# The impact of technology evolution and the access to fossil-fuels and electricity to land and labour productivity in Europe since 1970

Joan Lorente Ramos

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## Energy Engineering and Management

Supervisors: Prof. Tiago Morais Delgado Domingos
Prof. Tânia Alexandra Dos Santos Costa e Sousa

## Examination Committee

Chairperson: Prof. Edgar Caetano Fernandes
Supervisor: Prof. Tânia Alexandra Dos Santos Costa e Sousa
Member of the Committee: Prof. Carlos Augusto Santos Silva

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# DECLARATION:

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

# ACKNOWLEDGEMENTS:

I want to say thank you and express how grateful I am to everyone who made it possible for me to complete this thesis:

To my teachers, Tânia and Tiago. A special thank you goes to Tânia who gave me this interesting topic about farming. At first, I didn't think I would like this topic, but I found it really interesting, and I enjoyed learning about it.

To Paul Steenwyk for the work done that inspired me and was the starting point of this project.

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To my family. They have always supported me in everything I do and gave me the strength to keep going with this project.

# ABSTRACT:

Currently, global studies like the project by Paul Steenwyk have made significant strides in understanding the impact of technology evolution and the access to fossil-fuels and electricity to land and labour productivity. However, due to cultural and regional differences, as well as disparities in technological progress, these global datasets often fall short of providing an accurate representation for specific territories. Recognizing this gap in the research, this project aims to provide a more localized and detailed analysis, with a particular emphasis on Europe. This study uses data from 1970 and beyond, a time when we have a good and dependable database. By using this database and adding information from the Food and Agriculture Organization (FAO), the project provides a detailed look at Europe.

However, this thesis aims to do more than just collect and analyze data across Europe. This research also offers a significant solution to the urgent problems of our time. To this end, the project suggests a 100% renewable energy solution, which could help lessen the environmental harm caused by using fossil fuels in farming. The project imagines a future where farming thrives on renewable energy, adding to global efforts to combat climate change.

**Keywords:**

Energy, Muscle work, Electricity, Fuels, Farm, Solar

# RESUMO:

Atualmente, estudos globais, como o projeto de Paul Steenwyk, têm feito avanços significativos na compreensão do impacto da evolução tecnológica e do acesso a combustíveis fósseis e eletricidade na produtividade da terra e do trabalho. No entanto, devido às diferenças culturais e regionais, bem como às disparidades no progresso tecnológico, esses conjuntos de dados globais muitas vezes não fornecem uma representação precisa para territórios específicos. Reconhecendo esta lacuna na pesquisa, este projeto visa fornecer uma análise mais localizada e detalhada, com ênfase particular na Europa. Este estudo usa dados a partir de 1970, uma época em que temos uma base de dados boa e confiável. Ao usar esta base de dados e adicionar informações da Organização das Nações Unidas para Alimentação e Agricultura (FAO), o projeto fornece uma visão detalhada da Europa.

Mas esta tese visa fazer mais do que apenas coletar e analisar dados em toda a Europa. Esta pesquisa também oferece uma solução significativa para os problemas urgentes do nosso tempo. Para isso, o projeto sugere uma solução 100% renovável, que poderia ajudar a diminuir o dano ambiental causado pelo uso de combustíveis fósseis na agricultura. O projeto imagina um futuro em que a agricultura prospera com energia renovável, contribuindo para os esforços globais para combater as alterações climáticas.

**Palavras-chave:**

Energia, Trabalho muscular, Eletricidade, Combustíveis, Quinta, Solar

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# ACRONYMS:

**All acronyms used throughout the thesis.**

| | |
|---|---|
| AMW | Animal Muscle Work |
| BMI | Body Mass Index |
| DE | Digestible Energy |
| DA | Draft Animals |
| $E_p$ | Primary energy |
| $E_f$ | Final energy |
| $E_u$ | Useful energy |
| FAO | Food and Agriculture Organization |
| FU | Food Use per Day |
| FC | Consumed Feed |
| GE | Gross energy |
| HMW | Human Muscle Work |
| ILO | International Labour Organization |
| MW | Muscle Work |
| PFU | Primary Final Useful |
| WDPY | Days of Work per Year |
| WPFU | World Primary Final Useful |
| SoC | State of Charge |
| DoD | Depht of Discharge |
| PMP | Maximum Power Point |
| PPC | Power Plant Controller |
| PV | Photovoltaic |
| BESS | Battery Energy Storage Systems |
| CAP | Common Agricultural Policy |

# LIST OF SOFTWARE:

All software used throughout the thesis.

| | |
|---|---|
| Spreadsheet | Microsoft Office Excel |
| Text editor | Microsoft Office Word |
| Design of circuit | MATLAB SIMULINK |
| Graph Display | MATLAB |
| Plan Drawing | AutoCAD |

# 1. INTRODUCTION

## 1.1 Background and Motivation

The initiation of this study stemmed from a recognized need for an energy examination tailored to European farming. The intention is to continue the work done by Paul Steenwyk [1], titled "A worldwide time series of energy for human and animal muscle work for all industries and end-use"

In this project, the energy output of both animal and human work will be calculated, including both useful and final energy. The study will also utilize data from the FAO to determine the useful energy of electricity used in agriculture. Through the efficiencies of electric motors, the final electrical energy will be obtained. The quantity of fuels utilized in agriculture will also be calculated and converted into final energy through tractor efficiencies.

The land productivity for agriculture will be measured and compared at both a European and global level. Similarly, labor productivity will be calculated and compared across the same geographical scales. The final energy encompassing animal and human work, electricity, and fuels used in agriculture will also be evaluated.

In an effort to increase efficiency within the agricultural sector, the study proposes a solution to reduce the use of fuels entirely, envisioning a farm powered exclusively by renewable energy sources - in this case, solar power.

The proposed solution consists of a chicken farm for egg production and a vineyard. Real-case data from a vineyard in Alentejo will be incorporated into the study, while information related to the chicken farm will be derived from the literature - specifically, estimates of machine consumption within poultry farming. This data will enable the determination of a demand profile for the entire farm and a solar radiation profile for the Alentejo region. This in turn will facilitate the design of the electrical circuit for the farm, providing an understanding of the energy flow for battery charging and discharging, and satisfying the farm's eco-friendly energy demand.

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## 1.2 Objectives

Below are the detailed objectives that will guide this thesis:

- Complete a detailed study on energy use in agriculture in Europe, expanding on Paul’s research that couldn't be directly applied to specific regions.
- Use existing data sets to calculate both human and animal labour in terms of energy.
- Present simplified calculations of energy use to allow for global comparisons.
- Discuss and analyze the findings in search of trends or patterns and compare Europe to the rest of the world to understand the impact of technology and energy use on agriculture.
- Understand the specific needs of the agricultural sector to provide a more energy-efficient solution without compromising productivity.
- Design and simulate a self-sustaining farm powered by renewable energy, offering a more sustainable solution to the current farming model.

## 1.3 Structure of the Thesis

- Chapter 1 is the introduction of the topic to be discussed the related background and including the goals and structure of the work.

- Chapter 2 details the methodology used in this project. This includes the approach adopted from Paul Steenwyk's work, as well as the simplifications made due to the unavailability of certain data. This chapter also analyzes the sources of Paul's analysis.

- Chapter 3 provides an in-depth discussion of the specific case under study. It presents the findings and offers a thorough discussion on their implications.

- Chapter 4 outlines a proposed environmentally friendly solution. The design process for this solution is detailed, followed by an explanation of how it was tested through simulation.

- Chapter 5 shows the implementation of the solution and their simulations.

- Chapter 6 shows the temporal planning on the project.

- Chapter 7 shows the environmental impact of doing this thesis.

- Chapter 8 shows the economic cost of this study if you want to order to do it.

- Chapter 9 indicates the main conclusions of this thesis and provides a set of recommendations for further work.

# 2. METHODOLOGY

In this chapter, the method that was primarily used by Paul Steenwyk [1] in his project will be explained, but with modifications and simplifications made to suit the needs of this study. The origin of this methodology will be detailed, as well as the authors Paul used as references. This should provide a better understanding of the method.

## 2.1 Energy Chain Conversion

### *2.1.1 Introduction*

The method of observing the energy conversion chain offers insights into the transformation of energy from one form to another. It commences with primary energy sources, encompassing coal, oil, natural gas, nuclear power, and renewable energy sources. These sources then undergo conversion processes within power plants, refineries, and chemical plants, before reaching their end-use sectors. Here, the energy is applied for a variety of purposes, including transportation, heating, and electricity generation.

In the context of muscle work, this conversion process can be compartmentalized into three stages: primary energy, final energy, and useful energy, or muscle work. Primary energy stems from phytomass that nourishes the humans or animals performing muscle work. Phytomass encapsulates all crop components necessary for the production of the final product, including roots, stems, and leaves. Yet, a considerable portion of energy derived from phytomass might not be usable for human objectives and may not even be harvested.

Final energy represents the caloric content in food or feed given to the human or animal, inclusive of unconsumed food or feed that results in waste. Useful energy, characterized as muscle work, is the actual physical labour carried out by the human or animal.

### *2.1.1 Comparison of Muscle Work Methods*

Two primary methodologies for computing muscle work exist in academic literature. The first approach employs a constant conversion efficiency to transition food/feed energy to functional energy, while the second method directly calculates useful energy using power outputs of humans or animals and the duration of work ($E_u$ = (Power)Time). Scholars utilizing these methodologies have been examined and their techniques compared through Sankey diagrams, in which energy flows of identical types are represented by the same letter. Letters (A) through (E) respectively represent Muscle work, Food for basic daily metabolic needs, Food consumed, Food waste during harvest, transportation, or eating, and Food that cannot be metabolized for energy. The locations of Primary (P), Final (F), and Useful (U) energy stages are highlighted in white circles on each Sankey Diagram.[2]

The most commonly referenced method for calculating muscle work comes from Smil, who uses a conversion efficiency to calculate muscle work from food/feed intake. This approach estimates a conversion efficiency of 13%, representing the efficiency of transforming food intake to useful work. However, this value was inconsistently applied by different researchers, resulting in ric_A values ranging from 1.4% to 3.4%. None of the studies reviewed achieved ηc_A = 13% as suggested by Smil. The same researchers incorrectly assumed this conversion efficiency was a Final to Useful Energy conversion efficiency. In reality, it is not.

A Final to Useful (F-U) Energy efficiency would span from food supply to useful work. F-U conversion efficiencies were recalculated using each researcher's methodology and data, and were found to range from 2.2-9.4%, which is lower than Smil's proposed 11.6% (1.0 J/8.6 J).

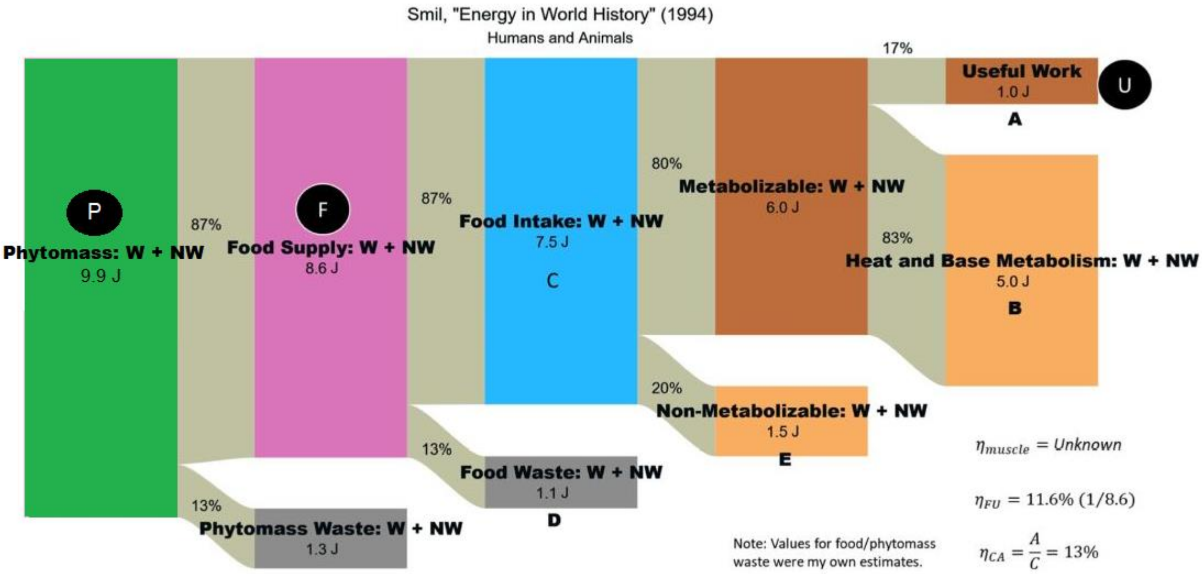

Figure 2.1 Energy calculation method used by Smil [2]

Smil's [2] energy calculation method in figure 2.1, as employed by Serrenho [3] interprets the 13% efficiency as representing the proportion of the digestible energy content of food required to power an 8-hour work period that is actually converted to muscle work. Heun and Brockway's application of Smil's 13% efficiency is described in Figure 2.2. For draft animals, this 13% efficiency indicates the proportion of all digestible energy from consumed food that is converted to useful work. Ayres and Warr employ different figures than Smil for conversion efficiencies. For humans, they report a muscle efficiency of 15%, which is the efficiency of converting the energy from food consumed during a workday (assumed to be 50% of their food) to useful work, as shown in Figure 2.2. For animals (not depicted), they report an efficiency of 5.4%, which aligns with "units of feed per units of work.

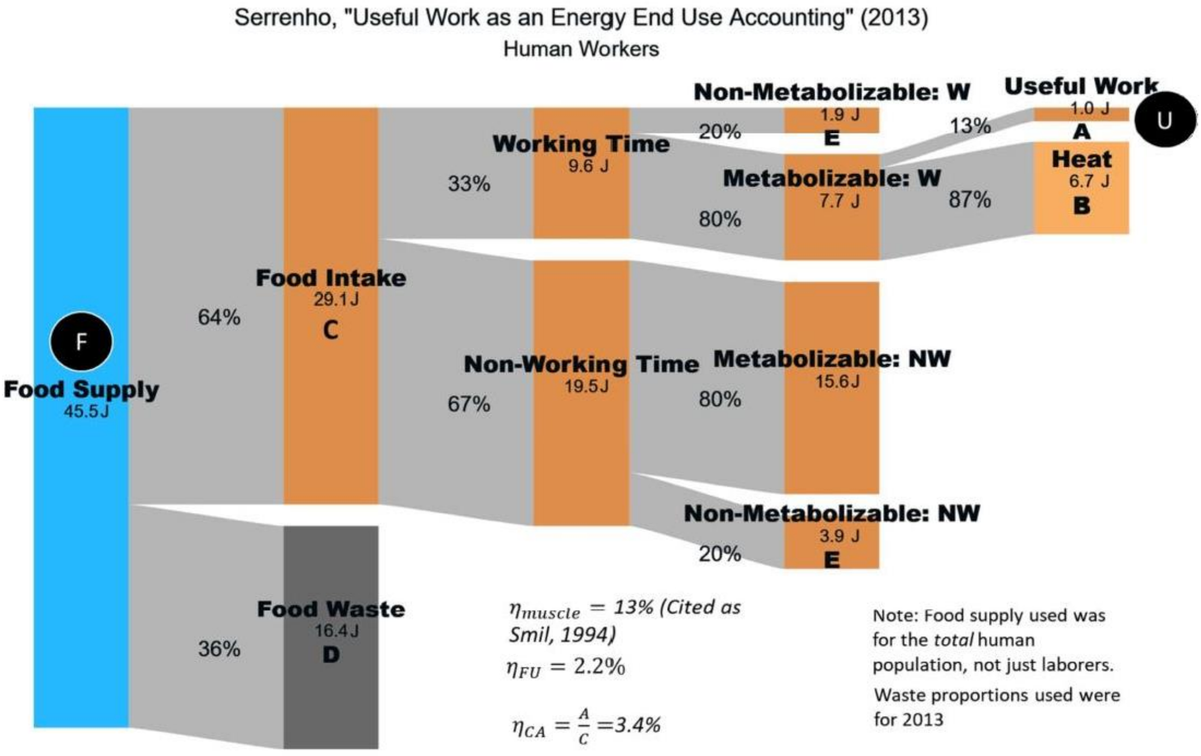

Figure 2.2 Energy calculation method used by Serrenho [3]

## 2.2 Muscle Work Method

Existing literature has presented inconsistent outcomes when deploying efficiencies to quantify muscle work. To address this, the researchers utilized the power output of each worker or animal and their respective working hours, as proposed by Kander and Henriques [4], to estimate useful work. Draft animals were treated as "machines" that convert raw final energy into practical energy. Final energy was identified as the complete amount of food consumed for all activities, inclusive of work and fundamental metabolic functions, as well as food that was wasted or spoiled. For humans, final energy was assessed based on the total food procured from a supermarket, encapsulating energy for work and metabolic functions, and wasted food.

Calculations for muscle work only incorporated the agricultural working population and accounted for all food/feed consumption and waste in the final energy computation. The WPFU muscle work database was employed to estimate final energy and physical work inputs to farms, but it did not quantify the Primary-Final-Useful (PFU) energy consumption on farms. It was assumed that all animals assigned for "mechanical work" were used on farms and animal energy data from the WPFU database for "mechanical work" was utilized. The farm-specific data was extracted and disseminated at the global level in the Supplementary Material spreadsheets. The WPFU database data for humans calculated the PFU energy consumption for primary industry workers, encompassing those in agriculture and forestry.

Energy consumption also comprises all food and feed intake, including wastage, for work purposes. This information from the WPFU database was used to calculate the final energy and physical work inputs for human labour in agriculture. Our methodology was predicated on the power output and working hours for each category of human worker, as proposed by prior research. To maintain consistency, we define final energy for both humans and animals as the total food/feed energy intake for all activities, including work and fundamental metabolic needs, plus any food/feed that is wasted or spoiled. This definition assumes that all food/feed bought from a supermarket carries the energy required to fuel both work and metabolic functions.

Farm-specific data from the WPFU muscle work database was used to estimate the final energy and physical work inputs to farms. This data contains the energy consumption for animals performing "mechanical" work and primary industry workers but does not encompass the Primary-Final-Useful (PFU) energy consumption on farms [5]. We assumed that the animals employed for "mechanical work" on farms are the same animals that plow and harvest crops. The data for farm animal energy is sourced directly from the WPFU database, specifically the section on animal energy for "mechanical work." This farm-specific data is shared at the global level in the online resource spreadsheets.

The study juxtaposes the energy output of agriculture and forestry (AF) workers, draft animals employed in agriculture, and tractors. By positing that AF workers possess similar work characteristics to those in the primary industry, the proportion of final and useful energy utilized for physical work on farms can be calculated based on the percentage of primary industry workers in Europe operating in AF. To ascertain the number of AF workers (WorkersAF), non-AF workers are deducted from the primary industry workers to determine the total AF workers [1].

$$MW_{animal,e,t,eu} = DA_{a,r,t} P_{a,r,t} T_{a,r,t} EU\%_{a,r,t} \qquad 2.1$$

$$MW_{human,r,t} = \sum_{i=1=2} Workers_{r,i,t} \; P_{i,r,t} \; T_{r,i,t} \qquad 2.2$$

The consumption of final energy for working draft animals is considered as the energy expended by "machines." This energy is quantified as the complete feed consumed by these animals, encompassing waste and feed that cannot be digested. The researchers derive regional final energy data for varying types of animals and regions across different time periods[1].

$$E_f = \frac{Workers_{r,i=AF,t}}{Workers_{r,i=agriculture}} E_{f,i=agriculture} \qquad 2.3$$

### 2.2.1 Animal Muscle Work Method

The process starts with input data, which includes information about the draft animals used for mechanical work and the working population in agriculture. This data is transformed to calculate the final energy, using the total amount of food consumed, both by humans and animals, taking into account the energy used for work, metabolic functions, and the food that gets wasted.

The next set of input data involves the power output and working hours of each worker or animal. This is transformed to estimate the useful work performed, using a method suggested by Paul Steenwyk.[1] But it doesn't include the feed wasted in transport/harvesting and the final energy in transport in the muscle work.

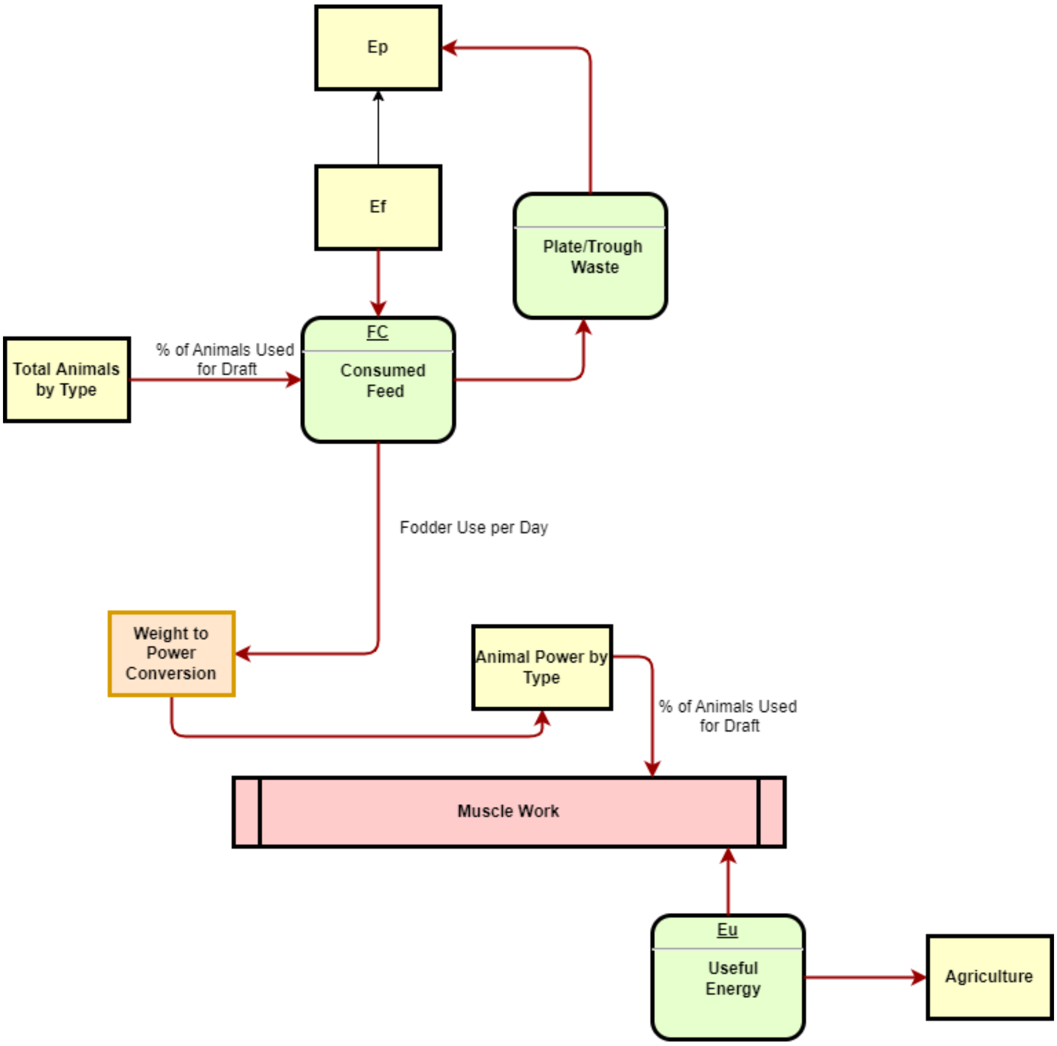

Figure 2.3 Animal Muscle Work Flow Chart

### *2.2.2 Human Muscle Work Method*

The approach for estimating human muscle work (HMW) closely resembles that of animal muscle work. The process begins with the collection of relevant input data, as displayed in the diagram, the inputs (colored in yellow) and conversions (shown in orange) are part of the methodology used for calculating HMW which includes details about the human workforce engaged in agriculture and the caloric intake, both used and wasted. This data helps calculate the final energy - the total food consumption of humans accounting for the energy expended in work, metabolic functions, and wasted food.

The succeeding set of input data comprises the power output and working hours of each human worker. This is manipulated to approximate the useful work performed, employing a methodology suggested by Paul Steenwyk.[1] But it doesn't include the feed wasted in transport/harvesting and the tertiary industry workers.

As displayed in the diagram, the inputs (colored in yellow) and conversions (shown in orange) are part of the methodology used for calculating HMW.

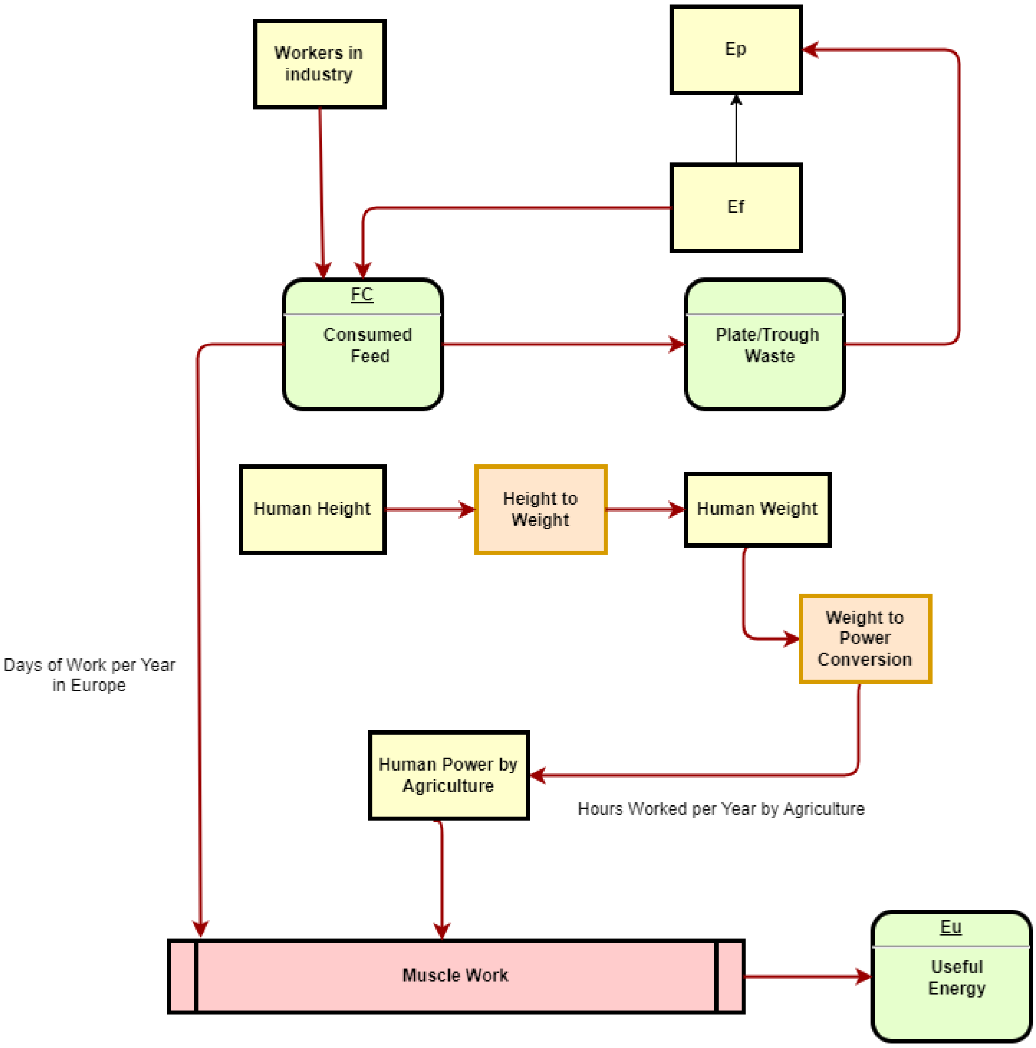

Figure 2.4 Human Muscle Work Flow Chart

## 2.3 Final Energy Method

The introduction to the section on final energy in this paper focuses on the concept of energy conversion efficiency, specifically from the final-to-useful energy stage. The final-to-useful energy stage refers to the conversion process where the final energy (energy ready for use, such as the energy in fuel) is turned into useful energy (energy used to perform tasks).

$$\eta_F - U_x = \frac{E_{ux}}{Efx} \qquad 2.4$$

The energy conversion efficiency of a human, an animal, or a machine, denoted as ($\eta_F$-$U_{,x}$) is defined as the ratio of the useful energy produced to the final energy consumed. In other words, it measures how effectively a human, animal, or machine can convert the energy it consumes into useful work.[1]

$$\eta_F - U_x = \frac{\sum x\, E_{ux}}{\sum x\, Efx} \qquad 2.5$$

When considering the entire agricultural industry, the overall energy conversion efficiency includes all humans, animals, and machines engaged in agricultural activities. This total efficiency is calculated as the ratio of the sum of all useful energy outputs from all the prime movers (workers or machines performing work) to the sum of all final energy inputs for the same movers. In this way, the paper presents an integrated perspective on energy efficiency in agriculture, accounting for both biological (humans and animals) and mechanical (machines) actors in the process.[1]

### 2.3.1 Final Energy Animal Work

Now, the calculation for final energy pertaining to animal muscle work is to be undertaken. The computation of muscle work for each region relies on the number of draught animals ($DA_{a,r,t}$), the average power output per animal ($P_{a,r,t}$), and the total hours they worked within a specific year ($T_{a,r,t}$). The tasks carried out by animals are categorized into two end-uses: mechanical (agricultural) and transport work. The percentage of the total draft animals allocated to each end-use (EU) category is depicted by $EU\%_{a,r,t}$. The subsequent equation is deployed to calculate the muscle work on a regional basis[1]:

$$FUDA\%_{a,r,t} = \frac{\sum countries\ DA_{estimate,country,a,rt}}{\sum countries\ Pop_{country,a,rt}} \qquad 2.6$$

Total feed consumption for the working animals ($DA_{a,r,t}$) is estimated based on the region-specific fodder requirements, using the formula:

$$FU_{animal,a,r,t} = (DA_{,a,r,t}(FU_{W,D,a,r,t}, WDPY_{a,r,t} + FU_{NWD,a,r,t}, (365 - WDPY_{,a,r,t}))) \qquad 2.7$$

In this formula, WDPY stands for the total number of working days per year. For animals, it is assumed that the WDPY remains constant for a given region.

The final energy related to animal muscle work is equivalent to the amount of feed a farmer would need to purchase from a vendor to fulfil all the consumption requirements of his animals. Therefore, the final energy incorporates the waste that happens after procuring the feed from a vendor, as shown in the following formula[1]:

$$E_{f,animal,r,t} = \frac{FU_{animal,a,r,t}}{1 - TroughWaste} \qquad 2.8$$

### 2.3.2 Final Energy Human Work

In order to determine the final energy for human work, the first step involves calculating the food consumption by individuals engaged in muscle work occupations (FUr,t). This is computed using the equation[1]:

$$FU_{r,t} = \sum_{i=1,2} Workers_{r,i,t}( FU_{rW,D,r,i,t}, FU_{rW,D,r,i,t}, FU_{rNWD,r,i,t}, (365 - FUWDPY_{,r,i,t})) \qquad 2.9$$

In this equation, 'Workers' signifies the quantity of workers involved. The terms 'FUwd' and 'FUnwd' represent the food energy necessary to sustain a worker on working days and non-working days, respectively.

The calculation of FU values for both working days (WD) and non-working days (NWD) is carried out using the equation[1]:

$$FU_{r,i,t} = \left(Multiplier_{i,t}\left[\frac{kcal}{kg - day}\right] Weight_{r,t} + Constant\left[\frac{kcal}{day}\right]\right) \qquad 2.10$$

This equation illustrates the breakdown of caloric intake by males and females operating at different activity levels, which correlate to different industries.

Within this equation, 'PAL' stands for Physical Activity Level and is signified by a number ranging between 1 and 2.1. This PAL multiplier provides a quantification of the increase in food intake required by highly active workers compared to their entirely sedentary counterparts.

The final energy required for human labour is computed using the equation[1]:

$$E_{f,human,r,t} = \frac{FU_{r,,t}}{1 - PlateWaste_{r,t}} \qquad 2.11$$

In this equation, 'FU$_{r,t'}$ represents the food consumed by human workers. The term 'PlateWaster($_{r,t}$)' denotes the proportion of food that is wasted by humans after they have procured it.

Thus, the equation takes into account both the energy intake through food consumption by the workers and the energy wasted in the form of food waste to arrive at the final energy used for human labour.

### *2.3.3 Final Energy Electricity*

The final energy in this study was calculated considering the efficiency of the most commonly used agricultural devices over the years, as well as the average yield in energy production. This process is visualized in a graphic that captures the data for these aspects.

Firstly, the efficiencies of the various agricultural devices were assessed. This included equipment like tractors, combine harvesters, irrigation systems, and others, depending on their prevalence in the farming practices of the time period being studied [15]. The efficiency of each device was represented as a percentage, indicating how much of the input energy was successfully transformed into useful output energy[1].

Next, the average yield in energy production was calculated. This encompassed all the energy produced by a given system (e.g., a farm or a particular agricultural region) divided by the amount of input energy, including the energy used to operate the devices and other energy expenditures like animal feed, fertilizers, etc.

By combining these two sets of data, the researchers were able to calculate the final energy. This calculation represented the net energy output, considering both the efficiency of the agricultural devices and the overall yield in energy production.

### *2.3.4 Final Energy Fuels*

In the process of calculating energy from fuels, the authors acknowledged the vast variety of machinery utilized in agriculture, with a range of efficiencies and fuel requirements. Attempting to track the efficiencies of all these various machines over time would have been an immensely complex task.

To address this challenge, the authors opted to use the efficiencies of tractors as a representative or proxy for all fossil fuel-powered machines. This decision is backed by the understanding that most machines employed in on-farm work are powered by diesel or gasoline engines, similar to tractors[1]. Therefore, the energy characteristics and efficiencies of tractors provide a reasonable approximation for the overall energy use and efficiency of agricultural machinery.

# 3. CASE OF STUDY

The case study is to continue the task that Paul Steenwyk started and get the results for Europe. At the end of each subpart of this chapter, there will be a comparison between the global results with Paul's simplified method and all of Europe.

## 3.1 Animal Muscle Work

In recent years, there has been a decline in the use of animal labour in agriculture both in Europe and worldwide. This decline can be attributed to the introduction of machinery and new agricultural techniques. These technological advancements have led to increased efficiency and productivity in the agricultural sector, resulting in a reduced reliance on animal labour.

Figure 3.1 represents animal muscle work in agriculture specifically in Europe. It illustrates a downward trend in the use of animal labour over time. As more efficient technologies such as tractors and specialized agricultural machinery have been implemented and adopted, the need for animals to perform agricultural tasks has decreased. This transition to mechanized methods has allowed for increased productivity and resource efficiency.

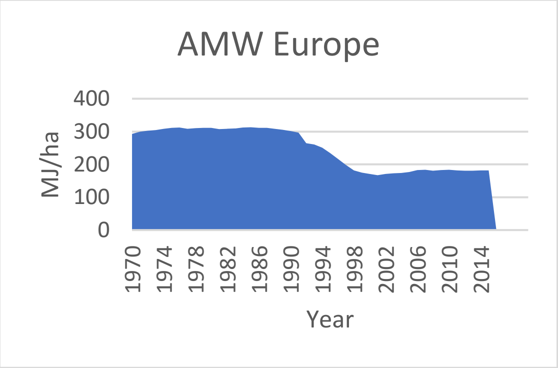

Figure 3.1 Animal muscle work in Europe [1] [6]

On a global scale, Figure 3.2 represents animal muscle work in agriculture. Although a decline in the use of animal labour is also observed, the decrease is slower compared to Europe. This is primarily due to the challenges faced by less developed countries in accessing and adopting new agricultural technologies, including resource limitations, inadequate infrastructure, and limited technical knowledge. In these regions, animal labour still plays a significant role in agriculture as they may not have the same ease of implementing advanced machinery.

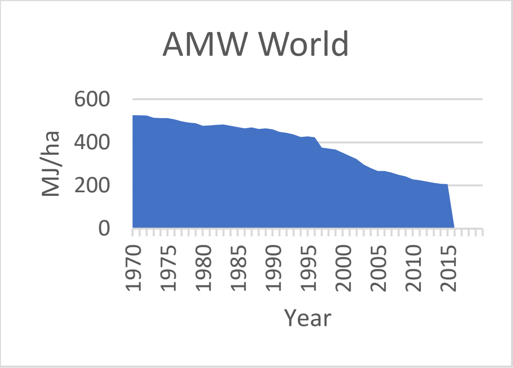

Figure 3.2  Animal muscle work in the World [1] [6]

In summary, there has been a reduction in the use of animal labour in agriculture both in Europe and worldwide due to the introduction of machinery and new agricultural techniques. However, the decline is more pronounced in Europe where the adoption of advanced agricultural technologies has been more rapid. Globally, the decline is slower due to the limitations and challenges faced by less developed countries in adopting new agricultural technologies. The transition to mechanized methods aims to improve efficiency and sustainability in agriculture by optimizing resource utilization and enhancing productivity in the agricultural sector.

## 3.2 Human Muscle Work

Over the past 40 years in Europe, the role of human muscle work in agriculture has undergone significant changes, influenced by various factors including historical events, technological advancements, and shifts in agricultural practices. Here is an overview of the evolution of human muscle work in agriculture in Europe, along with some examples of historical events that have shaped this trajectory.

It's important to note that while the overall trend in Europe has been a decrease in human muscle work in agriculture, there are regional variations. Some areas, particularly those with traditional or niche farming practices, may still rely more heavily on manual labour. Additionally, certain cultural and heritage practices may prioritize manual labour for specific agricultural activities, such as vineyard work or artisanal farming.

In developed countries such as the United States, Canada, and countries in Europe, the use of machinery and advanced agricultural technologies has significantly reduced the amount of human muscle work in agriculture. Tasks that were traditionally performed manually, such as plowing, planting, and harvesting, are now accomplished with the help of tractors, combine harvesters, and other specialized equipment. These technological advancements have increased efficiency, reduced labour requirements, and allowed for larger-scale farming operations.

In contrast, in many developing countries in Africa, Asia, and South America, the use of machinery and advanced technologies in agriculture is still limited. These regions often have smaller landholdings and limited access to capital, making it challenging to invest in expensive machinery. As a result, human muscle work remains a vital component of agricultural activities. Farmers in these regions continue to rely heavily on manual labour for tasks such as tilling the land, planting seeds, weeding, and harvesting crops.

For example, in countries like India and China, where small-scale farming is prevalent, a significant portion of agricultural work is carried out by manual labour. Farmers engage in physically demanding tasks, working long hours in the fields to ensure the success of their crops. Similarly, in several African countries, subsistence farming practices rely on human muscle work as the primary source of labour.

In Europe, human muscle work in agriculture has been consistently lower than the global average. This can be attributed to the region's advanced and modern agricultural technologies, which have been rapidly evolving since 1970. (Figure 3.3) The faster pace of industrialization in Europe compared to other parts of the world has contributed to a significant decrease in the reliance on human labour in agricultural activities.

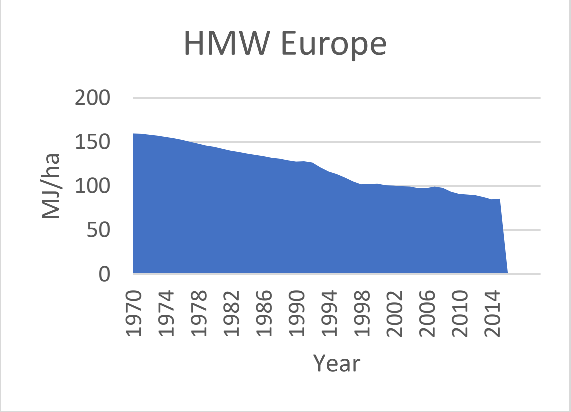

Figure 3.3 Human muscle work in Europe [1] [6]

The adoption of advanced machinery, automation, and precision farming techniques in European agriculture has led to increased efficiency, productivity, and reduced labour requirements. These technological advancements have enabled farmers in Europe to achieve higher levels of mechanization and automation, thereby reducing the need for human muscle work in various agricultural tasks.

However, it is worth noting that despite Europe's lead in agricultural technology, the trend of decreasing human muscle work is not exclusive to the region. Figure 3.4 illustrates that the global trend over the past 15 years also shows a decline in human muscle work in agriculture worldwide. This can be attributed to the increasing global adoption of modern technologies, improved farming practices, and the pursuit of agricultural efficiency and productivity.

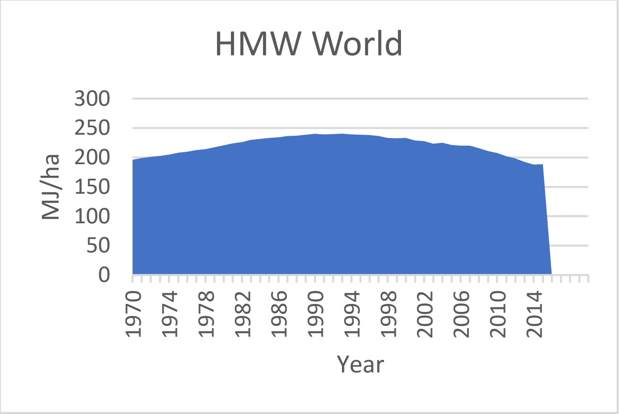

Figure 3.4 Human muscle work in the World [1] [6]

While Europe may have experienced a more accelerated decrease in human muscle work due to its advanced industrialization, the rest of the world is also witnessing a similar trend. This indicates a global shift towards greater reliance on mechanization, automation, and technological advancements in agriculture.

## 3.3 Use of Electricity in Agriculture

The usage of electricity worldwide has indeed significantly increased since the 1970s, a trend that can be inferred from your hypothetical graph in terms of megajoules per hectare (MJ/ha). This growth can be attributed to various reasons.

If the denominator (in this case, hectares of cropland) decreases while the total amount of energy used (MJ) remains the same or increases, the ratio of MJ/ha will indeed increase. The intensification of agriculture is a key aspect of this phenomenon.

The decrease in cropland could be due to several reasons [8]:

- **Urbanization**: Cities have expanded into previously agricultural areas, reducing the amount of available farmland.
- **Land Degradation**: Unfavourable farming practices can lead to soil erosion and nutrient depletion, making some land unfit for farming.
- **Change in Agricultural Practices:** Advances in farming methods and technology have allowed for higher yields on less land, meaning less total land is needed for agriculture.
- **Climate Change:** Alterations in weather patterns and increased incidence of extreme weather

events can render some agricultural land unusable.

- **Conservation Policies:** Some land has been intentionally taken out of agricultural production for conservation purposes, reducing the total cropland area.

At the same time, the increase in MJ/ha can be explained by the following factors:

- **Intensification of Agriculture:** With less land available, farming has become more intensive, with higher inputs (including electricity) per hectare. This includes more use of machinery, irrigation, and on-farm processing, all of which require electricity.
- **Technological Advancements:** New farming technologies that use electricity, such as precision farming and controlled-environment agriculture, have become more widespread. These technologies can increase output per hectare, but they require more electricity to operate.
- **Increased Irrigation:** As agriculture intensifies, irrigation becomes more critical. Electric pumps are commonly used for irrigation, contributing to an increase in electricity usage per hectare.
- **Shift towards Sustainable Practices:** As farmers adopt more sustainable practices, they may shift from fossil fuel-powered equipment to electric equipment, which would increase the electricity usage per

So, even though the total area of cropland has decreased, the intensity of electricity usage per hectare has increased due to changes in farming practices and technology, as well as shifts towards more sustainable and electricity-dependent methods. This leads to an overall increase in the MJ/ha ratio.

### *3.3.1 Electricity in Europe*

The marked increase in electricity usage in agriculture from 500 MJ/ha in 1986 to 3600 MJ/ha in 2015, particularly in Europe, can be attributed to a variety of historical, social, and economic factors.

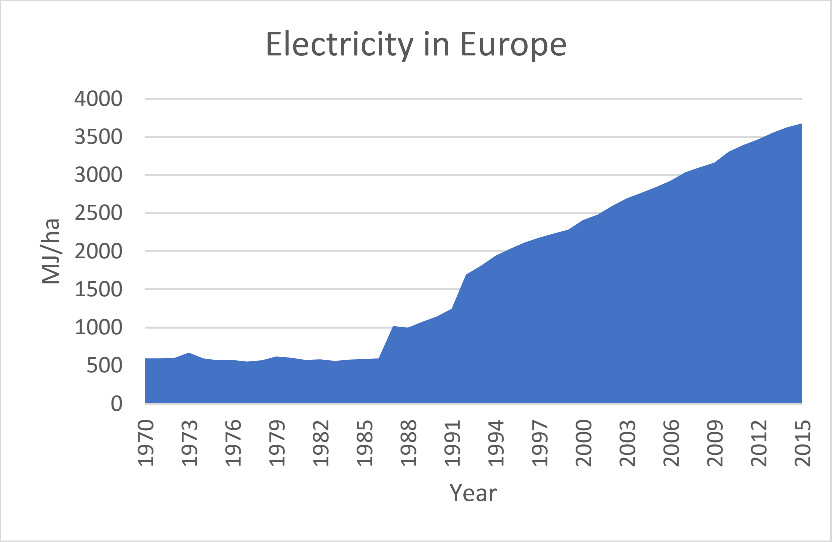

Figure 3.5 Electricity in Europe[6]

Remembering that specific events like the fall of the Berlin Wall (1989) and the ensuing political changes led to a massive restructuring and modernization of agriculture in Eastern Europe. The EU's eastward expansion in the early 2000s also played a role, as it brought many more farmers under the CAP, which has often encouraged modernization and increased productivity.

This modernization, coupled with technological advances and policy changes, are likely the main drivers behind the substantial increase in electricity usage in European agriculture during this period.

### *3.3.2 Electricity in the world*

Historical factors around the mid-1980s can help explain why the usage of electricity in agriculture globally started to increase substantially. Here are some key developments [7]:

- **Green Revolution's Second Wave:** The Green Revolution, which began in the late 1960s, had a second wave in the 1980s. It marked the broad adoption of new agricultural technologies worldwide, including irrigation systems, modern machinery, and facilities requiring electricity. This increased the demand for energy in agriculture, much of which was supplied by electricity.

- **Globalization and Market Liberalization:** The 1980s were also marked by increased globalization and market liberalization. This allowed for the free flow of goods and technologies around the world, leading to the rapid adoption of electricity-dependent technologies in developing countries' agriculture.

- **Irrigation Expansion:** The 1980s saw a significant expansion in irrigated agriculture, particularly in developing countries like India and China. Electric pumps became the primary means of extracting groundwater for irrigation, leading to an increase in agricultural electricity consumption.

- **Policy Shifts:** In some countries, there were shifts in energy policy that promoted the use of electricity in agriculture. These might include subsidies for electric pumps, electrification programs in rural areas, or the deregulation of electricity markets.

- **Technological Advances:** New technologies that came into wide use during this period, like automated milking systems, electric tractors, and other electric farm machinery, increased electricity usage.

- **Increased Refrigeration and Processing:** As farm operations modernized, on-farm refrigeration and processing of agricultural products became more common, leading to more electricity usage. This trend was part of a broader move towards "value-added" agriculture.

These historical factors are a key part of why the use of electricity in agriculture increased starting around 1984. By this point, electricity had become an essential input in modern agriculture, from powering machinery and irrigation systems to preserving and processing agricultural products.

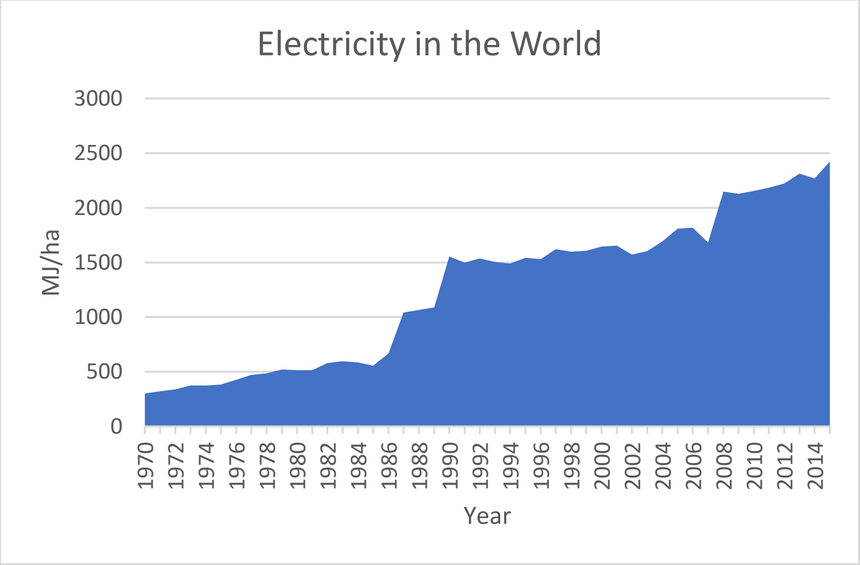

Figure 3.6 Electricity in the World[6]

### *3.3.3 Comparison Electricity Europe vs World*

Remembering that while the global trend is towards increased electricity use, there are significant regional and national variations. Some areas, particularly in the developed world, have seen slower growth or even a plateau in electricity usage due to energy efficiency improvements and changes in the structure of their economies.

Comparing the two graphs, it's clear that while the trend towards increasing electricity use in agriculture is global, it's more pronounced in Europe. This likely reflects the factors listed above: a move towards more intensive, technologically advanced farming that requires more electricity. However, the specific mix of factors would vary from country to country within Europe. For instance, the trend might be especially strong in countries with a lot of greenhouse agriculture or where policies favouring electrification are particularly aggressive.

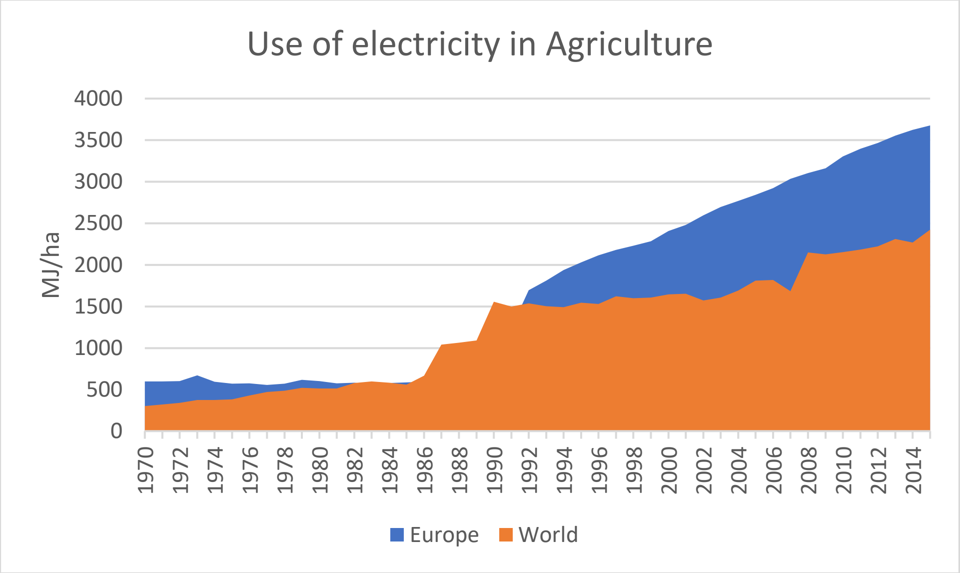

Figure 3.7 Use of electricity in Agriculture Europe vs World[6]

## 3.4 Liquid Fuels in Agriculture

Since the 1970s, the global trend of liquid fuel usage in agriculture, represented as megajoules per hectare (MJ/ha), has been increasing due to the growing mechanization and intensification of farming. Technological advancements have led to an upsurge in machinery and equipment powered by liquid fuels like diesel. Also, irrigation expansion, which often utilizes fuel-powered pumps, and increased on-farm processing have contributed to higher fuel consumption. Furthermore, the globalization of food supply chains necessitates more fuel for transportation. These factors have collectively intensified the use of liquid fuels in agriculture per unit of land.

### *3.4.1 Liquid Fuels in Europe*

In figure 3.8 the trend of increasing MJ/ha of liquid fuel use in agriculture in Europe stabilizing around the year 2000 at approximately 1400 MJ/ha can be attributed to several factors[7]:

- **Increased Energy Efficiency:** The early 2000s saw significant advances in the energy efficiency of agricultural machinery and equipment. These improvements meant that less fuel was required to perform the same tasks.
- **Shift to Renewable Energy:** Around this time, there was a significant push towards renewable energy sources in Europe. As a result, some of the energy demands of agriculture may have been met by renewables rather than liquid fuels.
- **EU Policy and Regulations:** The EU has been active in promoting energy efficiency and reducing greenhouse gas emissions. Regulations encouraging the use of more efficient machinery and renewable energy could have contributed to stabilizing the liquid fuel usage.
- **Changes in Agricultural Practices:** The early 21st century also saw changes in agricultural practices, including precision agriculture and organic farming, that may have reduced the demand for liquid fuels.
- While the use of liquid fuels in agriculture likely continues due to the necessity of machinery and transport, these factors may explain why the increase has stabilized since 2000.

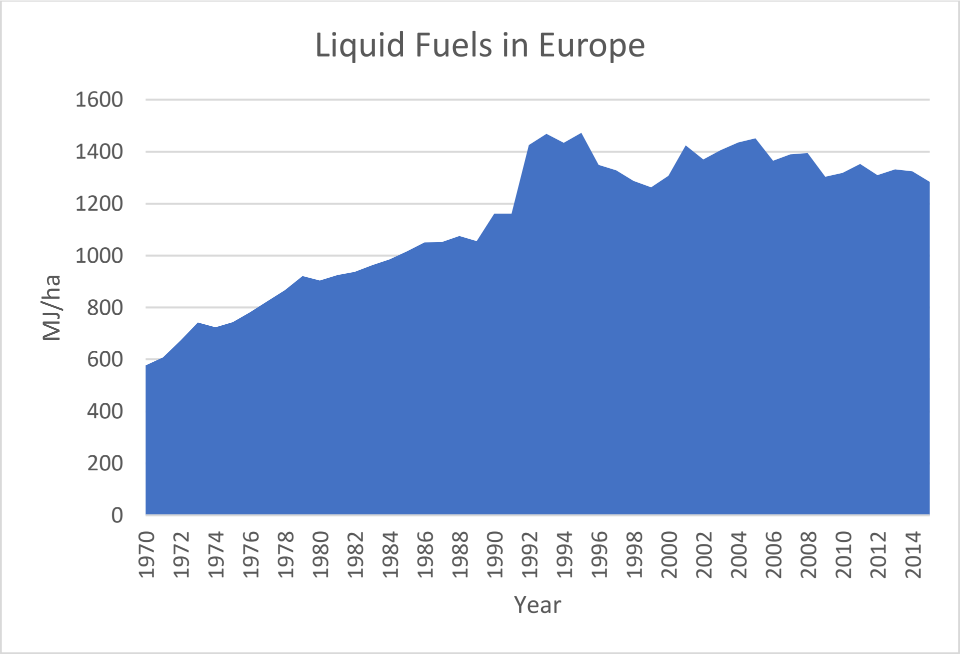

Figure 3.8 Liquid fuel in Europe[6]

### *3.4.2 Liquid Fuels in the world*

The lower global values of liquid fuel use in agriculture, expressed as MJ/ha, compared to Europe, can be attributed to various interplaying factors. Unlike Europe, many parts of the world, particularly developing regions, have not fully mechanized their agricultural practices and still rely heavily on manual labour, resulting in lower per-hectare liquid fuel usage.

The intensity of agricultural practices, such as the use of machinery, irrigation systems, and on-farm processing, also varies worldwide. Areas outside of Europe often have less intense farming practices, contributing to the lower MJ/ha values. Additionally, the reduction in the total cropland area might be less significant globally compared to Europe.

This lower rate of reduction in cropland could result in a lower MJ/ha ratio, even if the total energy usage remains the same or increases. Access to liquid fuels is another factor; not all regions have the same access, and in some places, other energy sources may be more readily available or economical. Lastly, Europe's generally favorable climate allows for more intensive agriculture, requiring more energy inputs per unit of land, which may not be the case in regions with less conducive climates. These combined factors explain why the MJ/ha values are lower globally than in Europe.

Despite a period of stabilization in the 1980s and 1990s, fuel use in agriculture has seen a marked increase over time, reaching up to 1400 MJ per hectare. This suggests a growing dependence on fuel-powered machinery in agricultural practices, highlighting the critical role of energy efficiency in managing our resources.

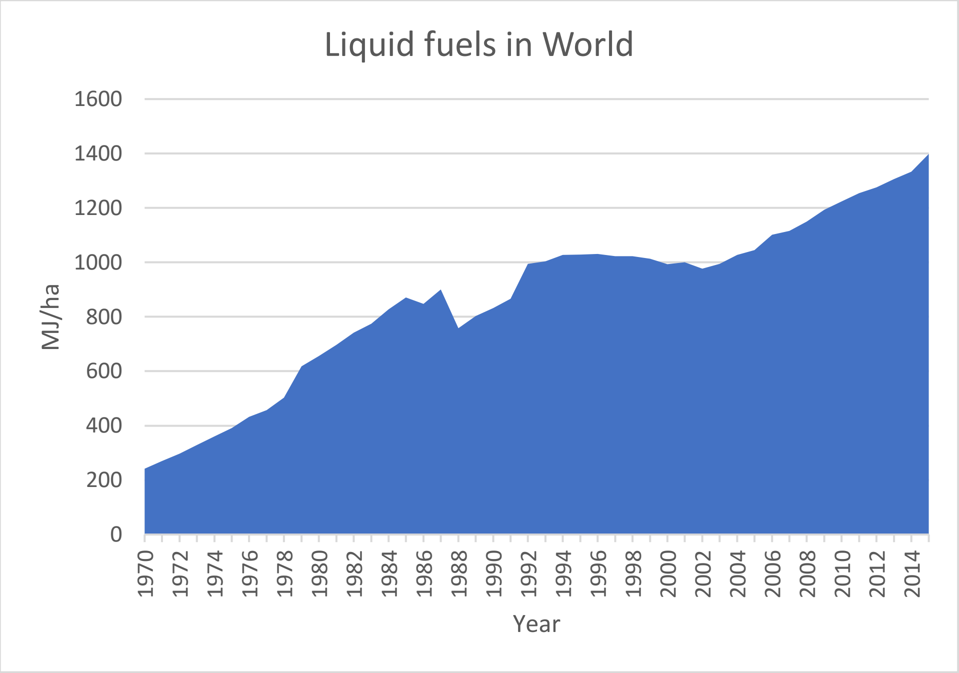

Figure 3.9 Liquid fuels in the world[6]

### *3.4.3 Comparison Liquid Fuels Europe vs World*

As mentioned earlier, the ratio in Europe is higher due to more intensive farming practices. However, over the last decade, the rest of the world has caught up to the European standards, leading to a similar 'MJ per hectare' ratio on a global scale [8].

This trend indicates a global intensification of agricultural practices, characterized by an increased use of energy-dense liquid fuels to meet the growing demand for food production. However, this also highlights the need for sustainable energy alternatives in agriculture, as intensive use of such fuels can have significant environmental implications.

Our project solution, focused on creating an energy self-sufficient poultry farm and vineyard using photovoltaic energy, could provide a practical solution to reduce reliance on traditional energy sources in agriculture, helping to move towards more sustainable farming practices.

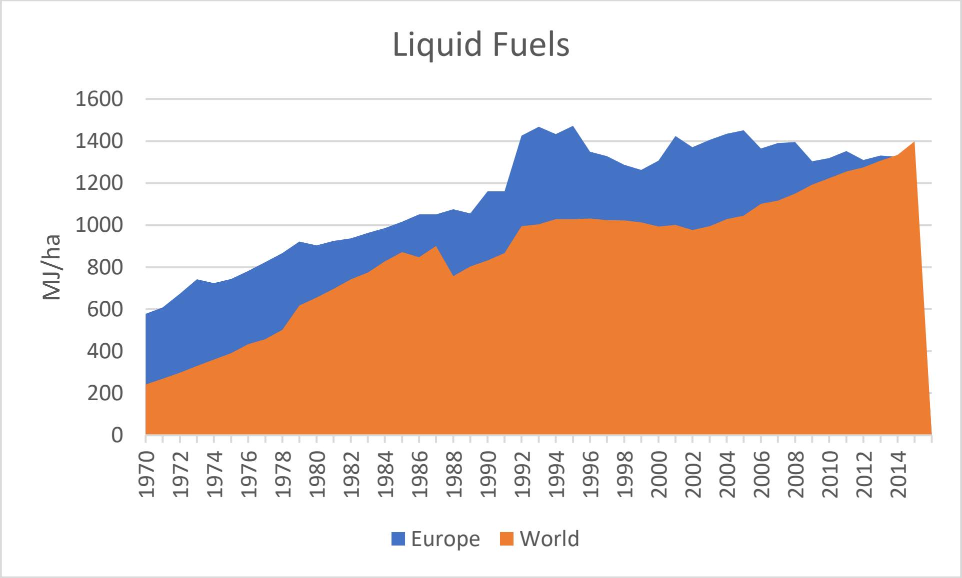

Figure 3.10 Liquid Fuels Europe vs World[6]

## 3.5 Final Energy

Final energy in agriculture is the total amount of energy used directly in agricultural operations. This takes into account various sources including human muscle work, animal muscle work, liquid fuels, and electricity.

Each energy source is calculated in a different way, and the total final energy in agriculture is the sum of all these:

**Human and Animal Muscle Work:** This is calculated based on metabolic efficiencies, which consider how much of the consumed energy (in the form of food) is converted into physical work. This calculation takes into account factors such as the energy content of the consumed food, the efficiency of the digestion process, and the efficiency of muscle contraction.

**Electricity:** The final energy contribution of electricity is calculated by multiplying the quantity of electricity consumed by the efficiency of the electric motors or other equipment using the electricity. Like engine efficiency, motor efficiency represents the proportion of the electrical energy that is converted into useful work.

**Liquid Fuels:** The energy content of liquid fuels is calculated based on the fuel's calorific value, which is the amount of heat energy released when a known quantity of the fuel is burned. To get the final energy contribution of liquid fuels, this calorific value is multiplied by the quantity of fuel used and the efficiency of the engines using this fuel.

### *3.5.1 Final Energy in Europe*

The dominance of electricity in the graph showing MJ/ha for agriculture indicates that it has become the primary source of energy for farming operations worldwide. The growth in the use of electricity can be attributed to the increased mechanization and automation of agricultural processes, as well as the shift towards more energy-efficient and environmentally friendly energy sources.

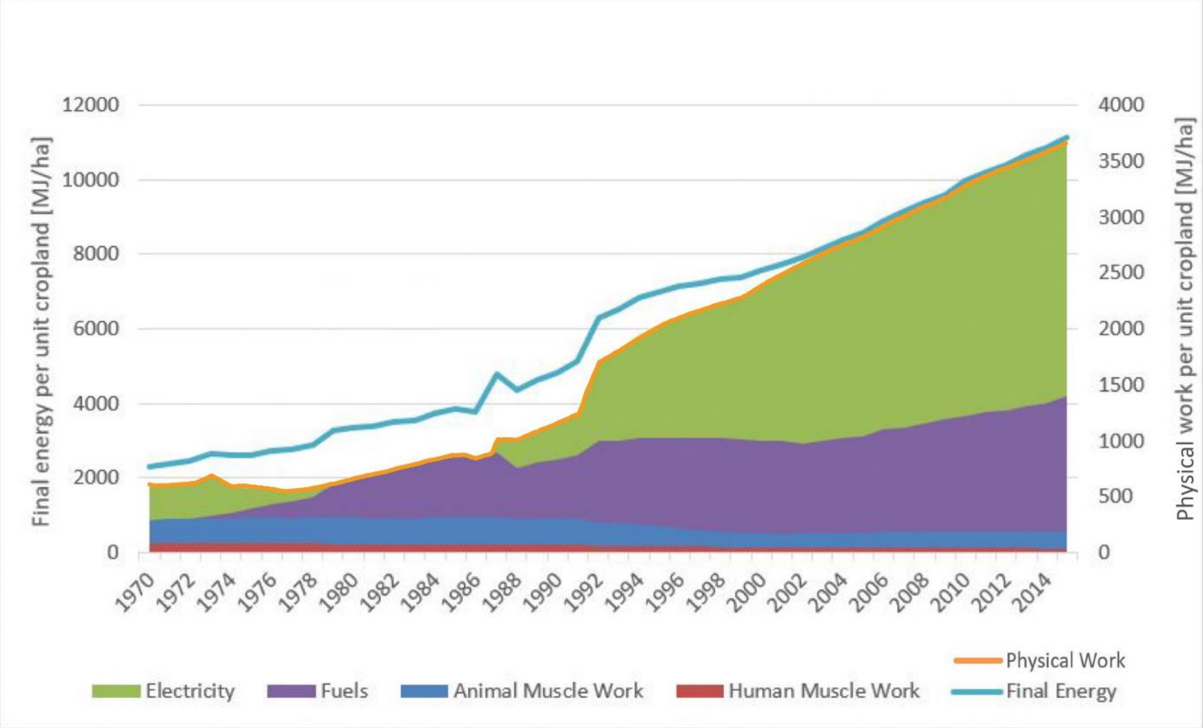

Figure 3.11 Final energy per unit of cropland and physical work per unit cropland in Europe

On the other hand, the graph also reveals the significant role liquid fuels continue to play in agriculture. The use of liquid fuels has also increased over time due to mechanization, expansion of irrigated lands, and increased transportation needs within the agricultural sector. However, the trend has shown signs of stabilization in recent years.

This stabilization can be attributed to several factors: improvements in the energy efficiency of machinery and equipment, an increased emphasis on renewable energy sources, changes in farming practices, and policy regulations aimed at reducing greenhouse gas emissions. Despite these changes, the continued presence of liquid fuels in the graph underscores their ongoing importance in many agricultural contexts, especially in areas where electric-powered options are not readily accessible or economically feasible.

### *3.5.2 Final Energy in the world*

In the global context, the graph showing MJ/ha for agriculture also emphasizes the significant role of electricity in farming operations, driven by widespread mechanization and a shift towards more efficient and environmentally friendly energy sources. However, the trend of liquid fuel usage differs from that observed in Europe.

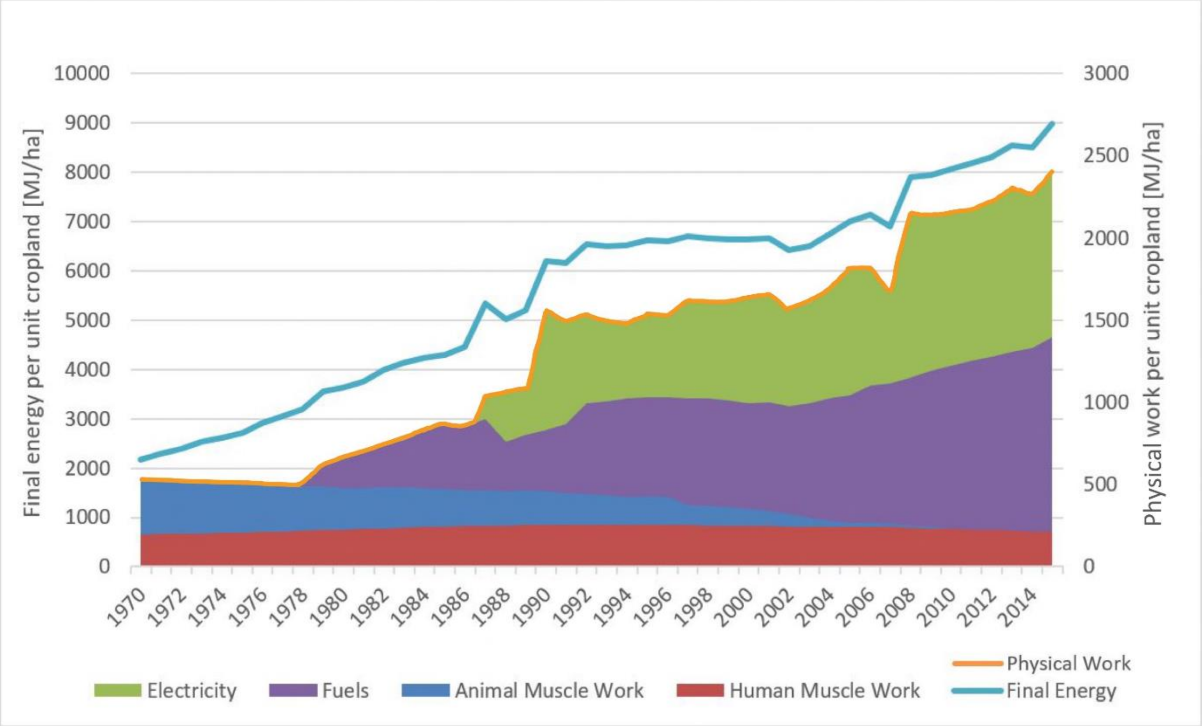

Figure 3.12 Final energy per unit of cropland and physical work per unit cropland in the World

Contrary to the European trend, liquid fuel usage in global agriculture has continued to increase, reflecting the ongoing mechanization and intensification of farming in many parts of the world, especially in developing regions. Here, the accessibility, cost-effectiveness, and reliability of liquid fuels make them an essential component of agricultural energy consumption.

The graph also shows a larger gap between final and useful energy globally compared to Europe. This discrepancy can be attributed to the lower efficiencies found in many parts of the world. Europe has generally been at the forefront of developing and adopting more efficient engines and machinery, leading to higher energy conversion efficiencies. In contrast, in many other regions, older, less efficient equipment might still be in use, leading to a greater loss of energy during conversion, hence a larger gap between the final energy (total energy input) and the useful energy (energy converted into useful work). This emphasizes the potential benefits of improving energy efficiency in agriculture worldwide.

## 3.6 Use of Fertilizer

Fertilizers play a critical role in modern agriculture by supplementing soil with essential nutrients, like nitrogen, phosphorus, and potassium, which are necessary for plant growth and development. This supplementation leads to increased crop yield and enhances the nutritional content and overall quality of crops. As a result, farmers can experience higher incomes due to increased productivity, and consumers can benefit from more affordable, nutritious food.

However, while the advantages of fertilizers are significant, their use also comes with potential drawbacks. Overuse or misuse can cause nutrient runoff into nearby water bodies, leading to water pollution and eutrophication—a process that spurs excessive growth of algae, degrades water quality, and harms aquatic life. Additionally, the excessive use of fertilizers can damage the soil by causing acidification or the buildup of harmful salts, compromising long-term soil health and productivity.

There's also a climate implication. The production and application of synthetic fertilizers, particularly those that are nitrogen-based, can contribute to greenhouse gas emissions, thereby exacerbating climate change. Consequently, achieving a balance between the benefits of using fertilizers and mitigating their environmental and health impacts presents a significant challenge for sustainable agriculture.

### 3.6.1 Fertilizer in Europe

The trend of increasing fertilizer use in Europe since the 1970s is likely due to the intensification of agriculture during this period. As demand for food rose, farmers turned to fertilizers to increase crop yields and maximize productivity. Fertilizers provide crops with essential nutrients, like nitrogen, phosphorus, and potassium, helping them grow more vigorously and producing larger yields.

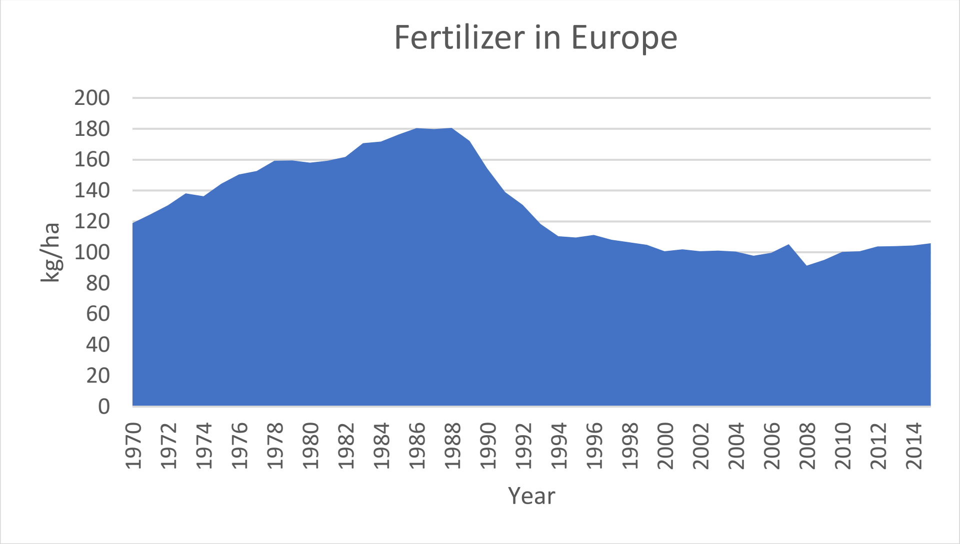

Figure 3.13 Quantity of fertilizer per unit cropland in Europe

### 3.6.2 Fertilizer in the World

The graph showing an increase in global fertilizer use in kg/ha since the 1970s can be attributed to the ongoing intensification of agriculture worldwide. The need to feed a growing global population has led to an increased reliance on fertilizers to boost crop yields and productivity, particularly in developing regions where agricultural practices are still evolving and intensifying.

Contrary to the trend in Europe, the use of fertilizers globally continues to rise due to several factors. In many parts of the world, particularly in developing regions, agricultural practices are still evolving, and the use of fertilizers is increasing as farmers adopt modern farming techniques. Moreover, the regulatory environment in many of these countries may not be as stringent as in Europe, allowing for more extensive use of fertilizers.

In terms of the kg/ha ratio, this could increase either due to an increase in kg (quantity of fertilizer) or a decrease in ha (cropland area). If the ratio is rising, it could indicate that more fertilizer is being used per unit of cropland. This could result from an intensification of agriculture, with farmers using more inputs to try to increase yields. Alternatively, it could also result from a reduction in the total area of cropland, leading to a higher kg/ha ratio even if the total quantity of fertilizer used remains the same.

However, it's essential to bear in mind that while fertilizers can boost crop productivity, their overuse can lead to environmental problems like water pollution from nutrient runoff and soil degradation. Balancing the benefits of fertilizer use with the need for environmental sustainability is a critical issue in global agriculture.

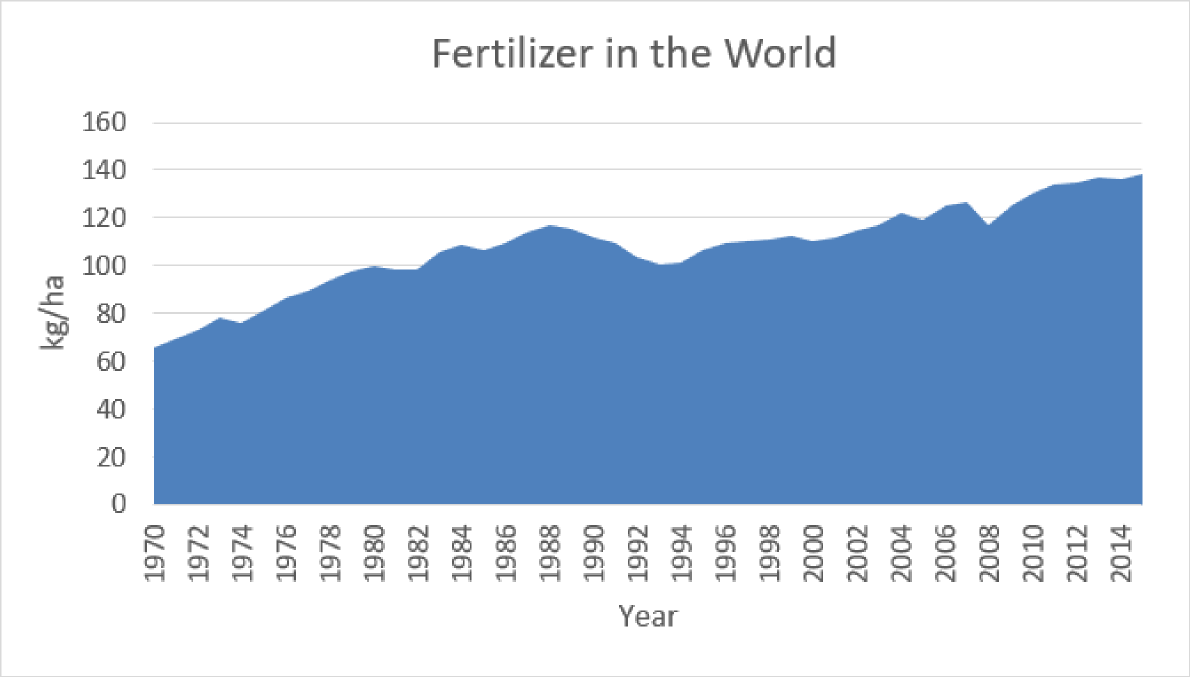

Figure 3.14 Quantity of fertilizer per unit cropland in the World

## 3.7 Land Productivity

Agricultural productivity refers to the efficiency with which agricultural inputs are converted into outputs. In simpler terms, it's about how much crop yield (output) a farmer can get for a given amount of inputs such as land, labour, and capital.

Crop yield, the amount of crop produced per unit of land, is a commonly used measure of agricultural productivity. Over time, advances in various aspects of farming—from plant breeding to the use of fertilizers and pesticides—have significantly increased crop yields.

Another aspect of agricultural productivity is labour productivity, which gauges the output relative to the labour employed in production. The mechanization of agriculture and technological improvements have allowed farmers to produce more with less labour.

A broader measure of agricultural productivity is total factor productivity (TFP). TFP considers all the inputs used in farming, including labour, capital such as machinery and buildings, and land. Growth in

TFP can be driven by more efficient use of these resources, perhaps through better farming practices or technological innovations, or from new resources like novel crop varieties.

While increasing productivity is a central goal in agriculture, it's crucial to balance this aim with sustainability. Practices that overuse resources like water or fertilizers might boost productivity in the short term, but they can lead to environmental degradation and eventually reduce productivity in the long term. This delicate balancing act—aiming to increase productivity while minimizing environmental impact—is a defining challenge of modern agriculture, often termed as sustainable intensification.

### *3.7.1 Land Productivity in Europe*

The increase in land productivity in Europe from the beginning of the 1970s could be attributed to several factors. First, the Green Revolution, which started in the mid-20th century and continued into the 1970s, brought significant advances in agricultural technology. This included the development of high-yielding varieties of crops, increased use of fertilizers and pesticides, and advancements in irrigation techniques. All of these changes helped increase agricultural output per unit of land, hence the rise in land productivity.

The stabilization of land productivity from the 1980s onwards could be due to several factors. One potential reason is that the gains from the Green Revolution technologies and practices may have reached a plateau in terms of their ability to further boost yields. Essentially, there are biological limits to how much a crop can produce, even with optimal inputs.

Starting in the 1980s and accelerating into the 1990s, there was increasing awareness and concern about the environmental impacts of intensive agricultural practices. In response to these concerns, the European Union implemented a range of policies and regulations aimed at promoting more sustainable farming practices. These included limits on the use of certain pesticides and fertilizers, and the promotion of organic farming and other low-intensity farming practices. While these measures likely helped mitigate environmental impacts, they may also have curtailed the continued growth of land productivity.

Lastly, European farmers may have chosen to prioritize other objectives over maximizing productivity. For instance, there has been a growing emphasis on improving the quality of agricultural products, maintaining biodiversity, and enhancing ecosystem services, which are not captured in a measure like kcal/ha.

However, it's worth noting that stabilization is not necessarily a negative trend. High levels of productivity are still being maintained, but it is now achieved with a greater focus on environmental sustainability and other important factors.

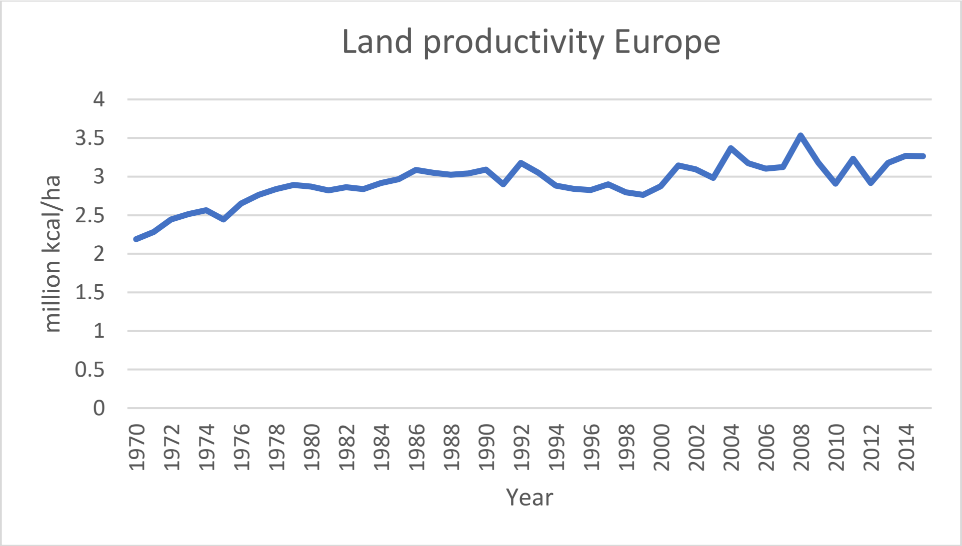

Figure 3.15 Land Productivity energy per unit of cropland in Europe

### *3.7.2Land productivity in the World*

The continued increase in land productivity worldwide can be attributed to several factors. First, the technologies and practices that boosted yields in developed countries are still being adopted in many parts of the developing world. This includes the use of high-yielding crop varieties, synthetic fertilizers and pesticides, and advanced irrigation techniques. As these technologies spread, they continue to drive increases in land productivity.

However, it's important to note that the continued increase in land productivity worldwide comes with its own set of challenges. These include the environmental impacts of intensive farming practices, such as soil degradation, water pollution from nutrient runoff, and loss of biodiversity. Like Europe, other parts of the world will need to find ways to balance increasing agricultural productivity with environmental sustainability.

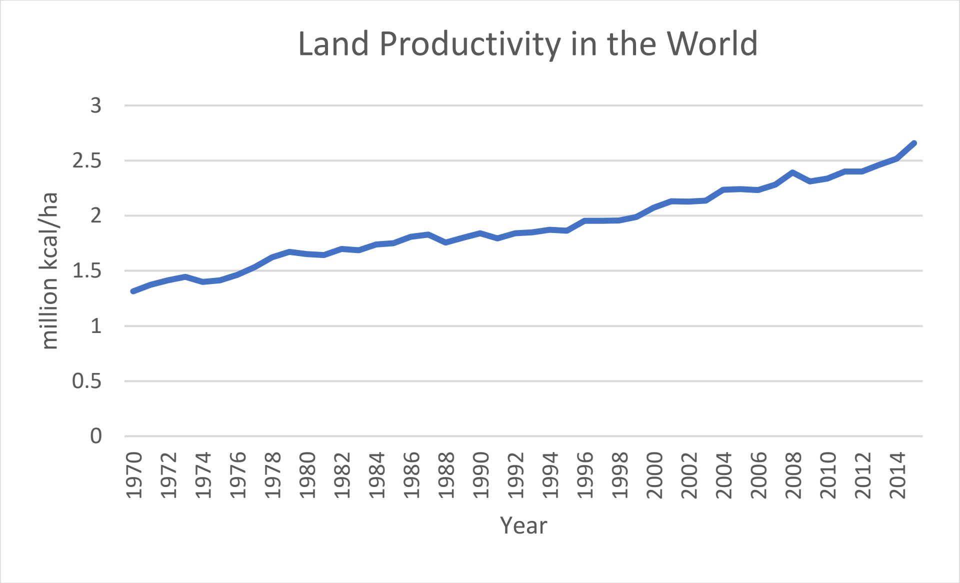

Figure 3.16 Land Productivity energy per unit of cropland in the World

### *3.7.3 Comparison Land productivity Europe vs World*

Let's now compare the graphs of 'Land Productivity in Agriculture' for Europe and the world at large. Here, 'million kcal/ha' refers to the energy output per hectare of cropland, measured in millions of kilocalories.

From the data, it's evident that both Europe and the world have seen an upward trend in land productivity over time. However, it's important to note that the ratio in Europe is almost double that of the global average. This indicates that European agricultural practices tend to yield higher energy output per unit of land area, demonstrating the efficiency of farming techniques used in this region.

However, while this higher productivity can be beneficial in terms of meeting the growing demand for food, it also implies a higher level of resource usage, including energy, water, and fertilizers, which can have significant environmental impacts.

This is another reason why our project, aimed at creating a solar-powered poultry farm and vineyard, is so important. By harnessing renewable energy sources for farming practices, we can help to enhance agricultural productivity while also reducing the environmental footprint of these operations.

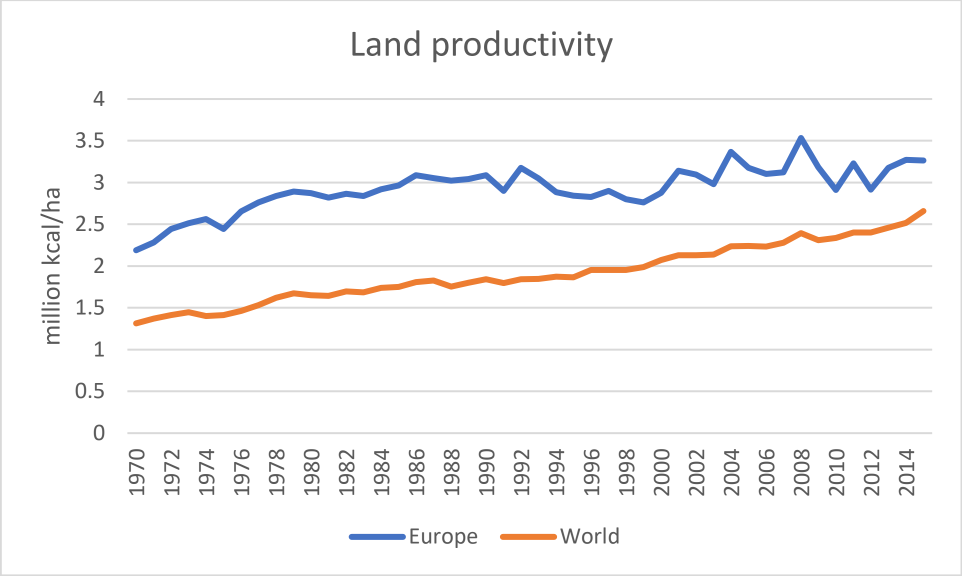

Figure 3.17 Land Productivity energy per unit of cropland Europe vs World

## 3.8 Labour Productivity

Labour productivity in agriculture refers to the amount of agricultural output (typically measured in terms of energy content, such as kilocalories of food) produced per unit of labour input (measured in terms of work done, such as kilojoules of work). It is a measure of the efficiency with which human labour is used in the production process.

An increase in labour productivity means that less human effort is required to produce a given amount of agricultural output. This could result from improvements in technology (such as the use of more efficient or automated farming machinery), better farming practices (like optimized planting and harvesting techniques), or more effective use of other inputs like land and capital.

For example, if a farmer can produce 2000 kilocalories of food with 1000 kilojoules of work, their labour productivity is 2 kcal/kJ. If they adopt a new farming technique that allows them to produce the same amount of food with only 800 kilojoules of work, their labour productivity increases to 2.5 kcal/kJ.

Monitoring labour productivity is important as it provides insight into the efficiency and competitiveness of the agricultural sector. It can also indicate the potential for growth and the sustainability of farming practices. However, while higher labour productivity is generally beneficial, it's also important to consider factors like job quality, worker well-being, and environmental impact.

### 3.8.1 Labour productivity in Europe

In Europe, the labour productivity in agriculture is higher compared to the rest of the world. This means that for every unit of work performed, European agriculture produces more food energy.

Figure 3.18 Labour Productivity in Europe

### 3.8.2 Labour productivity in the World

Many regions of the world still rely heavily on traditional and labour-intensive methods of farming, rather than the mechanized and technologically advanced methods common in Europe. This means that more human effort is needed to produce a given amount of food, which results in lower labour productivity.

Access to high-quality seeds, fertilizers, and other inputs that can boost yields is often limited in less developed regions. This can make farming less efficient, further lowering labour productivity.

Investment in agricultural research, education, and extension services, which help disseminate best practices and new technologies among farmers, is often lower outside of Europe. This means that farmers in these regions may not be fully benefiting from advances in agricultural science and technology.

Figure 3.19 Labour Productivity in the World

### *3.8.3 Comparison Labour Productivity Europe vs World*

Figure 3.20 Labour Productivity Europe vs World

If the slope of labour productivity in agriculture (kcal of food/kJ of work) since the 1970s is steeper in the world compared to Europe, it suggests that the rate of productivity growth has been faster globally than in Europe over this period. This could be due to several factors.

Europe already had a high level of agricultural labour productivity by the 1970s due to its early and extensive adoption of modern farming practices. As a result, the potential for further rapid gains in productivity was somewhat limited—a phenomenon known as diminishing returns.

In contrast, many regions of the world had lower levels of labour productivity in the 1970s and therefore had more room for improvement. The global trend of increasing productivity likely reflects the adoption of modern agricultural technologies and practices in these regions.

This trend could also be attributed to the efforts by many countries to boost agricultural productivity as a means of improving food security and rural incomes. These efforts often involved policies and programs to promote the use of modern inputs, provide agricultural training and extension services, and improve rural infrastructure.

It's important to note, however, that while a steeper slope indicates faster productivity growth, it doesn't necessarily mean higher absolute productivity levels. As of now, labour productivity in European agriculture remains higher than the global average, even though its growth rate has been slower since the 1970s.

# 4. SOLUTION DESIGN

## 4.1 Design of a self-sufficient farm

The project aims to harness the potential of sustainable agricultural practices for a forward-looking and cohesive future Europe. Set in the scenic Vale Carneiro, Portugal, close to Alqueva, Europe's largest artificial lake, the initiative entails designing an innovative farm powered by renewable energy sources, specializing in raising chickens for egg production and cultivating a vineyard.

The objective of this solution was to identify an agricultural activity that is not only representative worldwide but also suitable for the specific conditions of Portugal. Wine production was chosen due to the region's favorable land and climate conditions, making it a relevant local industry. Meanwhile, poultry farming was selected as it is a common agricultural activity prevalent across various countries, thus allowing for a wider scope of application for the findings of this study. This dual focus ensured that the results could be informative and applicable both locally and globally in the agriculture sector.

Figure 4.1 Sketch poultry farm and vineyard

This project was developed based on real data acquired from a wine producer, "Adega do Calisto." This opportunity arose following a conference with the European organization "EubyLakes," held in October in Reguengos de Monsaraz. During this conference, valuable insights were gathered regarding the specific electrical demand of a vineyard that produces around 350,000 liters of wine annually. The use of this real-world data provides a foundation for our project, allowing us to tailor our sustainable and innovative solutions to the specific needs of an operational vineyard.

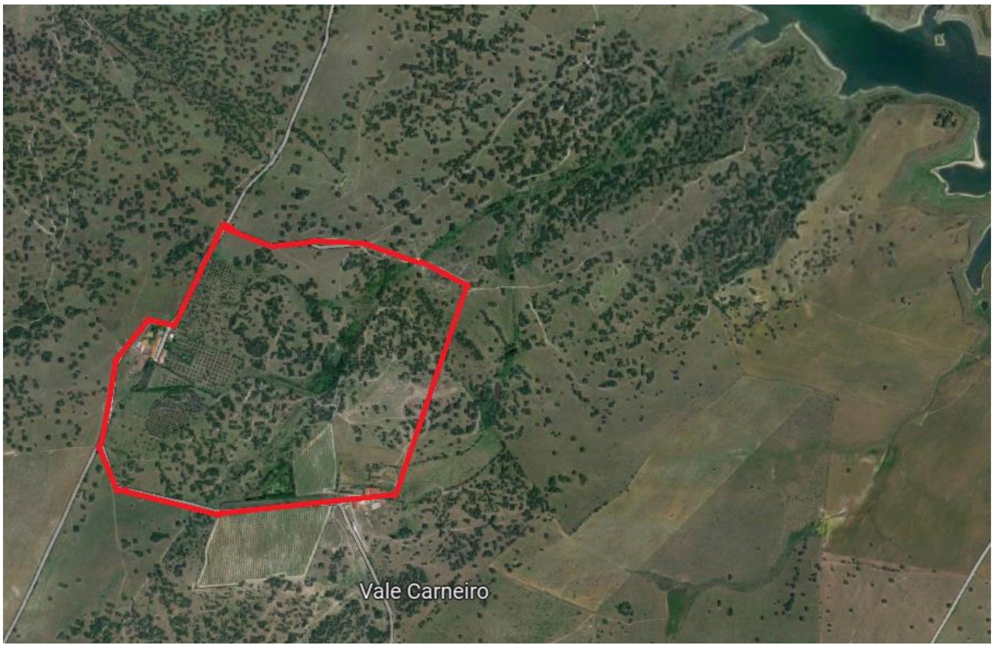

Figure 4.2 Sustainable farm Location (Portugal)

For the poultry farm portion of the project, an inventory was obtained from a chicken farm, allowing for the estimation of its energy demands. These demands were calculated based on its hours of operation throughout the year. The detailed inventory and operational data provided a comprehensive understanding of the farm's energy needs, enabling us to make accurate predictions and develop energy-efficient strategies tailored to the specific requirements of a functioning poultry farm.

## 4.2 Poultry farm

The setup under consideration is a newly constructed chicken farm, purpose-built to house a flock of 35,000 chickens (the number reduced to 32,000 in the summer due to higher temperatures).

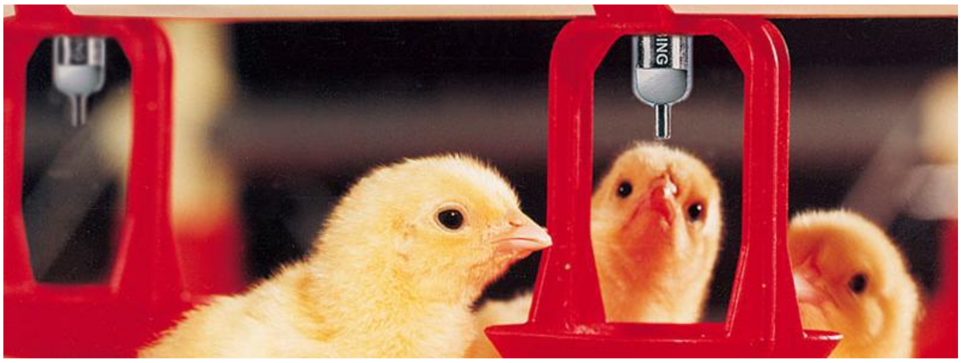

Figure 4.3 Chicken feeder on a farm

This modern facility is a fully enclosed building with no natural light, a design decision that allows the farmers to strictly control the behavioural patterns of the birds through artificial lighting. The farm also features forced ventilation systems to maintain optimal air quality and temperature within the structure, ensuring the health and comfort of the birds.

The use of photovoltaic technology in this setting showcases a commitment to sustainable farming practices, with solar panels providing a renewable source of energy for the artificial lighting and ventilation systems.

### *4.2.1 Poultry farm Consumption*

Agricultural farms, including poultry farms, often rely on various electrical systems for efficient operations. Here are some elements that consume electricity on such farms:

**Lighting Systems:** Artificial lighting is crucial, especially in enclosed facilities like poultry houses. It helps control the behavioural patterns of birds and ensures safety and visibility for workers.

**Ventilation Systems:** Ventilation is vital for maintaining air quality, controlling temperature, and managing humidity levels within agricultural buildings. It's particularly important in livestock farming where dense populations of animals can produce significant heat and moisture [9].

Figure 4.4 Ventilation fan [9]

**Heating and Cooling Systems:** Depending on the climate and the type of livestock, farms may need heating systems (like brooders in poultry farming) or cooling systems (like fans or air conditioners).[9]

Figure 4.5 Light heater [9]

Figure 4.6 Cooler system [9]

**Watering Systems:** Many farms use electric pumps for watering systems to ensure a consistent and clean water supply for the livestock.

**Feeding Systems:** Automated feeding systems, which distribute feed at scheduled times, are commonly used in large-scale farming. These systems save labour and ensure the animals receive consistent nutrition.

Below is a table in English that shows the devices consuming electrical energy and the number of hours of usage in a poultry farm:

| Receiver | Quantity | Power (W) | Overall (W) | Time hours/day | Energy (Wh) |
|---|---|---|---|---|---|
| **HATO LED luminaire** | 69 | 9 | 621 | 24 | 14904 |
| **Luminaire for Halogen Spotlight** | 5 | 400 | 2000 | 2 | 4000 |
| **LED fluorescent tube luminaire** | 9 | 23 | 207 | 1,5 | 311 |
| **Single phase fan** | 6 | 370 | 2220 | 5 | 11100 |
| **Three phase fan** | 6 | 1100 | 6600 | 5 | 33000 |

| | | | | | |
|---|---|---|---|---|---|
| **Single-phase water pump for evaporative panels** | 1 | 736 | 736 | 4 | 2944 |
| **Silo-hoppers single-phase motor** | 1 | 736 | 736 | 0,5 | 368 |
| **Hoppers-feeders single-phase motor** | 3 | 736 | 2208 | 0,5 | 1104 |
| **Feeders rise motor** | 3 | 736 | 2208 | 0,1 | 221 |
| **Drinker raising motor** | 4 | 736 | 2944 | 0,1 | 294 |
| **Well pump** | 1 | 2944 | 2944 | 2 | 5888 |
| **Well-tank pump** | 1 | 736 | 736 | 2 | 1472 |
| **Single phase sockets** | 8 | 250 | 2000 | 1 | 2000 |
| **Triphasic sockets** | 2 | 3000 | 6000 | 1 | 6000 |
| **TOTAL** | | | **32137** | | **83606** |

Table 4.1 Properties of devices with electrical consumption in the poultry farm [9]

### *4.2.2Poultry Farm Demand*

In the subsequent chart, the annual energy demand of the poultry farm is depicted. This graphical display provides an understanding of the energy consumption trends across the year, accounting for seasonal shifts and the operational requirements of the farm. Through the examination of this demand, informed decisions can be made about the energy infrastructure design and the sustainability of the farm.

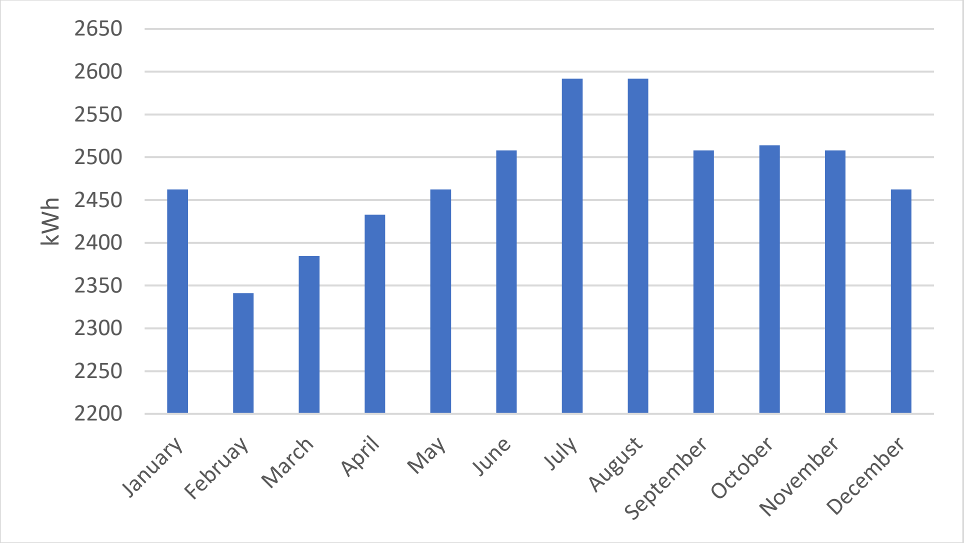

Figure 4.7 Poultry Farm Annual Demand

## 4.3 Vineyard

The decision to design a vineyard with a production capacity of 350,000 liters per year is strategically aligned with the location of the project in Alentejo, a region well-known for its exceptional wine production in Portugal. Alentejo's favorable climate and terroir have allowed it to develop a reputation for producing some of the finest wines in the country, making it an ideal location for a vineyard of this scale.

Integrating renewable energy, specifically photovoltaic energy, into the viticulture sector is of paramount importance for a number of reasons. Firstly, it addresses the pressing need for sustainability in all sectors, including agriculture and wine production. The use of solar energy reduces the reliance on fossil fuels, lowering carbon emissions and mitigating the industry's impact on climate change.

Secondly, it can result in substantial cost savings in the long term. While the upfront costs of installing solar panels may be high, the reduction in electricity costs over time provides significant financial benefits. The abundance of sunshine in regions like Alentejo offers an ideal condition for utilizing solar energy efficiently.

Lastly, the introduction of renewable energy in the viticulture sector aligns with Portugal's national goals and commitment towards renewable energy and sustainable practices. It presents an opportunity to lead by example in the global wine industry, showcasing how traditional practices can harmoniously coexist with innovation and sustainable development.

### *4.3.1 Vineyard Consumption*

In the wine-making process, there are several stages where machines consuming electricity are required, and these stages will be monitored closely in this project to ensure the vineyard operates sustainably.

First, the vintage, or grape harvesting, often involves machinery for picking, sorting, and crushing the grapes. Next, during alcoholic fermentation, temperature control systems are used to maintain the optimal environment for the conversion of sugar into alcohol by yeast.

In the filtration or clarification phase, electrically powered pumps and filters are often used to remove solid particles from the wine. Similarly, during the stabilization phase, cooling systems may be needed to precipitate tartrate crystals.

For the malolactic fermentation, which is a secondary process typically in red wine production, machines that control temperature and stirring might be necessary. The "breeding/storage/racking" stage refers to the aging of wine, where it's often stored in temperature-controlled cellars and transferred (or "racked") between barrels using pumps. During the bottling and dispatch phase, a range of machinery is used, including bottle washers, fillers, corkers, and labeling machines. Lastly, offices often consume energy for lighting, heating or cooling, and running electronic equipment. [10]

In this project, we will be closely monitoring and optimizing the energy consumption at each of these stages, with the goal of creating a truly sustainable vineyard.

Below is a table in English showing devices that consume electrical energy in a vineyard:

| EQUIPMENT | MODEL | POWER (W) | UNITS | TOTAL POWER (W) |
|---|---|---|---|---|
| **Treatment plant** | Vitamax V16EI | 3180 | 1 | 3180 |
| **Cold equipment** | Trane AquaStream2 | 157000 | 1 | 157000 |
| **Hopper** | - | 4000 | 1 | 4000 |
| **Destemmer-juicer** | Enoveneta Gamma 2 | 3000 | 1 | 3000 |

|  |  |  |  |  |
|---|---|---|---|---|
| **Press** | MPB PHN-34A | 10440 | 1 | 10440 |
| **Decoiler** | EGT30 | 4000 | 1 | 4000 |
| **Vintage pump** | DHM EFF2 | 4000 | 1 | 4000 |
| **Water Pump** | MVP AISI 304 | 1850 | 1 | 1850 |
| **Cold circuit pumps** | 3M 40-160/3 | 3700 | 2 | 7400 |
|  | 3M 40-125/2.2 | 2800 | 2 | 5600 |
| **Float pump** | Enolmix 500 | 3000 | 1 | 3000 |
| **Flexible rotor pumps** | Deloule i250 | 3200 | 2 | 6400 |
| **Piston pump** | XM200 | 24000 | 1 | 24000 |
| **Centrifugal pump** | ASEA | 2200 | 1 | 2200 |
| **Membrane filter** | Ebara JEXM/A 100 engine | 1330 | 1 | 1330 |
| **Earth filter** | Ebara engine 2CDXE 120/3D | 2500 | 1 | 2500 |
| **Filler** | GAI 1703-S01 | 3000 | 1 | 3000 |
| **Labeler** | enos gamma7021 | 4000 | 1 | 4000 |
| **Case erector** | Siat F104 | 200 | 1 | 200 |
| **Taper** | Siat SM11 | 260 | 1 | 260 |
| **Interior wine cellar lighting** | Metal halide | 250 | 49 | 12250 |
| **Exterior lighting** | halide metal | 4000 | 9 | 36000 |
| **Machine room/bottling plant lighting and registered office** | Fluorescent | 8000 | 30 | 240000 |

Table 4.2 Properties of devices with electrical consumption in the vineyard [10]

### *4.3.2 Vineyard Demand*

Moving forward in this project, we will be introducing a graph that displays the energy demand of the vineyard throughout the entire year, measured in kilowatt-hours (kWh). This graphical representation will allow us to visualize the fluctuations and patterns of energy consumption in each stage of wine production over time, providing valuable insights. It is an essential tool for effective planning, enabling the design of a sustainable energy system that aligns with the vineyard's unique requirements, ultimately contributing to a more efficient, environmentally friendly operation.

The annual energy demand for the project was accurately determined thanks to the collaboration with "Adega do Calisto" winery. They provided key data which enabled a precise design of a self-sufficient farm. Their input played a significant role in understanding the energy needs associated with wine production, facilitating a more accurate and real-world relevant approach to the farm's design.

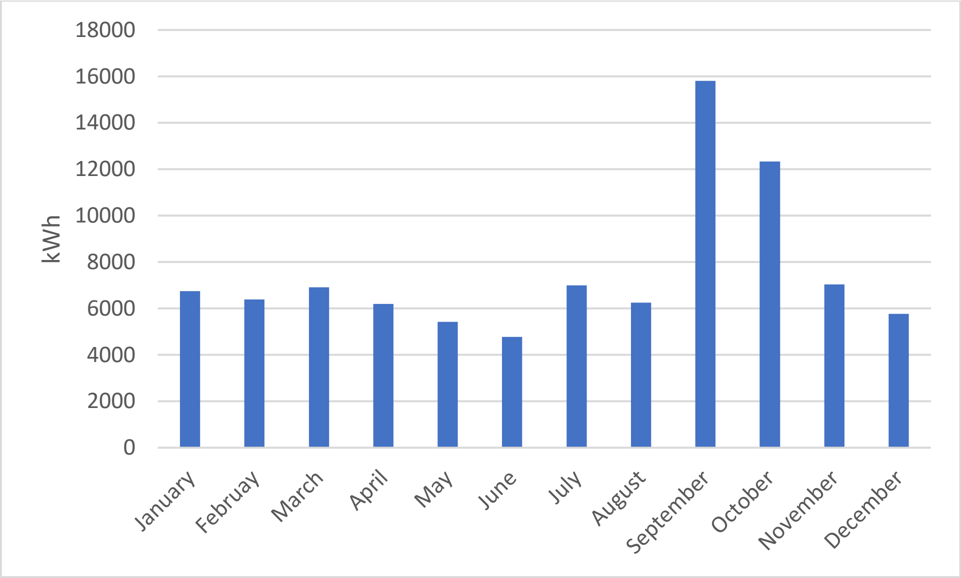

Figure 4.8 Vineyard Annual Demand

As can be observed from the graph, the months with the highest demand for energy are September through February. This is primarily due to the fact that these months coincide with the peak activity of the wine production cycle. To better understand this pattern, it's crucial to examine the timing of various stages of wine production and their corresponding energy needs.

The process begins with the 'Vintage' or harvest period, typically taking place in late summer or early autumn, depending on the grape variety and local climate. During this time, energy consumption spikes due to the use of machinery for harvesting and initial processing of the grapes.

Following the harvest, the grapes undergo 'Alcoholic fermentation', a critical phase where yeast converts the sugars in the grape must into alcohol. This process requires controlled temperatures, leading to increased energy use for cooling or heating systems.

The subsequent 'Filtration/clarification' phase involves removing solid residues from the wine, often requiring electrically powered machinery. Following this, the wine is 'Stabilized' to prevent undesirable changes after bottling – a process that can require temperature control and thus, additional energy.

Figure 4.9 Filtration process

The 'Malolactic fermentation' stage, which often occurs simultaneously with stabilization, involves a secondary fermentation process that reduces the wine's acidity and influences its flavor profile.

Figure 4.10 Fermentation process

The 'Breeding/Storage/racking' stage requires energy for climate-controlled storage, as the wine needs to be kept at optimal temperatures and humidity levels for aging. During the 'Bottling/Dispatch' stage, energy is required for the mechanized bottling process, labeling, and preparing the wine for shipment.

Figure 4.11 Complete bottling line

Finally, the 'Office' tasks involve administrative work, which also uses electricity for lighting, heating, cooling, and operating office equipment. The energy consumption in this phase, however, is generally less variable compared to the other stages of production.

Thus, by mapping the energy demand onto the wine production cycle, we can identify key periods of high energy use and plan our sustainable energy system accordingly. This approach will ensure that our renewable energy sources are utilized most effectively, leading to a vineyard operation that is not only more cost-efficient but also more environmentally friendly.

| **Operation** | **Sept.** | **Oct.** | **Nov.** | **Dec.** | **Jan.** | **Feb.** | **Mar.** | **Apr.** | **May.** | **Jun.** | **Jul.** | **Aug.** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vintage** | 🟪 | 🟪 | | | | | | | | | | |
| **Alcoholic fermentation** | 🟦 | 🟦 | | | | | | | | | | |
| **Filtration/clarification** | | | 🟦 | 🟦 | 🟦 | | | | | | | |
| **Stabilization** | | | | 🟨 | 🟨 | 🟨 | | | | | | |
| **Malolactic** | | | 🟦 | 🟦 | | | | | | | | |
| **Breeding/Storage/ racking** | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 |
| **Bottling/Dispatch** | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 | 🟧 |
| **Office** | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |

Table 4.3 Distribution of vineyard activities

## 4.3 Farm Demand

Once the electrical consumption patterns of both the poultry farm and the vineyard have been analyzed, we will proceed to aggregate these demands. This combined analysis will provide us with a comprehensive understanding of the annual energy demand for the entire operation. This crucial step allows us to accurately estimate the specifications of the photovoltaic plant needed to meet these energy demands sustainably.

By overlaying these energy requirements with the expected output of the proposed photovoltaic system, we can optimize the system design. The goal is to ensure the renewable energy source can meet the energy demands during peak periods, while also being cost-effective. Through this, we aim to create an agricultural operation that is not only productive and efficient but also environmentally sustainable, harnessing the power of renewable energy for a greener future.

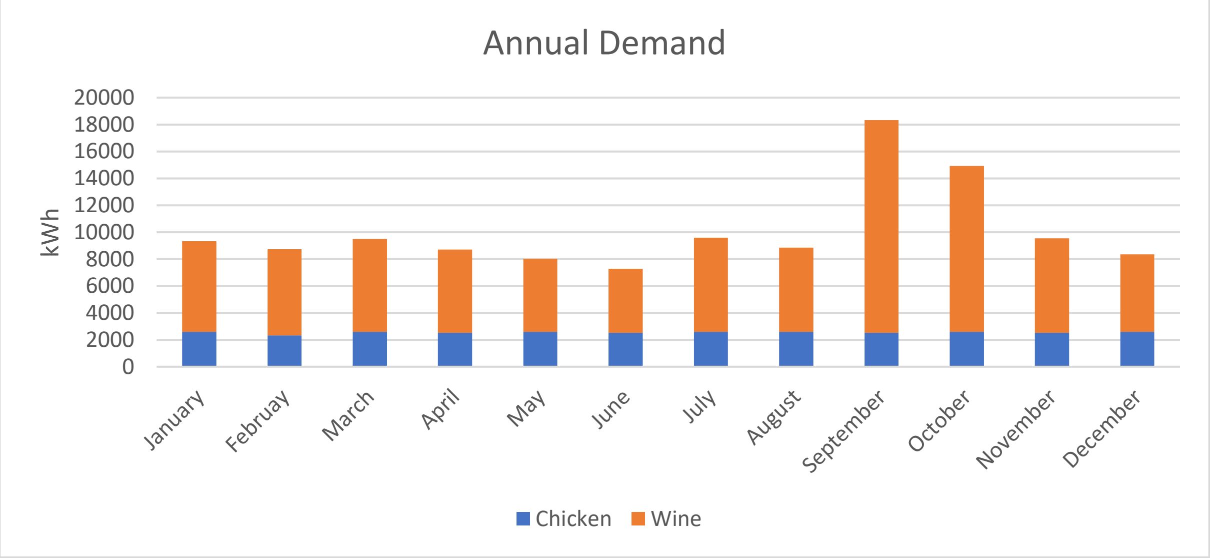

Figure 4.12 Annual demand in the whole self-sufficient farm

A graph is displayed showing the total energy demand when the poultry farm and vineyard are combined. As the vineyard activity increases from September to February, it is deemed critical to closely examine the energy profile during this period. Hence, we've decided to construct an hourly energy consumption profile for a day during the most intensive period of wine production, and another for a day during a less intensive period.

This approach allows us to better understand the temporal variation of the energy demand and will help guide our design of the photovoltaic system. It's critical to know not just how much energy is needed, but when it's needed, as the solar energy production fluctuates throughout the day. This detailed analysis will assist us in creating a photovoltaic system design that optimally matches the energy generation with the demand patterns.

The subsequent chart displays a power profile for a summer day, spanning from September to February. During this period, the vineyard's activity intensifies, resulting in a greater peak power demand. This profile is indicative of the energy requirements of the farm during its busiest season and helps in making more effective energy management decisions.

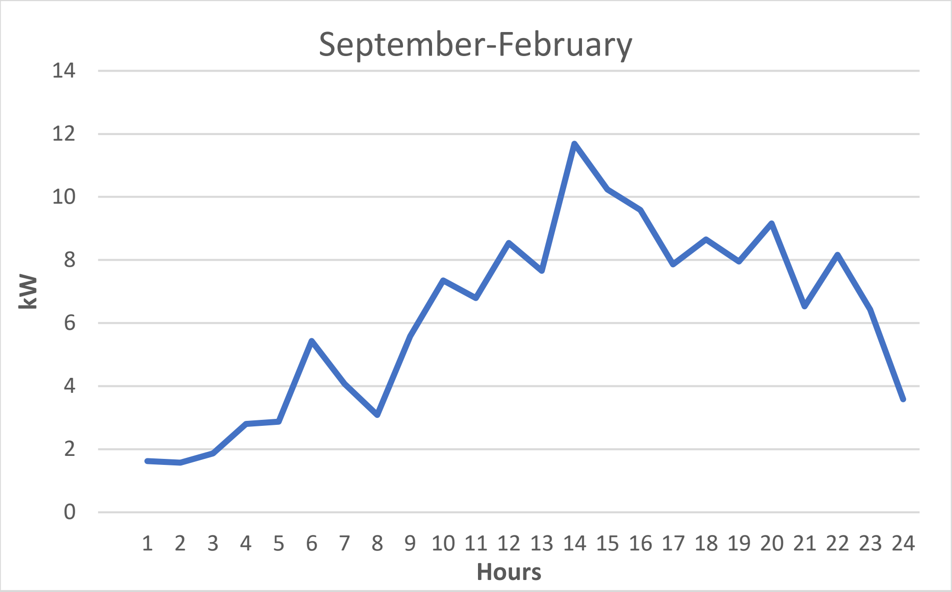

Figure 4.13 Power profile of a winter day

The following graph portrays a power profile for a winter day, which extends from March to August. This is a period of reduced vineyard activity, hence, the peak power demand is lower. This profile serves to illustrate the energy requirements of the farm during its off-peak season, which is critical for efficient energy management and planning.

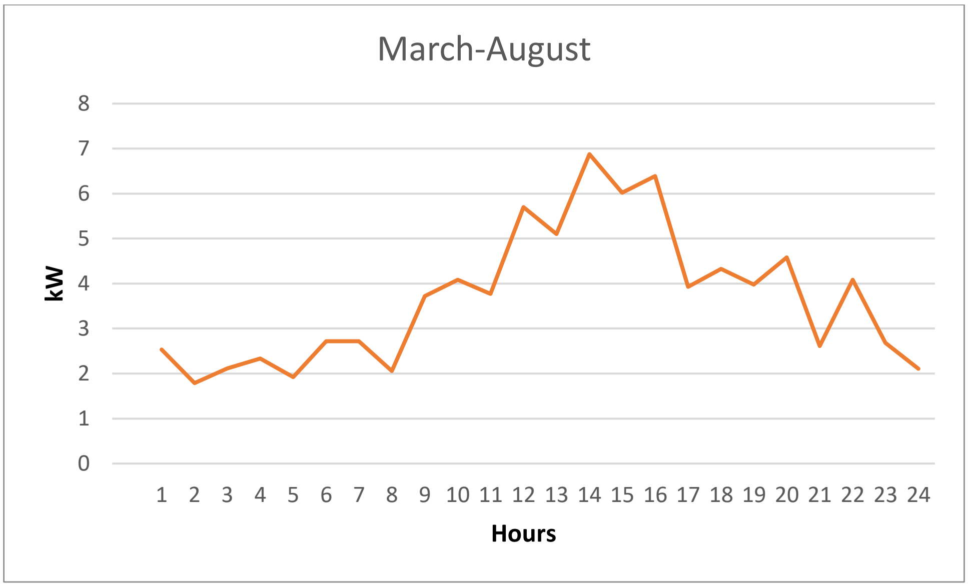

Figure 4.14 Power profile of a summer day

# 5. IMPLEMENTATION OF SOLUTION

In this chapter, the data and requirements derived from the previous analysis are used to design the photovoltaic plant, which serves as the primary energy source for the self-sufficient farm. This chapter goes deep into the specifics of how to implement a sustainable energy system, taking into account the unique energy consumption patterns and seasonal variations of the farm's operations. The goal is to design a system that doesn't merely meet the farm's energy needs, but also advances energy efficiency and sustainability.

This involves appropriate sizing of the photovoltaic plant, integration of energy storage solutions like battery systems, and implementation of suitable control strategies. By achieving this system implementation successfully, the potential of renewable energy sources in supporting and enhancing agricultural productivity is exemplified, thereby tying back to the broader theme of the thesis – the impact of technology and access to energy on improving land and labour productivity

## 5.1 System description

### *5.1.1 Introduction*

In this section, a description of the micro-grid under study is made and the characteristics of each of the elements that make up the system are defined. Thus, the micro-grid is made up of a photovoltaic generation plant, which represents the renewable energy resource with which all the energy consumed by the system in nominal operation is produced; by a Battery Energy Storage System (BESS), which has three banks of batteries, each managed by its own power inverter; by a variable load, which is the element that determines the power required at each moment by the energy generation and storage systems; and finally, by an emergency Diesel generator that only acts in the event that the renewable system is not able to provide the power necessary to satisfy the variable load.

### *5.1.2 Methodology*

One of the main characteristics of the virtual synchronous machine is that, unlike the Grid-Following converters, this control strategy allows operation on networks that are not previously energized. This is possible because its operating principle is not based on reading the mains frequency from a phase tracking loop, but instead generates its own system frequency through primary regulation.

Therefore, micro-grids can be implemented isolated from the main grids that operate in a stable and controlled manner composed 100% by power inverters, thus eliminating the need to have one or several conventional synchronous generators that impose the voltage and inertia of the system. In this way, this section simulates a micro-grid, isolated from the electrical grid, composed of a virtual synchronous machine and one load.

### *5.1.3 Energy Source*

The energy resource presented in this project is photovoltaic generation, which consists of the generation of electric current by a semi-conductor when it is under a certain solar irradiance. Based on the analyzed demand, we have decided to design the photovoltaic park for a nominal power of 30 kW. This power rating is obtainable from the plant only when there is solar irradiance of 1000W/$m^2$, which generally occurs during summer. However, during winter, the maximum solar irradiance drops to around 500W/$m^2$[16].

To compensate for this seasonal variation in solar irradiance and ensure a consistent energy supply, we have sized the battery system to have an autonomy of three days. This means that in the event of low or no sunlight (which is more common in winter), our battery system can support the farm's energy demand independently for up to three days.

This design strategy allows us to balance the photovoltaic system's output across the year and ensure that our operations, both at the poultry farm and the winery, can continue without disruptions regardless of the season. Thus, the primary element of this type of generation is the photovoltaic cell.

The BESS used in this case study consists of three lithium battery banks, each managed by its own inverter. One important parameter to consider when defining this component is the capacity of the battery banks. Battery capacity is measured in Ampere-hours (Ah), while the unit chosen to measure the stored energy is kilowatt-hours (kWh). To determine the appropriate capacity for the selected battery bank, it is necessary to analyze the characteristics of the system and the load it supports. Therefore, one of the factors to take into account in the design of the bank is how long the battery bank should be able to sustain the system load as the sole available energy source. However, there are various studies that present different methods for sizing batteries for microgrids, such as the one shown in [11].

The next characteristic parameter to determine for the chosen lithium batteries is the maximum charging and discharging power that the banks can support. In order to ensure proper operation and maintenance of these components, the maximum power generated by the BESS is 30 kW, both for charging and discharging. The choice for the farm's energy storage was a battery with a capacity of 270 kWh, designed to provide autonomy for 3 days. This decision was based on the energy demand analysis and the goal of maintaining consistent and reliable energy supply, even in scenarios of low renewable energy production or heightened usage. This significant capacity enables the farm to operate seamlessly, ensuring a steady workflow and meeting its energy needs effectively.

Figure 5.1 Battery of 270 kWh and 96V [13]

On the other hand, the lifespan of lithium batteries, typically measured in charge cycles, is highly sensitive to the operational conditions of the device. Thus, in order to maximize their lifespan and extract the maximum available performance at all times, additional parameters need to be monitored and managed besides the maximum allowed power. These parameters include Depth of Discharge (DoD), which refers to the extent of battery discharge, and operating temperature, among others.

Firstly, the Depth of Discharge (DoD) indicates the percentage of battery discharge relative to its total storage capacity, and it follows the expression 5.1 shown below. As can be observed, the DoD is the complementary term to the State of Charge (SoC).

$$DoD(t) = 1 - SoC(t) \qquad (5.1)$$

Therefore, in order to manage the Depth of Discharge (DoD), it is necessary to have a system that allows knowing the stored energy in the battery bank at any given moment. There are several methods available to estimate the state of charge of a lithium battery, such as fuzzy logic methods, Kalman filters, neural networks, and others. These methods, along with the method used in this study called Coulomb counting, are presented in [12]. The Coulomb counting method involves calculating the percentage of the battery bank's state of charge using expression 5.2, which depends on the initial state of charge, the nominal capacity of the battery bank, and the current input and output current flow.

$$SoC(t) = SoC_0 - \frac{1}{C_{nom}} \cdot \int_{t_0}^{t} i_{batt}(t)\, dt \cdot 100 \qquad (5.2)$$

Therefore, in order to prolong the lifespan of each of the battery banks that make up the BESS in this case study, the allowed State of Charge (SoC) is limited to the range of [20, 90] %. Any bank that reaches the lower or upper limit of SoC will have to stop its operation and therefore be taken out of service to protect the integrity of the device.

The operating temperature of the battery banks is also a factor that needs to be considered in controlling the lithium cells. Thus, the permitted temperature range for BESS operation is [-10, 50] °C.

## 5.2 Variable load

In order to determine the variable load of the system, we must first decide on its characteristics. In this case study, we consider the chicken farm that operates 24 hours a day, every day of the year, and the winery whose operation is more variable. However, there are certain devices that need to operate all year round such as refrigeration in wine cellars.

To determine the load profile and set the power for each of the 24 hours in which the system operates each day, it has extracted real hourly demand data from similar farms and wineries and perform a data treatment that consists of calculating the arithmetic mean of the electrical demand for each hour of the day.

## 5.3 Electric system modelling

In the subsequent phase of the project, the photovoltaic installation for the sustainable poultry farm and winery will be designed using MATLAB, a high-level technical computing language, and its accompanying tool, Simulink.

Simulink functions as a block diagram environment for multidomain simulation and model-based design. It facilitates simulation, automatic code generation, and the continuous testing and verification of embedded systems. Each element of the photovoltaic installation - including inverters, load, and resistive components - will be depicted as blocks in a system-level diagram within this environment.

Upon arranging the system's diagram in Simulink, the design can be further refined through MATLAB scripts. These scripts will incorporate real-world values and conditions pertinent to the project, such as the electrical demand calculated in earlier stages and operational specifics of the farm and winery.

By merging Simulink's potent graphical representation with MATLAB's data-driven approach, a robust, precise model of the photovoltaic installation can be constructed. This ensures the installation will fulfil project requirements and contribute to the sustainable functioning of the poultry farm and winery.

This part of the study will illustrate the process of electrically modelling the microgrid, which will be used subsequently to simulate the system of the photovoltaic installation for the self-sustainable poultry farm and winery project, considering the specifics defined earlier. With the circuit diagram as a reference, each component can be analysed in detail.

Commencing from the left, the first component encountered is the Power Plant Controller (PPC), the core manager of the installation. It determines the set points for the Battery Energy Storage System (BESS) inverter and the Photovoltaic (PV) inverter based on the load requirements.

Further into the circuit, several impedances are met. These represent the resistive and reactive attributes of the transmission lines in the system. Accounting for these is crucial, as they influence the system's power transfer capability and stability.

At the circuit's end, a variable component represented by a varying resistance serves as the load block. It is tied on its left side to a load profile, introduced from MATLAB. The electrical demand defined in previous sections is input here, offering a realistic representation of the electrical load the system will face. This enables the simulation of the photovoltaic system's operation under the actual load conditions of the sustainable poultry farm and winery.

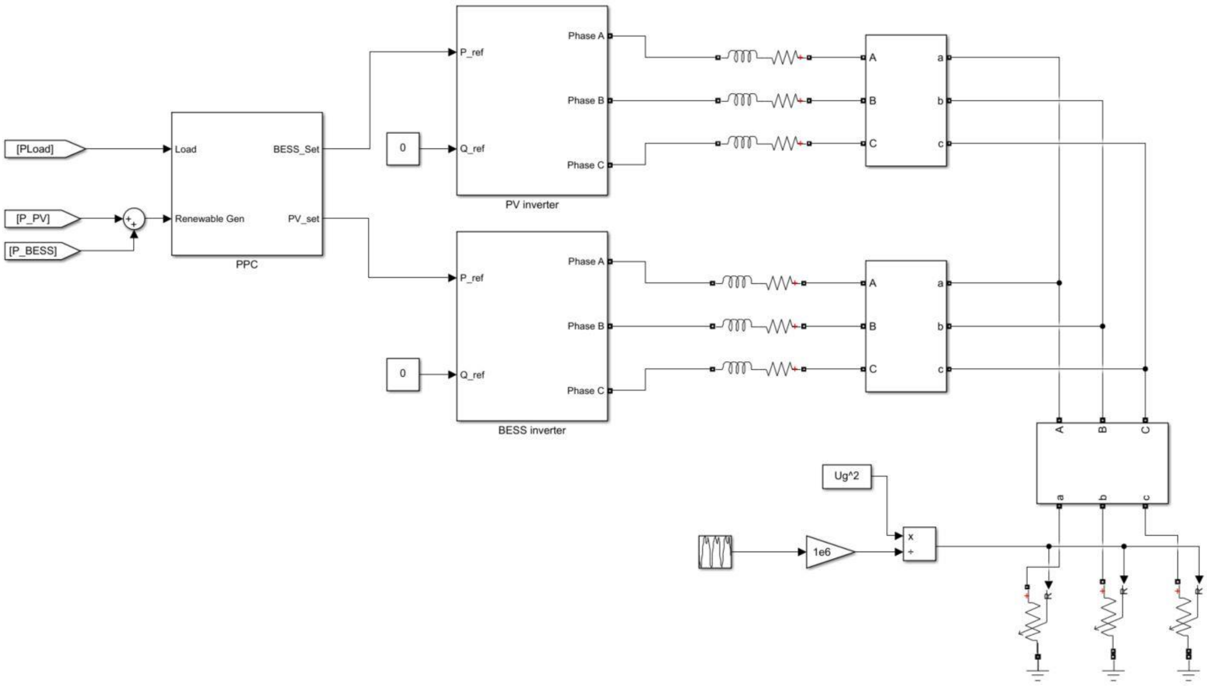

Figure 5.2 Scheme of System by SIMULINK

## 5.4 System Simulation

Once the controller of the microgrid under study has been implemented in the SIMULINK software, we proceed to simulate the system. To fully define the parameters of the simulation for this case study, we only need to determine the photovoltaic generation developed by the plant and the total duration of the simulation.

Figure 5.3 presents the normalization of the stable and unstable irradiance profiles utilized in this study. It can be seen that the time dimension of the irradiance profile is 288 seconds, thus simulating 24 hours of microgrid operation in 288 seconds.

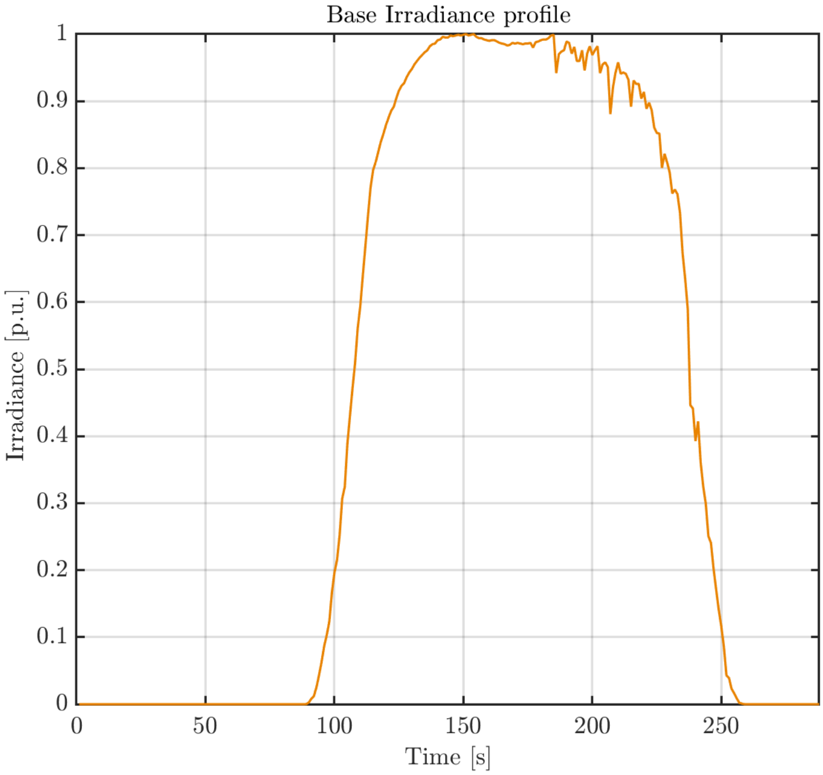

Figure 5.3 Irradiance profile normalized

This graph portrays the solar irradiance over a day at the photovoltaic plant. The y-axis shows the irradiance in per unit (p.u.), a dimensionless unit. This practice is common when dealing with variable conditions like solar irradiance, which can drastically change depending on the time of year and location.

Using the per unit (p.u.) system is beneficial in this context as it enables the adaptation of the same irradiance profile to both summer and winter seasons. This is crucial for year-round operations like a poultry farm and winery. In the summer, the peak solar irradiance reaches 1000W/m$^2$, while in winter this value reduces to a peak of 500W/m$^2$.

Normalizing the data provides flexibility to adapt to the changing solar irradiance throughout the year. This ensures that these changes can be accurately represented and responded to in the system model. It also aids in providing a more sustainable and reliable energy source for the operations, irrespective of the season.

The first simulation that we perform corresponds to a winter day when the solar irradiance is approximately 500 W/m$^2$. As you can see from the graph, during the night, the energy demand is covered entirely by the battery system. However, as the sun rises and the solar panels begin to generate power, both the photovoltaic system and the battery system work together to meet the farm's energy demand. This balance of power between the battery and the solar system is made possible by the use of a controller, which ensures that the sum of power from the battery and the photovoltaic system always matches the demand [17].

An interesting phenomenon to note is that when the solar energy production exceeds the energy demand, the surplus energy is used to recharge the battery system. This energy storage ensures a buffer for times of lower irradiance or during night hours when the photovoltaic system isn't generating power. As the solar irradiance starts to decrease, such as during sunset or cloudy periods, the battery system then kicks in, discharging stored energy to meet the demand.

This cyclical and efficient energy management optimizes the utilization of renewable energy and minimizes reliance on external power sources, making the farm self-sustainable and resilient to variations in weather or seasonal changes.

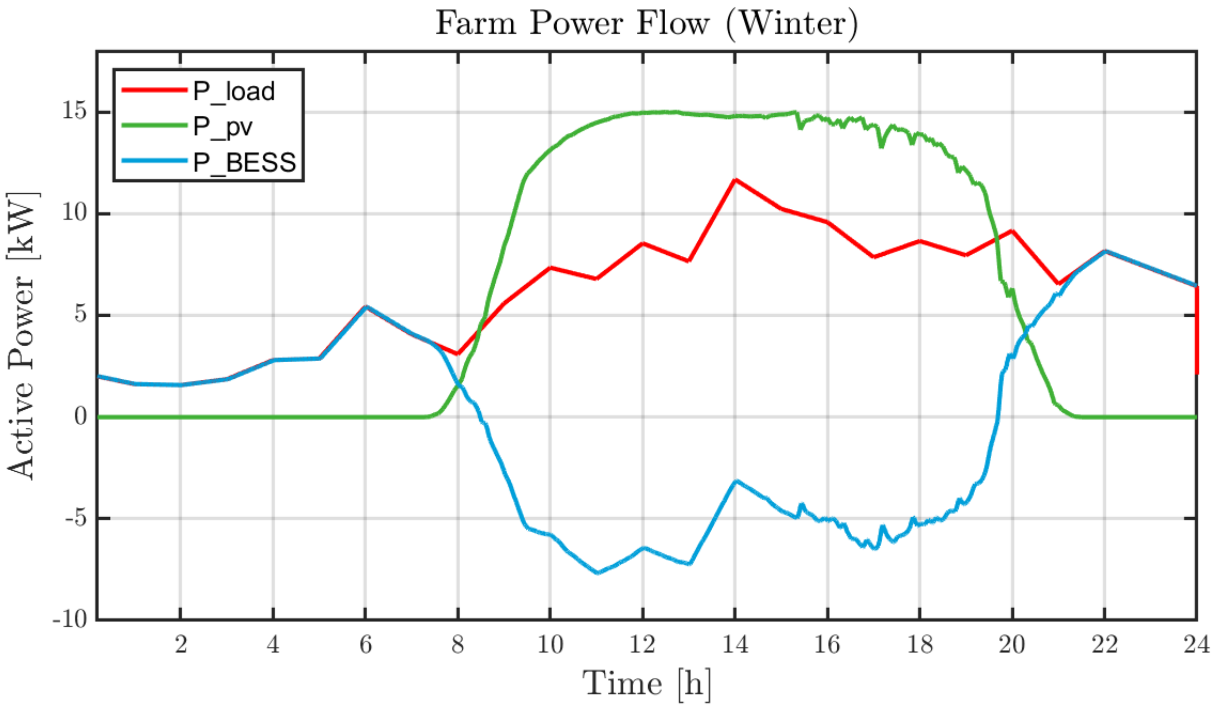

Figure 5.4 First simulation in a winter day

This step will now go into the process of battery charging and discharging, taking the simpler case of a winter day simulation as an example. Over the course of the day, the battery charges and discharges, but it doesn't reach its maximum capacity during charging hours. This process is vividly illustrated in the subsequent graph.

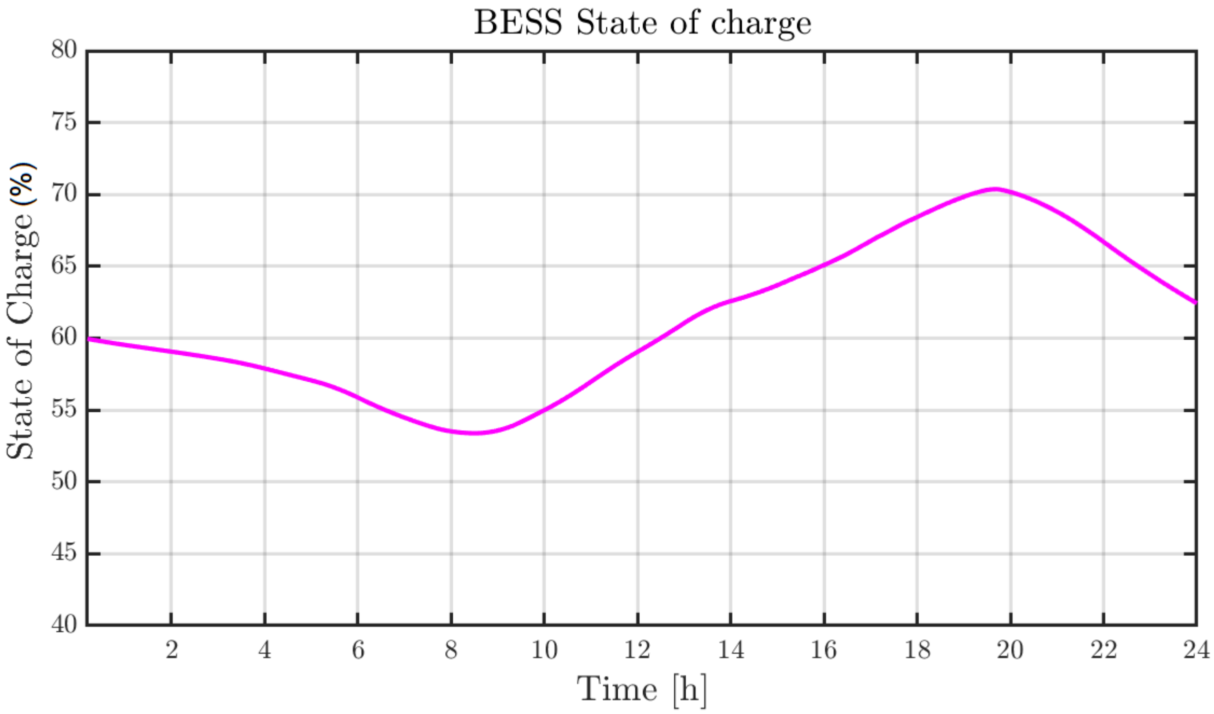

Figure 5.5 Case 1 BESS state of charge

The second simulation represents a summer day when the peak irradiance is 1000W/m$^2$. Until about 8 am, the behavior of the battery and demand is the same as on a winter day. However, the power production from the photovoltaic plant is significantly higher here. By 9 am, the power generated by the plant exceeds both the demand and the battery's charging power. At this point, there is a slight drop in power because the photovoltaic plant has regulated its output.

Then, around six in the evening, once the battery is fully charged, we can observe a change in the photovoltaic plant's behavior. It limits its power output and adjusts it directly to match the demand. This adjustment is crucial to prevent overproduction and ensure the efficient use of generated power, illustrating the adaptability of renewable energy systems to changes in environmental conditions and power demand [18]. The use of control systems to manage power production based on demand and battery status is a critical component of sustainable and efficient energy management.

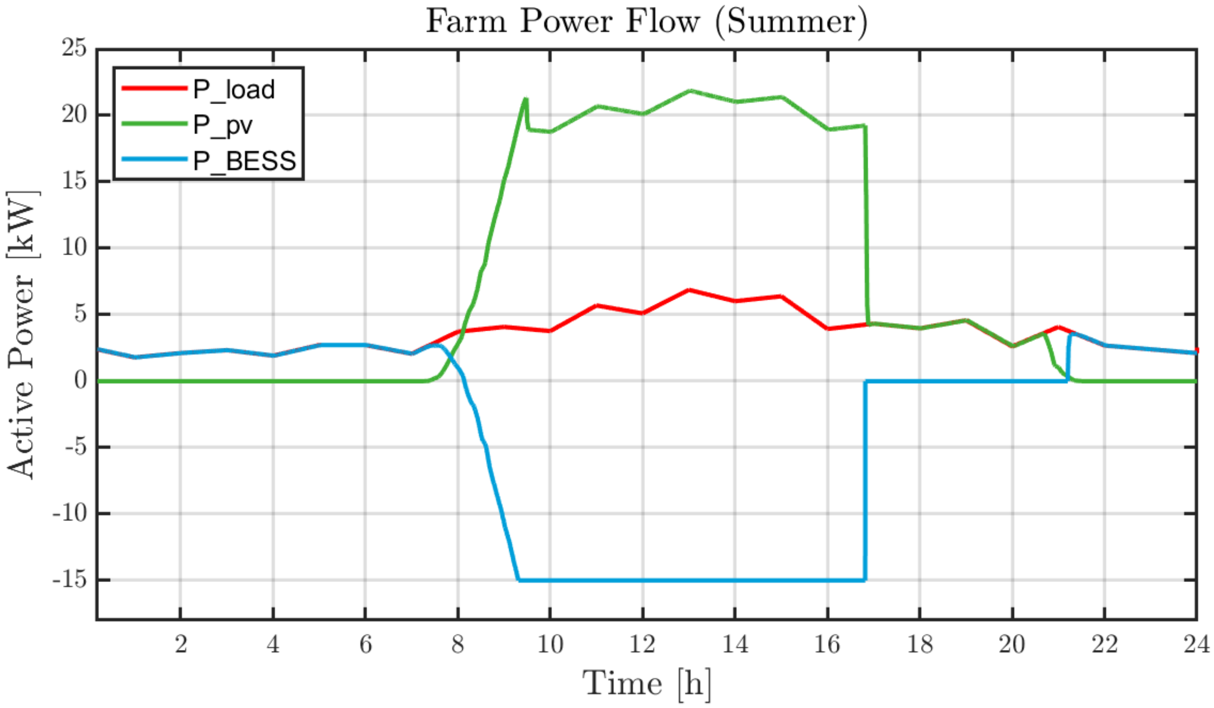

Figure 5.6 Second simulation in a summer day

Next graph shows battery charging on a summer day. We can observe how the battery discharges during the night while conversely, during the day, it's being charged. At a certain point, the battery completes its charging cycle, reaching its maximum capacity. As long as the photovoltaic production continues to cover the demand, the battery's capacity remains constant at 100%.

This behaviour of the battery underscores the importance of storage systems in renewable energy-based setups. Notably, during periods of excess energy production, the energy is not wasted but stored for use during periods of lower production or higher demand. This is especially important for solar power systems, where energy production varies significantly throughout the day. Thus, efficient battery management plays a crucial role in ensuring the continuous availability of power and the overall sustainability of the system. It further highlights the necessity of a well-designed control system to manage the interplay between power production, demand, and battery charge levels, optimizing system performance and longevity.

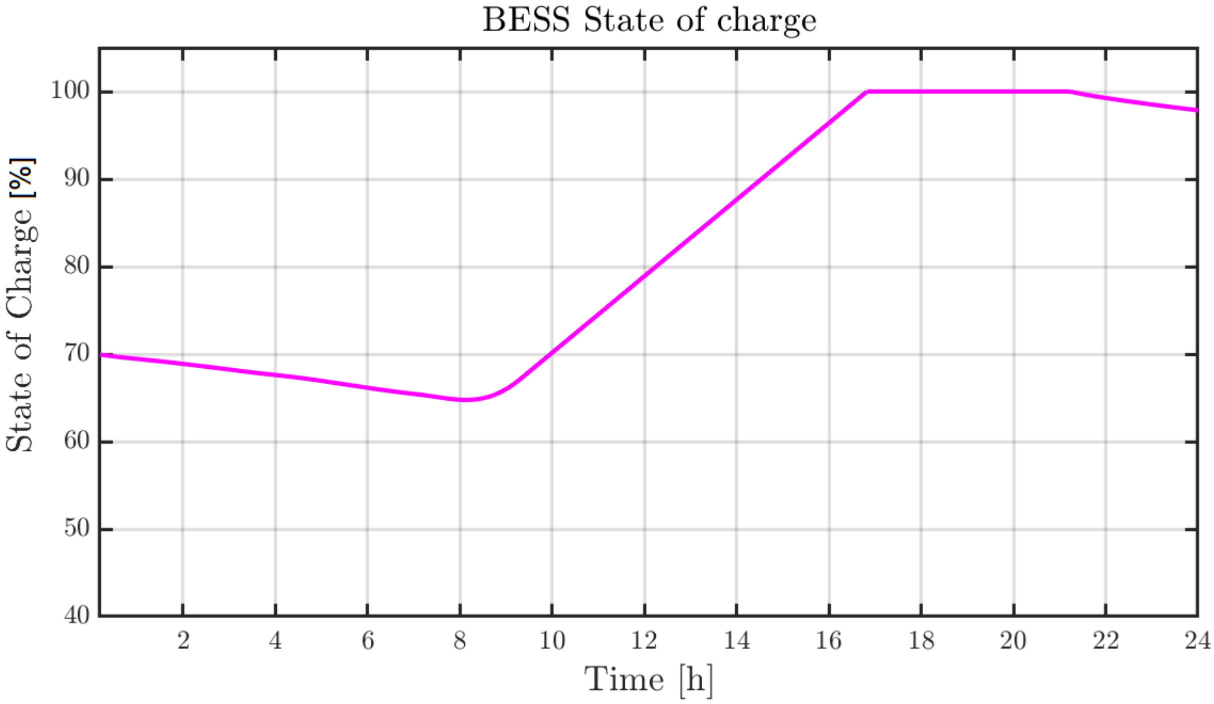

Figure 5.7 Case 2 BESS state of charge

# 6. TEMPORAL PLANNING

This chapter presents the temporal distribution of the completion of each task developed in this project by the author.

Thus, the tasks have been divided into:

- T1: Search and study of literature in the World and Europe Agriculture.
- T2: Obtain the data of different sources.
- T3: Implement the methodology chosen with data.
- T4: Find and fix outstanding data in Europe.
- T5: Design self-sufficient farm.
- T6: Implement and simulate the case of study.
- T7: Writing the project report.

Table 6.1 shows the project's Gantt chart.

| | Sept.-22 | Oct.-22 | Nov.-22 | Dec.-22 | Jan.-23 | Feb.-23 | Mar.-23 | Apr.-23 | May.-23 | Jun.-23 |
|---|---|---|---|---|---|---|---|---|---|---|
| T1 | X | X | | | | | | | | |
| T2 | | | X | | | | | | | |
| T3 | | | | X | X | | | | | |
| T4 | | | | | X | X | | | | |
| T5 | | | | | | | X | X | | |
| T6 | | | | | | | X | X | X | |
| T7 | | | | | | X | X | X | X | X |

Table 6.1 Project's Gantt chart

# 7. ENVIRONMENTAL IMPACT

This chapter discusses the environmental impact associated with the implementation of this project. Given that it's strictly a theoretical project and its practical aspect is based on computer software simulations, the direct environmental impact caused by this study primarily resides in the emissions related to the energy consumption that occurred during its development.

Thus, Table 7.1 provides a breakdown of the energy consumption linked to this project.

| **Energy Consumption** | | | | |
|---|---|---|---|---|
| **Element** | **Quantity** | **Power [W]** | **Hours** | **Consumption [kWh]** |
| Lamp | 3 | 9.5 | 840 | 23.94 |
| Laptop | 1 | 170 | 210 | 35.70 |
| **Total** | | | | **59.64** |

Table 7.1 Detailed overview of the energy consumption throughout the project execution

As can be observed, the total amount of energy dedicated to the development of this study is 59.6 kWh. Moreover, according to [14], the average CO2 emissions associated with electricity generation in the Spanish electric system from April 2022 to January 2023 is 0.156 t CO2/MWhe. Hence, the execution of this project has led to an estimated emission of 9.3 kg of CO2 into the atmosphere.

However, the environmental impact of this project should be considered beyond just the CO2 emissions generated. This study contributes to the development of new control strategies for power converters that open up fresh approaches to addressing the numerous technological challenges inherent in the operation and management of an electrical system where renewable energies constitute the majority of total electricity generation. Therefore, this project represents a small but important step towards achieving the objectives established to reach greenhouse gas emission neutrality by the year 2050.

# 8. ECONOMIC STUDY

In this section, we present the economic study of the project, considering all the expenses incurred in its development. As this is entirely a theoretical project, the only costs taken into account are those of material resources and software, as well as human resources invested in the project.

Consequently, Table 8.1 provides a detailed breakdown of the costs associated with office materials and the software required for the project's development.

| Cost of material and computer resources | | | |
|---|---|---|---|
| **Concept** | **Unit price** | **Depreciation** | **Amount** |
| Laptop | 1.000 € | 0,2 | 200,00 € |
| Microsoft Office Suite | 69 € | 0,4 | 27,60 € |
| MATLAB® | 2.150 € | 1 | 2.150,00 € |
| Simscape Electrical | 3.250 € | 1 | 3.250,00 € |
| Laptop | - | - | 30,00 € |
| **Total** | | | **5.657,60 €** |

Table 8.1 Detail of material and software costs

Additionally, Table 8.2 presents a detailed breakdown of costs associated with the human resources utilized.

| Cost of human resources | | | |
|---|---|---|---|
| **Concept** | **Price/hour** | **Hours** | **Amount** |
| Literature review | 30 € | 100 | 3.000,00 € |
| Data analysis | 30 € | 150 | 4.500,00 € |
| Model design | 30 € | 80 | 2.400,00 € |
| Simulations | 30 € | 110 | 3.300,00 € |
| Report writing | 30 € | 400 | 12.000,00 € |
| **Total** | | | **25.200,00 €** |

Table 8.2 Detail of human resource costs

Finally, Table 8.3 shows the total cost of the project, also taking into account the Value Added Tax (VAT) associated with it.

| Budget | |
|---|---|
| **Concept** | **Import** |
| Cost of material and computer resources | €5,657.60 |
| Cost of human resources | €25,200.00 |
| **Subtotal** | **€30,857.60** |
| **VAT (23%)** | €7,098.85 |
| **Total** | **€37,956.45** |

Table 8.3 Total project cost, including VAT

# 9. CONCLUSIONS

The conclusions drawn from the case study emerge with some notable differences found between the European analysis and the global analysis.

Beginning with animal work, the global decrease lags behind Europe by a decade. However, by 2015, both held the same ratio of 200 MJ/ha. In terms of human muscle work, the decline in Europe is more pronounced, but the world at large follows a more moderate pace. For instance, in the last decade, Europe has a MJ/ha ratio that's 60% less than the global average.

Electricity usage in Agriculture has stagnated globally since the '90s, while in Europe, growth is significant, reaching 3600 MJ/ha today. This represents a 40% increase compared to global levels.

In terms of liquid fossil fuel usage, the figures are more comparable in absolute terms. Nevertheless, it can be observed that European policies have effectively halted its increasing use. The next step would be to reduce it.

The study's finding related to work is highly relevant. To produce 1MJ/ha of physical work, it takes 3.6 MJ/ha of final energy (current global rate) and 3 MJ/ha of final energy (current European rate). Therefore, there's still a long way to go to reduce this proportion, beginning with reducing fuel usage and ensuring that electricity production becomes as sustainable and efficient as possible.

A similar case to liquid fuels occurs with the use of fertilizers and pesticides. At the European level, usage has stabilized at 100kg/ha, whereas globally we have 140 kg/ha currently.

All of these factors previously discussed are reflected in land productivity, which is clearly seen to be twice as high in Europe. This is further evidenced in labour productivity, with the European ratio being four times bigger than global scale.

The conclusions of our solution, focusing on poultry and wine production in the Alentejo region of Portugal, yields significant insights into the potential for self-sufficiency and sustainability in agricultural practices.

A key feature of the renewable energy systems implemented is their three-day autonomy. This capacity, perfectly suited to cover periods of reduced sunlight during winter, ensures continuous operation and production.

These findings could serve as a blueprint for other agricultural sectors situated in similar geographic locations. By prioritizing renewable energy and self-sufficiency, agriculture can not only endure but also flourish in a world grappling with the impacts of climate change. Therefore, this study accentuates both the potential and the pressing need to transition towards more sustainable and resilient agricultural practices.

Building upon the outcomes of this project, potential future research could involve a detailed analysis of a specific country, examining its data from recent years and comparing it with the broader European context. This targeted study could provide further insights into national trends and variations in agricultural practices and energy usage. It could also serve to highlight potential region-specific strategies for transitioning towards more sustainable agricultural systems.

As for the proposed renewable energy solutions, the integration of an emergency diesel generator could be a considered enhancement for the system. This modification would provide an added layer of resilience, ensuring that energy demands are met even in periods of high demand or reduced solar input.

Additionally, the electrical circuit could be redesigned to accommodate the simultaneous operation of both the diesel generator and the solar panels. Such a hybrid system could effectively address potential energy shortfalls during the day, further enhancing the reliability and flexibility of the system. By continuously refining the design and integration of renewable energy systems, we can ensure that they become ever more efficient and adaptable, enabling agriculture to increasingly move away from dependence on fossil fuels and towards a sustainable future.

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# APPENDIX 1 – INFORMATION FOR CAS STUDY

### Plate Waste, Extrapolations from Raw Data (%)

| Year | AF | EE | NA | SA | SEA | WE |
|---|---|---|---|---|---|---|
| 1970 | 4.6% | 28.0% | 25.0% | 14.6% | -0.5% | 30.2% |
| 1971 | 3.8% | 27.9% | 25.3% | 14.6% | 0.0% | 30.3% |
| 1972 | 2.1% | 27.2% | 25.6% | 13.4% | 0.4% | 30.4% |
| 1973 | 3.5% | 28.1% | 25.1% | 12.4% | 2.9% | 31.0% |
| 1974 | 5.4% | 28.8% | 24.9% | 15.7% | 4.2% | 30.4% |
| 1975 | 5.7% | 28.5% | 24.7% | 16.3% | 2.8% | 29.6% |
| 1976 | 5.7% | 29.8% | 27.8% | 17.2% | 2.5% | 30.9% |
| 1977 | 6.5% | 29.2% | 27.2% | 17.6% | 3.2% | 30.9% |
| 1978 | 7.6% | 29.7% | 27.4% | 18.4% | 5.3% | 32.3% |
| 1979 | 8.8% | 29.6% | 28.6% | 20.4% | 6.7% | 32.5% |
| 1980 | 10.3% | 29.6% | 27.9% | 20.8% | 7.9% | 32.7% |
| 1981 | 10.6% | 28.9% | 28.6% | 19.5% | 9.9% | 32.8% |
| 1982 | 10.8% | 29.0% | 28.1% | 19.0% | 8.8% | 33.6% |
| 1983 | 9.4% | 29.3% | 28.8% | 17.9% | 9.8% | 34.1% |
| 1984 | 8.2% | 29.5% | 29.9% | 17.9% | 10.9% | 34.2% |
| 1985 | 10.3% | 29.4% | 32.0% | 18.5% | 10.3% | 34.7% |
| 1986 | 11.7% | 29.3% | 31.5% | 18.8% | 11.1% | 34.5% |
| 1987 | 11.1% | 30.1% | 33.4% | 19.8% | 11.4% | 34.7% |
| 1988 | 11.9% | 30.1% | 33.3% | 19.6% | 12.8% | 35.3% |
| 1989 | 12.1% | 29.4% | 32.9% | 19.1% | 13.0% | 35.1% |
| 1990 | 12.6% | 29.5% | 33.9% | 18.4% | 9.9% | 33.8% |
| 1991 | 13.7% | 22.8% | 34.4% | 20.2% | 10.2% | 34.6% |
| 1992 | 13.6% | 22.9% | 35.1% | 20.9% | 12.0% | 35.4% |
| 1993 | 14.5% | 23.7% | 35.8% | 21.0% | 12.9% | 33.7% |
| 1994 | 15.0% | 21.6% | 36.9% | 22.0% | 14.8% | 33.4% |
| 1995 | 15.7% | 21.5% | 35.4% | 22.2% | 16.2% | 34.0% |
| 1996 | 16.1% | 20.2% | 35.6% | 22.6% | 17.1% | 34.4% |
| 1997 | 16.6% | 21.5% | 36.7% | 22.7% | 16.2% | 33.3% |
| 1998 | 17.3% | 22.0% | 36.9% | 22.4% | 16.8% | 34.8% |
| 1999 | 17.6% | 22.0% | 37.2% | 23.2% | 17.4% | 34.7% |
| 2000 | 17.6% | 22.5% | 38.3% | 23.8% | 17.8% | 35.3% |
| 2001 | 18.4% | 24.2% | 37.7% | 23.9% | 17.9% | 35.7% |
| 2002 | 18.9% | 25.5% | 38.9% | 23.1% | 19.1% | 36.3% |
| 2003 | 19.1% | 26.0% | 38.8% | 25.3% | 19.9% | 35.3% |
| 2004 | 19.5% | 27.2% | 39.3% | 25.6% | 20.8% | 35.3% |
| 2005 | 20.5% | 28.4% | 39.4% | 25.8% | 21.1% | 35.6% |
| 2006 | 21.1% | 29.1% | 38.7% | 26.2% | 22.2% | 35.6% |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2007 | 21.2% | 29.7% | 38.3% | 26.6% | 23.4% | 35.8% |
| 2008 | 21.7% | 29.9% | 37.5% | 28.0% | 24.2% | 36.2% |
| 2009 | 22.0% | 29.4% | 36.8% | 27.6% | 25.2% | 36.1% |
| 2010 | 22.6% | 29.6% | 36.5% | 28.4% | 26.2% | 36.1% |
| 2011 | 23.2% | 30.3% | 36.5% | 29.2% | 27.2% | 36.2% |
| 2012 | 23.3% | 30.6% | 37.0% | 28.8% | 28.1% | 35.6% |
| 2013 | 23.4% | 30.5% | 36.8% | 29.2% | 28.3% | 35.7% |
| 2014 | 23.0% | 30.2% | 36.6% | 28.8% | 27.4% | 35.8% |
| 2015 | 23.0% | 30.1% | 36.6% | 28.8% | 27.3% | 35.8% |

Table 10.1 Plate Waste, Extrapolations from Raw Data(%)[1]

| | **Workers in AF (Millions)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Year** | **SEA** | **WA** | **AF** | **WE** | **EE** | **NA** | **LA** | **World** |
| 1970 | 486.37 | 24.13 | 69.32 | 18.52 | 48.15 | 4.87 | 27.40 | 678.76 |
| 1971 | 494.03 | 24.52 | 70.38 | 18.22 | 47.67 | 4.85 | 27.80 | 687.48 |
| 1972 | 501.11 | 24.95 | 71.51 | 17.91 | 47.25 | 4.82 | 28.19 | 695.74 |
| 1973 | 507.90 | 25.40 | 72.76 | 17.60 | 46.83 | 4.79 | 28.56 | 703.85 |
| 1974 | 514.97 | 25.86 | 74.07 | 17.28 | 46.35 | 4.76 | 28.91 | 712.22 |
| 1975 | 522.21 | 26.34 | 75.44 | 16.97 | 45.80 | 4.74 | 29.30 | 720.79 |
| 1976 | 529.56 | 26.78 | 76.76 | 16.65 | 45.17 | 4.70 | 29.66 | 729.28 |
| 1977 | 537.61 | 27.23 | 78.25 | 16.34 | 44.48 | 4.67 | 30.03 | 738.60 |
| 1978 | 546.18 | 27.70 | 79.86 | 16.05 | 43.72 | 4.64 | 30.39 | 748.54 |
| 1979 | 555.64 | 28.20 | 81.61 | 15.76 | 42.98 | 4.61 | 30.76 | 759.56 |
| 1980 | 564.66 | 28.73 | 83.43 | 15.49 | 42.27 | 4.59 | 31.10 | 770.26 |
| 1981 | 573.65 | 29.27 | 85.21 | 15.20 | 41.55 | 4.55 | 31.41 | 780.85 |
| 1982 | 580.95 | 29.80 | 87.12 | 14.90 | 40.91 | 4.51 | 31.75 | 789.95 |
| 1983 | 591.22 | 30.33 | 89.23 | 14.59 | 40.32 | 4.46 | 32.07 | 802.22 |
| 1984 | 598.82 | 30.85 | 91.31 | 14.28 | 39.78 | 4.42 | 32.37 | 811.83 |
| 1985 | 605.78 | 31.37 | 93.48 | 13.98 | 39.25 | 4.37 | 32.65 | 820.87 |
| 1986 | 610.65 | 31.80 | 95.49 | 13.67 | 38.80 | 4.32 | 32.93 | 827.65 |
| 1987 | 615.36 | 32.13 | 97.63 | 13.37 | 38.33 | 4.27 | 33.22 | 834.30 |
| 1988 | 619.31 | 32.48 | 99.91 | 13.08 | 37.84 | 4.22 | 33.50 | 840.34 |
| 1989 | 622.43 | 32.88 | 102.35 | 12.81 | 37.34 | 4.18 | 33.76 | 845.75 |
| 1990 | 624.71 | 33.40 | 105.00 | 12.54 | 36.96 | 4.14 | 34.00 | 850.74 |
| 1991 | 623.99 | 33.53 | 107.60 | 12.26 | 36.53 | 4.11 | 34.21 | 852.24 |
| 1992 | 623.43 | 33.96 | 110.12 | 11.68 | 36.30 | 4.04 | 34.56 | 854.08 |
| 1993 | 621.26 | 34.15 | 112.27 | 10.99 | 34.90 | 4.03 | 34.86 | 852.44 |
| 1994 | 618.02 | 34.33 | 115.00 | 10.55 | 33.34 | 4.06 | 34.92 | 850.21 |
| 1995 | 612.81 | 34.56 | 117.61 | 10.26 | 32.15 | 4.06 | 34.61 | 846.06 |
| 1996 | 609.54 | 34.82 | 120.42 | 9.95 | 30.90 | 4.03 | 34.41 | 844.05 |
| 1997 | 604.19 | 35.03 | 123.16 | 9.71 | 29.45 | 4.04 | 34.89 | 840.47 |
| 1998 | 596.53 | 35.14 | 125.97 | 9.56 | 28.25 | 4.05 | 34.89 | 834.39 |
| 1999 | 589.59 | 35.25 | 128.92 | 9.40 | 28.47 | 4.05 | 34.56 | 830.24 |
| 2000 | 584.20 | 35.46 | 131.76 | 9.26 | 28.35 | 4.05 | 34.50 | 827.58 |
| 2001 | 576.02 | 35.49 | 134.46 | 9.03 | 27.79 | 3.96 | 34.68 | 821.42 |
| 2002 | 568.42 | 35.49 | 137.12 | 8.75 | 27.50 | 3.86 | 34.62 | 815.76 |
| 2003 | 561.78 | 35.52 | 140.18 | 8.45 | 26.94 | 3.79 | 34.73 | 811.39 |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| 2004 | 555.59 | 35.71 | 144.07 | 8.16 | 26.80 | 3.78 | 35.22 | 809.33 |
| 2005 | 549.92 | 35.77 | 147.71 | 7.95 | 26.80 | 3.78 | 35.52 | 807.46 |
| 2006 | 540.52 | 35.58 | 151.71 | 7.76 | 26.68 | 3.80 | 35.90 | 801.95 |
| 2007 | 531.84 | 35.49 | 155.63 | 7.59 | 26.98 | 3.76 | 36.02 | 797.31 |
| 2008 | 519.81 | 35.16 | 159.50 | 7.34 | 27.06 | 3.69 | 36.17 | 788.74 |
| 2009 | 507.28 | 34.75 | 161.00 | 6.82 | 26.05 | 3.48 | 35.54 | 774.91 |
| 2010 | 496.17 | 34.97 | 166.41 | 6.59 | 25.26 | 3.40 | 35.31 | 768.11 |
| 2011 | 483.80 | 34.60 | 170.08 | 6.30 | 25.16 | 3.40 | 35.25 | 758.60 |
| 2012 | 470.70 | 34.14 | 173.95 | 6.00 | 24.94 | 3.42 | 35.46 | 748.62 |
| 2013 | 458.78 | 33.77 | 179.00 | 5.74 | 24.76 | 3.43 | 35.22 | 740.70 |
| 2014 | 447.81 | 33.47 | 183.62 | 5.55 | 24.48 | 3.45 | 35.07 | 733.46 |
| 2015 | 436.24 | 33.08 | 188.05 | 5.39 | 24.28 | 3.48 | 34.76 | 725.30 |

Table 10.2 Worker in AF(Milions) [1]

# APPENDIX 2 – PROGRAMMING CODE OF SOLUTION AND DRAWINGS

```
close all
set(0, 'DefaultTextInterpreter', 'latex');
set(0, 'DefaultLegendInterpreter', 'latex');
set(0, 'DefaultAxesTickLabelInterpreter', 'latex');
set(0, 'defaultAxesFontSize');

h=figure('Position',[680 305 850 425]);

Pload=out.Pload;
Ppv=out.Ppv;
PBess=out.PBess;
SoC1=out.SoC1;
tsim=24;
t=0:tsim/(length(Pload)-1):tsim;
figure(1)
axes('Fontsize', 12, 'NextPlot','add','Linewidth',1.5);
,2);
box on
% plot(t,Bess_setpoint/1e6,'k--','Linewidth',2);
% plot(t,SoC1, 'm','Linewidth',2);
% plot(t,SoC2, 'r','Linewidth',2);
%legend('P Order PV','P Order BESS', 'FontSize', 15,'Location','east');
legend('P_load','P_pv','P_BESS', 'FontSize', 12,'Location','northwest');
%legend('P Meas BESS','BESS Setpoint', 'FontSize', 15,'Location','east');
%legend('SoC1','SoC2','SoC3','SoC4','SoC5', 'FontSize',
15,'Location','northeast');
ylim([-18 25]);
xlim([0.2 24]);


%% Hybrid Plots Frequency
Time_dat=200;
Irrad=readtable('GoodIrrad.csv');
Irradiance_arr=Irrad{:,2}/(max(Irrad{:,2}));
Times_arr=Irrad{:,1}+1;
Times_arr=Times_arr(1:288,1);
Irradiance_arr=Irradiance_arr(1:288,1)
% SIMULACIÓ 220 SEGONS


axes('FontSize', 16, 'NextPlot', 'add','LineWidth', 1.5 );
% plot(t, Pref ,'LineWidth', 1.5 ,'color',[196 38 46]/255);%[63 156 53]
% plot(t, Qref ,'LineWidth', 1.5 ,'color',[15 32 75]/255);%[15 32 75]
plot(Times_arr, Irradiance_arr ,'LineWidth', 1.5,'color',[233 131 0]/255);%[233
131 0]
% plot(t, Qreal ,'LineWidth', 1.5,'color',[233 131 0]/255);%[196 38 46]

grid on ;
box on
xlabel( ' Time [s]' , 'FontSize' , 16)
ylabel('Irradiance [p.u.] ' , 'FontSize' , 16) ;
title( 'Base Irradiance profile', 'FontSize' , 16);
% legend('Pref','Pmeas','Location','Northwest','FontSize' , 12)
```

```
% ylim([-0.05 1.05]);
xlim([0 288]);
%
% demanda=[2096.67,
%     1622.66,
%     1573.85,
%     1862.85,
%     2801.91,
%     2877.35,
%     5435.1,
%     4072.5,
%     3090.34,
%     5584.88,
%     7347.87,
%     6789,
%     8543,
%     7655,
%     11688,
%     10234,
%     9584,
%     7857,
%     8654,
%     7955,
%     9165.8,
%     6534,
%     8165,
%     6433];
% %
demanda=[2535.40625,
    1788.465909,
    2116.875,
    2334.925,
    1918.233333,
    2717.55,
    2715,
    2060.226667,
    3723.253333,
    4082.15,
    3771.666667,
    5695.333333,
    5103.333333,
    6875.294118,
    6020,
    6389.333333,
    3928.5,
    4327,
    3977.5,
    4582.9,
    2613.6,
    4082.5,
    2680.416667,
    2108.756788];

% % [0.820704520359286,
% %  0.7739411171320504,
% %  0.7392322859979527,
% %  0.7216872228922587,
% %  0.715085915524548,
% %  0.7241105187441534,
```

```
% %  0.7737804277663003,
% %  0.8460963542247905,
% %  0.8976188095358283,
% %  0.9415210431130586,
% %  0.971732328484587,
% %  0.9842227395688204,
% %  0.9918220864647167,
% %  1.0,
% %  0.9890092246467146,
% %  0.957722841449871,
% %  0.9411237625437483,
% %  0.8705530365484427]*0.5;
z=[0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,24]*12;


Em = sqrt(2)*Vg;    % [V]
xi_pll = 0.707;
wn2=4/(ts*xi_pll);
kp_pll = 2*wn2*xi_pll/Em;
tau_pll = 2*xi_pll/wn2;
ki_pll = kp_pll/tau_pll*1;
```

Figure 10.2 MATLAB’s scripts Part B

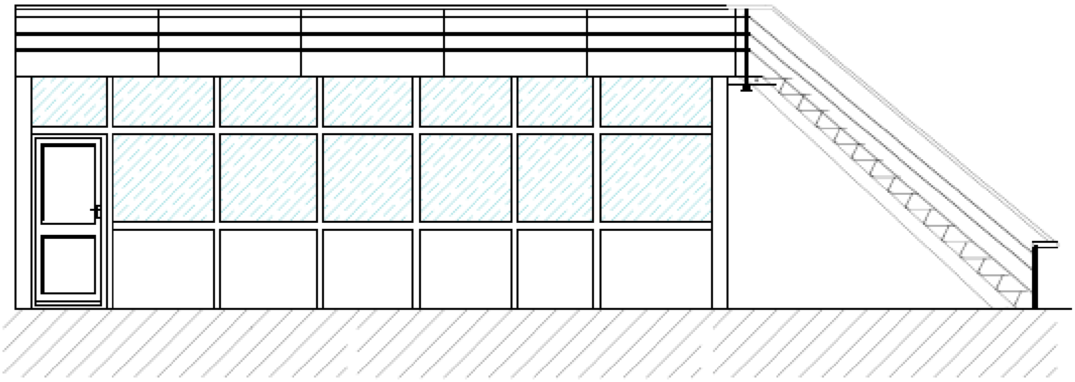

Figure 10.3 Front view of bottling area

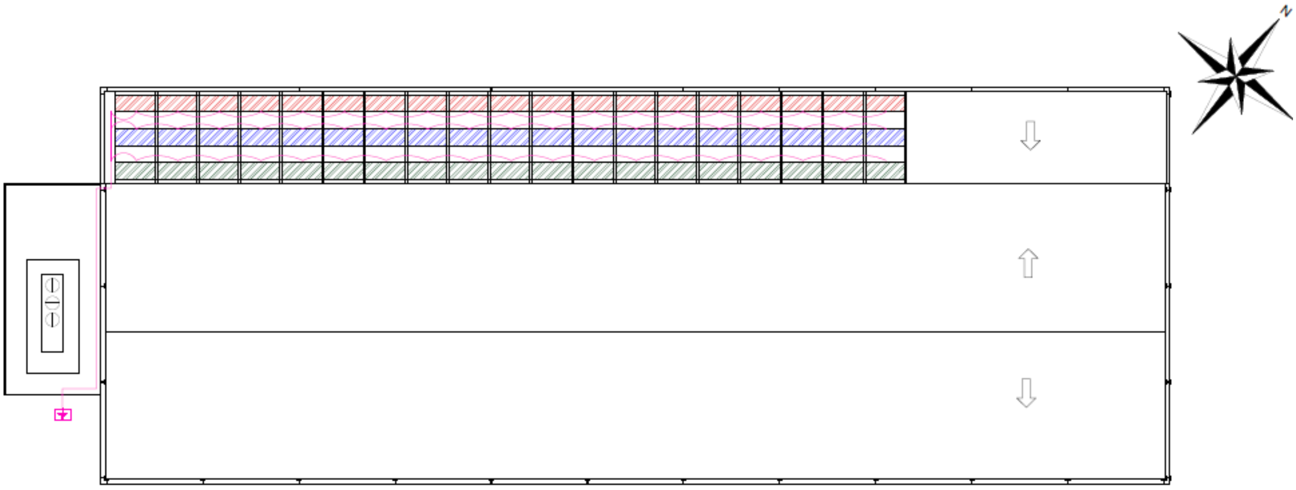

Figure 10.4 Poultry farm