integrated solution as the one presented in this study, it is completely necessary to fully understand every singularity of the case study being taken into account. For that purpose, the developed framework serves as a guide to know which data to be taken into account and what results to expect, although each case study is unique and this framework should be constantly evolving and adapting.

Another key aspect from this part of the project is how critical quality data are, as not always all the desired data can be found. When this happens, it is important to think outside the box in order to come up with new ways to obtain the desired data from other values and variables. In relation of this, a further research of the solar radiation reduction would be needed, depending on many different factors such as latitude, tilt of photovoltaic panels, separation between panels, and so on. For this project, a constant value of 30% reduction in solar radiation was taken. Apart from this, the assumption of starting from the maximum available depletion was also taken, in order to avoid an excessive irrigation the first day of study.

Regarding this case study, the results obtained show a clear overexploitation of the different water resources existing in the area, especially groundwater, where no restrictions on its use exist. If a more detailed study was conducted for each cropfield and each farmer was told exactly how much water should be used to irrigate the surface meant for agriculture, the current situation on water could be reversed to the point that not only the different resources would not be stressed, but also to let them recover from the previous pressure that all of them have been under in past recent years.

Another interesting feature of the framework is that it is interactive, letting the user specify how much water will be extracted from each water source, in order to come up with the strategy that better suits the area of study. It also automatizes the calculations, making the user to just fill the input data sheet to obtain the different results with their representations.

Regarding people wellbeing and accessibility to food, two different indicators help understand that situation, being how much produced food should be sold locally to meet food supply demands and how much percentage of a household salary should be invested into buying the necessary amount of each crop. For this case study, these two indicators were too high, in the first one because many crops had to be imported no matter what in order to meet the demands and the second one because to invest more than 4% of the salary, without having taken into account many different important crops which are not cultivated in the area, suppose a great stress on household in their struggle to acquire all the daily food needed.

As a final comment on the area analysis part, it has been shown how some of the current structures and technologies used to enhance crop yield among other parameters are obsolete, some of them relying on broken loans or unstable greenhouses. The modernization of the region towards an agrivoltaic area would also allow farmers to improve on the quality and safety of their facilities, while benefiting from the update.

Regarding the second part of the study, the trickiest aspect is to find the right catalogues, existing in the region of study, from where have access to the technology needed for the project. Nevertheless, many model runs with different parameters and technologies can be performed, as in this case study, to properly narrow the options towards an optimal solution.

The methodology presented in this study along with the most important variables to take into account can be easily adapted to many different case studies, always leaving some free room for improvement on the utilized methods or for adaptation to more relevant variables depending on the area of study.

It is also worth noting that this is an iterative process, where the results obtained on the implementation of the technology, technical or economical outcomes, may force the researcher to modify the inputs in the framework to obtain different values for water extracted, energy required by the different assets of the area or any other parameter, in order to re-run the implementation model with the new input data to finally obtain the most optimized results possible. As for the energy distribution over day and night, different runs were implemented by assigning a proportion of one to nighttime and another value to daytime, meaning that if that value chosen is five, the energy requirements over day would be five times bigger than during the night. This distribution was made following the most logical usage of water, but depending on the management of the different facilities and how flexible the production is, this distribution could greatly vary.

Focusing on the results, the most noticeable aspect is the expansion of the desalination plant on its capacity from 2030. This will not only affect the water produced, but also the energy requirements from the plant as many more processes will have to be powered with electricity. As for how the model works, everything would have to be installed by the beginning of the project and, due to this expansion, from 2030 it would be necessary to start using diesel generators to supply the remaining energy needed at night, as the installed capacity of photovoltaic panels would not be enough. A good option to ease this problem is to start installing the remaining capacity of photovoltaic panels once the expansion has begun and it is official that it will be built and implemented to the existing plant, as there would be enough time to adapt to the new situation and be ready for when this new energy requirement settles into the region.

Another important aspect of this study is the area occupied by the photovoltaic panels. From the selected configuration, the total area equals 656.39 hectares, which a priori supposes a great effort on convincing and making a deal with many different farmers, and receiving the permission from the government, but when this area is compared geographically with the total area of study, it is clear that it is completely feasible to instal that capacity into the region.

Finally, the way to implement that capacity may vary depending on many variables. As commented in the Results section of the implementation, agrivoltaics can be installed above open cropfields, introducing a new asset into the field without substituting or improving any structure. When greenhouses are the centre of attention, these can be either replaced or adapted into accepting the photovoltaic panels, depending on the concept of each greenhouse whereas its purpose is to just cover the field or to actually create an environment inside the greenhouse to enhance as much as possible the yield of the crop, apart from reducing the required irrigation water.

In summary, this study showcases a methodology to not only implement photovoltaic panels, but also to perform a complete analysis of a limited area, selecting the most interesting indicators depending on the case study. Nevertheless, there are some areas that have not been taken into account in this study such as a stakeholders analysis, legal matters to be taken into account for implementation, local surveys between local farmers or a life cycle thinking perspective to take into account all the stages of the project, not only the implementation itself, but also the processing of the materials to be used, the construction of the photovoltaic panels, their transportation, and their disposal/reuse.

Conclusion

First of all, this project presented a methodology to fully understand an interesting area to be integrated into a sustainable solution by identifying all the different indicators through a framework and acknowledging which are the area to tackle in order to reverse the situation.

In this case, agrivoltaics suppose a great opportunity to enhance all the aspects of the Water-Energy-Food nexus, as water scarcity would be diminished by an irrigation reduction of around 20%, energy would be provided to the desalination plant and the different assets from the photovoltaic panels, a renewable energy source, and food would be obtained from the crops, which would not only be secured, but also could be expanded thanks to the new irrigation requirements and better allocation of water thanks to the analysis obtained from the framework

Secondly, this study shows how the project can be implemented. By using the software MicroGridsPy or any similar one, many different runs and strategies could be implemented and modelled in order to achieve the best possible setting of photovoltaic panels, apart from getting a summary of the most relevant costs and the associated CO2 emissions.

Finally, if this exact project was to be implemented and developed in real life, there are many complications not taken into account in this study, such as legal conditions of each country, reception of the implementation from local communities, budget financing, or a life cycle thinking perspective, but with a team working on the different aspects to be accounted for, an analysis of the stakeholders, among other studies, it has been proven that these kind of projects can be implemented in real life and suppose a great improvement to the area of study.

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Appendix

Specific calculations per year and per month of the irrigation requirements for "Tomato":

For 2013:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	8.925354	0
May	83.37949	65.25406
June	107.3844	84.7254
July	158.6836	126.8344
August	181.1288	151.7438
September	118.8691	95.80729
October	83.57324	69.11297
November	0	0
December	0	0
Total	741.9441	593.478

Table 17 - Irrigation requirements per month for tomato year 2013

For 2014:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	20.55488	3.277055
May	83.37488	67.61492
June	119.3707	96.95303
July	144.4796	114.2081
August	152.5745	122.2583
September	109.4754	87.16823
October	106.7743	94.06241
November	0	0
December	0	0
Total	736.6042	585.542

Table 18 - Irrigation requirements per month for tomato year 2014

For 2015:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	8.08302	0
May	80.17735	61.64732
June	103.6202	82.92359
July	172.9222	142.7474
August	136.7543	109.5106
September	112.3364	91.98481
October	59.91382	51.44085
November	0	0
December	0	0
Total	673.8073	540.2546

Table 19 - Irrigation requirements per month for tomato year 2015

For 2016:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	45.44942	30.51255
April	36.50672	33.04545
May	58.8869	44.76086
June	110.4772	88.73817
July	145.2525	118.35
August	173.6569	143.5712
September	107.3575	86.55462
October	73.67053	60.6036
November	0	0
December	0	0
Total	751.2577	606.1364

Table 20 - Irrigation requirements per month for tomato year 2016

For 2017:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	31.3552	16.41798
May	75.43546	60.68437
June	121.4727	97.89763
July	136.3828	106.8215
August	168.8321	140.4654
September	121.071	98.4624
October	112.2469	97.3046
November	0	0
December	0	0
Total	766.7963	618.0539

Table 21 - Irrigation requirements per month for tomato year 2017

For 2018:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	41.16734	24.39905
May	69.18066	56.43461
June	100.0816	80.02362
July	143.6334	113.7519
August	137.7609	110.2313
September	135.4593	113.8692
October	69.51984	57.11826
November	0	0
December	0	0
Total	696.803	555.8279

Table 22 - Irrigation requirements per month for tomato year 2018

For 2019:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	36.393	18.93876
May	70.99936	56.95429
June	109.9041	90.27251
July	136.5985	108.9127
August	142.4847	117.3954
September	114.2048	93.273
October	84.14227	68.85388
November	0	0
December	0	0
Total	694.7268	554.6005

Table 23 - Irrigation requirements per month for tomato year 2019

For 2020:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	14.94687	5.083451
April	51.49209	46.10295
May	71.83115	57.25528
June	112.1464	91.03418
July	146.0645	117.5387
August	157.0626	129.154
September	117.4142	96.49071
October	75.69676	62.4885
November	0	0
December	0	0
Total	746.6545	605.1477

Table 24 - Irrigation requirements per month for tomato year 2020

For 2021:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	0	0
April	20.59502	7.029501
May	74.91954	60.92272
June	105.2072	84.26771
July	141.5175	112.8986
August	140.61	113.9563
September	115.6139	94.25558
October	73.84538	60.64774
November	0	0
December	0	0
Total	672.3086	533.9782

Table 25 - Irrigation requirements per month for tomato year 2021

For 2022:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	13.65911	4.167012
April	45.31391	37.19792
May	70.29949	52.70653
June	94.81902	70.83803
July	130.7458	96.37155
August	116.101	85.02461
September	87.97433	66.37676
October	99.12522	83.64196
November	0	0
December	0	0
Total	658.0379	496.3244

Table 26 - Irrigation requirements per month for tomato year 2022

For 2023:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
January	0	0
February	0	0
March	18.83169	6.498326
April	65.61923	58.12065
May	80.60677	66.80848
June	114.4794	92.01578
July	145.9343	114.5105
August	177.528	146.4771
September	122.0928	99.38399
October	111.297	99.34121
November	0	0
December	0	0
Total	836.3891	683.156

Table 27 - Irrigation requirements per month for tomato year 2023

Mean values for all these years:

	Irrigation requirements under normal conditions (mm/y)	Irrigation requirements under agrivoltaic conditions (mm/y)
Tomato	725.03	579.32

Table 28 - Mean irrigation requirements throughout all the years for tomato