Study and Design of an Agricultural Vehicle Using an alternative Energy Source

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Abstract

Modern agriculture practiced in developed countries is highly dependent of mechanization. Powerful, effective and specialized machines are used to prepare, take care and harvest the crops each time faster. These products are essential to a growing human population and more demanding, not only in terms of quantity but also in terms of quality of what consumes.

Mechanization brings two important questions nowadays: the consumption of fuels with fossil origin and the subsequent effect of greenhouse gases.

Given the urgent need to find solution to both questions that are directly related, a study was performed to find an answer to the main question: is it possible to develop a solution for an agricultural vehicle using an alternative energy source to fuels of fossil origin?

The study is based on an existing vehicle which was developed for a specific application, namely in vineyards of mountains, through rough country. The adaptation should respect and keep the original use conditions and at the same time operate having as energy source a pack of batteries.

The solution of using electric energy was chosen on the basis of the impact concerning energy consumption and CO_2 emissions.

During the study several activities were performed based in the MIT-Portugal curricula, as a survey during the Agriculture National Fair to owners and users of tractors, the collection of user's needs, benchmark with the existing vehicle and the development of a solution to the replacement of a diesel internal combustion engine for a batteries/electric motor solution.

The participation of agriculture associations and a Port wine producer were a positive asset to the study, once allowed to clearly identify user's real needs and critical comments sustained by years of experience on the ground.

Keywords: Agriculture vehicles, alternative energies, batteries, electric motors, energy efficiency, CO_2 emissions

Estudo e Desenvolvimento de um Veículo Agrícola com fonte energética alternativa

Resumo

A agricultura moderna praticada nos países desenvolvidos é altamente dependente da mecanização. Máquinas cada vez mais potentes, eficazes e especializadas são utilizadas para preparar, tratar e colher no mais curto espaço de tempo os produtos cultivados. Esses produtos são essenciais para uma crescente população humana, cada vez mais exigente não só em quantidade mas também na qualidade do que consome.

A mecanização comporta duas questões importantes nos nossos dias: o consumo de combustíveis de origem fóssil e as subsequentes emissões de gases com efeito de estufa.

Dada a necessidade urgente de encontrar soluções para ambas a questões, que estão diretamente ligadas, foi desenvolvido um estudo que pudesse responder a uma questão principal: será possível desenvolver uma solução para um veículo agrícola que use uma fonte energética alternativa ao uso de combustíveis de origem fóssil?

O estudo realizado baseou-se num veículo já existente, que foi desenvolvido para uma utilização específica, nomeadamente em vinhas de montanha. A adaptação deveria respeitar e manter as condições de utilização e ao mesmo tempo funcionar tendo como fonte de energia um conjunto de baterias.

A solução de utilização de energia eléctrica foi escolhida tendo como base o impacto no que respeita ao consumo energético e às emissões de CO_2.

Durante o estudo foram desenvolvidas várias atividades baseadas no curricula do curso MIT-Portugal, tais como a realização de um inquérito durante a Feira Nacional da Agricultura a utilizadores e proprietários de tractores, a determinação das necessidades dos clientes e o desenvolvimento de uma solução para a substituição do motor térmico a diesel por uma solução baterias/motor eléctrico.

A participação de associações agrícolas e de uma empresa produtora de vinhos do Porto foi uma mais-valia para o estudo, uma vez que permitiu identificar com clareza as reais necessidades dos utilizadores e comentários críticos sustentados por anos de experiência no terreno.

Palavras-chave: máquinas agrícolas, energias alternativas, baterias, motor eléctrico, eficiência energética, emissões de CO_2.

Acknowledgments

What started as an idea to take a small step to find alternatives to current agriculture energy source solutions ended to involve a large and interested group of persons and entities along the way.

First I would like to thank to my supervisor, António Araújo, for his support and continuous pushing, always searching for different answers and leading the way when difficulties were ahead.

To António Baptista, my co-supervisor, also a special thank for the opening-up of new opportunities, such as the one who led to this study, for the contacts and visits that helped to clear and define the path to be taken.

I would like to thank Professor Jean Pol Piquard for the constant challenges in each step that he placed, not to make the work harder but to ensure that those steps were safe, and pursuing a strategy.

To Professor Bessa Pacheco, who dedicated several days to this study, I would like to express my gratitude for his willingness, his advices and the share of his large experience with machines in the industrial world.

To the ADVID, to the responsible for the management and the technicians of Quinta das Carvalhas and Quinta do Noval, which allowed me visiting the two farms to a much better understanding not only of the technical aspects of the vineyards in Douro region but also the impact that the wine, the final product has on their lives and on the region economy.

A special note for José Eduardo Costa from Quinta do Noval by sharing of his experience, the interest showed along the study and the clear needs that a machine must comply to work on Douro region.

António Silva and Rui Ferreira from Maria Alice gave an excellent contribution by opening greenhouse doors to visits and testing that helped to widen the scope of the work.

Suppliers contributed to the success of the conversion made. All were very patient with questions and requests and without their expertise it would be much more difficult to carry out.

To all Engenhotec employees that shared their comments to help to achieve the final goal. Vitor Canedo deserves a special word for his patience, dedication, care and hours spent to find, design and build solutions for the machine.

I am grateful to all my colleagues and teachers of MIT-Portugal program. Without this program, the knowledge acquired during this 4 years and the help and fellowship of whom I had the chance to contact along this period, it would be impossible to go through.

My parents gave me the chance to start this path a long time ago and without their commitment it was not possible to reach so far. For all the opportunities, I am in debt to them.

And at last but for sure not least, to Marta and Maria Eduarda my last words. Countless hours and days out of home and working late will never be compensated. I hope all their effort pay off some day. Without their love, care, understanding, all of this have been in vain.

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List of abbreviations

2WD – Two wheel drive

4WD – Four wheel drive

AC – Alternating Current

ADVID - Associação para o Desenvolvimento da Viticultura Duriense

AFOLU - Agriculture, Forestry and Other Land Use

BEV - Battery-Electric Vehicle

b – Billion (10^9)

BRIC – Brazil, Russia, India, China

BtL - Biomass-to-Liquid

CEVD - Centro de Estudos Vitivinícolas do Douro

CFFP - Cold Filter Plugging Point

CoG - Center of Gravity

DC - Direct Current

DICI – Direct Injection Compression Ignited engine

DISI –Direct Injection Spark Ignited engine

DSM - Design Structure Matrix

EIA - Energy International Agency

EDAM - Engineering Design and Advanced Manufacturing

EU – European Union

FAME - Fatty Acid Methyl Ester

FAO – Food and Alimentation Organization of the United Nations

FAOSTAT – FAO Statistics Division

FCEV – Fuel Cell Electric Vehicle

FEUP – Faculdade de Engenharia da Universidade do Porto

G7 – Group of the 7 most industrialized countries

GDP - Gross domestic product

GHG - Greenhouse Gases

hp – horse power

Hybrid DICI - Hybrid Direct Injection Compression Ignited engine

Hybrid DISI – Hybrid Port Injection Spark Ignited engine

HVO - Hydrotreated Vegetable Oil

ICE - Internal Combustion Engine

INEGI - Instituto de Engenharia e Gestão industrial

IPCC - Intergovernmental Panel on Climate Change

IST – Instituto Superior Técnico

kW – kiloWatt

LPG - Liquefied Petroleum Gas

M – Million (10^6)

MIT - Massachusetts Institute of Technology

NAFTA - North American Free Trade Agreement

OEM - Original Equipment Manufacturer

PHEV20 DICI - Plug-In Hybrid Vehicle with Direct Compression Spark Ignited engine with an electric driving range of 20 km (NEDC)

PHEV20 DISI – Plug-In Hybrid Vehicle with Direct Injection Spark Ignited engine with an electric driving range of 20 km (NEDC)

PISI – Port Injection Spark Ignited engine

PTO – Power Take-Off

REEV80 SI – Range-Extender Electric Vehicles with an electric driving range of 80 km (NEDC) and a Spark Ignited engine as Extender.

TTW - Tank to Wheel

UAS - Used Agricultural Surface

UN – United Nations

US – United States

US$ - United States Dollars

UTAD - Universidade de Trás-os-Montes e Alto Douro

VDMA - Vertritt den Maschinenbau und den Anlagenbau

WTT - Well to Tank

WTW - Well to Wheel

1 Introduction

Human civilization faces today several challenges, in terms of sustainability. There are two main issues that even looking separate, are close connected: population growth and global warming. The expected increase of population for the next 15-20 years and the threat that global warming places to arable lands, due to climate changes, that may reduce or even impede crops to be cultivated are directly related.

1.1 Scope

This thesis focus on the goal to demonstrate that there is an alternative for the use of fossil fuel on agriculture vehicles, towards environmental sustainability and to help reducing the problem of global warming.

To validate the use of an alternative energy source, a prototype must be designed and built to allow testing and comparison with the existing vehicles.

To perform the design of the prototype, a development process was followed as guideline and the methodology of the design also followed the chosen reference; and widely supported by experimental testing in near to, or in real use, conditions.

Having a previous experience and knowledge with Ulrich and Eppinger [1] product design and development process, it was selected to adapt this method, once it proved to be successful in one lecture of the course. It was also an opportunity to further training and implementation of it, which can be useful for future developments.

Some other approaches were considered, like the Design Structure Matrix (DSM) from Eppinger and Browing [2], Product Development Flow from Reinersten [3] and a Smith and Reinersten proposal for a faster Development Process [4]. All these approaches could be considered and used as the reference for supporting the development process. They were not used when the design of the prototype started because Ulrich and Eppinger [1] method was considered the most adequate.

Being a thesis of the deep study and design of an alternative energy source for agricultural vehicles, it is interesting to contextualize agriculture. In relation to crop farming and livestock farming, the term “agriculture” may be defined as: the art and science of growing plants and other crops and the raising of animals for food, other human needs, or economic gain [5] or the science, art, or practice of cultivating the soil, producing crops, and raising livestock and in varying degrees the preparation and marketing of the resulting products [6].

Since our ancestors started to realize around 10 000 years ago that by sowing some seeds, taking care of the growing plants and harvest the crops, agriculture became one of the touchstones of our civilization.

It is due to the development of agriculture and related through centuries that human race was able to have the conditions to self-development, once it allowed to populations to settle around plantations, leading to the start of small settlements, that later evolved to small villages, small cities and so on. On the 5 century BC there were already large cities as Babylon, with around 150 000 -200 000 inhabitants [7].

It was possible to have such population back then because there were already fields being cultivated around Babylon that supported that number of persons living there.

It was largely due to agriculture that human race evolved to the level we are today. Currently, less than 1/3 of World's population is working on agriculture, releasing the remaining population for other activities.

Agriculture, combined with medicine, evolution of household conditions, and others, are the reason to sustain the number of actual habitants on Earth. Nowadays, human population is more than 7 billion persons. It is expected to ramp up to 9 billionby 2030, figure 1.01. [8]

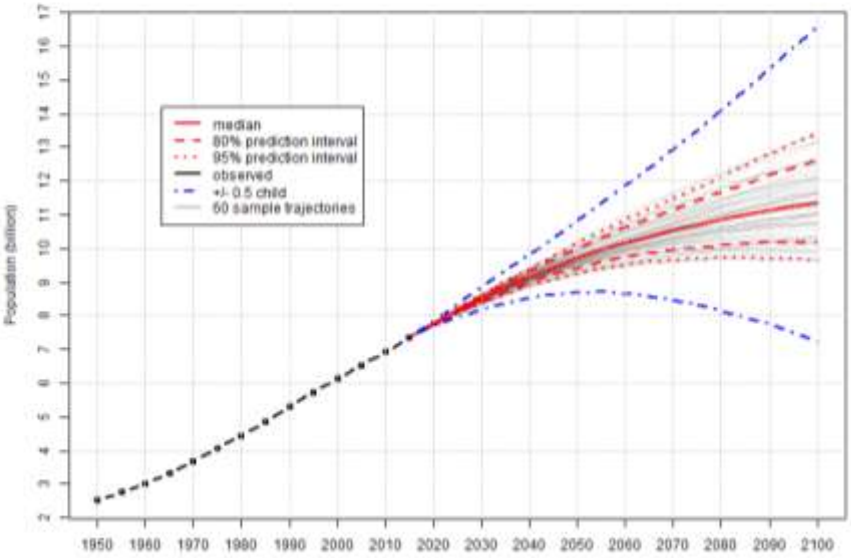


Figure 1.01 – World population evolution forecasts [8]

It is a challenge of our civilization to ensure that there will be food for everyone. Agriculture will be one of the domains that will be more pressured to output enough food and related products to feed humans and provide raw materials for textiles, medicines, etc.

Modern agriculture demands a huge amount of energy. Not only for the machines but also for fertilizers, food conservation, transport, livestock.

Diesel for agricultural machines and for road transportation, marine fuel for the overseas transport, electricity, natural gas for conservation and fertilizers production, just to mention the main energy use, are the energy sources for the main applications. Most of them rely on fossil fuels, which load our planet with more CO_2 in the atmosphere and other pollutants like CO, NO_x, SO_x, particles that poison the very air we breathe, contaminate soil and water. Fossil fuel extraction has plenty of hazards, from destroying natural habitats on ground and water, its transport by pipelines may spill to the ground, sea transportation by large super oil carriers may result in disaster. Refining oil also requires large amounts of energy, pollutes the air in the surroundings, risk of explosion of big barrels is also there.

Also the oil producing countries dependency gives no warranties about regular production, once most of them have no political stability like Iraq, Iran, Venezuela and Nigeria.

Even with new techniques to extract oil from huge ocean depths, horizontal drilling, fractal extraction or new raw sources like shale oil or gas, which keeps current production, around 90 million barrels per day, there are two main questions:

- Fossil fuels don't last forever, even considering peek oil is constantly moving forward, new reserves are found, new extracting techniques and efficiency allows to extract more from each well, the truth is that its quantity is finite and what took millions of years to be produced by Nature, squeezing and processing death plants and animals, resulting in different type of coals and hydrocarbons, in some decades will be draught;
- The amount of CO_2 in the atmosphere keeps rising even in recent years where some anti-CO_2 measures are already implemented but with the economic growth in China, India, Vietnam, Philippines, Russia, just to mention the most populated ones, have led to bigger energy consumption, once people have more cars, household appliances and also other food habits.

There is another variable with a large impact in our lives: oil price. In the last ten years, we have experience a large variation on oil price: from a stable price varying from 20 to 40 US$/barrel on the decade of 1995-2005, to a steady grow from 2005 until the peak in the middle of 2008, where it reached 147 US$/barrel, a massive plunge in the following months, going down to 38 US$/barrel, followed by an slow increase from 2009 until 2011, where it ranged between 80 and 110 US$/barrel [9]. In 2015, price has plummeted to around 40 US$. These variations are shown in figure 1.02. These huge variations normally implies raising refined fuels retail prices when oil price goes up but small decreases when oil price goes down.

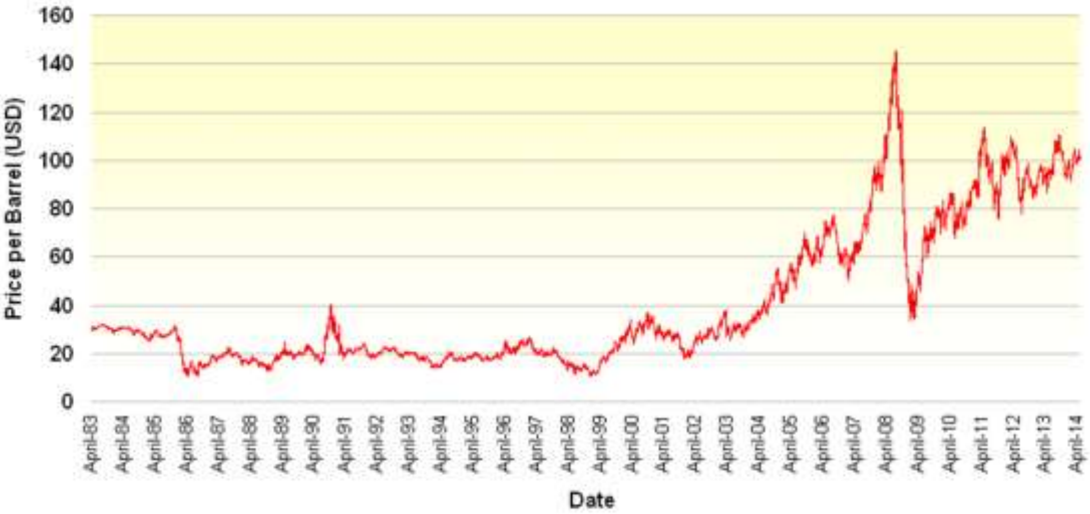


Figure 1.02 – Crude oil price variation 1993-2014 [9]

For agriculture, high fuel price means higher production costs and this means higher cost for the product. In 2008, when oil price reached its peak, some very important products to human feed hit a price peak two.

The influence of fuel oil price reflects on the evolution of food commodities and Food Price Index released by Food and Alimentation Organization (FAO) [10]. It is possible to see that food commodities have followed the plummeting of oil price during 2015, figures 1.03 and 1.04.

Figure 1.03 – FAO Food price index 2011-2015 [10]

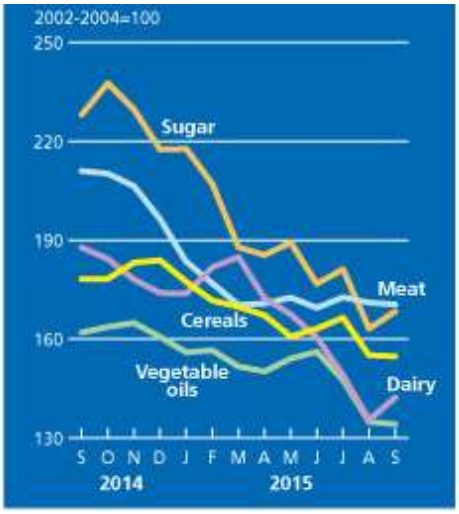


Figure 1.04 – FAO Food commodity price indices 2011-2015 [10]

This means that on the next oil price increase, food prices will also raise, which is affordable for rich and developed countries but a huge problem for poor and under developed countries. Nowadays, United Nations (UN) estimates around 1 billion persons living with hunger, if food price increase, these people will have no resources and other will join to increase the group.

The combination of need of fuel/fuel price/food price rebounds in three major issues: availability of fuel; prices; environment.

Some considerations were already made about these issues. Regarding environment, some others may be done:

- Currently 38.4% of Earth surface is used for agriculture or related activities;
- A constant transition from rural areas to cities is under way. More than 50% of humans are living now in cities;
- Wrong techniques, over exploration of soils may destroys its capacity to produce food;
- Climate changes are transforming arable areas on deserts or semi-deserts areas, changing original conditions for some crops to grow.

If arable conditions are not preserved, the existing capacity will no longer be able to satisfy current demand and for sure it will be below the needed capacity for the next decades.

The need to preserve ecosystems or agro-systems depends on the change from massive use and dependence of fossil fuels to the use of renewable energy sources. Using renewable/alternative energy sources will reduce the amount of oil extracted, releasing fewer quantities of CO_2 and other pollutants, which will slow down the effects of climate changes.

1.2 Motivation and background

My personal background on agriculture is reduced, limited to some weekend experiences, sowing peas, beans and broad beans. To farm a small 500 m^2 field, I have bought a small tractor, once time limitations did not allowed me to manual work. Having had some years before some contact with electric motorcycles, even co-worked to make an adaptation from an Internal Combustion Engine (ICE) into a battery – electric motor powertrain, an idea came up which was converting my small tractor from a Diesel powertrain to a battery – electric motor one.

This idea hardly had the chance to go forward but a contact in 2010 with the MIT (Massachusetts Institute of Technology) Portugal Program, where I was asked to present a thesis proposal for the doctorate students, brought in to my mind that there was an opportunity to put this idea onto a real project, if I had an obligation to make a thesis.

My background is a degree and a Master degree in Mechanical Engineering and since I graduated I started to work on the industry. Professional experience started as a trainee in an aluminum casting company, then as tool designer in the workshop of a metal mechanic company. Two years after graduation I started a Product Development company and some years later, in 2004, I started another company in the same area, adding prototypes and tools - Engenhotec.

It is under Engenhotec purpose to diversify business that this theme was presented. The challenge to enter in a different business area could not be made in an amateur way. That is why Engenhotec supported financially and make available its facilities, machines and personal to reach the final goal of having a prototype ready for testing in the field.

It was also clear that it was not possible to perform such task without external collaboration and the MIT Program offered the chance to conciliate an academic background with the industrial experience. It also provided theoretical and practical knowledge that would be helpful not only during this thesis but also to project a product development in the future.

Being a doctorate course directed to industry leaders it also provided training and insights to managing development, production and engineering systems projects, which were also helpful across the study.

1.3 Objective of the thesis

The main objective of this thesis is to validate the use of an alternative energy source to fossil fuels for agricultural vehicles. In order to achieve that, some alternatives were considered:

- Develop from scratch an agriculture vehicle, making use of an alternative power train;
- Adapt an existing vehicle, replacing its diesel powertrain by an alternative one;
- Use of an existing vehicle, using alternative fuels with non-fossil origin.

The initial idea was to choose the second alternative: taking a conventional tractor and replace its diesel powertrain by a battery – electric one. On early 2010 decade, some electric car started to have some commercial success or at least more acquaintance by general public and minds started to open to a new era of electric mobility, to what car’s concern. Models like Nissan Leaf, Chevrolet Volt and more recently Tesla Model S were seen on public roads, showing that car drivers were accepting them not only for the technology breakthrough but also they realize their advantage in having to tail pipe emissions and low cost for km, when compared to diesel/gasoline cars.

These models have helped the decision not only to propose such theme for the thesis but also served as examples that solutions could be implemented and tested to validate the idea.

In order to do so, some steps needed to be taken and they are described along this thesis. Also there was a shift on the type of vehicle used for the adaptation, from a conventional tractor to a specific vehicle designed for narrow and sloped vineyards in the mountains.

1.4 Research questions

Main research question is:

- MRQ - "Is it possible to use an alternative energy source for agricultural machines?" This question has a major technological aspect but also deals with the mind opening of users, if they are prepared for different challenges.

From the main research question, there are three sub research questions that can be addressed:

- SRQ1 – "With the present technology, is it possible to adapt or design agricultural machines with alternative energy sources?"
- SRQ2 – "Can an agricultural or farm machine equipped with an alternative energy source perform the same operations as one running on fossil fuels?"
- SRQ3 – "What are the economic and environmental impact of the conversion from fossil fuels to alternative energies?"

1.5 Organization of the thesis

The work presented in this thesis was organized in 8 chapters. Detailed description follows.

Chapter 1 makes the introduction to this work, scope, motivation, reasons, objectives and organization.

Chapter 2 makes a description of the current status of agriculture. Relevant data about agriculture's economy, agriculture's employment, agriculture Greenhouse Gases – GHG. Being one of the most important activities for the human kind, it is important to have a good overview about the main aspects connected to agriculture, namely the vehicles used for agriculture activities and also the energy sources that they use.

Chapter 3 is dedicated to the status of agriculture in Portugal. A quick overview of the evolution of most relevant data on the latest years is shown. In this chapter a characterization of the agricultural vehicles machinery is made and their distribution over the territory.

Chapter 4 documents the approach that was performed to make the decision about the agricultural vehicle in which this work would focus. It describes some initial considerations, visits to farms, the contact with the Douro valley vineyards and the knowledge about their needs and the reasons under the final decision about the vehicle.

Chapter 5 describes the steps taken to adapt the existing machine, powered by a conventional Diesel engine, to a battery – electric motor solution. The description of the original machine, the major constraints it shows, and the tasks it was designed to perform.

The description and explanation of each of the changes made in the vehicle is one of the most important parts of the thesis and is a relevant part of this chapter.

Chapter 6 reports the tests and data collected both on hard ground and on Douro vineyards. There are relevant results on the use of the adapted vehicle on both situations that gave not only a good figure of the vehicle but also some hints for further developments. A comparison with an original vehicle was made to have a better understanding about the pros and cons of the electric solution and to validate the initial hypothesis.

Chapter 7 presents a new concept of what can be the next step of the use of a battery – electric motor vehicle.

Chapter 8 finalizes the thesis manuscript with the conclusions extracted from this work and hints for future developments on this theme.

1.6 Entities involved

During this study some entities were involved, some from the beginning, others joined during the course.

- Engenhotec – Promoter of the study, it is a product development services provider, prototypes maker and tool builder. Located in Gondomar, Portugal, is a SME with 15 workers, with customers from automotive, energy components suppliers, water heaters, aeronautics. This project was the first approach to a new business.
- MIT-Portugal Program – A doctorate program designed by the Massachusetts Institute of Technology (MIT) that counts with three Engineering schools in Portugal: Faculdade de Engenharia da Universidade do Porto (FEUP), Instituto Superior Técnico (IST) and Minho Engineering School. One focal area of application is the Engineering Design and Advanced Manufacturing (EDAM), where this thesis fits.
- FEUP – Engineering Faculty of Porto, Portugal, one of the most important engineering schools in Portugal with 176 years of history.
- INEGI (Instituto de Engenharia e Gestão industrial) – An R&D Interface Institute between University and Industry-Economy, located in Porto, Portugal. Related to FEUP, is an important entity that performs applied research, product and technology development and technology transfer to industry.
- Quinta das Carvalhas - A Douro wine producer, located in Pinhão. Belongs to Real Companhia Velha, the oldest Port wine company.
- Quinta do Noval – A Douro wine producer, located in Alijó. One of the most recognized Port wine brands.
- Maria Alice Company – A dairy vegetables producer, located in Póvoa do Varzim.

2 World of Agriculture

This chapter shows data related to what is contemporary agriculture. World data is used to compare most wealth countries to emerging countries and world's average, to identify main differences.

A brief description of evolution of agriculture machines, dependence of modern agriculture on mechanization and a collection of data of agriculture machinery production, its distribution by main areas, main markets are addressed in this chapter.

The impact of agriculture emissions is analyzed and the identification of emissions due to agriculture machinery in the United States (US) ends this chapter.

Humans need energy to live, as any living being. From FAO "The human body requires energy for all bodily functions, including work and other activities, the maintenance of body temperature and the continuous action of the heart and lungs. In children, energy is essential for growth. Energy is needed for the breakdown, repair and building of tissues" [12].

The source of human's energy is food. Humans eat a large variety of food, depending on the place they live, season of the year, availability of food and wealth. Despite the variety, food is distributed in 7 groups in the food wheel, figure 2.01 [13].

Figure 2.01 – Food wheel [13]

From the picture is easy to conclude that the majority of food humans need is obtained directly or indirectly from agriculture:

- fruits and vegetables, tubers, rice, beans, peas are all products that are croped in the fields;
- bread, pasta, are produced from a wide range of cereals, being wheat the most important one ;
- oils, butter, are produced from vegetable or animal fat;
- milk, cheese, yogurts are produced from livestock, fed by cereals and vegetables rations
- meat and fish. Once meat comes from earth mammals, a large quantity of livestock is nurtured with rations produced in dedicated crops.

It is easily understood that for the range of food described, agriculture is the main source. Because of that, agriculture is one of the most important economic and business sectors in the World today. Not only because of our dependence on food, but also due to globalization. As an example, food available in New York has its origin from many foreign countries like Vietnam, New Zealand, South Korea and other parts of the world, traveling in some cases more than 14 000 Km by plane, just to satisfy luxury restaurants [14].So we can realize that food is not only used for our survival but also for human pleasure and delight, the only reason that explains why kiwis and apricot will travel thousands of km by air plane just to be available on the table of refined restaurants.

Next chart, figure 2.02, shows 2007 production of all commodity groups in their primary form, including animal feed products [15].

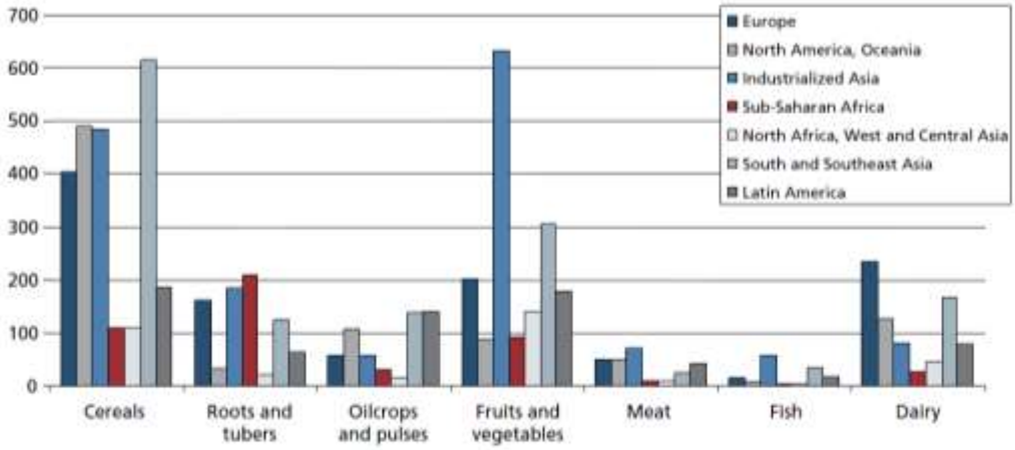


Figure 2.02 – Production of food commodity groups [15]

2010 data for total agriculture production was 4 billion ton. Cereals account for around 2/3 of production, reaching 2.47 billion ton. Rice is the main cereal produced, with a production of 701 128 ton followed by wheat with 653 355 ton [16].

2.1 What is agriculture today

Despite employing almost one third of human's population, agriculture only contributes to World's Gross Domestic Product (GDP) with 2.9% of its total. World's GDP in 2011 was 68 474 billion US$, agriculture's contribute was 1 985 billion US$, which is a very low value when compared with industry and services output, figure 2.03 [16].

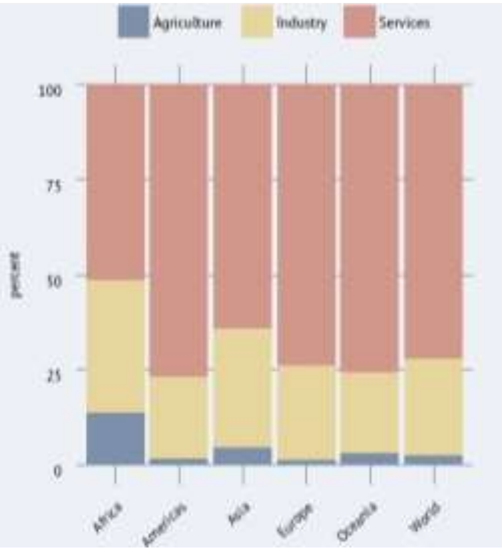
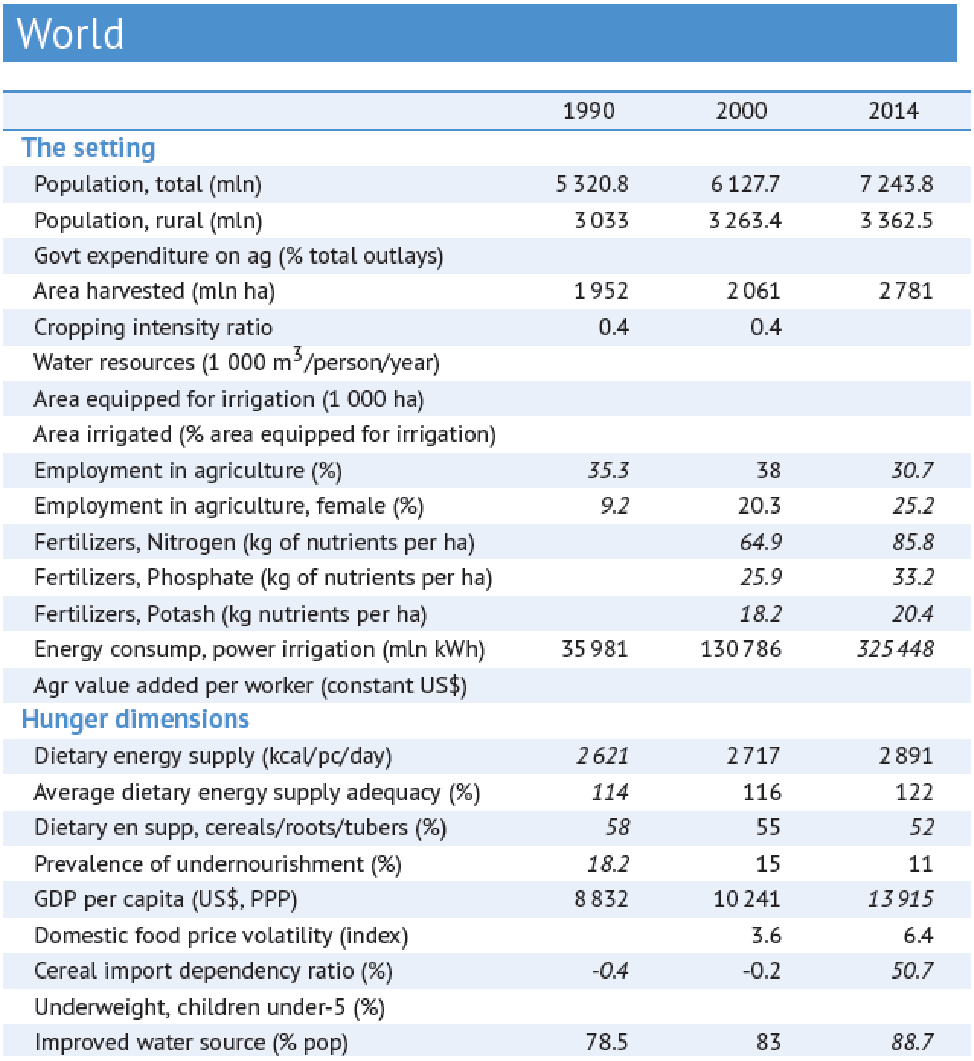


Figure 2.03 – Value added in agriculture, industry and services as shares of GDP (2009) [16]

To have a better outlook of what is related to agriculture, tables 2.01 and 2.02 from the last FAO Statistical Pocketbook World Food and Agriculture 2015, compares agricultural data between 1990, 2000 and 2014 [17].

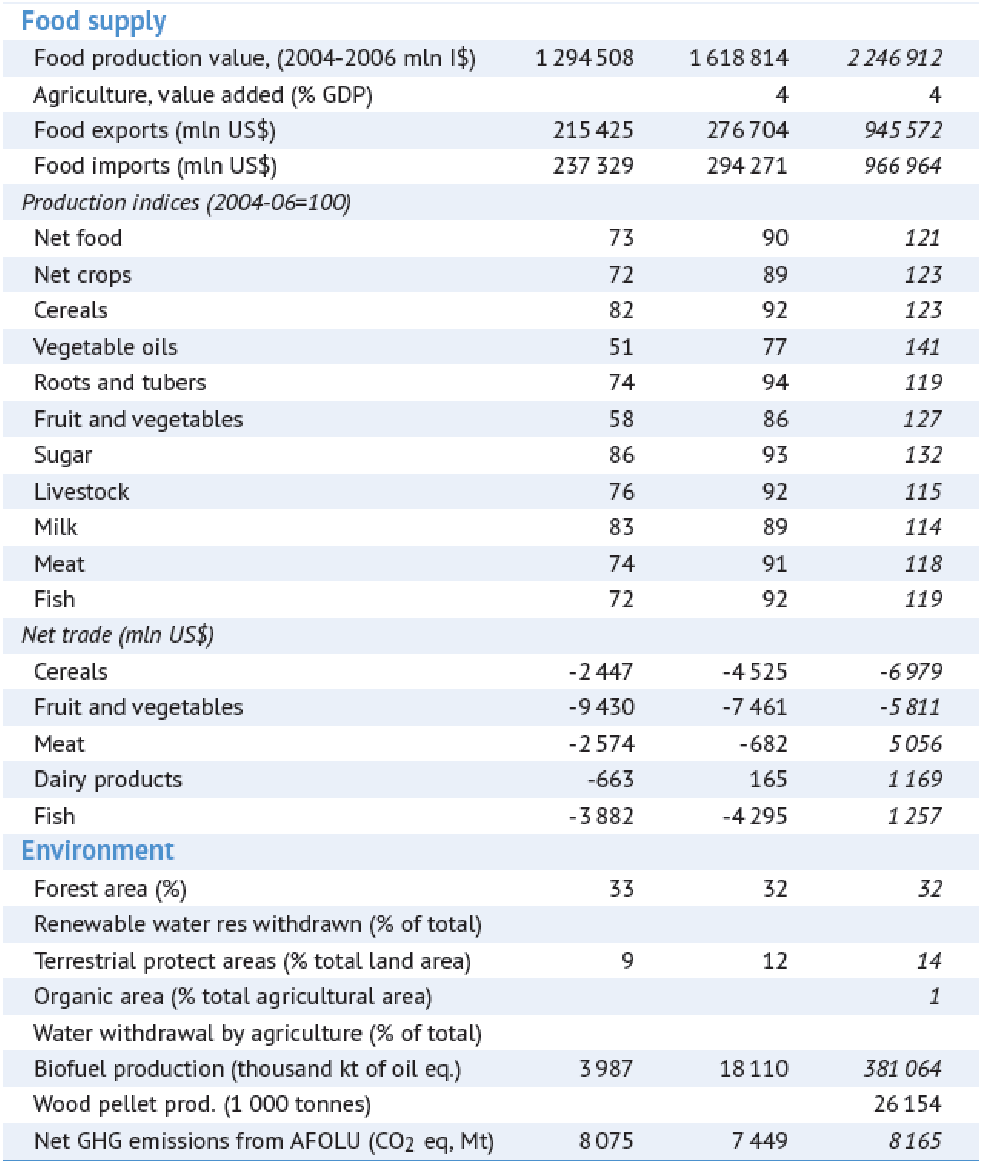
Table 2.01 – World’s agricultural data between 1990, 2000 and 2014, part 1 [17]



World

	1990	2000	2014
The setting			
Population, total (mln)	5 320.8	6 127.7	7 243.8
Population, rural (mln)	3 033	3 263.4	3 362.5
Govt expenditure on ag (% total outlays)			
Area harvested (mln ha)	1 952	2 061	2 781
Cropping intensity ratio	0.4	0.4	
Water resources (1 000 m^3/person/year)			
Area equipped for irrigation (1 000 ha)			
Area irrigated (% area equipped for irrigation)			
Employment in agriculture (%)	*35.3*	38	*30.7*
Employment in agriculture, female (%)	*9.2*	20.3	*25.2*
Fertilizers, Nitrogen (kg of nutrients per ha)		*64.9*	*85.8*
Fertilizers, Phosphate (kg of nutrients per ha)		*25.9*	*33.2*
Fertilizers, Potash (kg nutrients per ha)		*18.2*	*20.4*
Energy consump, power irrigation (mln kWh)	35 981	130 786	*325 448*
Agr value added per worker (constant US$)			
Hunger dimensions			
Dietary energy supply (kcal/pc/day)	*2 621*	2 717	2 891
Average dietary energy supply adequacy (%)	*114*	116	122
Dietary en supp, cereals/roots/tubers (%)	*58*	55	*52*
Prevalence of undernourishment (%)	*18.2*	15	11
GDP per capita (US$, PPP)	8 832	10 241	*13 915*
Domestic food price volatility (index)		3.6	6.4
Cereal import dependency ratio (%)	*-0.4*	-0.2	*50.7*
Underweight, children under-5 (%)			
Improved water source (% pop)	78.5	83	*88.7*

Table 2.02 – World’s agricultural data between 1990, 2000 and 2014, part 2 [17]



Food supply			
Food production value, (2004-2006 mln I$)	1 294 508	1 618 814	*2 246 912*
Agriculture, value added (% GDP)		4	4
Food exports (mln US$)	215 425	276 704	*945 572*
Food imports (mln US$)	237 329	294 271	*966 964*
Production indices (2004-06=100)			
Net food	73	90	*121*
Net crops	72	89	*123*
Cereals	82	92	*123*
Vegetable oils	51	77	*141*
Roots and tubers	74	94	*119*
Fruit and vegetables	58	86	*127*
Sugar	86	93	*132*
Livestock	76	92	*115*
Milk	83	89	*114*
Meat	74	91	*118*
Fish	72	92	*119*
Net trade (mln US$)			
Cereals	-2 447	-4 525	*-6 979*
Fruit and vegetables	-9 430	-7 461	*-5 811*
Meat	-2 574	-682	*5 056*
Dairy products	-663	165	*1 169*
Fish	-3 882	-4 295	*1 257*
Environment			
Forest area (%)	33	32	*32*
Renewable water res withdrawn (% of total)			
Terrestrial protect areas (% total land area)	9	12	*14*
Organic area (% total agricultural area)			*1*
Water withdrawal by agriculture (% of total)			
Biofuel production (thousand kt of oil eq.)	3 987	18 110	*381 064*
Wood pellet prod. (1 000 tonnes)			26 154
Net GHG emissions from AFOLU (CO_2 eq, Mt)	8 075	7 449	*8 165*

There are a few interesting results from the report:

- Food production value is around 2 250 billion US$, for a total population of 7 243.8 million of habitants. This give a value of 310 US$ per capita a year, a relative low value. As a comparison, in the US the same ratio gives 669 US$, more than double of World’s average;
- Rural population is stabilizing around 3 300 million from 2000 to 2014, while total population has climbed from 6 127 to 7 243 millions, a rise of 18%, while the ratio of rural population over the total declined from 53.2% to 46.5%. 2008 was the shifting year, when urban population passed the rural population, figure 2.04;

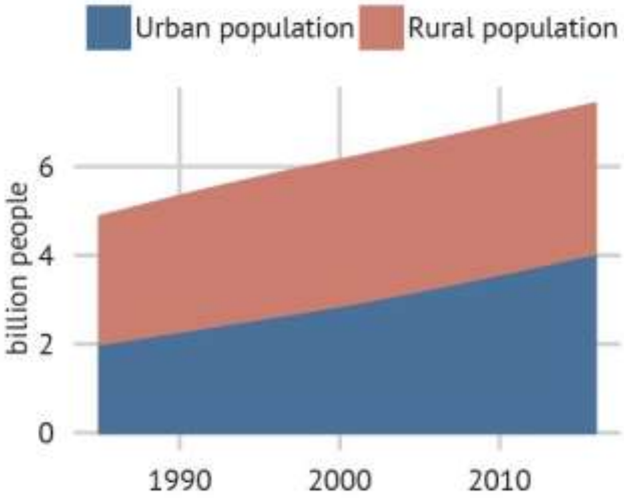


Figure 2.04 - World rural and urban population (1985 to 2016) [17]

- Agriculture employment reaches 30.7% in 2014 in the active population of the labour force or working population, in front of industry – 23.2% but far from services – 45.5 % [18];
- Food production value increased 25.0% from 1990 to 2000 and 38.8% from 2000 to 2014 compared with GDP per capita of 15.9% and 35% on the same periods. This means food production had a higher growth when compared to GDP resulting in a larger contribute of agriculture for the world wealth;
- Net Green House Gas (GHG) emissions from Agriculture, Forestry and Other Land Use (AFOLU), have reached a total of 8 165 M t CO_2 eq in 2014, 9.2% above 2000 level but only 1.1% higher when compared to 1990. This means that in 2000 emissions registered a down peak;
- Domestic food price volatility index has risen from 3.6 in 2000 to 6.4 in 2014. This means food prices variation is higher, stressing people with fewer resources.

From tables 2.01 and 2.02, it was observed that agriculture weight has grown in the World's Economy in the past 25 years. Nevertheless the observed growth, agriculture is under pressure to ensure that will be possible to feed a World's population estimated to reach 9 000 million humans by 2030, 24.5% more habitants when compared to 2014 level, a higher rate of growth when compared with 2000-2014, where the growth was of 18%.

2.2 G7 and BRIC countries agriculture

The developed country status in this work will be assigned to the countries that belong to G7 group: Canada, France, Germany, Italy, Japan, United Kingdom and US [19].

Tables 2.03 and 2.04 below presents the 2014 data for the parameters commented in the previous point for each G7 country and the World's average.

Table 2.03 – G7 countries agriculture data [17]

2014 data	Canada	France	Germany	Italy	Japan	UK	US
Total population (M)	26	65	83	61	127	64	323
Rural population (M)	7	8	21	19	9	13	54
Rural / total population (%)	26.7	12.7	25.6	31.1	6.9	20.1	16.9
Food production value (2004-2006 M US$)	27 181	37 188	32 193	29 303	17 730	15 878	215 750
Food production value per capita (2004-2006 US$)	1 066	576	389	480	140	249	669
Agriculture employment (%)	2.4	2.9	1.5	3.7	3.7	1.2	1.6
GDP per capita (US$ PPP)	41 899	37 217	42 884	33 924	35 614	36 932	51 340
Agr value added per worker (constant US$)	-	84 574	39 490	52 411	50 720	29 212	69 457
Domestic food volatility (index)	7.1	4.8	5.6	5.0	5.6	5.0	0.0
Net GHG emissions from AFOLU (Mt CO_2eq)	200	44	-19	-1	-113	41	-58

Table 2.04 – G7 and World’s comparative agriculture data [17]

2014 data	Average G7	Total G7	World	% of World
Total population (M)		747	7 424	10.0
Rural population (M)		131	3 363	3.9
Rural / total population (%)		17.6	45.3	
Food production value (2004-2006 M US$)		375 223	2 246 912	16.7
Food production value per capita (2004-2006 US$)	510	-	303	168
Agriculture employment (%)	2.4	-	30.7	7.9
GDP per capita (US$, PPP)	39 973	-	13 915	287.3
Agr value added per worker (constant US$)	54.311	-	-	-
Domestic food volatility (index)	4.7	-	6.4	73.4
Net GHG emissions from AFOLU (Mt CO_2 eq)	-	94	8 165	1.1

Some comments to tables 2.03 and 2.04:

- Although accounting with 10.0% of total population, food production value of G7 is 16.7% of world’s total, meaning better productivity;

- G7 agriculture's employment is 2.4% of population, comparing world's average of 30.7%. With a workforce 10 times below world's average G7 countries produces 1.7 times world's average;
- Net GHG emissions from G7 AFOLU represent 1% of world's emissions. This is quite impressive once it was expected that for the production levels, emissions resulting from those countries followed production level.

To compare performance between developed countries and emergent economies, the same data was collect for the BRIC [20] countries, tables 2.05 and 2.06 [17].

Table 2.05 – BRIC countries agriculture data [17]

2014 data	China	Brazil	India	Russia
Total population (M)	1 425.0	202.0	1 267.4	142.5
Rural population (M)	641.6	29.4	857.1	36.6
Rural / total population (%)	45.0	14.6	67.6	25.7
Food production value (2004-2006 M US$)	518 851.0	140 046.0	236 540.0	46 439.0
Food production value per capita (2004-2006 US$)	364.1	693.3	186.6	325.9
Agriculture employment (%)	49.8	15.3	47.2	9.7
GDP per capita (US$, PPP)	3 780.0	14 555.0	5 244.0	23 564.0
Agr value added per worker (constant US$)	-	5 470.0	689.0	5 973.0
Domestic food volatility (index)	10.8	4.4	8.4	5.2
Net GHG emissions from AFOLU (Mt CO_2 eq)	544.0	1.255.0	532.0	25.0

Table 2.06 – BRIC countries, G7 and World's comparative agriculture data [17]

2014 data	Average BRIC	Total BRIC	Average G7	Total G7	Ratio BRIC/G7	World	% BRIC/ WORLD
Total population (M)	-	3 037	-	747	4.1	7 424	40.9
Rural population (M)	-	1 565	-	131	11.9	3 362.5	46.5
Rural / total population (%)	-	51.5	-	17.6	2.9	45.3	113.8
Food production value (2004-2006 M US$)	-	941 876	-	375 223	2.5	2 246 912.0	41.9
Food production value per capita (2004-2006 US$)	392	-	510	-	0.8	302.7	129.7
Agriculture employment (%)	30.5	-	2.4	-	12.6	30.7	99.3
GDP per capita (US$, PPP)	11 786	-	39 973	-	0.3	13 915	84.7
Agr value added per worker (constant US$)	-	-	54 311	-	-	-	-
Domestic food volatility (index)	7.2	--	4.7	-	1.5	6.4	112.5
Net GHG emissions from AFOLU (Mt CO_2 eq)	-	2 356	-	94	25.1	8 165.0	28.9

Some comments to tables 2.05 and 2.06:

- BRIC's countries represents 40.9% of world's total population and 46.5% of world's rural population;
- BRIC's countries food production value is 41.9% of world's production, 2.5 times the G7 production, for a total population 4.1 times higher;
- Agriculture employment corresponds to 30.5 %, in line with world's average but 12.6 times the G7 average;
- GDP per capita is below World's average and 30% of G7 average;
- Net GHG emissions represents 28,9 % of World's total but 94 times G7 total emissions.

The most impressive observation is the disparity between the net GHG emissions between G7 and BRIC countries. For a production value 2.5 times the G7, BRICs countries emits 94 times GHG, meaning that for the production for the same unit of food production value, BRIC countries emits 37.6 times GHG. The difference cannot be explained only for the use of the most advanced technologies in G7 but also for what is produced. For example, Brazil is a large producer of meat, and livestock is one of the largest contributors of GHG.

Considering only European Union (EU) countries, production of agriculture in 2014 was sharply below the peak of 2013, 393 against 403 billion Euros, figure 2.05 [21].

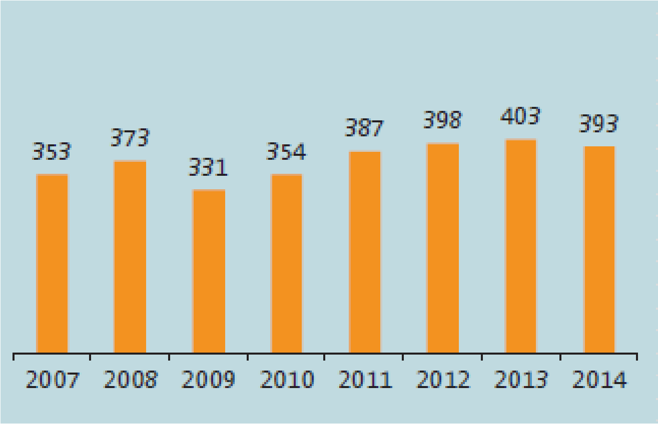


Figure 2.05 – Agricultural production value in EU [21]

EU countries production is higher than G7 countries. Although there are 3 EU countries belonging to G7, in 2014 EU total was 393 billion Euros against 282 billion Euros of G7. (Considering an average Euro/Dollar exchange ratio of 1.33 in 2014) [22].

2.3 Dependence of agriculture machinery

From the tables of 2.2, there is one evidence: developed countries produce a large amount of food, employing a small fraction of its working force. In the G7 countries, agriculture employment varies from 1.5 to 3.7%, while achieving a large productivity per capita.

This is only achieved recurring to machines. In those countries, which are the richest countries in the world, there are economic conditions to invest in machines to perform agricultural tasks. From World Bank data [23] for the G7 countries, the number of agricultural machines per 100 km^2 is shown in table 2.07:

Table 2.07 – G7 number of agricultural machine per 100 km^2 [23]

2009 data	Canada	France	Germany	Italy	Japan	UK	US	Euro area
Agricultural machinery tractors per 100 km^2	162.5	635.3	838.3	2 117.1	4 532.1	-	271.2	815.1

There is a large variation between the two extreme values; the reason is because of the size of the properties and type of machines used in those properties. While in US and Canada the average size of farm is 176 ha [24] and 315 ha [25], in Japan average size is 5.5 ha [26].

For the BRIC countries, data is on figure 2.08:

Table 2.08 – BRIC number of agricultural machine per 100km^2 [23]

2009 data	Brazil	China	India	Russia
Agricultural machinery tractors per 100 km^2	116.9	81.8	128.5	27

Comparing the data with the G7, there is a huge gap in terms of number of machines. Russia has an abnormal very small number, while values for China and India can be explained by the very large number of people actually working in agriculture using harm’s force or animals. In Brazil the size of its farm explains why the number is not so expressive.

Even depending of each country’s natural conditions, like open areas with no orographic accidents, like mountains, valleys, it is easy to assume that a high value of machines per unit of area means that the level of use of machines in agriculture is expressive and leads to higher levels of productivity per capita.

2.4 Evolution of agriculture machines

In the middle of the 19th century, using modified steam powered plowing engines, was the beginning of the first attempts to build machines to perform agricultural tasks. The first tractors have been developed by 1860 using steam technology which has endured until the 20th century.

The first gasoline powered tractor was design in the US in 1892, by John Froelich. He used a Van-Duzen single cylinder on a Robinson engine chassis. Froelich designed the gearbox which controlled the vehicle [27].

First tractor running with an oil engine was invented in Great Britain by Herbert Akroyd Stuart in 1896 with a 20 horse power (hp) engine. In the following year this company performed the first recorded sale in Britain of a tractor [28].

From then until 1960, gasoline was the dominant fuel for tractors; in some cases kerosene and ethanol were used as alternative. Diesel started to have the dominance for the tractors powertrain from 1960 and it lasted until nowadays.

Only for small manual devices as tillers, figure 2.06 [29], and lawners, figure 2.07 [30], gasoline is still used due to the low cost, simple technology involved, once they are used in small gardens and backyards, with no special demands.

Figure 2.06 - Honda F560 [29]

Figure 2.07 - Honda HF 2315 [30]

Tractor’s power starts from 10 hp up to 400 hp for regular tractors. For special applications like harvesters, power can build up to 850 hp, like the Fendt Katana 85 of figure 2.08 [31].

Figure 2.08 - Fendt Katana 85 [31]

Between the two extreme solutions mentioned before, the tillers for the small gardens and large harvesters and combines for huge plantations, there are some variations in what tractors can offer. The most common is the standard tractor, in which drive is on rear wheels – Two Wheel Drive (2WD) - or both front and rear – Four Wheel Drive (4WD); front wheels are usually smaller than the rear ones. They can be open, figure 2.09 [32], or cabined, figure 2.10 [33].

Figure 2.09 - New Holland TT4 [32]

Figure 2.10 - New Holland T4000 [33]

There are some special tractors for specific applications like orchards and vineyards, which require narrow tractors to let them pass between the lines of fruit and vine trees , as shown in figure 2.11, representing New Holland TF4 wide options [34].

Figure 2.11 - New Holland TF4 wide options [34]

When traction is critical and wheel tractors with rubber tires do not guarantee the needed traction, crawler tractors are available. They are designed for rough terrains, high slopes and when turning radius is very limited as they can rotate over their center, like the tractor of figure 2.12 [35].

Figure 2.12 - New Holland tk4000-crawler [35]

2.4.1. Industrial references for agriculture machines

There are three large industrial groups that dominate the medium and large machines: John Deere, CNH and AGCO. These three groups account for dominate around 2/3 of the world market. These companies do not only operate in agriculture but also in land moving, forest machines and engine production. Plants are distributed around the globe, including base components and products manufactured in each region are adapted to the demand and technology level of each market [36].

AGCO group includes brands as Fendt, Valtra, Massey Ferguson, Challenger and AGCO. CNH group includes brands as Case IH, New Holland and Steyr. John Deere has a different approach, all products are sold as John Deere and when acquires other brands, they are incorporated in John Deere line-up.

There are other groups, smaller than the three references above, which revenues do not pass 1b Euros: Argo, Claas and Same-Deutz Fahr. Argo group brands are McCormick, Landini and Valpadana; Claas has its own machines and Same Deutz-Fahr has Same, Lamborghini, Hurlimann and Deutz-Fahr.

Kubota is another group, from Japan, with dominance in the low power tractors, being the world leader in low power engines for agriculture, industry and gardens.

For special low power tractors, Italian brands dominate the European market, like Antonio Carraro, BCS, Ferrari, Pasquali, Goldoni, with the competition from Asian manufacturers like Iseki, Kioti, LS, Mitsubishi and Yanmar.

2.4.2 Power train manufacturers

Current tractors rely on diesel powertrains. There are a few manufacturers that produce engines for agricultural applications; some of those connect to the tractors groups Original Equipment Manufacturer (OEM) [36]:

- AGCO Sisu Power: belongs to AGCO group, provides all the brands of this group, excepts Fendt;
- Cummins: provider of JCB and McCormick;
- Deutz AG: supplies all Same Deutz-Fahr brands but also Fendt and Claas;
- Fiat Power Train (FPT): belongs to CNH group, provides engines inside the group;
- Deere Power Systems (DPS): provides engines to all John Deere machines and also to Claas;
- Perkins along with Caterpillar: provides engines to AGCO machines, Claas, Landini and Lindner;
- Same: provides low power engines for its own brand;
- Mercedes: for high power engines;
- Kubota, Lombardini, VM and Yanmar: producers of low power engines.

2.4.3 Transmissions manufacturers

As for the engines manufacturers, there are some companies specialized in the development and production of transmissions for tractors. Normally each tractor OEM produces its own transmission systems but there are companies like Carraro and ZF that are specialists in transmissions that supply high tech solutions. In some cases competitors build joint ventures like the case of AGCO and Claas. In other cases, competitors supply systems to each other, like Funk belonging to John Deere Group that supplies CNH and ARGO [36].

2.5 Agriculture machinery data

To have an outlook of the business related to agricultural machinery, it is important to know some figures, not only globally but in the most important production and market countries.

2.5.1 World agriculture machinery production and sales

According to Vertritt den Maschinenbau und den Anlagenbau (VDMA) 2015 Report, Global Agricultural Machinery Production, world market for agricultural machinery is estimated to be around 91 billion Euro, against 101 billion Euro in 2014 and 103 billion Euro in 2013, figure 2.13 [21].

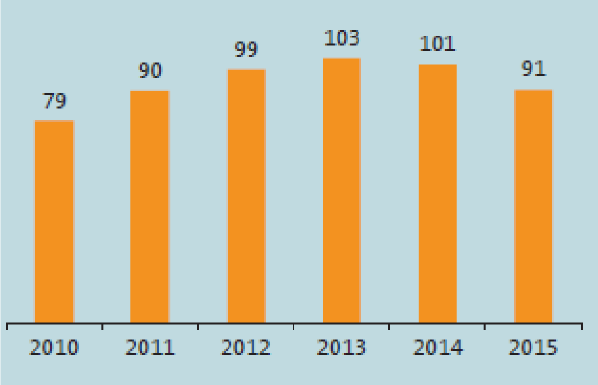


Figure 2.13 – Global agriculture machinery production. Values in billion Euros [21]

In terms of worldwide production, figure 2.14 shows the distribution of agricultural machinery by the main economic areas [21]. European Union is the biggest production area in the 2012-2014 period, accounting for a share of 26%. North American Free Trade Agreement (NAFTA) countries follows with a share of 22% and China appears in third spot with 15%.

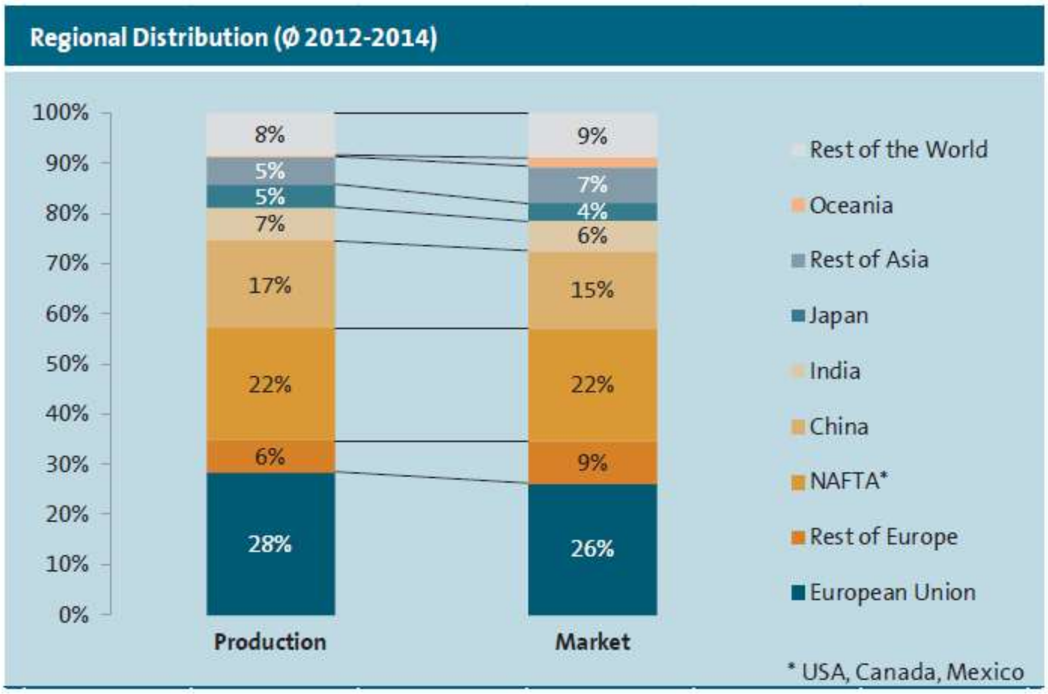
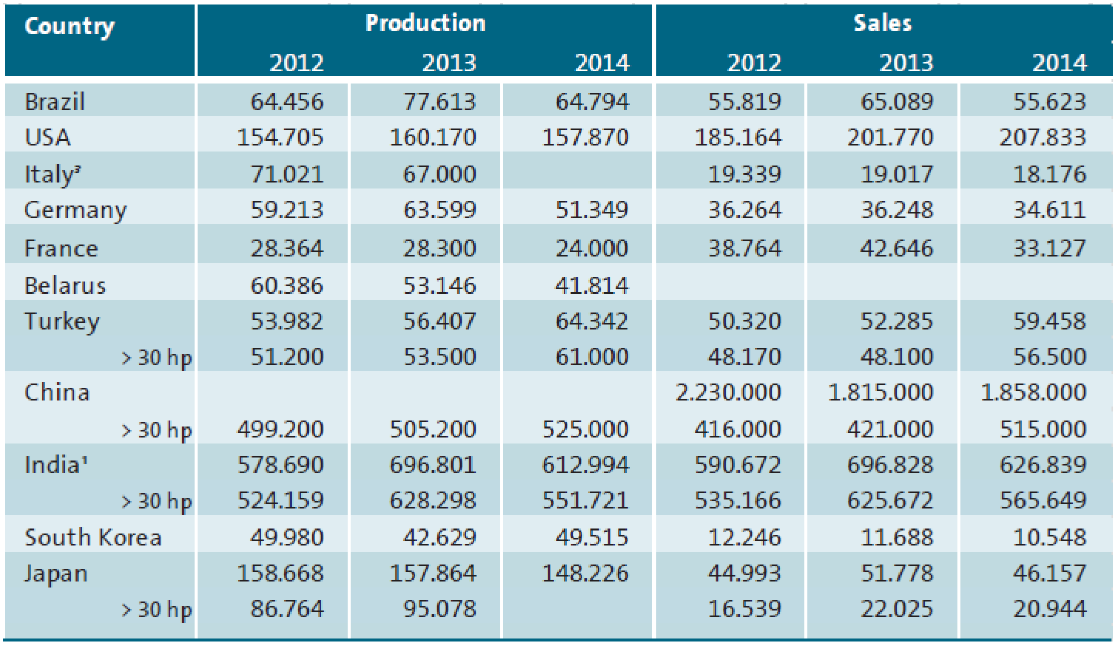


Figure 2.14 – Worldwide production of agricultural machinery [21]

Comparing the production origin and destination market, it is quite balanced. The biggest gap is in European countries not belonging to EU, where market share is 9% of world's total and production is 6% of world's total. Those countries are net importers of agricultural machines, figure 2.15.

Table 2.09 – Tractor production and sales on selected countries 2012-2014 [21]



Country	Production			Sales		
	2012	2013	2014	2012	2013	2014
Brazil	64.456	77.613	64.794	55.819	65.089	55.623
USA	154.705	160.170	157.870	185.164	201.770	207.833
Italy[3]	71.021	67.000		19.339	19.017	18.176
Germany	59.213	63.599	51.349	36.264	36.248	34.611
France	28.364	28.300	24.000	38.764	42.646	33.127
Belarus	60.386	53.146	41.814			
Turkey	53.982	56.407	64.342	50.320	52.285	59.458
> 30 hp	51.200	53.500	61.000	48.170	48.100	56.500
China				2.230.000	1.815.000	1.858.000
> 30 hp	499.200	505.200	525.000	416.000	421.000	515.000
India[1]	578.690	696.801	612.994	590.672	696.828	626.839
> 30 hp	524.159	628.298	551.721	535.166	625.672	565.649
South Korea	49.980	42.629	49.515	12.246	11.688	10.548
Japan	158.668	157.864	148.226	44.993	51.778	46.157
> 30 hp	86.764	95.078		16.539	22.025	20.944

In table 2.09, is shown a comparison of production and sales in the largest agriculture machinery country producers. China is the largest producer and the largest market. It is essentially a small tractor market with 78% of sales on machines with less than 30 hp. India is the second largest, with an almost even distribution of small and bigger tractors. US is the third largest and is a bigger tractor market, as seen in table data, where 73.5% of tractors have more than 40 hp.

2.5.2 US agriculture machinery data

Although being No. 3 in terms of production and sales, there is data available from US market. US figures, according to US Agriculture Census 2012 [24], for the existing agricultural machines is shown in table 2.10. The classification is determined by the Power Take Off (PTO) output.

Table 2.10 – US existing number of agricultural machines [24]

Tractors	Number	Percentage
Less than 40 hp (PTO)	1 107 528	26.5%
40 to 99 hp (PTO)	1 886 032	45.1%
100 hp (PTO) or more	1 184 740	28.4%
Total	4 178 300	100%

For special agriculture machines, figures are in table 2.11:

Table 2.11 – US existing number of special agricultural machines [24]

Type	Number
Grain and bean combines	346 632
Cotton pickers and strippers	20 227
Forage harvesters	72 389
Hay balers	731 771

2.5.3 Japan agriculture machinery data

Japan ranks No. 4 for the largest producer of agricultural machinery. Japan exports around 2/3 of its production. Types of machines produced in 2013 are shown in table 2.12 [26]:

Table 2.12 – Japan 2013 production of agricultural machines [26]

Type	Number
Tractors	157 959
Less than 20 hp	18 623
Between 20 and 30hp	44 186
More than 30hp	95 150
Rice planting machine	32 994
Combine	24 466

According to a 2010 survey [26], existing agriculture machinery in Japan is shown in table 2.13:

Table 2.13 – Japan existing number of agricultural machines [26]

Type	Number
Tractors	1 910 724
Rice planting machine	1 232 018
Combine	972 168

Japan has a specific market for rice planting machines. Reason is the need for such machines to be used on the rice crops fields.

2.5.4 European agriculture machinery data

Considering European countries, overall market for 2014 was around 175 000 units, below 2011-2013 levels, where it was around 190 000 units, table 2.14 [21]. From those 175 000 units, 150 000 were tractors with more than 37 kilowatt (kW), nearly 86 % of market.

Germany and France are the top 2 selling countries, competing to be Europe’s No. 1, while Italy goes into 3rd place. These 3 countries together, represent around 50% of European market.

Table 2.14 – European tractor registrations 2010-2014, in units [21]

	2010	2011	2012	2013	2014	of which: > 37 kW
Germany	28.587	35.977	36.264	36.248	34.611	28.444
France	29.123	35.409	38.764	42.632	33.127	28.501
Italy	23.323	23.429	19.343	19.017	18.176	15.061
Poland	14.731	17.035	19.113	14.968	14.172	12.886
United Kingdom	14.486	15.217	14.964	13.490	13.526	12.421
Spain	10.547	10.002	8.647	8.894	10.029	9.018
Austria	7.921	7.766	8.294	8.031	6.494	6.020
Sweden	4.098	4.877	4.165	4.027	4.593	3.056
Belgium	2.858	3.281	3.377	3.248	3.586	2.730
Netherlands	3.480	4.069	3.835	3.728	3.559	3.079
Portugal	5.517	4.793	3.986	3.496	3.451	3.233
Norway	3.232	3.829	3.655	3.831	3.149	3.020
Switzerland	2.746	3.083	3.330	3.115	2.820	2.608
Czech Republic	1.864	2.321	2.257	2.585	2.613	2.089
Denmark	1.791	2.286	2.185	2.968	2.361	1.829
Finland	4.292	4.561	2.828	2.557	2.096	2.081
European Union	**168.000**	**191.000**	**190.000**	**188.000**	**175.000**	**150.000**

Besides standard tractors, there is some specific machinery not included on table 2.14. For German market, for the 2010-2014 period, table 2.15 shows tractors and other machinery sales [21].

Table 2.15 – Germany agricultural machines total sales 2010 – 2014, in units [21]

	2010	2011	2012	2013	2014
Tractors	28.587	35.977	36.264	36.248	34.611
Combine harvesters	1.457	2.015	1.964	2.058	1.865
Balers	1.915	2.144	2.384	2.339	2.144
Forage harvesters	608	695	678	528	531
Mowers	8.439	9.681	11.077	10.799	10.080
Tedders and rakes	7.231	8.702	10.678	10.265	9.913

Number of tractors is still higher when compared to the other machines, being mowers a specific machine mostly for gardens and tedders and rakes equipment to attach to tractors itself.

2.6 Energy sources for agriculture machinery

Performing a search on the websites of tractor manufacturers, almost all the powertrains use diesel powered engines. Only for very small machines like tillers, gasoline still dominates, because of the good relation cost/power/weight.

Actual Diesel engines are extremely evolved, making use of state of the art technology like direct injection, turbo charging, common rail, to achieve the best performance, with low consumptions.

Diesel has some advantages over gasoline, like higher torques at low revolutions, less fuel consumption, good reliability and higher levels of efficiency.

2.7 Environment impact of agriculture machinery

2.7.1 Global emissions

There is a serious problem theatening the future of the environment in planet Earth due to the current level of CO_2 concentration on the atmosphere. But it is not only the current level, it is the effects it already caused so far and the trend on CO_2 and other Green House Gases (GHG) emissions that will cause huge changes in the climate conditions.

According to the Climate Change 2014 Synthesis Report, belonging to the Fifth Assessment Report, performed by the Intergovernmental Panel on Climate Change (IPCC), GHG emissions in 2010 reached a total of 49 Gt CO_2 equivalent [37]. From that total, Agriculture, Forestry and Other Land Use (AFOLU) contributed with 24% on the direct GHG emissions, one of the largest contributers, figure 2.15.

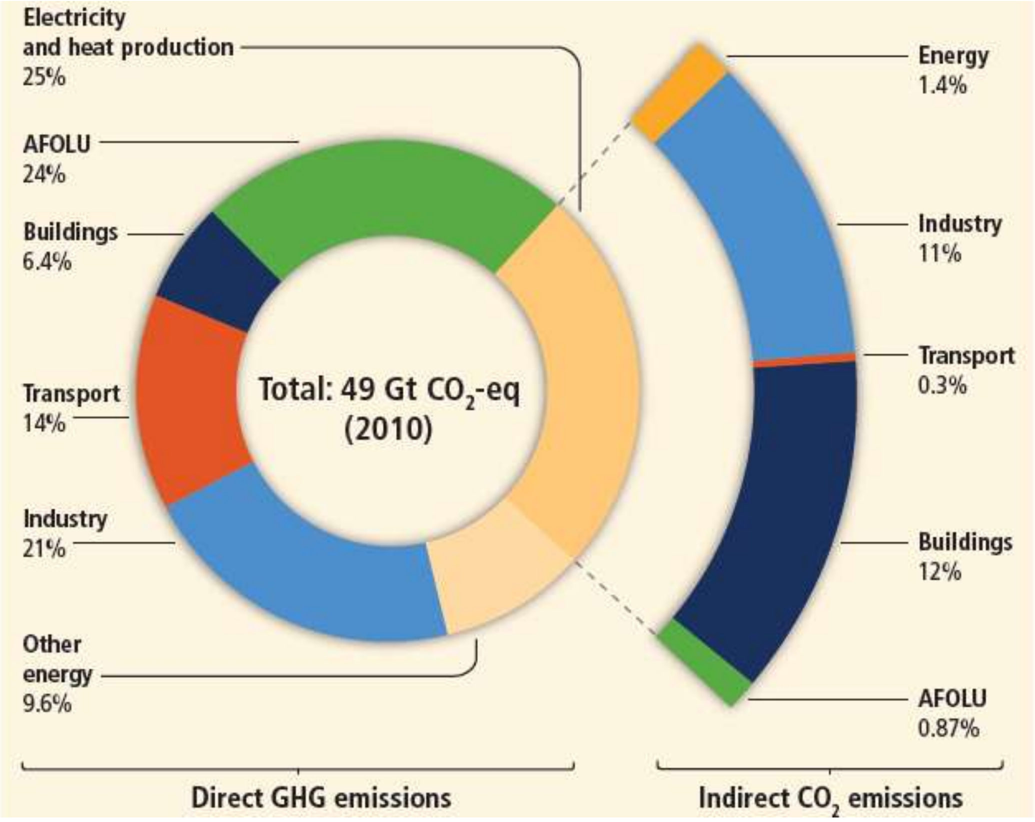


Figure 2.15 – Greenhouse gas emissions by economic sector [37]

From the same report, CO_2, CH_4 and N_2O concentrations are shown from 1850 until 2000, with the forecast until nowadays, figure 2.16. It is observed that the concentrations of these gases have been raising since 1850, with a low rate until 1900, a slight increase until 1950, ramping up from then until now. Even with public acknowledge of this major issue, the truth is that there is no evidence that the growth is stabilizing, even decreasing.

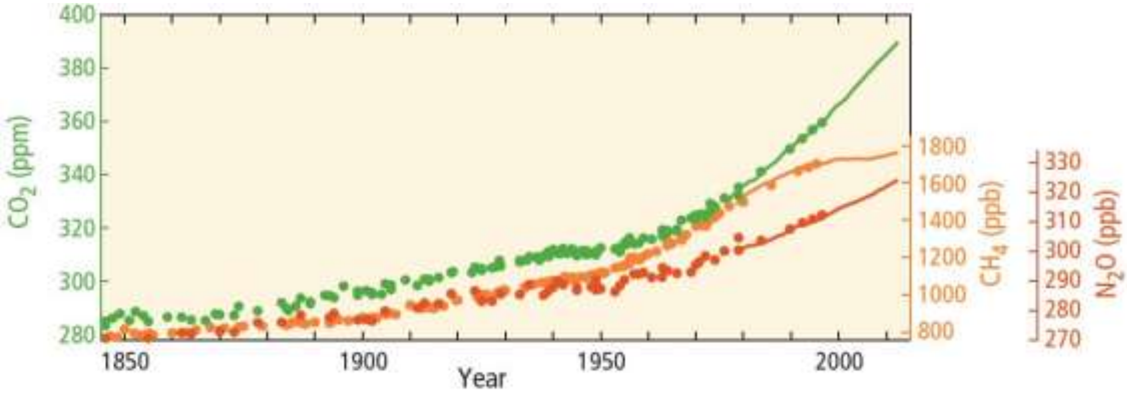


Figure 2.16 – Global average greenhouse gases concentrations 1850 – 2010 [37]

When we look closer to the concentration of CO_2 in the atmosphere and compare the level in 1850 (figure 2.16) and in 2010, figure 2.17, there is an increase from around 280 ppm to almost 400 ppm, a 40% increase. According to the report, there are no doubts that the increase is largely due to anthropogenic emissions, which started with the Industrial Revolution.

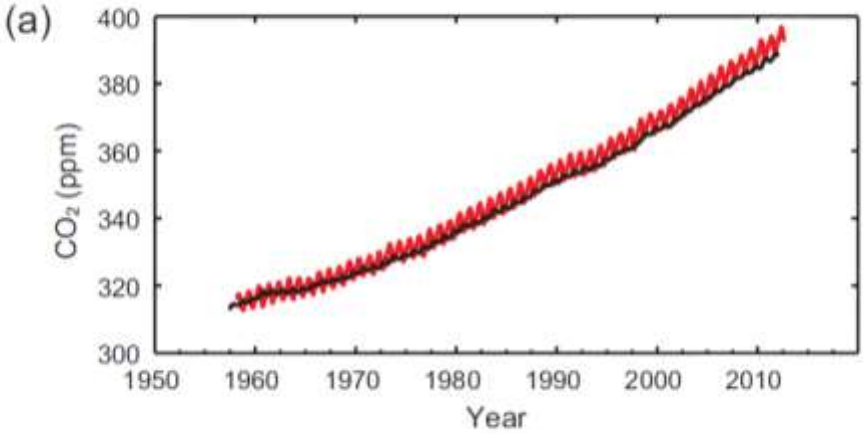


Figure 2.17 – Atmospheric CO_2 concentrations 1960 – 2010 [37]

2.7.2 Agriculture emissions

As seen in previous point, AFOLU represents almost one quarter of GHG emissions. Once agriculture use different kind of resources and covers different applications, it is important to separate the sources of the emissions, to better understand the cause of the impact of agriculture in the world.

From FAO Statistics Division (FAOSTAT) database it is possible to access to 2012 data for agriculture, figure 2.18 [38]. Filtering by sector, the largest contributor is enteric fermentation, a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal. This sector is responsible for 38.6% of emissions. Adding the emissions caused by manure applied to soils (3.5%), left on pasture (15.4%) and management (6.8%) along with enteric fermentation, almost 2/3 of agriculture emissions are caused by livestock production (64.3%). Synthetic fertilizers account for near 15% and rice cultivation for almost 10%.

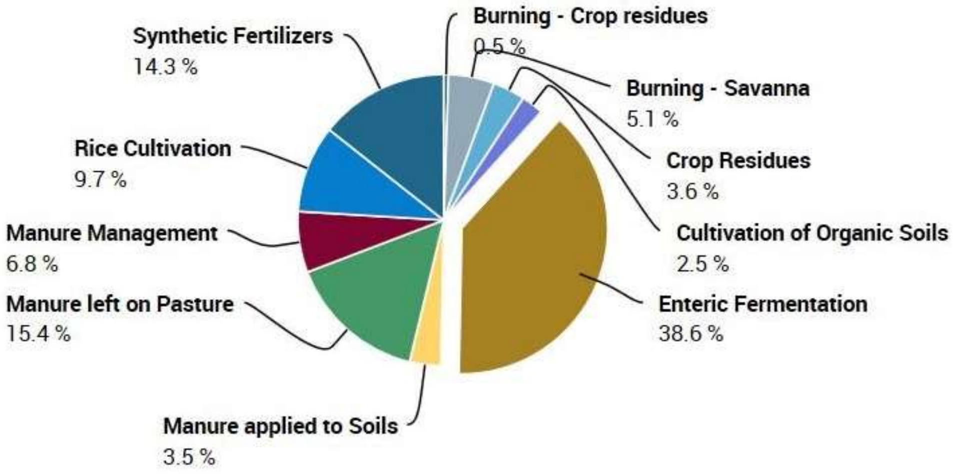


Figure 2.18 – Agriculture GHG emissions by sector – 2012 [38]

From the figure 2.18 it is not possible to extract the level of emissions due to the use of machinery. Those emissions are embedded in some sectors, like cultivation of organic soils and rice cultivation, but its total value is not accessible directly.

Continent emissions distribution places Asia in first spot with 45.7%, followed by far by Americas, with 24.4%. Africa is ahead of Europe, 14.8% against 10.7% and Oceania is the smallest contributor with 4.4%.

Considering the distribution by the 10 top emitter countries, China is the leader, followed by India and Brazil. US is fourth, with no European country entering the Top 10, figure 2.19.

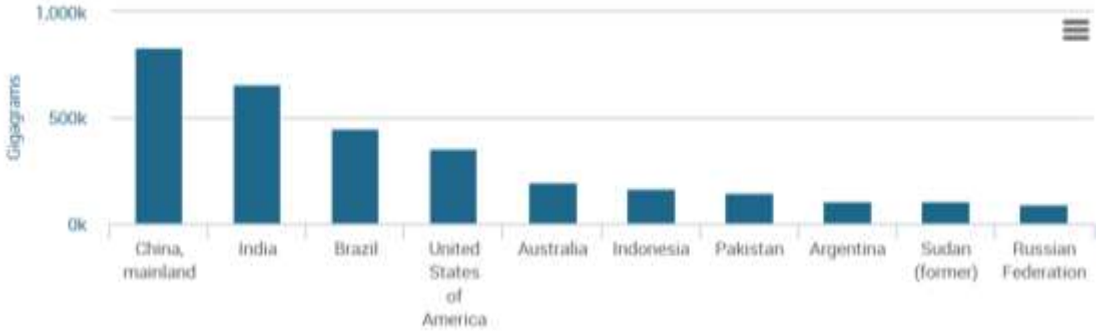


Figure 2.19 – Top ten CO_2 equivalent emitters – 2012 [38]

2.7.3 Energy emissions

FAOSTAT also shows the emissions of carbon dioxide, methane and nitrous oxide gases associated with fuel burning and electricity generation in agriculture (including fisheries). Filtering by emissions by energy carrier used, the main fuel responsible for emissions is Gas-Diesel oil, close to half of emissions with 44.9%. Electricity stands very close, with 41.5%. Gasoline is only responsible for 2% of energy emissions, justifying the small use and impact it has in agriculture applications, as a fuel for the tractors and other agricultural machines, figure 2.20.

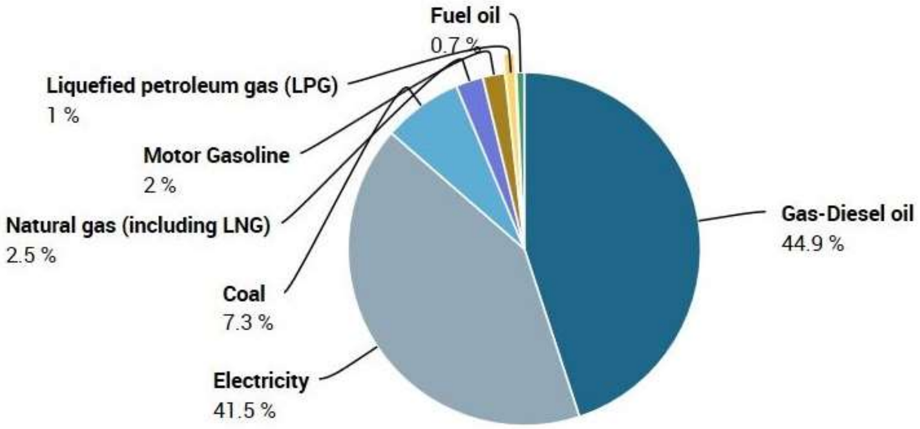


Figure 2.20 – CO_{2eq} emissions by energy carrier used – 2012 [38]

Addressing by continents, Asia is the main emitter, with 58%. Europe and Americas race for the second spot, with 16.8 and 16.4% respectively. Africa stands for 7.3 and Oceania only for 1.5%, figure 2.21.

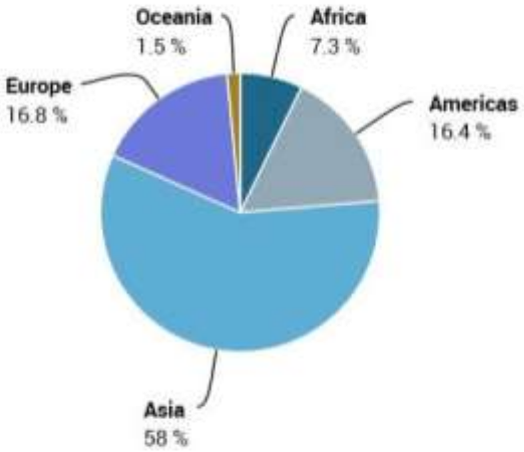


Figure 2.21 – CO_{2eq} emissions by continent – 2011 [38]

2.7.4 United States performance

Being US one of the largest emitters of GHG and due to the availability of data, it is possible to identify the impact of GHG produced by agricultural machinery.

In 2013, US greenhouse gas emissions totalized 6 673 million metric tons of carbon dioxide equivalent. Agricultural activities were responsible for 515.7 million metric tons of CO_{2eq}, 7.7% of US GHG emissions. Also in the US, livestock production accounts for a large stake of agriculture emissions – 48% - weighting 3.7% of the total of all GHG emissions [39].

Fossil fuel combustion for the agricultural machines powertrains accounted for 49.7 million metric tons, a share of 0.7% of US emissions [39].

It is a marginal value if compared to the transport end-use sector. Transport sector emits 1 722.4 million metric tons, 33.4 % of all CO_{2eq} emissions. Passenger cars were responsible for 42.7% and freight trucks for 22.8%, respectively 14.2 and 7.6 % of all GHG emissions [39].

Even counting with a low percentage of all US GHG emissions, it is not a negligible value - 49.7 million metric tons – and all the possible contributions to reduce this amount can be considered as a help to reduce the quantity of GHG emissions.

2.8 Chapter 2 conclusions

From the data collected there are some main points to recall:

- Agriculture accounts for 30.7% of World's population, agriculture worth only for 2.9% of World's GDP;
- G7 countries agriculture employment is 2.4% of population. With a workforce 10 times below world's average, G7 countries agriculture production is 1.7 times world's average;
- Net GHG emissions from G7 AFOLU represent 1% of world's emissions, while BRIC's Net GHG emissions represents 28,9 % of World's total, 94 times of G7 total emissions;
- In 2015, World's machinery business reached 91 billion Euros, being Europe the main producer, followed by China and Nafta countries;
- Agriculture, Forest and Other Land Use (AFOLU) is one of the largest GHG emitters, while Diesel is the major source for emissions
- In US, fossil fuel combustion for the agricultural machines powertrains accounts for a share of 0.7% of US emissions.

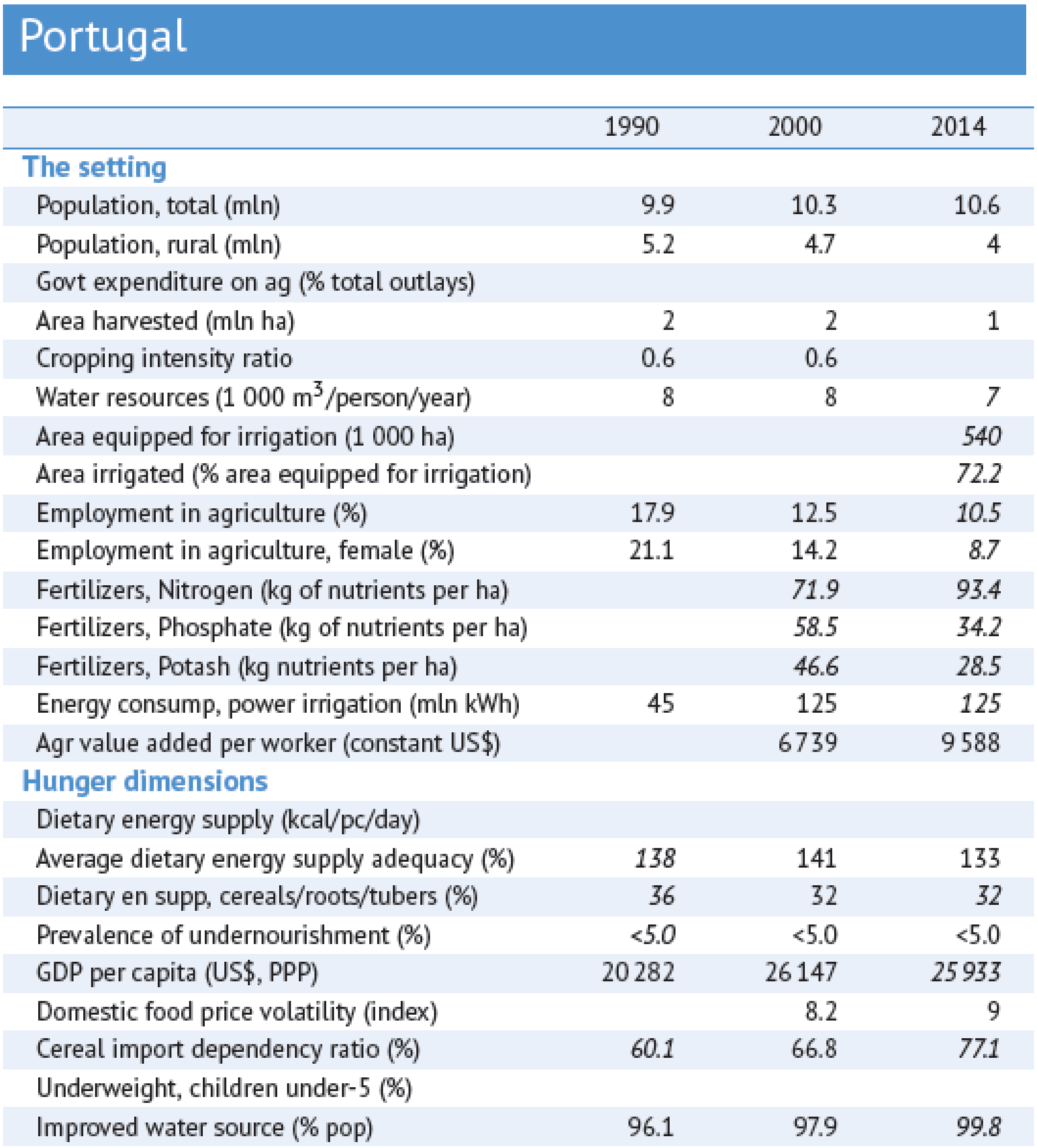
3 Agriculture in Portugal

In this chapter it is performed a brief description of the status of agriculture in Portugal, also comparing with the benchmarking countries of chapter 2. A collection of the agriculture's machinery is shown, along with consumption of fuel and related emissions.

3.1 Agriculture data in Portugal

Tables 3.01 and 3.02 below are from the last FAO Statistical Pocketbook World Food and Agriculture 2015, where it compares agricultural data between 1990, 2000 and 2014 [17].

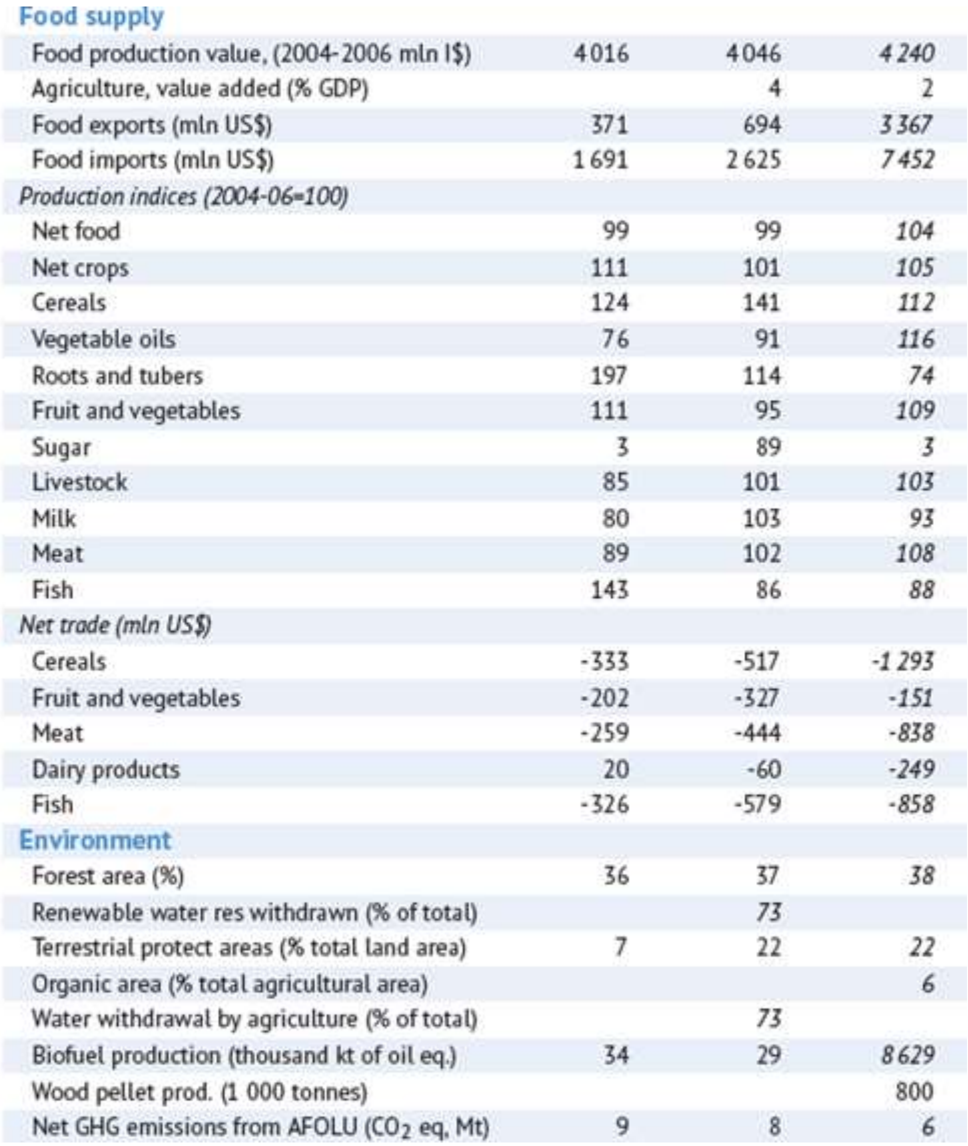
Table 3.01 – Portugal's agricultural data between 1990, 2000 and 2014, part 1 [17]



Portugal

	1990	2000	2014
The setting			
Population, total (mln)	9.9	10.3	10.6
Population, rural (mln)	5.2	4.7	4
Govt expenditure on ag (% total outlays)			
Area harvested (mln ha)	2	2	1
Cropping intensity ratio	0.6	0.6	
Water resources (1 000 m^3/person/year)	8	8	*7*
Area equipped for irrigation (1 000 ha)			*540*
Area irrigated (% area equipped for irrigation)			*72.2*
Employment in agriculture (%)	17.9	12.5	*10.5*
Employment in agriculture, female (%)	21.1	14.2	*8.7*
Fertilizers, Nitrogen (kg of nutrients per ha)		*71.9*	*93.4*
Fertilizers, Phosphate (kg of nutrients per ha)		*58.5*	*34.2*
Fertilizers, Potash (kg nutrients per ha)		*46.6*	*28.5*
Energy consump, power irrigation (mln kWh)	45	125	*125*
Agr value added per worker (constant US$)		6 739	9 588
Hunger dimensions			
Dietary energy supply (kcal/pc/day)			
Average dietary energy supply adequacy (%)	*138*	141	133
Dietary en supp, cereals/roots/tubers (%)	*36*	32	*32*
Prevalence of undernourishment (%)	<*5.0*	<5.0	<5.0
GDP per capita (US$, PPP)	20 282	26 147	*25 933*
Domestic food price volatility (index)		8.2	9
Cereal import dependency ratio (%)	*60.1*	66.8	*77.1*
Underweight, children under-5 (%)			
Improved water source (% pop)	96.1	97.9	*99.8*

Table 3.02 – Portugal’s agricultural data between 1990, 2000 and 2014, part 2 [17]



Food supply			
Food production value, (2004-2006 mln I$)	4 016	4 046	4 240
Agriculture, value added (% GDP)		4	2
Food exports (mln US$)	371	694	3 367
Food imports (mln US$)	1 691	2 625	7 452
Production indices (2004-06=100)			
Net food	99	99	104
Net crops	111	101	105
Cereals	124	141	112
Vegetable oils	76	91	116
Roots and tubers	197	114	74
Fruit and vegetables	111	95	109
Sugar	3	89	3
Livestock	85	101	103
Milk	80	103	93
Meat	89	102	108
Fish	143	86	88
Net trade (mln US$)			
Cereals	-333	-517	-1 293
Fruit and vegetables	-202	-327	-151
Meat	-259	-444	-838
Dairy products	20	-60	-249
Fish	-326	-579	-858
Environment			
Forest area (%)	36	37	38
Renewable water res withdrawn (% of total)		73	
Terrestrial protect areas (% total land area)	7	22	22
Organic area (% total agricultural area)			6
Water withdrawal by agriculture (% of total)		73	
Biofuel production (thousand kt of oil eq.)	34	29	8 629
Wood pellet prod. (1 000 tonnes)			800
Net GHG emissions from AFOLU (CO_2 eq, Mt)	9	8	6

Some comments to tables 3.01 and 3.02:

- Rural population ratio is falling from 52.5% in 1990 to 37.8% in 2014;
- Employment in agriculture has fallen, especially for women;
- GDP has raised in the 1990-2000 period 26% but stalled in the 2000-2014 period;
- Food production value was flat between 1990 and 2000, with a slight improve of 5% in 2014. World’s performance was an increase of 73.5% in the same period;
- Agriculture’s value added represents only 2% of 2014 GDP;
- Food import is almost the double than food exports. In 2014 the ratio export/import was of 45%, despite being better than in 2000 – 26% - and in 1990 – 22%;
- Portugal is a net importer of food, especially of cereals, that imported 77.1% of cereal needs in 2014;
- Biofuel production has had a tremendous increase, nearly inexpressive in the 1990-2000 period but reaching more than 8 000 Mt of oil equivalent in 2014;

- Net GHG emissions from AFOLU have decreased from 9 Mt CO_2 eq. in 1990 to 6 Mt CO_2 eq. in 2014.

Following table shows a comparison of the most relevant data from Portugal with G7 and BRIC countries.

Table 3.03 – Portugal agriculture comparative data with BRIC, G7 and the World

2014 data	Portugal	World	Average BRIC	Total BRIC	Average G7	Total G7
Total population (M)	10.6	7 423.8	-	3 036.9	-	747.2
Rural population (M)	4.0	3.362.5	-	1.564.7	-	131.2
Rural / total population (%)	37.7	45.3	-	51.5	-	17.6
Food production value (2004-2006 M US$)	4 240	2 246 912	-	941 876	-	375 223
Food production value per capita (2004-2006 $)	400.0	302.7	392.5	-	509.7	-
Agriculture employment (%)	10.5	30.7	30.5	-	2.4	-
GDP per capita (US$. PPP)	29 333.0	13 915.0	11 785.8	-	39 972.9	-
Agr value added per worker (constant US$)	9 588.0	-	-	-	54 310.7	-
Domestic food volatility (index)	9.0	6.4	7.2	-	4.7	-
Net GHG emissions from AFOLU (Mt CO_2 eq)	6.0	8 165.0	-	2 356.0	-	94.0
Net GHG emissions from AFOLU (Mt CO_2 eq)/ Total population (M)	0.566	1.100	-	0.776	-	0.126

Some comments to the table above:

- Food production value per capita is above World’s average, sharply ahead of BRIC’s average but represents 78.4% of G7’s average;
- Agriculture employment is three times below World’s and BRIC’s countries but 4 times above G7’s average;
- Agriculture value added per worker is 17.6% of the average of G7 countries;
- Domestic food volatility index is higher in Portugal compared with World’s, BRIC’s and G7’s average;
- The ratio of Net GHG over total population is 0.566 Mt CO_2 eq. M^{-1}, below World’s and BRIC’s average but more than 4 times G7’s average.

Although the apparent effort placed in Portugal’s agriculture, the truth is that the productivity is far away from developed countries achievements, namely G7 countries.

3.2 Agriculture machines data in Portugal

One of the reasons for the underperformance of Portugal’s agriculture can be the low level of mechanization. By comparing the number of agricultural machines per km^2 in Portugal and in Euro area, it is easy to verify that it is not the case. The number of machines per 100 km^2 is 1 380.2, almost 70% more compared to Euro area, table 3.04 [23].

Table 3.04 – Number of agricultural machines per 100 km^2 in Portugal

2009 data	Portugal	Euro area
Agricultural machinery tractors per 100 km^2	1 380.2	815.1

As seen in point 2.3, the number of machines depends on the average size of properties. In Portugal average size of properties is 14 ha [40], meaning that the size and power tractors should be small/medium.

Figure 3.01 and figure 3.02 show the average size of properties and the number of tractors per 100 ha of Superfície Agrícola Utilizada (Used Agricultural Surface-UAS) [41].

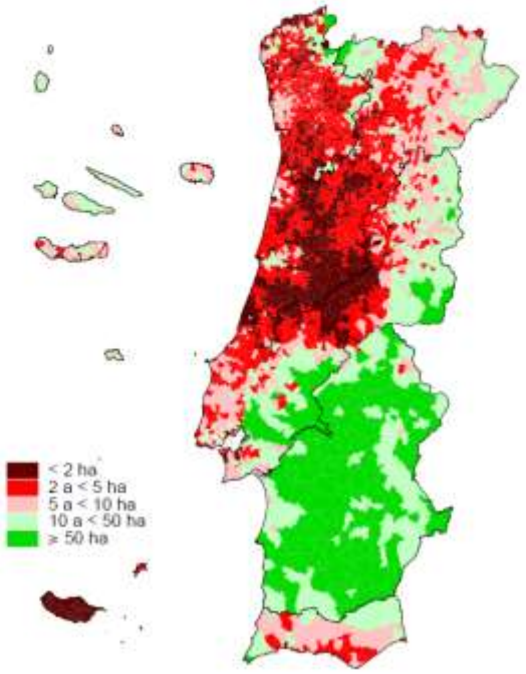


Figure 3.01 – Portuguese property average size 2009 [41]

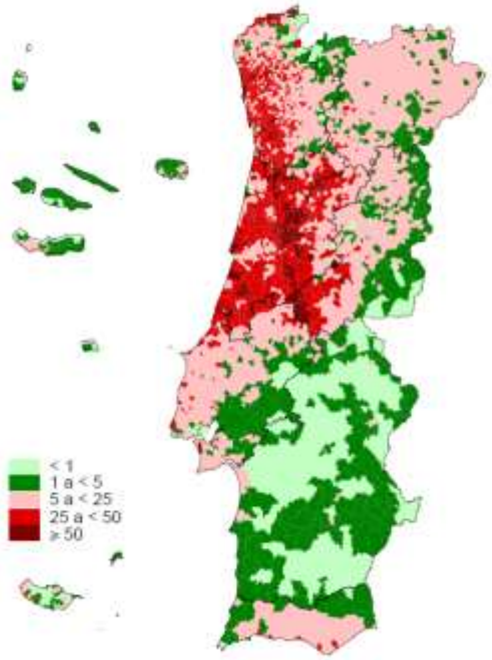


Figure 3.02 – Portuguese number of tractors per UAS 2009 [41]

Portugal has some asymmetries concerning to the size dimension of properties. In the North and Middle of Portugal, close to the Atlantic Ocean, there is the biggest concentration of population, from the north border with Spain until Lisbon, and from the Atlantic Ocean shore to around 50 Km inland. This is one of the reasons why landscape is fragmented. The other reason is orography. In the North and Middle of Portugal there are mountains, which also limits the size of properties, once on sloped areas there is mainly forest. In the South, in Alentejo, the landscape is essentially flat, with almost no mountains. Population density is very scarce, so there are bigger areas per property.

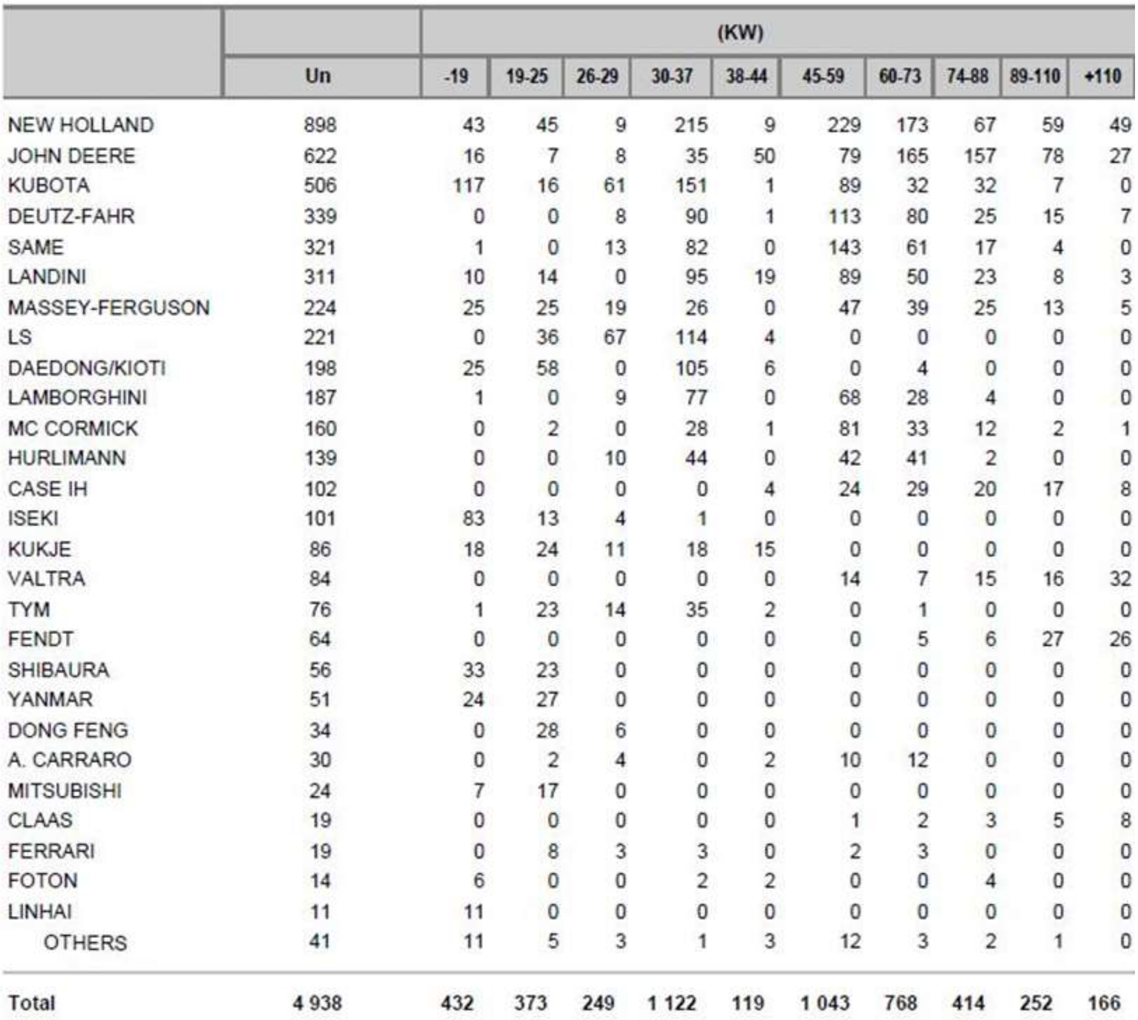
Different climates contribute to different types of crops. In the North and Middle, due to the mountains, the levels of rain are reasonable, so it is possible to cultivate some various crops and orchards. In Alentejo, climate is drier, keener to cereals, with extensive areas.

The distribution of tractors follows essentially the same pattern. In Alentejo, due to the greater extent of properties, the number of tractors is roughly below 5 units per 100 ha of UAS. In the Middle and North, in some regions the ratio overtakes 50 units per 100 ha of UAS.

Table 3.05 shows the sales of tractors in 2013. The total overall number of tractors sold was 4 938 units, where New Holland of CNH group was the top seller, followed by John Deere and Kubota [42].

In terms of power figure 3.03 shows the distribution of tractors sold.

Table 3.05 – Tractors sales in Portugal, 2013 [42]



		(KW)									
	Un	-19	19-25	26-29	30-37	38-44	45-59	60-73	74-88	89-110	+110
NEW HOLLAND	898	43	45	9	215	9	229	173	67	59	49
JOHN DEERE	622	16	7	8	35	50	79	165	157	78	27
KUBOTA	506	117	16	61	151	1	89	32	32	7	0
DEUTZ-FAHR	339	0	0	8	90	1	113	80	25	15	7
SAME	321	1	0	13	82	0	143	61	17	4	0
LANDINI	311	10	14	0	95	19	89	50	23	8	3
MASSEY-FERGUSON	224	25	25	19	26	0	47	39	25	13	5
LS	221	0	36	67	114	4	0	0	0	0	0
DAEDONG/KIOTI	198	25	58	0	105	6	0	4	0	0	0
LAMBORGHINI	187	1	0	9	77	0	68	28	4	0	0
MC CORMICK	160	0	2	0	28	1	81	33	12	2	1
HURLIMANN	139	0	0	10	44	0	42	41	2	0	0
CASE IH	102	0	0	0	0	4	24	29	20	17	8
ISEKI	101	83	13	4	1	0	0	0	0	0	0
KUKJE	86	18	24	11	18	15	0	0	0	0	0
VALTRA	84	0	0	0	0	0	14	7	15	16	32
TYM	76	1	23	14	35	2	0	1	0	0	0
FENDT	64	0	0	0	0	0	0	5	6	27	26
SHIBAURA	56	33	23	0	0	0	0	0	0	0	0
YANMAR	51	24	27	0	0	0	0	0	0	0	0
DONG FENG	34	0	28	6	0	0	0	0	0	0	0
A. CARRARO	30	0	2	4	0	2	10	12	0	0	0
MITSUBISHI	24	7	17	0	0	0	0	0	0	0	0
CLAAS	19	0	0	0	0	0	1	2	3	5	8
FERRARI	19	0	8	3	3	0	2	3	0	0	0
FOTON	14	6	0	0	2	2	0	0	4	0	0
LINHAI	11	11	0	0	0	0	0	0	0	0	0
OTHERS	41	11	5	3	1	3	12	3	2	1	0
Total	**4 938**	**432**	**373**	**249**	**1 122**	**119**	**1 043**	**768**	**414**	**252**	**166**

In terms of power figure 3.03 shows the distribution of tractors sold.

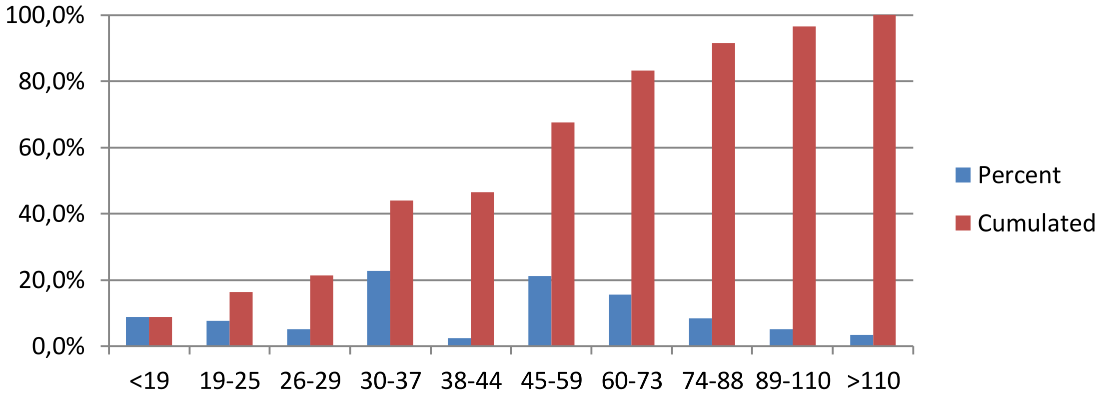


Figure 3.03 – Power range distribution of tractors sold in Portugal 2013 [43]

There are two ranges with some relevance: between 30 and 37 kW and between 45 and 59 kW. Cumulated values of tractors from 0 up to 45-59 kW correspond to 67.6%, meaning 2/3 of all sales are below 59 kW.

This means that tractors are bought bearing in mind the small property area, where small/medium tractors make more sense to be used.

The number of existing tractors in Portugal is 249 562 units [41]. Figure 3.04 shows the distribution per power range.

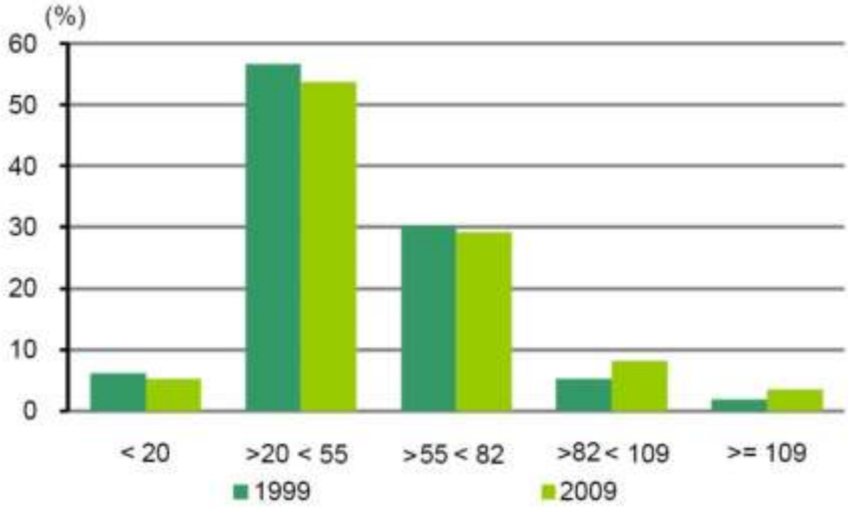


Figure 3.04 – Power range distribution of existing tractors in Portugal 1999 – 2009. Units hp. [41]

Comparing with the sales of new tractors, we can see some consistence, once the range from 20 to 55 hp (14.5 – 40 kW) has more than half of existing tractors, followed by the range of 55 up to 82 hp (40 – 60 kW) with less than 30 %. Other ranges have less than 10%.

In terms of tractors age, only 12 % have less than five years. From 5 to 10 years there are 21%, from 10 to 20 years there are 29% and with more than 20 years the percentage is 37%.

This means that in the period of 2005 – 2009, there were a disinvestment in tractors acquisitions, once in the period of 1999 – 2004, the number of existing tractors sold on that period is higher than the sold in 2005 – 2009.

Other observation is that the tractors with more than 10 years represent 2/3 of the total existing tractors and 37% have more than 20 years. This means that the park of tractors is relatively aged. Although main functions of tractors remain the same all over the years, efficiency, emissions control, safety, comfort have had large improvements, which are only used by a minor fraction of users.

Figure 3.05 shows the distribution of tractors per age, for several regions of Portugal [41].

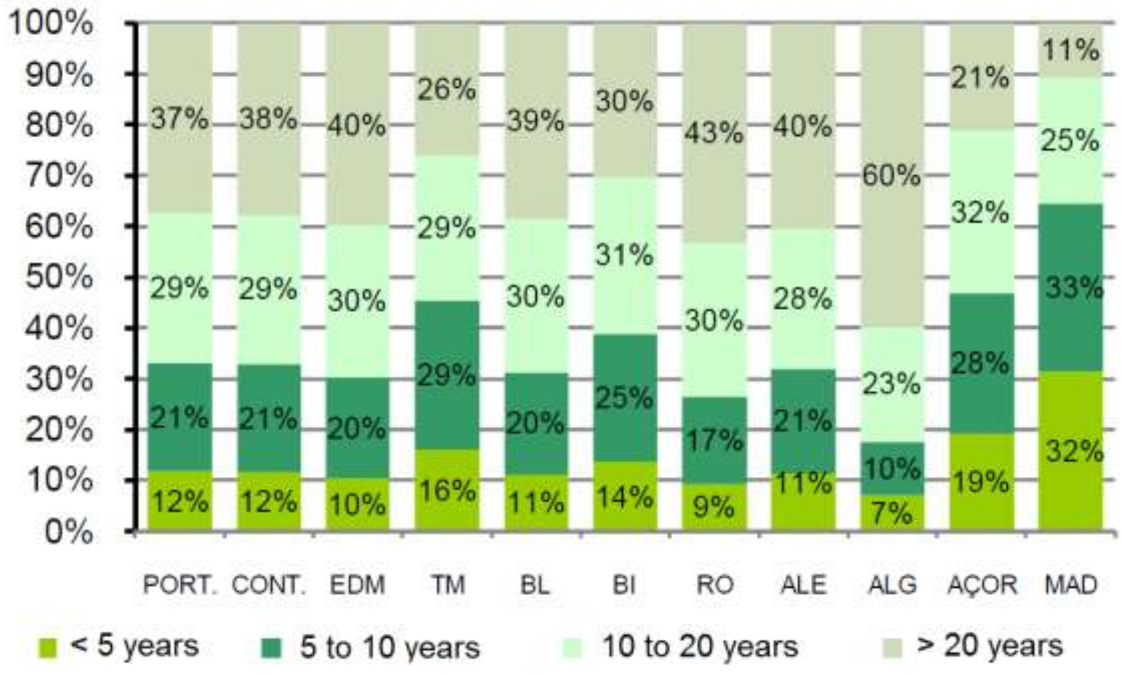


Figure 3.05 – Distribution of tractors per age in Portugal 2009 [41]

Although same variations from regions to regions, the ones who show bigger differences to the national numbers is Algarve (ALG), where 60% of tractors have more than 20 years and Madeira Island (MAD), where only 11% of tractors have more than 20 years old and tractors up to 5 years represent 32%. This means that in Madeira there were been an investment in tractors in the most recent years.

3.3 Energy sources for Portuguese Agriculture

In Portugal farmers registered in the Portuguese Agriculture Ministry have access to fuel with fiscal bonus. It is called "Gasóleo Agrícola" – Agricultural Diesel. The main difference from the road diesel is the partial or total exemption of consumption tax [43]. This represents around 40% less of final retail cost of diesel to farmers. This is conceded only to agricultural and forest purposes, reducing the overall cost for fuel.

Data of Agriculture Diesel are available and we can observe the evolution from 2006 to 2013 in table 3.06 and figure 3.06 [44].

Table 3.06 – Number of farmers and volume of agriculture diesel 2006-2013 [44]

Year	Farmers	Diesel Volume (m^3)
2006	141 978	230 603
2007	139 358	242 291
2008	137 369	246 992
2009	130 578	229 413
2010	133 172	235 040
2011	138 132	232 942
2012	141 731	232 909
2013	146 290	247 593

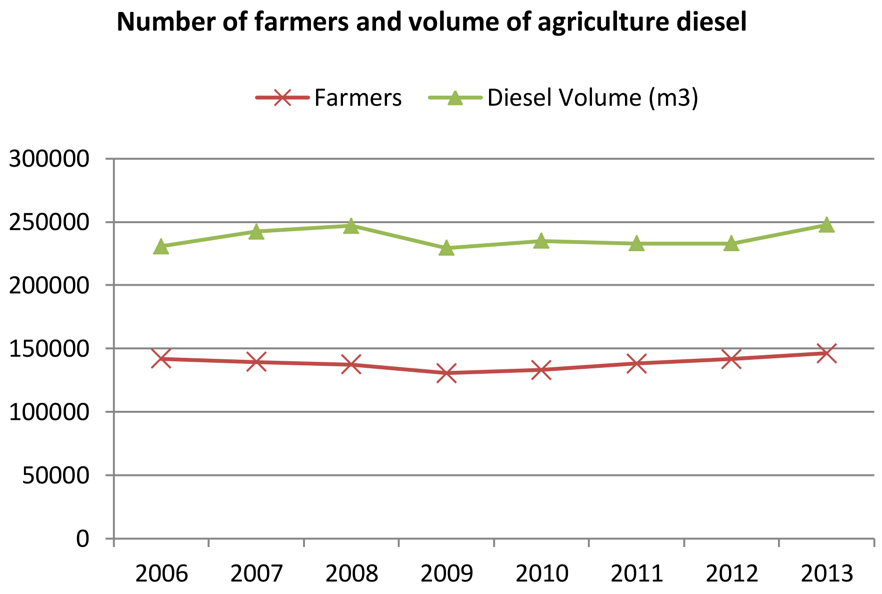


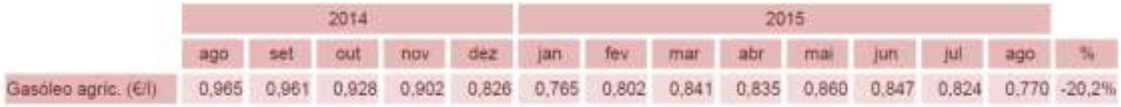
Figure 3.06 – Number of farmers and volume of agriculture diesel 2006-2013 [44]

We can observe that during the financial crisis peak period between 2009 and 2011, both number of farmers and diesel consumption had fallen. A recovery is seen in 2012, where the number of farmers reached pre-crisis values and even overpassed it in 2013. For diesel consumption, 2013 showed an increase of 6.3% when compared to 2012, even passing the 2008 value.

One data we can get from the table is the average diesel consumption by farmer. In the 2006-2013 period, it varied around 1 650 liters per farmer.

Observing the prices of Agriculture Diesel in the period of August 2014 – August 2015, table 3.07, there was a significant reduction of the price in the last year of 20% [45]. Average price during the period was 0.855 €. Taking into account the average consumption of Agriculture Diesel, in average a farmer had spent 1 412 € in a year.

Table 3.07 – Price evolution of agriculture diesel August 2014 – August 2015 [45]



	2014					2015								
	ago	set	out	nov	dez	jan	fev	mar	abr	mai	jun	jul	ago	%
Gasóleo agric. (€/l)	0,965	0,961	0,928	0,902	0,826	0,765	0,802	0,841	0,835	0,860	0,847	0,824	0,770	-20,2%

From 2009, fuel suppliers were forced to introduce an amount of bio diesel to diesel fuel. The amount is regulated by law 89/2008, of May 30th [46]. It is mandatory to incorporate a minimum percentage of 5% of biodiesel in terms of volume. Currently, fuel suppliers declare a use of 7% - Cepsa, Prio and Repsol. Galp declares only 5,5%.

3.4 Environment impact of agriculture machinery in Portugal

3.4.1 Agriculture emissions

Taking in account the FAOSTAT data for Portugal [38] the total emissions related to agriculture where around 6 300 Gigagrams of CO_2 equivalent in 2012. Figure 3.07 shows a minimum in 2010, due to the crisis, where all economic sectors went down. There was a recovery in 2011 and 2012 but below 2007 value.

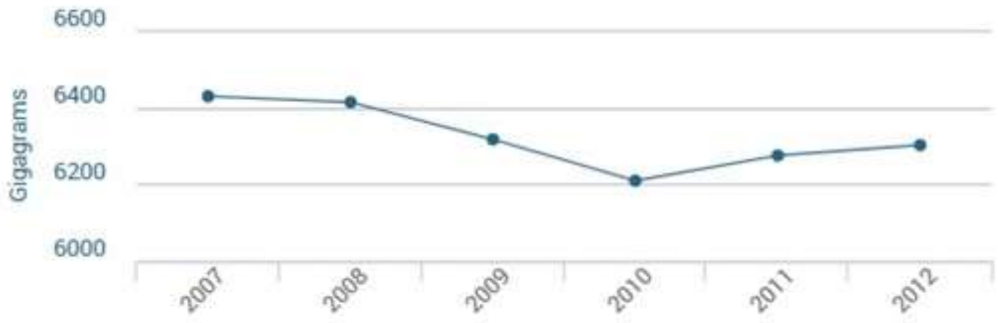


Figure 3.07 – Portugal CO_2 agriculture emissions 2007-2012 [38]

3.4.2 Agriculture energy emissions

Regarding the emissions of carbon dioxide, methane and nitrous oxide gases associated with fuel burning and electricity generation in agriculture (including fisheries) in Portugal, in this case between 2007 and 2011, there was a decrease of 17%, see figure 3.08. One explanation for this may be the stricter emissions regulations for tractors engines, which force fuel consumption reductions and therefore CO_{2eq} emissions.

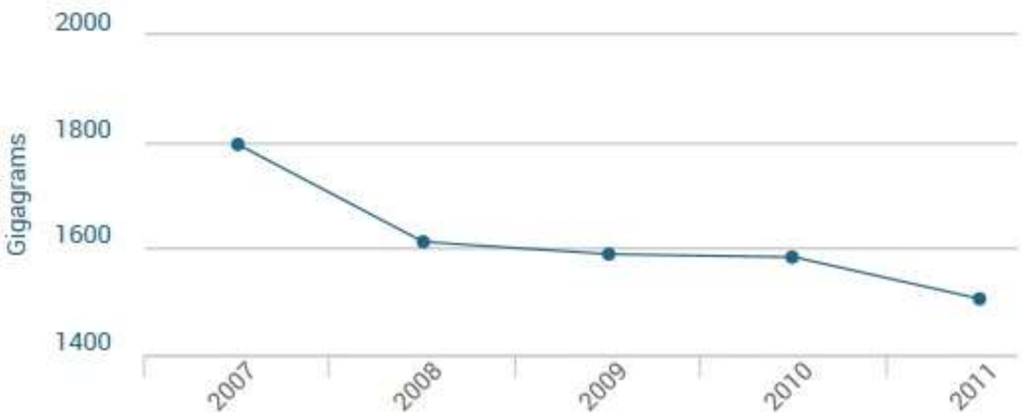


Figure 3.08 – Portugal CO_{2eq} agriculture energy emissions 2007-2011 [38]

Analyzing by energy carrier used, in Portugal there is a dominance of Diesel consumption. Figure 3.09 shows the distribution by energy carrier in 2011 and Diesel is responsible for almost 3/4 of emissions. Electricity trails far behind, with 21.6% and other have marginal values. Gasoline engines represent only 0.4% of total, showing the inexpressive use.

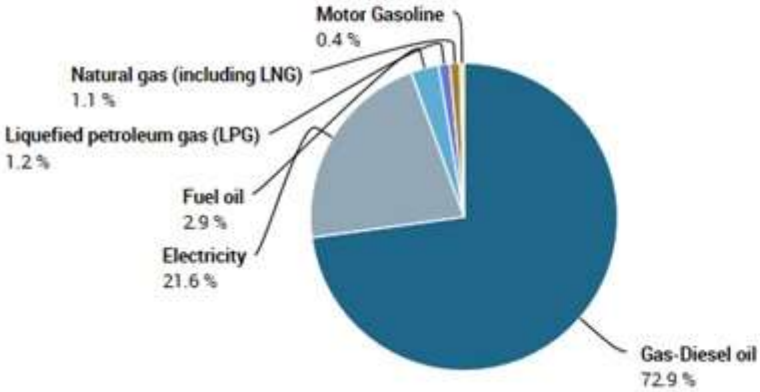


Figure 3.09 – Portugal CO_{2eq} agriculture energy emissions by energy carrier 2011 [38]

3.5 Chapter 3 conclusions

From the data collected in chapter 3 there are some main points to recall:

- Food production value was flat between 1990 and 2000, with a slight improve of 5% in 2014. World's performance was an increase of 73.5% in the same period;
- Agriculture value added per worker is 17.6% of the average of G7 countries;
- Portuguese machinery number is small and old. From 5 to 10 years there are 21% of existing machines, from 10 to 20 years there are 29% and with more than 20 years 37%;
- In average, a farmer had spent 1 412 € on Diesel fuel in 2015;
- Diesel is the main energy source for agriculture emissions, in 2011, accounting for 72.9% of total.

The average cost with Diesel fuel for each farmer is a relative low value but with the results from a survey described in Chapter 4, around 50% of the farmers spend more than 2 500 Euros in fuel annually. With this input, the reduction with fuel cost becomes a more interesting issue to consider.

4 Case Study

This chapter describes the previous tasks performed before the design and prototype building.

The initial idea is presented with a brief explanation.

To better understand tractor's users and owner's needs, a survey was prepared and conducted in the Agriculture National Fair. The most important results are presented and commented.

A search was made to find alternatives presented on the past or nowadays, that could give some hints about the direction for the study. To have a better perception about what main players were working on and disclosure to public, a visit to one of the biggest fairs related to Agriculture – AgriTechnica – was done in 2013.

Also in 2013, some visits were made to the Douro Valley region by this work coordinators. Douro Valley is one of the most famous wine regions in Portugal and recognized worldwide, once there were technical journeys occurring with vineyards owners and experts, to discuss solutions for the needs and problems that the operations in that specific area demand.

After some rounds of visits, a chance was identified to study/solve two distinct problems: energy source and improve adaptation to work on Douro Valleys vineyards. The first problem was related to the aim of this work, the second was due to the difficulty in for the owners to have one machine that could tackle some of the most important constraints: size, equipment availability, weight.

In the end of the chapter an assessment of consumption and emissions of several energy sources is presented, based on the Well to Tank (WTT), Tank to Wheel (TTW) and in the combination of both - Well to Wheel (WTW).

Final decision about the type of machine to be used as the base for the study is presented and justified.

4.1 Initial Idea

Like mentioned in Chapter 1, the purpose of this work was to study an alternative energy source for agricultural machines. The main idea was to adapt a small tractor, around 16/20 hp, to have an electric powertrain, supplied by batteries. This idea took some considerations:

- Purchase a used tractor to perform the change;
- Search for batteries that could fit into available space and economically accessible;
- Search for an electric motor that could replace with no significant loss of available power the original ICE running on Diesel;
- Perform a study how to pack the minimum number of batteries that could guarantee a minimum range.

Due to previous experience with a small tractor, it seemed appropriate to use one of those machines and make the adaptation to battery-electric motor. It would pass to select a used tractor, even with an engine problem, once it wouldn't be needed, take out the ICE engine, commonly a Diesel one and then perform the study to make the adaptation. The kind of tractor to be selected would be a small Japanese tractor, up to 20 hp, like the one in figure 4.01, a Kubota B7001 [47].

Figure 4.01 - Kubota B7001 [47]

Main features of Kubota B7001 are listed in table 4.01 [48]:

Table 4.01 – Main features of Kubota B7001 [48]

Item	Data
Manufacturer	Kubota
Country of origin	Japan
Engine	Kubota 0,8 l 3 Cylinder Diesel
Power	16 hp (11.9 kw)
PTO	13 hp (9.7 kw)
Wheelbase	125 cm
Weight	476 kg
Front tire	5.00 – 12
Rear tire	8-16
Fuel tank capacity	around 10 liters

These features are common to tractors within the same power range, like the Yanmar 1300, Mitsubishi D1300F, Yzeki TS 1610, in which wheel sizes are equal among then.

These tractors have a very simple mechanic, where engine, fuel tank, exhaust are in front of driver. They have a direct steering, with no hydraulic power, once they are quite light and front wheels are small. Normally there is only one clutch, controlled by pedal that drives power to the wheels and also to the Power Take-Off (PTO). There is a three point bridge on the rear, controlled by a simple hydraulic cylinder, powered by a small hydraulic pump connected to engine.

Taking out the engine-transmission package, figure 4.02, it would be replaced by the batteries and electric motor, figure 4.03, which would be connected to the clutch. This might take some chances to be done, once clutch is part of the engine-transmission package and therefore a new clutch would have been needed to adapt to replace the original one.

In terms of schematic, it would be like this:

Figure 4.02 – Placement of engine/transmission in a small tractor

In the place of engine/transmission, a pack of batteries, electric motor, controller and some other components would replace them, figure 4.03.

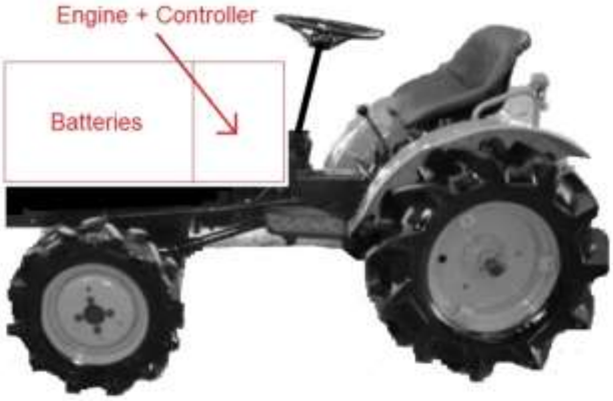


Figure 4.03 – Placement of batteries and electric motor in a small tractor

Batteries initially considered for this application would have been lead-acid, once the cost was the lowest while weight was not a major concern. The biggest issue would have been the quantity needed to ensure a minimum time range and the implications in terms of volume. In this kind of small tractors, front wheel normally stays below the frame, but they have some tilt play, to ensure both front wheels are in contact with the ground, while bigger rear wheels ensure traction.

Even though it would be feasible to pack batteries outside original front body, without interfering with wheels displacement and increasing tractor’s width.

4.2 Survey at Agriculture National Fair – June 2013

During the lectures of the academic year, it was demonstrated the importance of being collected the needs and opinions of end-users of products.

To have a better outlook of the use and some other information about the use of tractors in Portugal, it was considered to perform a survey with tractor owners and users.

During research, it was found a survey performed in Spain in 2005/2006 that involved almost 4 000 tractor owners, on an estimated base of 980 000 existing tractors [49]. The survey was requested by the Agriculture Ministry of Spain and was conducted by a private company under Ministry supervision. In this survey, interviewers gone directly to the properties where the tractors were working.

For the purpose of this study, it was impossible to perform such kind of survey in Portugal. Although the dimension of Portugal is 5 times smaller than Spain, it would involve a dedicated team to define the dimension of the sample, power range, tractor age, location. The time and cost that such survey would require was out of question.

To overcome the impossibility of perform a survey similar to the Spanish one, it was considered to make a survey at the Agriculture National Fair. This Fair takes place every year in Centro Nacional de Exposições – Exhibitions National Center (CNEMA) in Santarém in June. It is the most important event related to Agriculture in Portugal and it lasts for 9 days.

The organization was contacted to know if it was possible to perform a survey with the visitors of the Fair. The reply was positive and the questions form started to be prepared one month before. The final form is presented in Annex 01.

The form had two pages that were asked visitors to answer, if they were tractor owners or users. The form was filled by a contracted person that was following the questionnaire, asking the questions to the interviewed.

The survey started on the first day of the fair and it lasted until the last one. About 140 persons were interviewed, totalizing 196 tractors. Some interviewed had two or more tractors, so the number of tractors overtook the number of owners or users.

4.2.1 Survey results

From the several results of the survey, only a few will be presented.

Interviewed type – the majority of interviewed were individual entrepreneurs, 25% were occasional users and around 10% were workers or managers, figure 4.04.

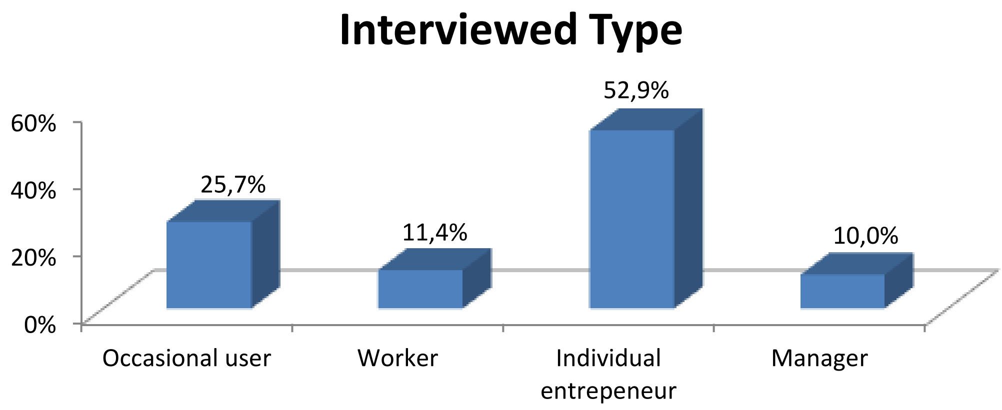


Figure 4.04 – Type of interviewed persons, survey result

Power – Tractors under 40 hp were only 6.6 % of the sample. Tractors in the range of 41-60 hp account for almost 30 %, while ranges 61-80 and 81-100 hp account nearly to 22% each.

Tractors with more than 101 hp worth 20 % of the sample. Power distribution of figure 4.05 is not exactly the same but similar to the one of point 3.3.

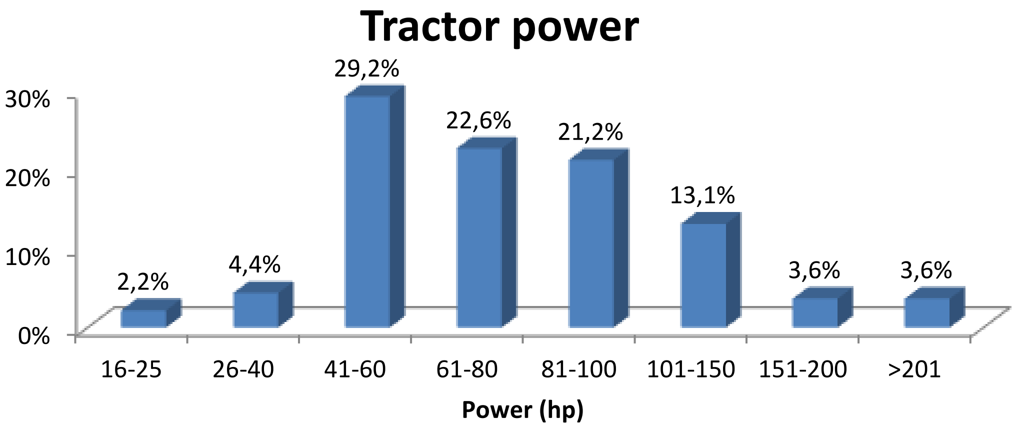


Figure 4.05 – Tractors power range, survey result

Yearly hours of use – more than 50% of tractors are used less than 500 hours in a year, figure 4.06.

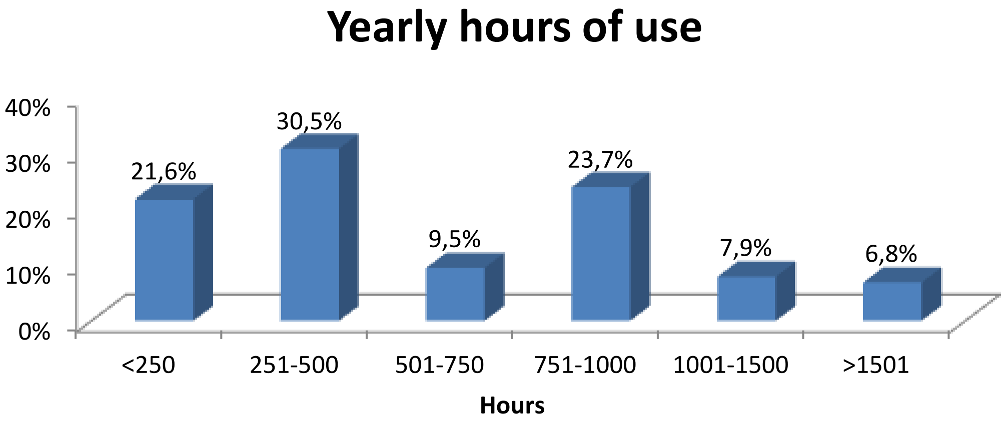


Figure 4.06 – Yearly hours of use, survey result

Main tasks – In the form it was asked to identify the three main agriculture tasks performed by the tractors. Figure 4.07 show that almost 2/3 of the tractors were used in plowing, 39.5 % in harrowing, 36.3 % in transport, 24.4 % in harvest, 15.3 % in spraying and 13.7 % sowing. The two mains tasks are related to soil handling.

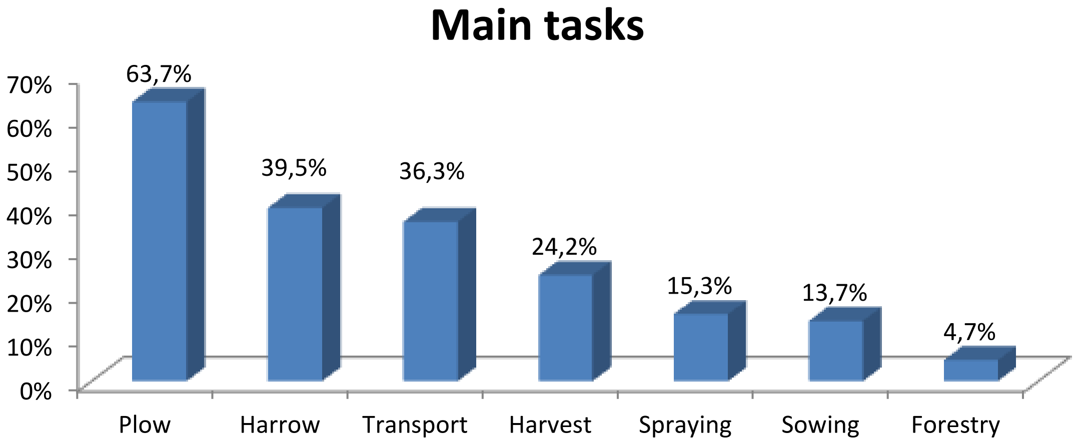


Figure 4.07 – Main tasks, survey result

Annual Fuel Cost – The range between 5 000 and 10 000 euros had 24.7%, the higher compared with other ranges. It is interesting to notice that almost 20% on interviewed does not have an idea about how much they spend in fuel, figure 4.08.

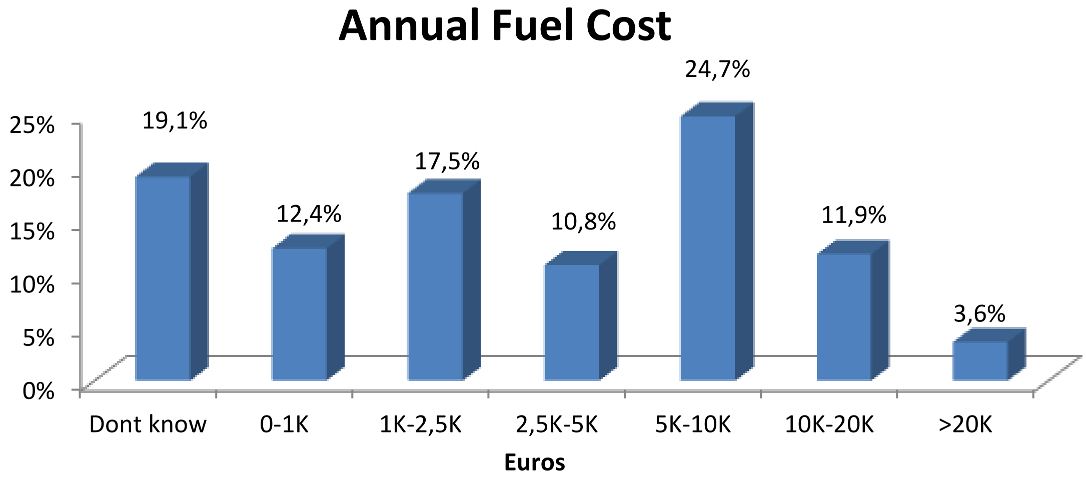


Figure 4.08 – Annual Fuel Cost, survey result

Distance garage – Work spot – 72% of tractors made less than 5 km from the garage where they are parked until the working area. Only 10% made more than 15 km to get the working area, figure 4.09.

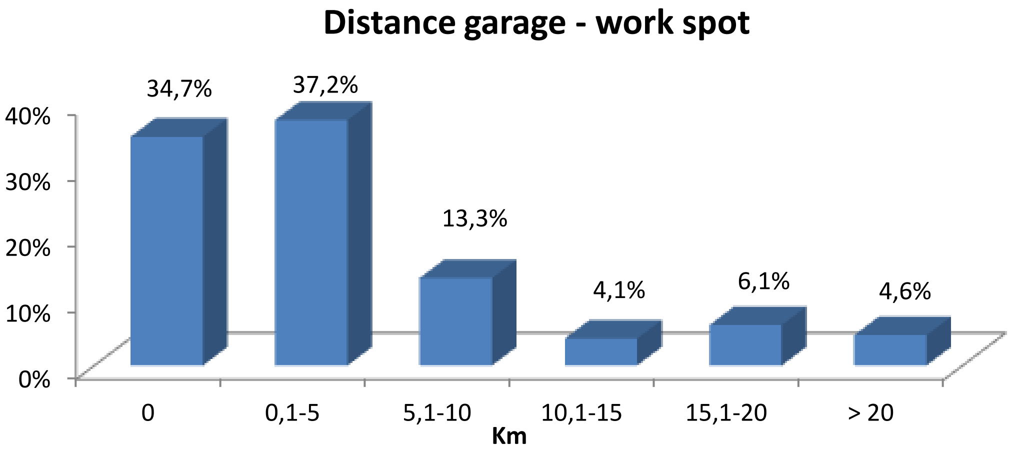


Figure 4.09 – Distance garage - work spot, survey result

Refueling distance – More than 75% of tractors do not travel to a gas station to refuel. They usually are refueled using a jerrycan. Fuel is bought at a gas station with a jerrycan and then this is used to fill tractor fuel tank. This way, tractor does not have to burn fuel or waste time in a non-productive operation.

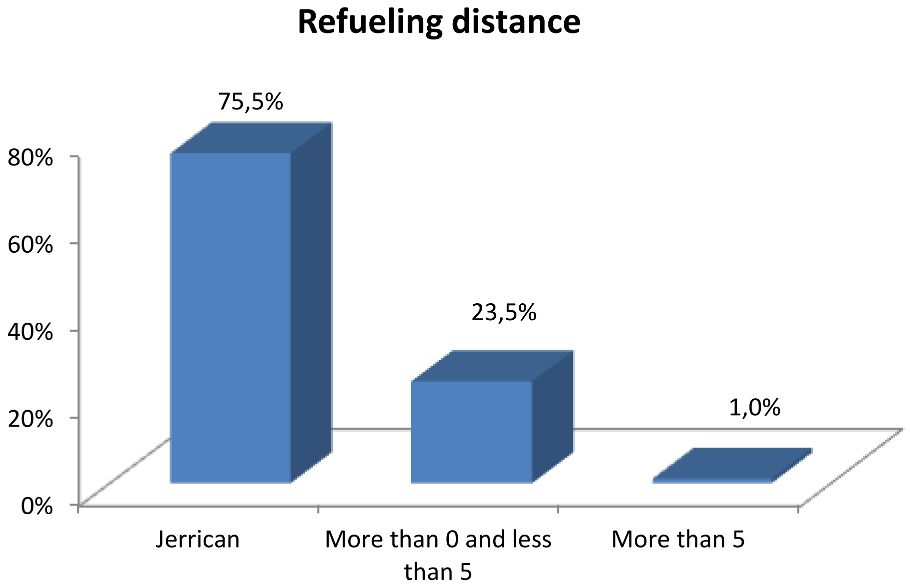


Figure 4.10 – Refueling distance- work spot, survey result

Characteristics – The last section of the questionnaire was to ask the interviewed to rate from 1 to 6, being 1 irrelevant and 6 unquestionable, some characteristics that could be important in the purchase of a tractor.

Table 4.02 shows the results. The characteristic that owners and users consider the most important is the final price, with an average of 5.6. Consumption was the second most important, followed by quality, both with 5.3.

Table 4.02 – Characteristics, survey result

	Score						
Item	1	2	3	4	5	6	Average
Maintenance cost	0	4	13	31	20	21	4.5
Size	0	5	19	18	21	26	4.5
Equipment	0	0	19	23	23	24	4.6
Robustness	0	1	10	34	21	23	4.6
After sales	0	0	15	23	25	26	4.7
Hydraulic slots	0	1	7	22	30	29	4.9
Reliabilty	0	0	4	28	29	28	4.9
Comfort	0	2	6	17	24	40	5.1
Power	0	1	2	21	24	41	5.1
Quality	0	0	2	15	30	42	5.3
Consumption	0	1	2	12	25	49	5.3
Price	0	1	2	5	12	69	5.6

All the data gathered in the survey is available in Annex 02.

4.3 Technical visits

While the initial idea was being considered, at the same time, a program of technical journeys in Douro Valley vineyards, gathering owners, managers, technicians, to discuss some important matters that concern the production of wine.

4.3.1 Douro Valley

Douro valley is a famous wine region, the first one in the world recognized as that, back in 1756, by the Marquês de Pombal [50].

It spreads along of Douro river banks, in the Northeast of Portugal, between the Spanish border in Freixo de Espada à Cinta until Mesão Frio, occupying an area of proximally 250 000 ha, figure 4.11.

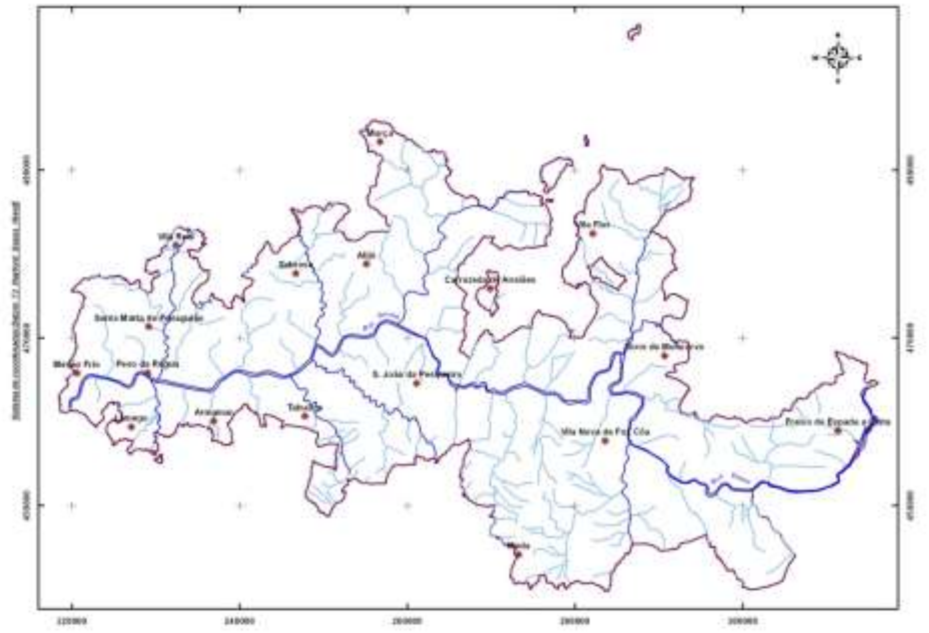


Figure 4.11 – Port wine region [50]

The river runs through a rocky terrain, surround by mountains. It is the combination of the location, climate and geology that makes it suitable for the production of liqueurs wines, with a high alcohol grade .

The most famous product of this region is Port wine, upgraded with grape spirit, which elevates the alcohol grade to 20% in volume. There are dozens of brands of Port wine but only some have international recognition and market. These ones normally belong to the most important Port wine companies that have grape production, wine extraction and treatment, storage, bottling and sales. Some are centennial companies like Real Companhia Velha, Symington, Sogrape, Sogevinus, just to mention the most important.

Port wine currently produced is a blend of tradition and modern technology. New vineyards prepared for mechanization stand side by side with vineyards where a man barely can walk properly, but being this ones the ultimate quality grade . “Old vines” are responsible for the most appreciated wines and the prices follow that rating. Technology is making its way in this region, where manpower and animal power were the drivers to transform a vast landscape along Douro river banks and beyond.

4.3.2. Technical journeys

Wine producers in Douro valley had joined together in an association: ADVID [51]. ADVID is the abbreviation of Associação para o Desenvolvimento da Viticultura Duriense – Douro Viticulture Development Association.

It has more than 100 associates, divided by effective, collective, individuals and honorary. ADVID was the promoter of technical journeys that took place between 2012 and 2014. The technical journeys focused in several themes:

- Environment
- Machines
- Spraying

For each theme there were workshops that took place in farms, visiting their vineyards to watch and discuss *in loco* the relevant issues presented by the attendants.

The contact and participation in these technical journeys only started in July 2013 and ended in May 2014. The description of main issues for each visit is described below.

4.3.2.1 Quinta das Carvalhas – 18th July 2013

Quinta das Carvalhas is a property of Real Companhia Velha, located in the south bank of Douro river, in Pinhão. It occupies a total area of 600 ha, of which 120 ha are dedicated to vineyards [52]. It is a property of great beauty, spreading from the Douro shore until the top of the hill, located at 550 m of altitude, figure 4.12.

Figure 4.12 – Quinta das Carvalhas view

In this technical journey dedicated to the mechanization and pulverization theme, it was the first contact with the characteristics of Douro vineyards. The size of Quinta das Carvalhas allows various types of vineyards, from the centennials to the ones designed for mechanization, and even in this case, with different approaches.

In the demonstration of spraying, a tractor pulling a reservoir of water and a fito treatment element was being pulverized with a mist blower sprayer, figure 4.13.

Figure 4.13 –Spraying demonstration at Quinta das Carvalhas

Performing the spraying from both sides of the vineyard, the technical responsible ensured that all plants were treated, with a minimum spent of time, if compared to a task performed by man with individual sprayers. The amount of the fito treatment element spend with this solution was higher but compensated by the less time spent.

It was interesting to watch and heard other person's opinions, once there was no agreement among the attendants about this kind of solution and the debate that followed was about the pro and cons of their current practices.

4.3.2.2 Maria Alice Company – 5th August 2013

During the initial phase where it was under thought to make an adapted tractor to batteries-electric vehicle (BEV) a horticulture farm was visited in 5th August 2013. The farm was located in Póvoa do Varzim, where there are several horticulture farms that produce vegetables. The farm visited was Maria Alice Company, from which its responsible Rui Ferreira gave some explanations about the main cultures they produce. This farm has open fields and greenhouses.

In the open fields they produced mainly cabbages and inside greenhouses tomatoes, lettuces, onions, French garlic, beans.

All tasks were manually operated except for spraying where a crawled machine was used. Brand was unknown but a 5.5 hp Honda powertrain engine was recognizable, figure 4.14. It had a structure with two wheels which served as a support for the driver, figure 4.15.

The Honda engine had to deliver power not only for the machine movement but also for the spraying equipment.

At the time of the visit, it was harvest period for tomatoes. Tomato's plants were disposed in bands, where each band had two lines of plants, distanced of 40 cm. The distance between lines was of 1.10/1.20 meters. The previously described machine had to operate in these conditions.

Figure 4.14 – Machine for greenhouse spraying

Figure 4.15 – Stand machine for greenhouse spraying

4.3.2.3 Horpozim – 9th October 2013

This meeting was in the sequence of the visit in August to Maria Alice Company. There was some interest in knowing some more details about the practices of the horticulture producers. Horpozim had, at the time, around about 700 associates, in a total of almost 2 000 horticulture farms, in the municipalities of Vila do Conde, Póvoa do Varzim and Esposende.

Through the meeting some relevant data was presented:

- Horticulture area is around 500 ha, 50 % of the one of greenhouses;
- Summer cultures are tomato, lettuce;
- Winter cultures are lettuce, turnip, cabbage and French garlic, these last two in open fields;
- The size of the farms determines the size of the tractor used;
- 80 % of farms have tractor;
- Some farms have a smaller tractor for sanitary treatments;
- Farmers like to buy the biggest tractor to show off;
- There are no subcontracts. Only one company offer services to farms.

Greenhouses and horticulture seemed a good target to perform the study for the alternative energy power source: soil operations are soft, main operation is spraying, there is no rain, no dust and ground is leveled and with no rocks.

4.3.2.4 Quinta das Carvalhas – 7th October 2013

Once in July it was possible to attend the mechanization journey, the technical responsible of Quinta das Carvalhas, Álvaro Martinho, was contacted in order to know if it was possible to make a new visit, to try to see the existing level of mechanization. The answer was positive and the visit took place on October 7th.

By that time it was the grape harvest all along the region and it was possible to observe the operation in a vineyard with top – bottom development. The harvest was being done by 30 workers, supported by two crawled tractors. Workers take the grapes from the vine, place them into boxes and then the tractor carry those boxes from top to bottom. The most noticeable issue was the difficulty that both tractors had to turn down the line of vines. When turning, the rear of the tractor was touching the last vine of the line and the front was touching the vines limiting the way.

In another part of the farm, there was a chance to make the first contact with a 70 years old vineyard. The development is by terrace field, with the following features:

- Uneven terrain, normally with a groove in the middle due to the use of animals that perform the hard work;
- Loose rocks along the paths;
- Ground consistency is very low, with a person weight, it deforms;
- Vines with twisted trunks "invading" the path, limiting the useful wide for a machine. Distance between lines is around 1 000 mm but with the twisted trunks, it is reduced to 600/700 mm.
- Grass and roots along the paths;
- Transitions between terraces with small space and in some case with high slopes.

By observing figures 4.16 and 4.17, it is easy to identify the description.

Figure 4.16 – Old vineyard lines, right view

Figure 4.17 – Old vineyard lines, left view

These types of vineyards are very special for these properties, once they produce the wine with the highest quality and price. There is interest in apply mechanization to this vineyards but due to the constraints, only men and horses or donkeys can maneuver in such close spaces.

4.3.2.5 Quinta das Carvalhas – 8th November 2013

In this technical journey, some more elements related to this work joined the event. It was dedicated to vineyard mechanization.

It was hosted by Eng. º Álvaro Martinho, Technical responsible of Quinta das Carvalhas. There were participants from INEGI/FEUP, ADVID and Sogevinus.

The type of vineyards focused were the traditional ones but already prepared for mechanization, like the ones of figures 4.18 to 4.21.

Figure 4.18 – New vineyard lines, side view 1

Figure 4.19 – New vineyard lines, top view

Figure 4.20 – New vineyard lines, overall view

Figure 4.21 – New vineyard lines, side view 2

Some properties prefer this kind of vineyards because they found an advantage in having a high density of vines per ha. The reason is the less space a vine has, it will concentrate its output in a smaller quantity but better quality grape. In some cases, density can reach 9 000 trees grape plants/ha.

Main characteristics of these vineyards are:

- Very steep slopes, reaching 70 % (around 35 °);
- Terraces are very narrow, with around 1.2 m, where in some parts, due to the twisted trunks, may be limited to 0.8 m;
- Uneven ground and with loose rocks, with areas with no grass;
- Broader access is done by roads on the top and sides of each vineyard.

Although the mentioned constraints, the importance of this kind of vineyard is such that a new vineyard was being prepared, in a very sloped portion, using the traditional approach, figure 4.22.

Figure 4.22 – New vineyard terrain preparation

The next step was to visit the machinery existing for the tasks. Besides some regular tractors that were on the fields, there was a special machine designed to work on narrow and sloped vineyards. It was a Niko machine, model Hydro 6, with an output of 44 kW, built in 2007, figure 4.23 [53]. It is a crawled machine, with several hydraulic connectors to apply equipment.

Figure 4.23 – Niko Hydro 6 machine

This model has a width of 900 mm and was bought with the purpose to work on vineyards starting with a 1.2 m wide. It weights around 1 150 Kg.

It was fitted with an equipment to shred branches after the pruning which was demonstrated to the audience.

The opinion about this Nikko machine was not very positive:

- Low reliability, it was a lot of time broke down due to constant failures. The main reason was because the hydraulic system overheats.
- High cost of rubber bands, due to the fact that its life was around 150 hours.

A description of all tasks performed during the vineyard season was presented:

- Pre-pruning – if possible to cut major branches, manual pruning would be faster (It is not performed in traditional vineyards);
- Branch shredding – shredding the pruning branches in the vineyard contributed to its fertilization and avoid of manual removal;
- Soil mobilization – to allow fertilization of soil, it is done with animal traction;
- Grass maintenance – reduces erosion and keeps water at ground level;
- Spraying – to perform phyto treatments, perhaps the most important task to guarantee a good health of vines and to have sound grapes at the end;
- Green pruning – cut of branches to control vegetal growth, increasing air circulation and access of sprayed products to all leafs;
- Harvest – done manually, tractors remove boxes along the terraces.

4.3.2.6 Technical visit – UTAD / Quinta D. Matilde 20th March 2014

About 4 months later after the visit to Quinta das Carvalhas, a new visit was made to the Universidade de Trás-os-Montes e Alto Douro (UTAD), to the Centro de Estudos Vitivinícolas do Douro (CEVD) and Quinta D. Matilde, with the purpose to gather important information. In this visit there were attendants form INEGI, FEUP, Engenhotec and ADVID.

Visit to UTAD – UTAD is located in Vila Real, in the boundaries of Port wine region. It has an agronomy department, belonging to the Agrar Science and Veterinary School. One of the goals of the agronomy department is to study the mechanization of Douro region. A study was conducted in 2000, about the mechanization of traditional vineyards on the Douro Region [54]. The study focused on different tasks performed in the Douro region and the selected machine to use on the study was a Chappot Multyjip with an output power of 36 hp.

The responsible for the study was Professor Fernando Santos that hosted the visit group to the agronomy department facilities. This department has some machines and equipment to perform some tests, namely a dynamometer bench that is installed in a trailer and can easily be transported to farms, to a power evaluation of tractors and other machines. It is useful equipment, once it allows to tractor owner's to save time and money in traveling to Vila Real.

During the visit there was a chance to discuss the study already mentioned about vineyards mechanization, about the pro and cons of the Multyjip solution. Basically it is an interesting machine, which can perform several tasks but it had some major inconvenient: low weight, instability, low reliability, high investment cost on machine plus equipment.

Visit to CEVD – CEVD is located in Régua. It belongs to the Agricultural Regional Services of Trás-os-Montes, a branch of Portuguese Agriculture Ministry. Its main tasks are to cooperate with other entities on R&D activities, study and definition of grape species, study of knowledge adaptation to the region, training of technical and auxiliary staff of wine production, research experimental management and technical support to sectors related to vineyards and wine production [54].

In CEVD there was a chance to see the machine used on the study performed in 2000 by UTAD. The machine, a Chappot Multyjip [56], was not in working conditions at the time of the visit, but it was told that it normally works and a task was already schedule for it, figures 4.24 and 4.25. The machine had a spraying tank installed and it was normally used like that, to apply phyto sanitary treatments in an experimental vineyard at CEVD.

Figure 4.24 – Chappot Multyjip front view

Figure 4.25 – Chappot Multyjip rear view

There was also the chance to hear some opinions about the machine, by the regular users. Its major inconvenient are the hydraulic system, especially the pipes that may crack, low weight for ground moving operations, bad ergonomic position for the driver, low side stability, cost and low safety due to the command joystick.

Quinta D. Matilde – Quinta D. Matilde is located in Bagaúste, on the north bank of Bagaúste dam, in Régua. It has 93 ha, which 28 ha are grade A vineyards. The visit was hosted by José Carlos Oliveira. This farm has some types of vineyards, from traditional to mechanize design ones, figures 4.26 and 4.27.

Figure 4.26 – Quinta D.Matilde level vineyard

Figure 4.27 – Quinta D.Matilde top-down vineyard

During the visit was demonstrated the use of a crawled tractor. It was a New Holland, model TK 4020F. The driver performed some rounds in a top-down vineyard, to show how easy it can perform its tasks, maintaining a good grip on the steeped terrain, figures 4.28 and 4.29.

Figure 4.28 – Crawled tractor moving upwards

Figure 4.29 – Crawled tractor moving downwards

The top-down vineyard had a distance between lines of 2/2.2 meters and a slope of 40%. The tractor cost was 28 000 Euro, had a consumption of 25 liters per 8 working hours, in average.

Quinta D. Matilde has a 400 liters tank, which is refueled by a diesel provider company that brings diesel that supplies the farm’s tank. It is a service that many farms use to contract.

For the traditional vineyards, there is not a mechanized solution, even for spraying, workers take individual tanks and perform spraying manually.

4.3.2.7 Technical visit - Quinta do Noval – 15th April 2014

Next technical visit was held in Quinta do Noval, in Pinhão, Alijó. Quinta do Noval is located around 5 km north to Pinhão and it is exposed to all cardinal points. Its altitude varies from 100 to 500 m. Quinta do Noval has several of the most awarded Port Wines and it is recognized by the excellency of its wines.

This visit was organized with the agronomy technician José Eduardo Costa. During the visit at CEVD in the previous month, we had the information that Quinta do Noval had two Chappot Multyjip machines, so there was an obvious interest to see what the use those machines were subject to.

Quinta do Noval occupies a total area of 147 ha, divided by:

- 58 ha are in terraces with distance between vine lines of 1.60/1.70 m
- 110 ha in terraces with distance between vine lines of 2.00/2.10 m
- 10 ha in top-down vines with distance between vine lines of 2.00/2.10 m

Therefore Quinta do Noval has already a reasonable area prepared for mechanization, figures 4.30 and 4.31.

Figure 4.30 – Quinta do Noval top view

Figure 4.31 – Quinta do Noval level vineyard

In terms of machines, Quinta do Noval had the following:

- A crawled Valpadana tractor, with 1.12 m wide
- A wheeled New Holland tractor T4020 V
- A crawled Chappot Multyjip 45 hp, 900 mm wide, figure 4.33
- A crawled Chappot Multyjip 36 hp, 800 mm wide, figure 4.32

The 45 hp Multyjip was in working conditions and it was made a demonstration of the mobility inside the terraces and also in the turning between lines. Due to crawlers, it is rather easy to make the exit and entry on a new line, once the radius of rotation can be nearly zero, because one crawler can rotate in the opposite direction of the other, causing a rotation around the center of the machine.

The 36 hp Multyjip was without use for some time. It is equal to the one that belongs to CEVD. The reasons pointed to the lack of use were:

- Low reliability. It had some mechanical problems that affect availability;
- Low stability. Due to the smaller width, it is more unstable when compared with the 45 hp model;

It was also reported that Quinta da Romaneira, which belong to the same owner of Quinta do Noval, had another Chappot Multyjip, with metal crawlers, instead of rubber crawlers of Quinta do Noval machines. The reason was that in two years they had to change 3 times the rubber crawlers due to wear and they expected to have less wear with the metal ones.

Figure 4.32 – Quinta do Noval 36 hp Multyjip

Figure 4.33 – Quinta do Noval 45 hp Multyjip

Mutijyp's use in Quinta do Noval is for the following tasks:

- Spraying;
- Grape harvest transport;
- Ground mover;
- Green pruning;

For these tasks, Chappot Company provided specific equipment.

There were also some interesting information provided by José Costa:

- Multyjip is used between spring and fall. On Winter time, there are no tasks to perform;
- Reversible seat is an advantage, once machine does not need the front end to be faced to the direction of movement;
- Work speed around 1.5 /2 km/hour;
- There is only one company that provides technical assistance in Portugal;
- The 45 hp Multyjip costs around 45 000 Euros;
- Quinta do Noval has placed an order for another 45 hp machine;
- Each pair of crawlers costs 500 Euros;
- The Multyjip needs 3 m to change direction while the New Holland needs 4 m;
- 45 hp Multyjip weights 950 kg, plus 250 kg for the equipment, plus driver, meaning a total weight of 1 300 kg;
- Daily use of 8 hours;
- Fuel tank capacity of 20 liters;
- In green pruning operation it consumes more than one tank each day and it is the most critical task, due to the raise of gravity center, causing more instability;

- Average consumption: 3 liters/hour
- Refueling with a jerry can;
- Yearly use of around 500 hours;
- Fertilizing is one task they were interested that Multyjip could perform;
- There is a lack of operators of these machines. If there were more available, these machines could have more use;

4.3.2.8 Technical visit - Quinta do Noval – 27th May 2014

A new visit was made in 27th May to assist a demonstration of the 45 hp Multyjip. The operation the machine was performing was cutting the upper branches of the vines – green pruning, figure 4.34. This operation is to reduce the amount of mass of the vine, in order to the plant do not waste energy in growing wood mater but to focus on the fruit, the grapes.

In this operation, the 45 hp Multyjip was equipped with a special equipment to perform this task. It consists in a rotating disc with two blades that due to the rotational movement of the disc, cuts the upper part of the vines.

Figure 4.34 – 45 hp Multyjip performing green pruning

The rotation of the disc is made by a hydraulic motor that receives hydraulic fluid from one the exits of fluid available in the front of the Multyjip. It has two guides, from each side of the equipment that helps the operator to align the tool to the center of the line of vines.

The result is shown in figure 4.35, where it is possible to see the top of the vines cut.

Figure 4.35 – Green pruning result

The purpose is to cut the vines around 20/30 cm above the last steel wire that supports the vines.

In this operation, 45 hp Multyjip has autonomy for 6/8 hours, consuming practically all the fuel available in the fuel tank.

4.4 Agritechnica – Hanover 15-16th November 2013

To have a better outlook about the latest products and technology trends, a visit was made to Agritechnica, in 15 and 16th of November 2013. This exhibition takes place at Hanover Messe, a large exhibition center in Hanover. It is spread over 27 pavilions and also an outdoor area.

It is a huge exhibition, where all the biggest manufacturers show all the range of machines, equipment and solutions for agriculture applications but where it is possible to see all kind of other manufacturers, suppliers, services providers, energy solutions. It gives a good survey of the state of the art of technologies related to agriculture.

There was a race between the bigger manufacturers to offer the most powerful tractor, combine or harvester. In terms of emissions regulations, there was a concern all over manufacturers to comply with the latest limits. Ad Blue solution is being used to comply with the latest NO_x limits.

Regarding to the purpose of the visit, there were only a few products which powertrain was not a diesel or gasoline engine.

Merlo presented a front telehandler with a hybrid solution, figure 4.36.

Figure 4.36 – Merlo TF40.7 Hybrid [57]

According to Merlo [57], it was the following features:

- The adoption of a “downsized” 56 kW engine, smaller than the traditional 90 kW version;
- Reductions in fuel consumption and polluting emissions of up to 30%;
- Reduction in noise when working (the electrical function practically eliminates noise altogether);
- Ability to work in close contact with animals and/or food (0 emissions in full electric mode);
- Performance in line with equivalent model equipped with 90 kW internal combustion engine;
- High operational autonomy from 2 to 4 hours depending on use.

These achievements are due to the use of a 30 kWh lithium battery that can provide energy to the electric motor. Battery can be charged also by the diesel engine, when the machine is moving forward and then diesel engine provides power to the movement and charges battery. This prototype was awarded by Agritechnica jury with the Gold Medal, the highest award granted to exhibitors, due to the innovative solution.

Weidemann presented a farm loader, the Hoftrac 1160e, figures 4.37 and 4.38.


Figure 4.37 – Weidemann Hoftrac 1160e – side view


Figure 4.38 – Weidemann Hoftrac 1160e – rear view

It features a travel drive motor with 6.5 kW and hoist motor with 9 kW [57]. It offers two battery options: a standard with 48 V and 240 Ah and an optional also with 48 V with 300 Ah. It was the only non-diesel powertrain in Weidemann portfolio for farm loaders.

John Deere presented a Multi-Fuel tractor, the 6210 RE.


Figure 4.39 – John Deere Multi-Fuel tractor 6210 RE

This Multifuel tractor has only one fuel tank that can be filled with mineral or vegetal fuel. It has sensors to detect the fuel composition and adapt combustion parameters accordingly. It has a 20 kW generator that can be used as an extra boost for transportation or to supply 230 and 400 V plugs, to connect electric equipment [59].

4.5 Comparison between several energy sources

To compare the characteristics of the several energy sources, a search was performed to find academic or institutional research which compared energy sources.

A study on Well to Wheel of European Commission [60] made a comparison between several energy sources and the effects on CO_2 emissions and energy consumption. The analysis is divided in three parts: Well to Tank (WTT), Tank to Wheel (TTW) and finally the junction of the Well to Wheel (WTW).

WTT makes the analysis of the processes needed to make the energy arrive to the energy reservoir, TTW makes the analysis of the energy spend to make a vehicle move and the WTW makes the overall assessment, joining the WTT and TTW. WTW is a relevant evaluation about the efficiency and footprint of each energy source considered.

4.5.1 Well to Tank (WTT)

Each energy source may be produced by different ways, so what is presented are average values. Table 4.03 and figure 4.40 shows WTT values, the energy needed to produce 1 MJ of fuel (MJ_{xt}/MJ_f) and CO_2 emissions (gCO_2eq/MJ_f) [61].

Table 4.03 – Well to Tank energy and emissions for different energies [61]

Energy	**Energy** [MJ_{xt}/MJ_f]	**Emissions** [gCO_2eq/MJ_f]
Gasoline	0.14	12.5
Diesel	0.16	14.2
GPL	0.12	8.0
Biodiesel	1.17	44.3
Alcohol	1.72	22.8
Natural gas	0.25	16.8
Hydrogen	1.06	85.6
Eletricity	1.44	76.4

MJ_f represents one MJ of the finish fuel delivered into the vehicle fuel tank. MJ_{xt} represents the total primary energy expended regardless of its origin to produce one MJ_f of the finished fuel.

Emissions values represent the total grams of CO_2 equivalent grams emitted in the process of obtaining 1 MJ_f of the finished fuel.

In table 4.03, alcohol is considered to be obtained from European crops like sugar beet, wheat, wheat straw and wood/farm wastes.

In this report an additional credit is allocated for the fuels with biomass origin, equal to the amount of CO_2 generated by complete combustion of the fuel. By this way, the TTW CO_2 emission only accounts the fuel composition and not its origin.

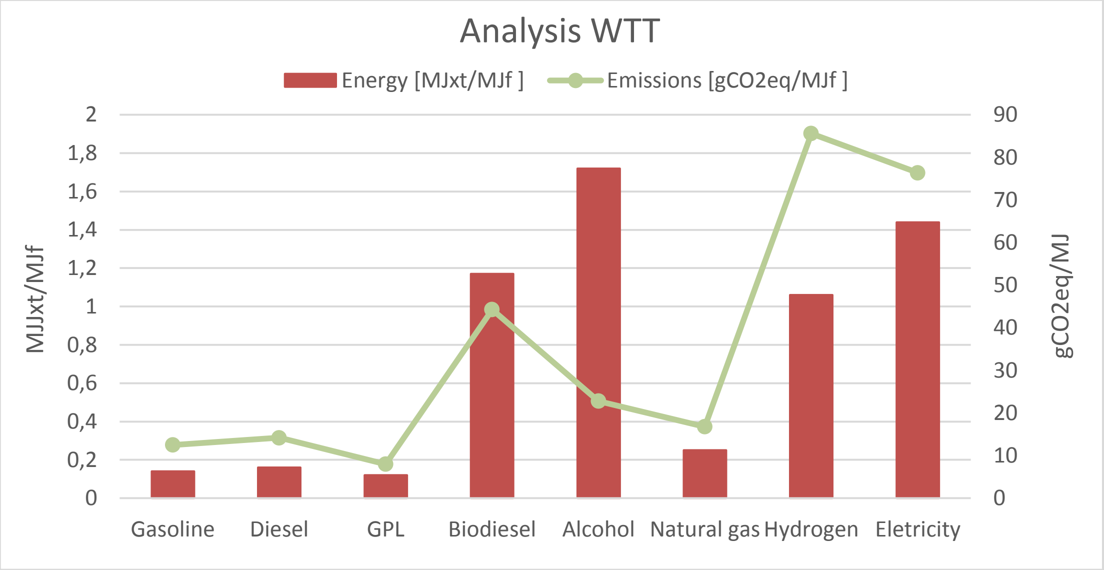


Figure 4.40 – Well to Tank energy and emissions for different energies [61]

It is clear that the fuel that requires less energy and emits less CO_2 to produce one unit of energy is GPL, followed by gasoline and diesel. Electricity, in the other hand, is the second largest emitter of CO_2 and second most demanding in terms of energy. However, the results associated to electricity concern the production from fossil fuels. If production of electricity is from renewable energy sources, like solar, wind, hydric or thermal, the impact on energy consumption and emission drops considerably.

4.5.2 Tank to Wheel (TTW)

Tank to Wheel results compares the consumption of energy and CO_2 emissions resulting of the use of the energy source in a vehicle.

Energy is measured in MJ / 100 km and emission in gCO_2eq / km, table 4.04 and figure 4.41. For agriculture purposes, the energy consumption for each 100 km and gCO_2 for km is not reasonable. Consumption in agriculture machines is normally measured in liters/ hour. Nevertheless, once the study was conducted with road cars, it is acceptable that those results are compatible for agriculture use.

Table 4.04 – Tank to Wheel energy and emissions for different powertrains and energies

Powertrain	Energy source	Energy (MJ/100 km)	Emissions (gCO_2eq/km)	Fuel consumption (MJ/100 km)	Electric consumption (kWh/100 km)
PISI	Gasoline	221.30	155.8	221.30	
	LPG	215.70	142.5	215.70	
	CNG	232.30	132.6	232.30	
	E85	207.10	148.9	207.10	
DISI	Gasoline	203.80	150.3	203.80	
	LPG	207.80	137.3	207.80	
	CNG	211.80	121.0	211.80	
	E85	198.60	142.8	198.60	
DICI	Diesel	162.50	120.2	162.50	
	Biodiesel (FAME)	162.50	125.0	162.50	
Hybrid DISI	Gasoline	114.70	105.6	114.70	
	E85	138.10	100.3	138.10	
Hybrid DICI	Diesel	128.0	95.6	128.0	
	Biodiesel (FAME)	128.0	99.4	128.0	
PHEV20 DISI	Gasoline	115.85	75.3	101.2	4.07 (14.65 MJ/100 km)
	E85	113.25	71.6	98.6	4.07 (14.65 MJ/100 km)
PHEV20 DICI	Diesel	106.50	68.1	91.6	4.14 (14.90 MJ/100 km)
	Biodiesel (FAME)	106.50	70.9	91.6	4.14 (14.90 MJ/100 km)
REEV80 SI	Gasoline	76.59	25.9	34.9	11.58 (41.69 MJ/100 km)
	E85	75.59	24.4	33.9	11.58 (41.69 MJ/100 km)
BEV	Electricity	52.16	0.0	0	14.59 (52.16 MJ/100 km)
FCEV	CGH2	74.99	0	74.99	

PISI / DISI – Port Injection / Direct Injection Spark Ignited engine
DICI – Direct Injection Compression Ignited engine
Hybrid DISI / DICI – Hybrid Port Injection Spark / Direct Injection Compression Ignited engine
PHEV20 DISI – Plug-In Hybrid Vehicle with Direct Injection Spark Ignited engine with an electric driving range of 20 km (NEDC)
PHEV20 DICI - Plug-In Hybrid Vehicle with Direct Compression Spark Ignited engine with an electric driving range of 20 km (NEDC)
REEV80 SI – Range-Extender Electric Vehicles with an electric driving range of 80 km (NEDC) and a Spark Ignited engine as Extender.
BEV – Battery Electric Vehicle
FCEV – Fuel Cell Electric Vehicle
LPG – Liquefied Petroleum Gas
FAME - Fatty Acid Methyl Ester

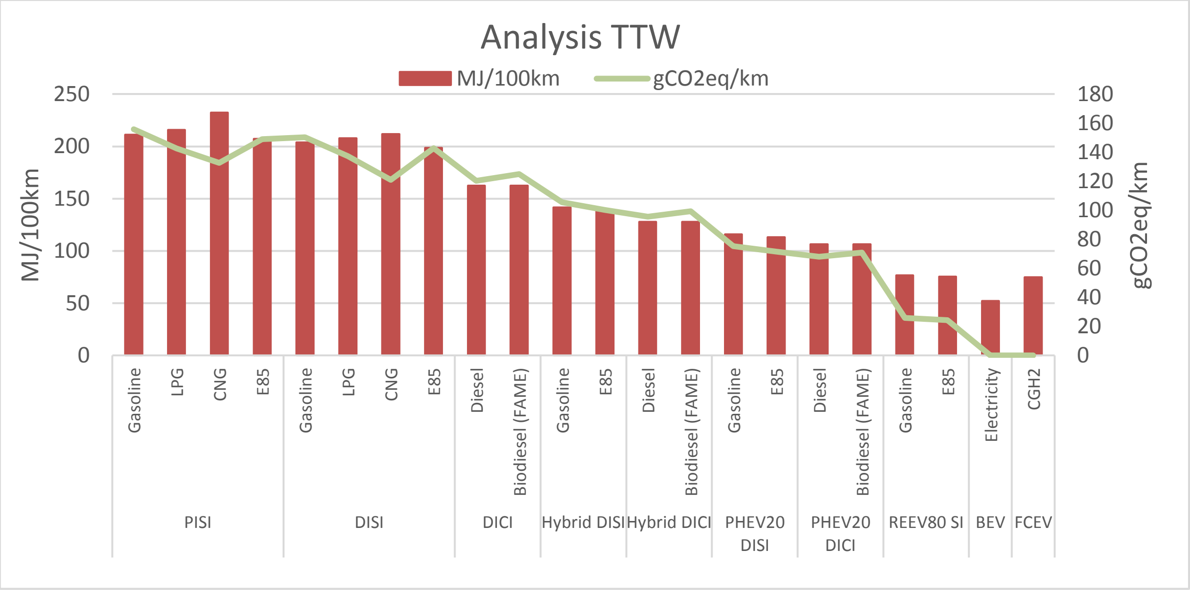


Figure 4.41 – Tank to Wheel energy and emissions for different powertrains and energies

In terms of energy required and tailpipe emissions to make 100 km the best is electricity. It requires only 52.16 MJ and emissions are zero, once there are no fuel combustion. Second best is FCEV, with 74.99 MJ and also zero emissions and REEV SI – Alcohol is third, very close to FCEV in terms of energy but releasing 24.4 g CO_2.

The comparison between diesel and BEV powertrains, in terms of energy gives:

$$Ratio\,\frac{Diesel}{Electricity} = \frac{162.50}{52.16} = 3.12 \quad (4.1)$$

To cover the same distance a diesel powertrain requires more than 3 times the energy of an electric one. Also means diesel powertrains have 32.1 % of the efficiency of an electric one.

Figure 4.42 show the comparison between the 2010 status and the expected 2020 status in result of technology evolution.

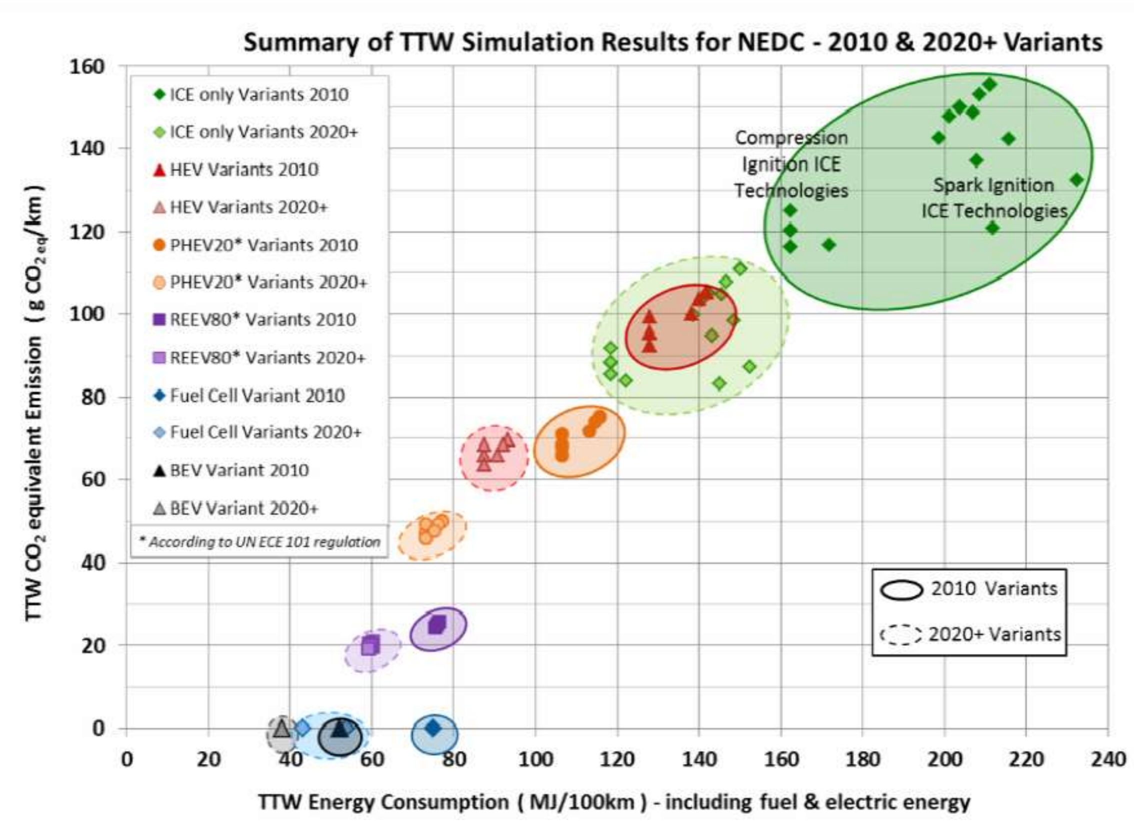


Figure 4.42 – TTW summary results for NEDC – 2010 and 2020 [61]

Despite the positive evolution expected for Internal Combustion Engines (ICE), there will be a considerable gap between them and electric powertrains like BEV and FCEV solutions. In these two cases, emissions are impossible to improve, once they are zero but even energy consumption is expected to decrease, keeping the efficiency ratio more or less at the same level as in 2010.

4.5.3 Well to Wheel (WTW)

In this section one combines the production and transport (WTT) with consumption (TTW), being the combination the best way to show the impact on energy and emissions.

To combine the results of WTT and TTW sections, equation 5.1 is used to determine the total energy required and equation 5.2 to determine the total gCO_{2eq} required.

Total WTW energy (MJ/100 km) =

$$\mathrm{TTW\ energy(MJf/100\ km\ )x\ (1\ +\ WTT\ total\ expended\ energy(MJxt/MJf\ )}\quad (4.2)$$

WTW GHG (gCO_{2eq}/km) =

$$\mathrm{TTW\ GHG(gCO2eq/km)} + \frac{\mathrm{TTW\ energy(MJf\ /100km)}}{100} \mathrm{x\ WTT\ GHG(gCO2eq/MJf\ )}\quad (4.3)$$

Table 4.05 and figure 4.43 show the results for the WTW analysis.

Table 4.05 – Well to Wheel energy and emissions for different powertrains and energies [61]

Powertrain	Energy source	Energy MJ/100 km	Emissions gCO_2eq/km	Fuel energy MJ/100 km	Electric energy MJ/100 km
PISI	Gasoline	240.88	182.2	240.88	
	LPG	241.58	159.8	241.58	
	CNG	289.99	171.7	289.99	
	E85	563.31	196.1	563.31	
DISI	Gasoline	232.33	175.8	232.33	
	LPG	232.74	153.9	232.74	
	CNG	264.40	156.7	264.40	
	E85	540.19	188.1	540.19	
DICI	Diesel	188.50	143.3	188.50	
	Biodiesel (FAME)	352.08	197.0	352.08	
Hybrid DISI	Gasoline	161.54	123.3	161.54	
	E85	375.63	131.8	375.63	
Hybrid DICI	Diesel	148.48	113.8	148.48	
	Biodiesel (FAME)	277.33	156.1	277.33	
PHEV20 DISI	Gasoline	151.07	99.1	115.37	35.70
	E85	303.89	84.5	268.19	35.70
PHEV20 DICI	Diesel	142.57	92.5	106.26	36.31
	Biodiesel (FAME)	234.78	122.9	198.47	36.31
REEV80 SI	Gasoline	141.35	62.1	39.79	101.57
	E85	193.78	64.0	92.21	101.57
BEV	Electricity	127.09	39.8		127.09
FCEV	CGH2	154.20	64.2	154.20	

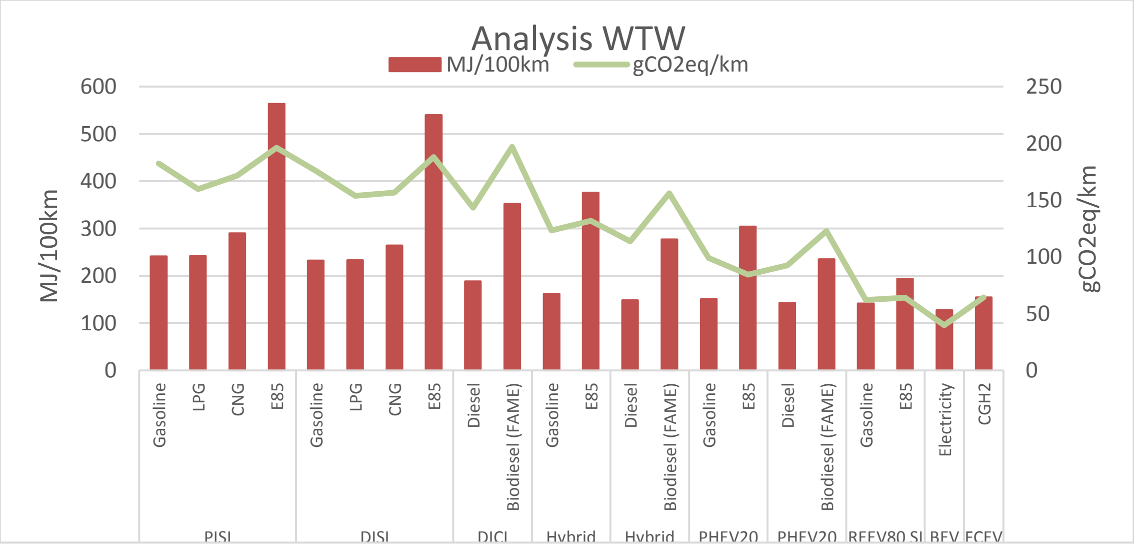


Figure 4.43 – Well to Wheel energy and emissions for different powertrains and energies [61]

4.5.4 Cost of energy sources

Despite the aim of the study is to validate an energy source with a smaller impact in terms of emissions, it is important that the energy source may be economically feasible. Therefore it is important to assess the cost of the various energies.

An analysis of the retail price of several fuels is presented next, not just for Portugal but also for Brazil, USA and UK, once there are some fuels that are not available in Portugal.

4.5.4.1 Gasoline, Diesel and LPG

Table 4.06 presents the gasoline, Diesel and LPG prices across EU28 countries in 11/2016 [62]

Table 4.06 – Gasoline, Diesel and LPG prices across EU28 countries [62]

Country	Unleaded 95 RON		Diesel		LPG	
Austria	€ 1.098		€ 1.038		€ 0.659	
Belgium	€ 1.379		€ 1.277		€ 0.447	
Bulgaria	€ 1.023	BGN 2.020	€ 1.003	BGN 1.980	€ 0.456	BGN 0.900
Croatia	€ 1.222	HRK 9.210	€ 1.153	HRK 8.690	€ 0.541	HRK 4.080
Cyprus	€ 1.158		€ 1.143		-	
Czech Republic	€ 1.088	CZK 29.400	€ 0.995	CZK 26.900	€ 0.463	CZK 12.500
Denmark	€ 1.503	DKK 11.190	€ 1.315	DKK 9.790	-	
Estonia	€ 1.149		€ 1.149		€ 0.519	
Finland	€ 1.404		€ 1.255		-	
France	€ 1.326		€ 1.174		€ 0.691	
Germany	€ 1.339		€ 1.159		€ 0.539	
Greece	€ 1.419		€ 1.097		€ 0.697	
Hungary	€ 1.124	HUF 351.10	€ 1.162	HUF 363.00	€ 0.640	HUF 200.10
Ireland	€ 1.319		€ 1.199		€ 0.619	
Italy	€ 1.516		€ 1.363		€ 0.539	
Latvia	€ 1.104		€ 1.009		€ 0.509	
Lithuania	€ 1.079		€ 0.979		€ 0.499	
Luxembourg	€ 1.132		€ 0.978		€ 0.460	
Malta	€ 1.270		€ 1.140		-	
Netherlands	€ 1.621		€ 1.295		€ 0.756	
Poland	€ 1.000	PLN 4.310	€ 0.974	PLN 4.200	€ 0.436	PLN 1.880
Portugal	€ 1.499		€ 1.284		€ 0.583	
Romania	€ 1.125	RON 5.080	€ 1.105	RON 4.990	€ 0.438	RON 1.980
Slovakia	€ 1.150		€ 1.000		€ 0.390	
Slovenia	€ 1.245		€ 1.149		€ 0.615	
Spain	€ 1.185		€ 1.087		€ 0.553	
Sweden	€ 1.274	SEK 12.690	€ 1.279	SEK 12.740	€ 0.904	SEK 9.000
United Kingdom	€ 1.294	GBP 1.160	€ 1.315	GBP 1.179	€ 0.659	GBP 0.591

There are significant differences between fuel prices between EU countries. Despite some variations with raw material – crude – the biggest reason for the differences is the taxes applied. That is why in Poland has the cheaper price in gasoline and diesel, The Netherland the most expensive gasoline and UK the most expensive diesel. Regarding LPG, Poland has the cheapest and Sweden the most expensive, more than double of the Polish price.

4.5.4.2 Agriculture Diesel

Agriculture diesel was mentioned in 3.4 and it is used widely in Portugal by farmers. Its cost in March 2014 and November 2016 is on table 4.07 [63]:

Table 4.07 – Agriculture diesel prices in Portugal [63]

Fuel	18/03/2014	01/11/2016
Diesel	1.389€	1.299€
Agriculture Diesel	0.989€	0.829€

In Portugal Agriculture Diesel benefits from a tax exemption of the Petroleum Products Tax, which allow it to cost 71.2% of diesel in March 2014 and 63.8% in November 2016.

4.5.4.3 Biofuels

Biofuels are probably the easier alternative fuels to replace fossil fuels. Mainly the ones that are commercialized in liquid are quite easy to replace diesel or gasoline in ICE. Considering this, a better description of the available and in development bio fuels is presented.

According to Energy International Agency (EIA), biofuel refer to liquid or gaseous fuel produced with plants or animals organic derivatives and can be divided in 3 generations [64]. EIA classifies bio fuels by the maturity of technology and comments that advanced biofuels performance not always is higher than conventional bio fuels. There are several technologies to obtain the same type of bio fuel (different is their chemical properties) starting from different raw materials. For example, bio fuel production from biomass can be made with three technologies: physical-chemical, biochemical and thermochemical. Each one of those technologies has different complexities and different ways of obtaining bio fuels [65]. Figure 4.44 show the processes to obtain bio fuel, from raw material to final use. Figure 4.45 show a similar scheme, dividing raw material by the level of maturity [66].

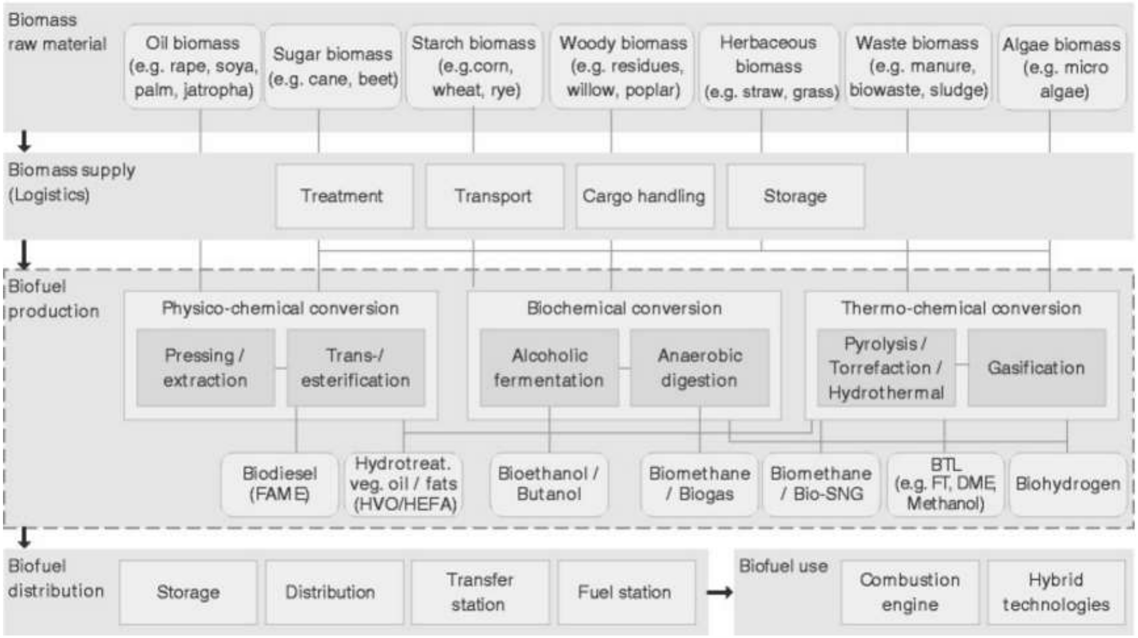


Figure 4.44 – Bio fuels production process [65]

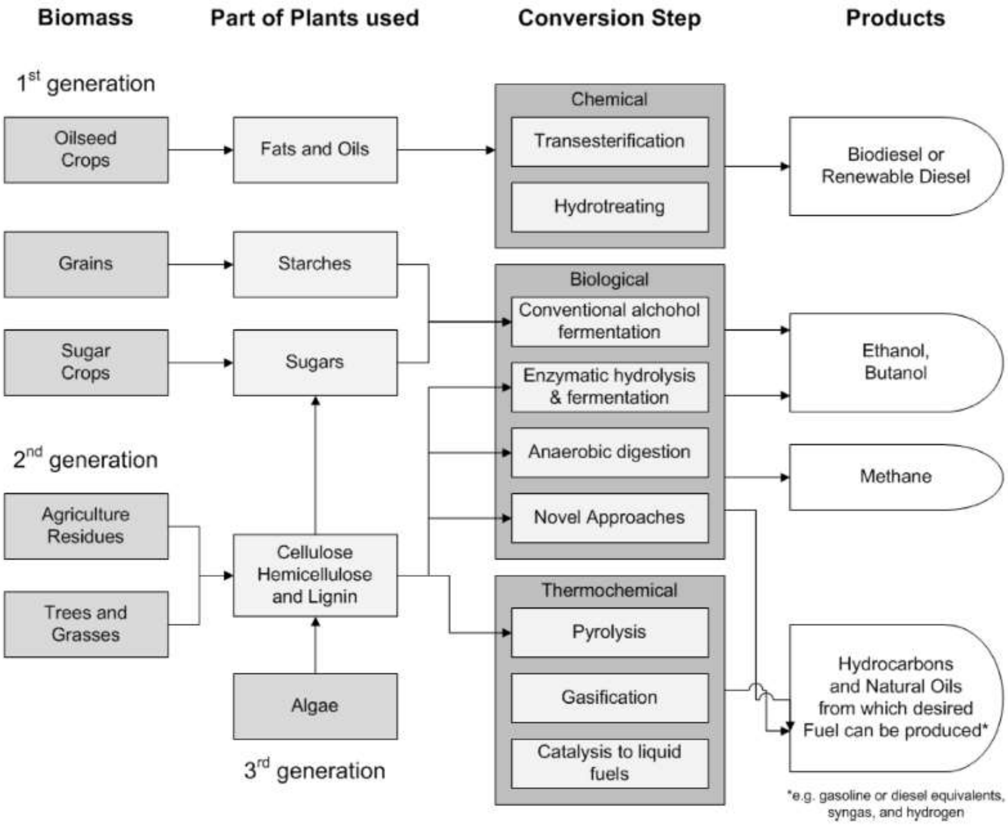


Figure 4.45 – Bio fuels production scheme by level of maturity [66]

EIA considers that conventional technologies for bio fuel production are the ones that use mature production processes, which allow bio fuel production at a world scale. In this case are considered first generation bio fuels like ethanol, obtained from amide and sugar, bio diesel obtained from vegetation and bio gas obtained from anaerobic digestion also designated by bio gasification or bio methanization.

Raw materials in these processes are: sugar cane, sugar beet, corn and wheat grains, vegetable oils like soy and palm, animal fat and used kitchen oil. Advanced technologies to obtain bio fuels are the ones that are still in R&D phase or demonstration. These bio fuels are designated by second or third generation. Here is included hydrotreated vegetable oil (HVO), which base is vegetable and animal fat; bio fuels with base in lignocellulosic biomass (dry vegetable raw material) like cellulosic-ethanol, BtL-diesel (biomass-to-liquid BtL) and bio-synthetic gas (bio-SG). In this category area also inserted new technologies like bio fuels obtained from algae and conversion of sugar in bio diesel using biologic or chemical catalyst.

Main attention will be given to biodiesel and hydrotreated vegetable oil (HVO), the ones who replace fuel in tractors diesel ICE.

4.5.4.3.1 Biodiesel

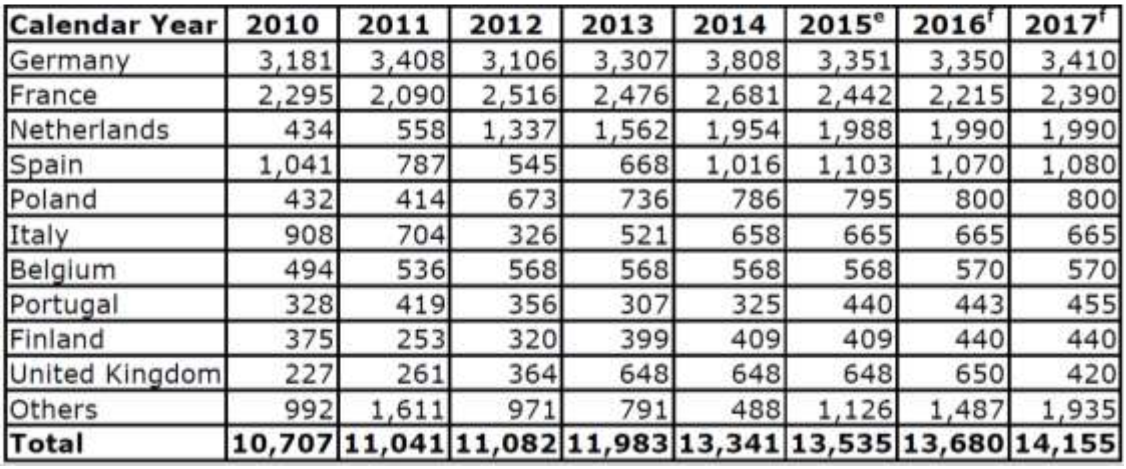
Biodiesel was the second most produced biofuel in 2013 behind ethanol, representing 22.6% of world's production, totalizing 26.2 billion liters, for which Europe contributes with 40%.

Chemical structure of bio diesel contains oxygen, beyond hydrogen and carbon, resulting in inferior physical-chemical properties to diesel. Due to a higher freezing point of biodiesel when compared to diesel, it is blended in small quantities with diesel, if fuel is to be used at low temperatures.

The 2016 Biofuels Annual Report [67] includes first generation of biodiesel (fatty acid methyl ester – FAME) and hydrogenated vegetal oil (HVO) representing 80% of the world biofuels market.

Most of European countries produce biodiesel. In 2014 biodiesel production grew 11% due to the consumption in Germany and Spain. Table 4.08 shows the main biodiesel European producers and figure 4.46 show the evolution of biodiesel consumption, production, import and export in Europe.

Table 4.08 – Production of biodiesel in the main European producers (million liters) [67]



Calendar Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015e**	**2016f**	**2017f**
Germany	3,181	3,408	3,106	3,307	3,808	3,351	3,350	3,410
France	2,295	2,090	2,516	2,476	2,681	2,442	2,215	2,390
Netherlands	434	558	1,337	1,562	1,954	1,988	1,990	1,990
Spain	1,041	787	545	668	1,016	1,103	1,070	1,080
Poland	432	414	673	736	786	795	800	800
Italy	908	704	326	521	658	665	665	665
Belgium	494	536	568	568	568	568	570	570
Portugal	328	419	356	307	325	440	443	455
Finland	375	253	320	399	409	409	440	440
United Kingdom	227	261	364	648	648	648	650	420
Others	992	1,611	971	791	488	1,126	1,487	1,935
Total	**10,707**	**11,041**	**11,082**	**11,983**	**13,341**	**13,535**	**13,680**	**14,155**

e = estimate / f = forecast EU FAS Posts. Source FAZ EU Posts based on information in MT and converted to liters using a conversion rate of 1 MT = 1.136 liters.

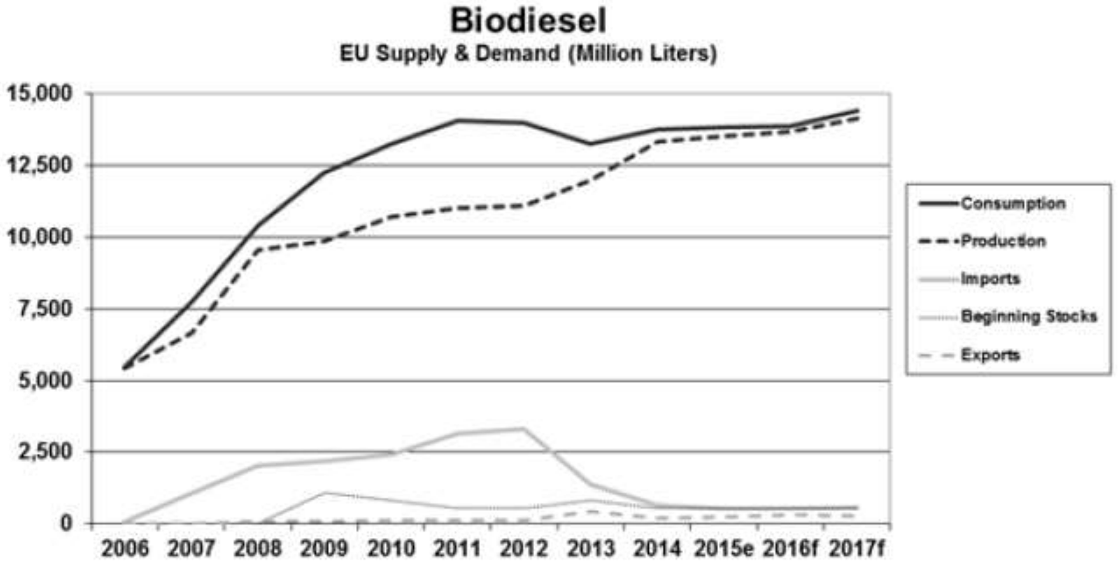


Figure 4.46 – Biodiesel supply and demand in EU [67]

Until the spring of 2015 Portugal only produced biodiesel. From then bio-ETBE production started, obtained from bioethanol destined to European gasoline market [68]. Most of the production capacity was installed between 2006 and 2009, with an increase between 2013 and 2013 which allowed reaching 650 M ton per year [69].

According to the Direção Geral de Energia – Energy General Directorate (DGEG), there is no station selling 100% biodiesel in Portugal [70]. In March 2014 there was at least one station, practicing prices similar to diesel, table 4.09.

Table 4.09 – Biodiesel prices in Portugal [70]

Fuel	18/03/2014	01/11/2016
BioDiesel	1.394€	n.a.

In US, Biodiesel is distributed in two products: B20 and B99/B100. B20 means fuel has 20 % of biodiesel and 80% is conventional diesel. B99/B100 means that fuel has only 100% biodiesel. Their costs across US, in July 2016 are in tables 4.10 and 4.11 [71]:

Table 4.10 – Biodiesel (B20) and Diesel prices in USA [71]

Biodiesel (B20) and Diesel Average Retail Prices by Region

Region	B20 Prices ($/gal)	Diesel Prices ($/gal)	Price Difference*
New England	$2.62	$2.56	$0.06
Central Atlantic	$2.68	$2.83	-$0.15
Lower Atlantic	$2.20	$2.28	-$0.08
Midwest	$2.42	$2.28	$0.14
Gulf Coast	$2.34	$2.15	$0.19
Rocky Mountain	$2.43	$2.31	$0.12
West Coast	$2.83	$2.75	$0.08
NATIONAL AVERAGE	$2.54	$2.46	$0.08

*Negative numbers represent average B20 prices that are lower than diesel, on a $/GAL basis.

Table 4.11 – Biodiesel (B99/B100) and Diesel prices in USA [70]

Biodiesel (B99/B100) and Diesel Average Retail Prices by Region

Region	B99/B100 Prices ($/gal)	Diesel Prices ($/gal)	Price Difference*
New England	$2.22	$2.56	-$0.34
Central Atlantic	$2.55	$2.83	-$0.28
Lower Atlantic	$3.14	$2.28	$0.86
Midwest	---	$2.28	---
Gulf Coast	$2.17	$2.15	$0.02
Rocky Mountain	---	$2.31	---
West Coast	$3.26	$2.75	$0.51
NATIONAL AVERAGE	$3.03	$2.46	$0.57

*Negative numbers represent average B99/B100 prices that are lower than diesel, on a $/GAL basis.

By July 2016, B20 price was aligned, in average, with conventional diesel. B99/B100 is in average US$0.57 more expensive than conventional diesel and varies from US$2.17 in Gulf Coast to US$3.26 in West Coast, a US$1.09 difference.

4.5.4.3.2 Hydrotreated Vegetal Oil - HVO

Hydrotreated Vegetal Oil (HVO) is a first generation biofuel that presents the best quality in terms of physical-chemical properties, even if its raw material can have lower quality than the one used to produce biodiesel. Neste Oil, a Finish company is world leader in HVO production, with a 69% share of world market.

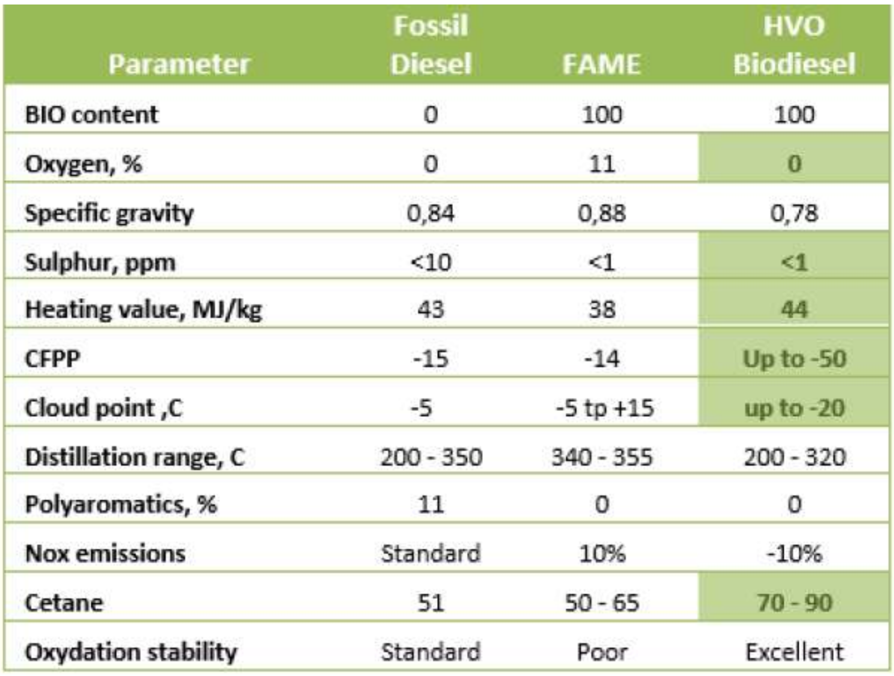
To obtain HVO, hydrogen is used as catalyst instead of methanol, used in biodiesel. Sub product is not glycerin, which is a raw material for bio methanol but propane gas. Another difference for biodiesel is that the HVO process eliminates all oxygen present in the vegetable oils, helping to prevent oxidation. HVO can be blended with conventional diesel in any percentage without need to change engine components. A HVO refinery can be used also to produce Green Jet Fuel, Green Naphtha and Green LPG, beyond propane and other sub products inherent to HVO production.

It is important to mention that HVO production respects UE values for a reduction of 35% in GHG until 2017 and 50% beyond. The investment in HVO refineries is high due to the equipment needed to perform hydrogenation. This investment is compensated by the used of low quality raw material: kitchen used oil, animal fat and palm oil, and also by the fact that subproducts have a higher value when compared to glycerin obtained in biodiesel process.

Main strong advantages of HVO are: high cetane number, high Energy density and absence of oxygen. But main advantage is that Cold Filter Plugging Point (CFPP) can go below -20ºC or even -50ºC. This makes HVO an ideal fuel to be used in cold weather conditions and in aviation. CFPP is the lower temperature which fuel still flow through a specific filter [72].

All diesel fuels have grease in liquid state, which is essential for a good cetane level. However this grease crystallizes at low temperatures, clogging fuel filters. Cetane level is an indicator of combustion speed and compression for ignition. In table 4.12 the differences between diesel fuels are presented [73].

Table 4.12 – Comparison of several diesel types qualities [73]



Parameter	Fossil Diesel	FAME	HVO Biodiesel
BIO content	0	100	100
Oxygen, %	0	11	0
Specific gravity	0,84	0,88	0,78
Sulphur, ppm	<10	<1	<1
Heating value, MJ/kg	43	38	44
CFPP	-15	-14	Up to -50
Cloud point ,C	-5	-5 tp +15	up to -20
Distillation range, C	200 - 350	340 - 355	200 - 320
Polyaromatics, %	11	0	0
Nox emissions	Standard	10%	-10%
Cetane	51	50 - 65	70 - 90
Oxydation stability	Standard	Poor	Excellent

HVO has better properties than fossil diesel like a smaller specific gravity, less content of sulfur, a lower value of CFPP, reduction of 10% in NOx emissions, a higher level of cetane and excellent oxidation stability. Production of HVO in EU is presented in table 4.13.

Table 4.13 – Production of HVO in the main European producers (million liters) [67]

Calendar Year	2010	2011	2012	2013	2014	2015^{e}	2016^{f}	2017^{f}
Netherlands	0	0	410	872	1,013	1,013	1,218	1,218
Italy	0	0	0	0	462	462	462	577
Finland	430	430	430	430	430	545	545	545
Spain	0	28	73	197	377	262	260	160
France	0	0	0	0	0	0	0	192
Portugal	0	0	0	0	0	0	0	31
Total	**430**	**467**	**933**	**1,531**	**2,388**	**2,356**	**2,558**	**2,865**

e = estimate / f = forecast EU FAS Posts. Source FAZ EU Posts based on information in MT and converted to liters using a conversion rate of 1 MT = 1.282 liters.

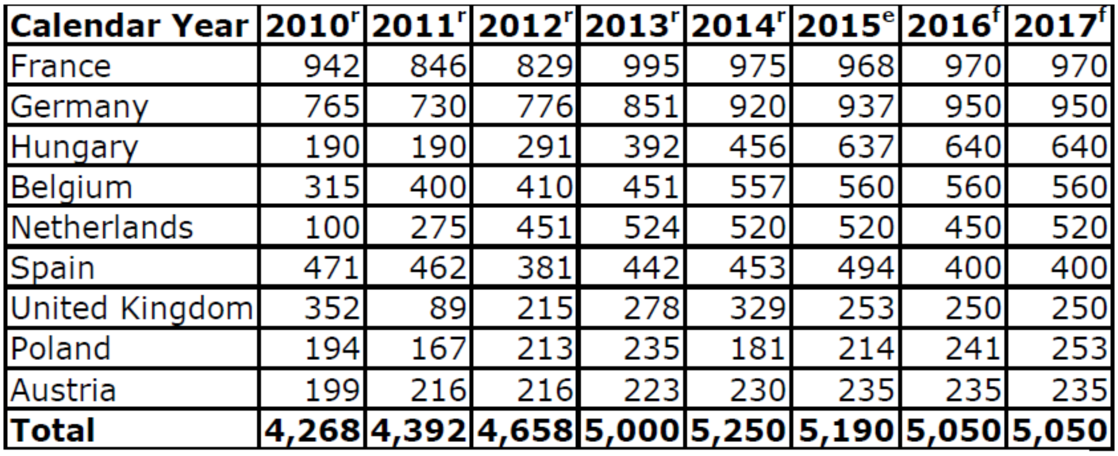
HVO volume in 2010 was inexpressive but it had a big increase between 2011 and 2014, reaching a volume in 2014 five times higher than in 2011. Compared to biodiesel production, in 2010 it represented only 3% but in 2016 it is estimated to reach 18%.

4.5.4.3.3 Ethanol

Bioethanol (ethyl alcohol) or ethanol in Europe is obtained mainly through fermentation of corn or wheat grains and plant sugar components (sugar beet) [61].

Production of ethanol in Europe is shown in table 4.14

Table 4.14 – Production of ethanol in the main European producers (million liters) [67]



Calendar Year	2010^{r}	2011^{r}	2012^{r}	2013^{r}	2014^{r}	2015^{e}	2016^{f}	2017^{f}
France	942	846	829	995	975	968	970	970
Germany	765	730	776	851	920	937	950	950
Hungary	190	190	291	392	456	637	640	640
Belgium	315	400	410	451	557	560	560	560
Netherlands	100	275	451	524	520	520	450	520
Spain	471	462	381	442	453	494	400	400
United Kingdom	352	89	215	278	329	253	250	250
Poland	194	167	213	235	181	214	241	253
Austria	199	216	216	223	230	235	235	235
Total	**4,268**	**4,392**	**4,658**	**5,000**	**5,250**	**5,190**	**5,050**	**5,050**

r = revised / e = estimate / f = forecast EU FAS Posts. Source EU FAS Posts

Ethanol is sold blended with 15% gasoline, identified as E85. This fuel has an octane level of 107, higher when compared to Super Plus gasoline with 98 octane content. However due to the lower level of fossil fuel, engines running with E85 have a higher consumption. These engines are called Flex Fuel and can run either on pure gasoline or E85.

4.5.4.3.4 Biomethanol

Methanol is used mainly for production of formaldehyde, acetic acid and in products such as paints and polymers. Methanol is obtained mainly from syngas (synthetic natural gas) which is produced from fossil sources like natural gas and coal. Biomass can be used to obtain syngas allowing synthesis of biomethanol.

4.5.4.3.5 Biogas

Biogas European sector is very diverse and depends on the priorities of each country. Biogas can be used for residual management, used as a renewable Energy source or in a combination of both. 93% of biogas produced in Germany – responsible for 63% of biogas production in Europe in 2014 – is produced from fermentation of agriculture residuals while in other countries like Portugal, biogas sources are sanitary landfill and sewers. Biogas production has a main benefit, 1 kW of electricity produced with biogas prevents emissions of 7 000 kg of CO_{2eq} to the atmosphere [74].

4.5.4.4 LPG, CNG, LNG

According to the Direção Geral de Energia (DGEG), there are around 50 gas stations selling LPG, 6 selling CNG and 5 selling LNG in October 2016 [75]. Average prices are listed in table 4.15.

Table 4.15 – LPG, CNG, LNG prices in Portugal [75]

Fuel	01/11/2016
LPG	0.519 € / l
CNG	0.873 € /m^3
LNG	1.039 € / kg

4.5.4.5 Electricity

There are various options for residential customers in Portugal. For the case of recharging batteries, a household would require an electrical installation above 6.9 kVA. Considering off peak hour period, for bi or tri-hourly periods, cost is 0.1010 €/kWh [76], table 4.12.

Table 4.16 – Electricity prices in Portugal [76]

		Up to 6,9kVA			Above 6,9kVA		
Price	Hour period	March / 2014	November 2016	Variation	March / 2014	November 2016	Variation
Simple <2,3 kVA	-	0.1317	0.1408	6.91%	-	-	-
Simple >2.3 kVA	-	0.1528	0.1634	6.94%	0.1543	0.1641	6.35%
Bi-hourly	Peak hours	0.1785	0.1909	6.95%	0.1821	0.1947	6.92%
	Off-peak	0.0946	0.1002	5.92%	0.0955	0.1010	5.76%
Tri-hourly	Peak hours	0.2029	0.2169	6.90%	0.2066	0.2208	6.87%
	Full hours	0.1613	0.1716	6.39%	0.1642	0.1747	6.39%
	Off-peak	0.0946	0.1002	5.92%	0.0955	0.1010	5.76%

4.5.5 Cost of energy sources for each 100 km for different powertrains

With the goal to compare the different energy sources in terms of cost, in this section the calculation of cost per 100 km for the different powertrains will be performed. This will be done by joining energy sources price with WTW analysis.

This calculation is done considering that prices in some cases are per liter, others per m^3 and others per Kg. In other to establish a baseline, the properties related to density and energy per Kg of energy sources are in table 4.17 [60].

Table 4.17 – Energy source properties [60]

Energy source properties		
Energy source	Mass density (kg/m^3)	Specific energy (MJ/kg)
Gasoline	745	43.2
Diesel	832	43.0
LPG	550	46.0
Biodiesel	890	37.2
Alcohol	786	29.2
CNG	0.790	45.1
Hydrogen	0.084	120.1

To calculate the cost with fuels per each 100 km:

$$\text{Energy cost} = \frac{\text{Fuel cost}}{\text{Specific energy}} \times \text{Energy spent} \qquad (4.4)$$

To calculate the cost wit electricity per each 100 km:

$$\text{Electricity cost} = \text{Electricity price} \times \text{Energy spent} \qquad (4.5)$$

Table 4.18 shows the results for the considered energy sources in March 2014 [77]:

Table 4.18 – Cost of 100 km for different energy sources [77]

Powertrain		PORTUGAL	BRASIL		USA		UK	
		€/100km	R$/100km	€/100km	$/100km	€/100km	£/100km	€/100km
PISI	Gasoline	11.98	23.20	7.09	6.82	4.90	9.66	11.52
	LPG	8.50						
	CNG	4.72						
	E85		58.91	18.00				
DISI	Gasoline	11.55	22.38	6.84	6.58	4.72	9.31	11.11
	LPG	8.19						
	CNG	4.30						
	E85		56.49	17.26				
DICI	Diesel	7.36	12.56	3.84	5.41	3.89	7.15	8.53
	Agriculture Diesel	5.20						
	Biodiesel	14.35	11.70	3.57				
Hybrid DISI	Gasoline	8.03	15.56	4.75	4.57	3.28	6.47	7.73
	E85		39.28	12.00				
Hybrid DICI	Diesel	5.80	9.90	3.02	4.26	3.06	5.63	6.72
	Agriculture Diesel	4.10						
	Biodiesel	11.30	9.21	2.82				
PHEV20 DISI	Gasoline	7.51	14.55	4.45	4.28	3.07	6.06	7.22
	E85		31.78	9.71				
PHEV20 DICI	Diesel	5.57	9.50	2.90	4.10	2.94	5.41	6.45
	Agriculture Diesel	3.93						
	Biodiesel	9.57	7.80	2.38				
REEV80 SI	Gasoline	7.03	13.62	4.16	4.00	2.87	5.67	6.76
	E85		20.26	6.19				
BEV	Electricity	5.45						
FCEV	CGH2						5.38	6.42

By then, the most economical solution would be the PHEV 20 DICI, running with agriculture diesel, with a cost of 3.93€/100 km.

However, if in the case of BEV, the energy required to have 1MJ is 1.44 MJ, an average value from WTT report [61]. If electricity is considered to be produced from a renewable source, like wind or solar, the WTT will be nearly zero, figure 4.44.

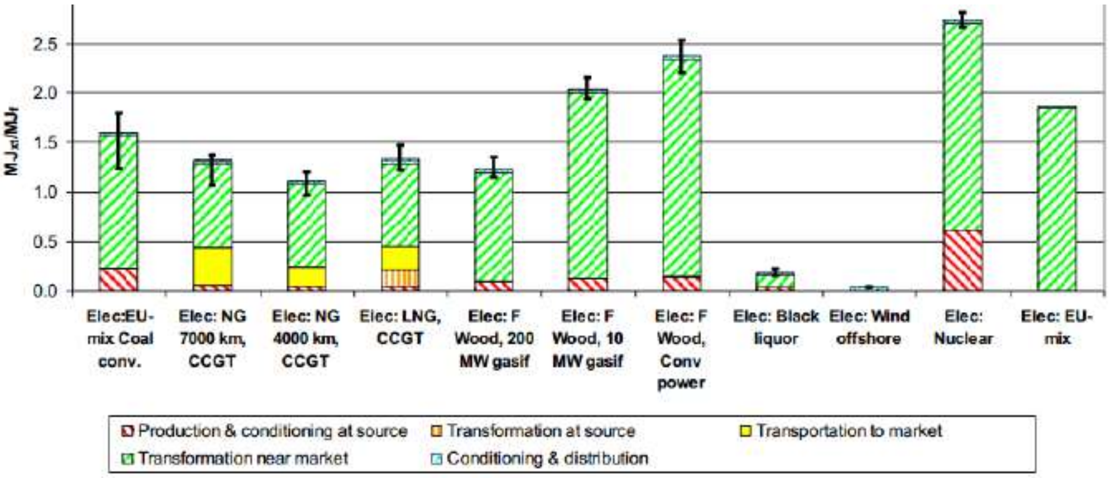


Figure 4.47 – WTT for different electricity production sources [61]

In this case, once WTT is close to 0 MJ of energy spend to produce 1 MJ of electricity, applying equation 4.2, WTW will assume TTW value, which is 52.16 MJ/100Km. Converting to kWh we have [78]:

1 kWh = 3.6 MJ → 52.16 MJ / 3.6 = 14.49 kWh

Therefore the consumption in kWh gives 14.49 kWh/100 km.

Taking equation 4.5 and considering a cost of electricity of one kWh of 0.0946€ in off peak period in March 2014 , the cost to to perform 100 km :

0.0946€/kWh x 14.49 kWh/100 km = 1.37€/100 km

Having this in consideration, BEV option is the most economical solution and joined with the fact of zero emissions, justifies the choice for electricity as the solution for the study of the alternative energy source for agricultural machines.

4.6 From initial idea to final decision

Like described in 4.1, the original idea was to convert a standard diesel powered tractor to a battery – electric motor. The survey described in 4.2 was in line with the initial plan. It was important to know some information about the use, refueling, distance from park to working spot of tractors.

The visit to Agritechnica described in 4.4 showed that only a marginal number of exhibitors were presenting products or even prototypes with other energy sources, leaving space to innovate in this area.

The comparison between energy sources that can be used to power agriculture machines presented in 4.5 showed that BEV vehicles have the lowest CO_2 emissions and lowest cost to run the same distance.

With the visits to Douro vineyards described in 4.3 and the discussions between the members of MIT-Portugal Project members a new idea arose: convert a specific machine for the Douro vineyards, with a battery – motor electric powertrain.

This new idea had some more challenges, when compared with the initial one: stability of the machine, packaging of batteries/electric motor, connection to the hydraulic system, use on the Douro terraces.

When compared with a regular open field operation, the vineyards in terraces have the issue of entry/exit in the lines which are steep and narrow.

Also was taken into account that a machine that could face the tough operations conditions in Douro region, like the extreme temperatures in Summer time, reaching 40°C, low temperatures in Winter time, sometimes below 0°C, rough terrain with loose rocks, it would be a very demanding test that if passed, it meant that the solution would easily be replicated to other sort of terrains.

There were two machines that could be used with this purpose, both 36 hp Multyjip: one belonging to CEVD and the other belonging to Quinta do Noval. The CEVD machine, being property of Portuguese Ministry, was considered to be too time consuming, once belonging to an entity of Portuguese Government, the bureaucracy and need to contact with a cascade of responsible to approve the selling, would take a lot of time. The Quinta do Noval machine was a real chance and was decided to contact the responsible to understand if the machine could be sold.

The question if the 36 hp Multyjip was available to be sold was made in the 27th May technical visit. Once the machine was not being used, a purchase proposal was sent to the Quinta de Noval board and it was accepted.

The deal was closed in June 2014 and on that month, the 36 hp Multyjip was picked up in Quinta do Noval and brought to Engenhotec facility.

5 Making the Prototype

This chapter presents the tasks performed to integrate an electric powertrain in Multyjip. The description of the user's need and target specifications were defined, the assessment of Multyjip's architecture to the study what may be kept or changed, the sourcing of the components to install, the alternative designs, the production of components and the assembly of prototype with the new components are described below.

After the decision of going forward with the adaptation of a special machine for narrow vineyards and the subsequent purchase of the Quinta do Noval 36 hp Multijyp, some tasks were needed to do:

- Assess the Multijyp architecture
- Disassemble the Multijyp to separate all the major components apart
- Remove engine and related components
- Source the batteries, electric motor, controller and other electric components
- Study the packaging of the components and the changes needed to do in it
- Design the components to make the prototype
- Manufacture components or subcontract
- Assembling, control and adjustments
- Test the functioning of the solution in the workshop
- Perform a test outdoors and get data
- Validate the solution

One important task was to make an assessment of the solution with batteries – electric motor. It is expectable that an electric motor is a reliable, efficient and economical solution for transport applications. Electric traction is used in trains, subways, fork lifters for years and more recently is spreading to cars, motorcycles, and bicycles.

Also in industrial applications electric motors are used in a vast array of applications, from conveyers, air conditioning, hydraulic systems, etc.

Since the demonstration made by Michael Faraday in 1821 that was possible to convert electric energy in mechanical movement using electromagnetism properties, electric motors have been used ever since to provide power to a wide range of processes for daily applications.

5.1 Multijyp Specifications

Quinta do Noval's Multijyp is equal to the one belonging to CEVD. It is a specific machine for narrow and steep vineyards, with low width and rubber tracks traction.

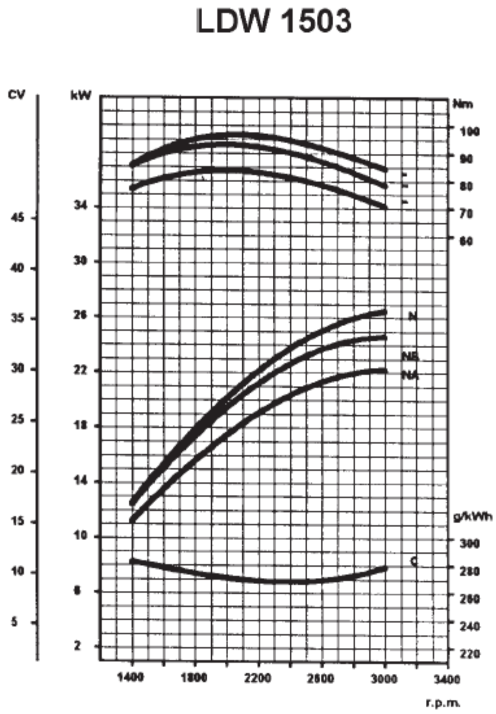
5.1.1 Engine specifications

36hp Multijyp has a Lombardini's LDW 1503 diesel engine with 3 cylinders, 1553 cm^3, with a peak power of 35 hp. In table 5.01 there are the main specifications of Multijyp's engine [79]:

Table 5.01 – Lombardini’s LDW 1503 diesel engine specifications [79]

Engine LDW 1503	Specification
Cylinder nº	3
Bore	88 mm
Stroke	85 mm
Displacement	1 551 cm^3
Compression ratio	22:1
Maximum rotation speed	3 000 rpm
Power NB N80/1269/CEE – ISO 1585 – DIN 70020	26.4 kW
Max. torque	85.4 Nm @ 2 100 rpm
Minimum specific fuel consumption	268 gr/kW.h @ 2 300 rpm
Oil consumption	0.024 kg/h
Dry weight	155 kg
Combustion air volume at 3 000 rpm	2 326 l/min
Max permissible driving shaft axial load in both directions	300 kg
Max inclination - Max 60 seconds	35°
Max inclination – Lasting up to 30 seconds	25°
Firing order	1-3-2

Engine’s output diagram is shown in figure 5.01.



N: 80/1269/CEE – ISO 1585

NA: ISO 3046 – 1 IFN

NB: ISO 3046 – 1 ICXN

Figure 5.01 – Lombardini’s LDW 1503 output diagram [79]

Lombardini’s engine is the power source for Multijyp. It is the driver for the Multijyp’s hydraulic system. Connected to the engine´s crankshaft is a triple pump package. Two are for the hydraulic motors and other for the main hydraulic pump. There is an auxiliary hydraulic pump connected to a side power output.

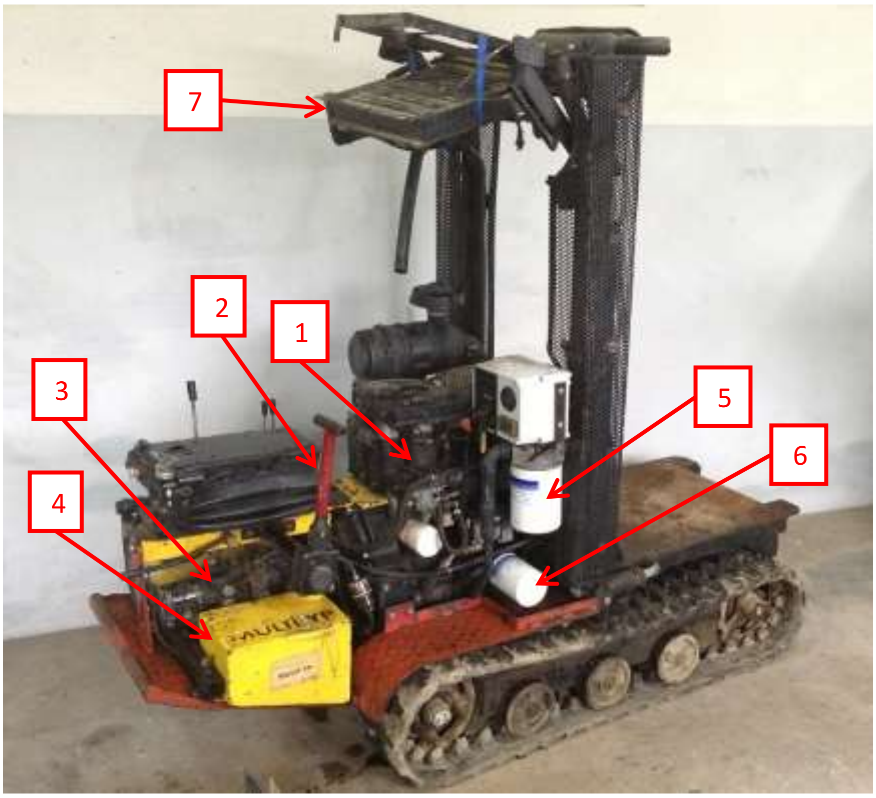
For the PTO there is a centrifugal clutch that when engine is idle PTO is not working but as engine speed increases the centrifugal clutch starts to transmit engine power to PTO. This clutch is connected directly to engine's crankshaft.

Engine speed is controlled by a manual throttle, located in front of driver's seat.

Engine consumption was not available but information from Quinta do Noval user, it is around 3 liter/hour.

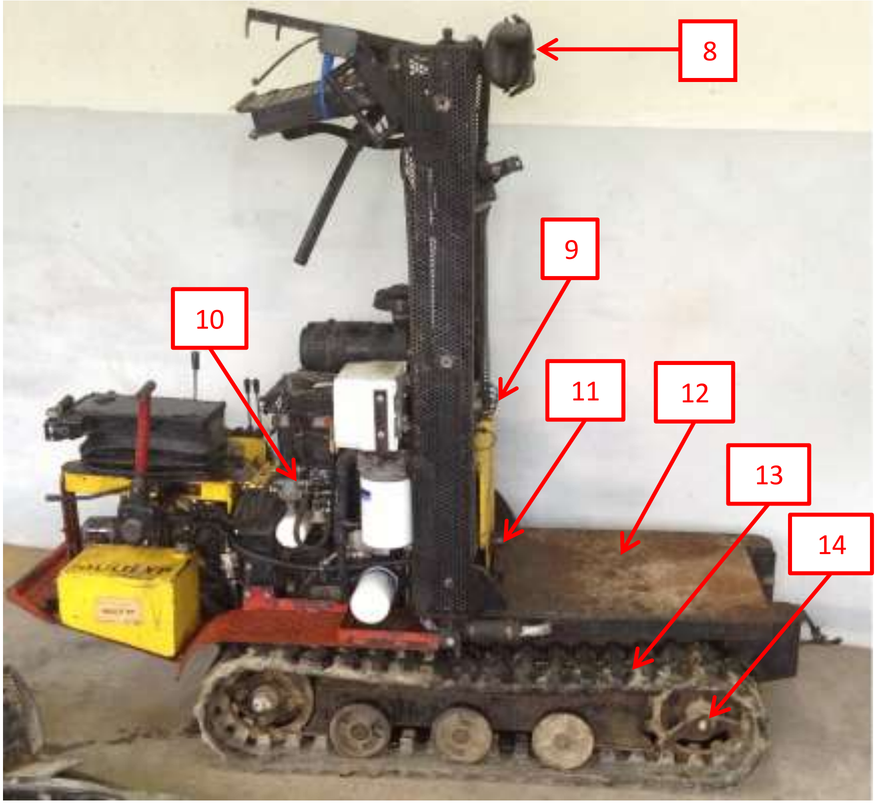
5.1.2 Multijyp layout

Figures 5.02 and 5.03 identify main Multijyp's components.



1 - Lombardini's engine
2 - Movement's joystick
3 - Diesel fuel tank
4 - Triple pump assembly
5 - Main oil filter
6 - Secondary oil filter
7 - Oil radiator

Figure 5.02 – 36 hp Multyjip rear main components



8 - Exhaust silencer
9 - Hydraulic connections
10 - Secondary oil pump
11 - PTO
12 - Oil reservoir
13 – Crawl
14 - Power wheel

Figure 5.03 – 36 hp Multyjip front main components

Engine (1) has no gearbox, in the rear end the engine shaft is connected to triple pump (4) and in front end is connected to centrifugal PTO (11). Engine fuel is stored in two separate fuel tanks (3), on each side in the lower rear. There an exhaust collector on the left side of the engine and an exhaust tube that is part of the left side safety frame, ending at the exhaust silencer (8), on the top of safety frame. Engine is cooled down by a water radiator, placed on the top of the safety frame, not shown in pictures.

Hydraulic oil is pumped from the reservoir (12) whose top face is also the base for the placement of equipment. Before reaching pumps, oil passes though the main (5) and secondary (6) oil filters. Before the return to the reservoir, oil is cooled down in the oil radiator, positioned in the top of safety frame.

Triple pump assembly (4) is responsible for the machine’s movement. When the user maneuvers the movement’s joystick (2), the two bidirectional pumps send oil to the hydraulic motors directly connected to left and right power wheels (14). Each power wheel has a crawl (13), responsible to convert motors rotation into linear movement.

5.1.3 Movement control

Multijyp’s movement control is done by a movement joystick, located in the right side of the machine and reached by the driver’s hand. When the joystick is pulled to front or back, both hydraulic motors rotate in such a way that crawlers movement is in the same direction, front or reverse, respectively.

When joystick is rotated clockwise, right crawler moves backward and left crawler moves forward, making the machine rotating clockwise. When joystick is rotated counter clockwise, the opposite happens and machine rotates counter clockwise. Figures 5.04 and 5.05 show how motors work to perform what driver maneuvers in the joystick.

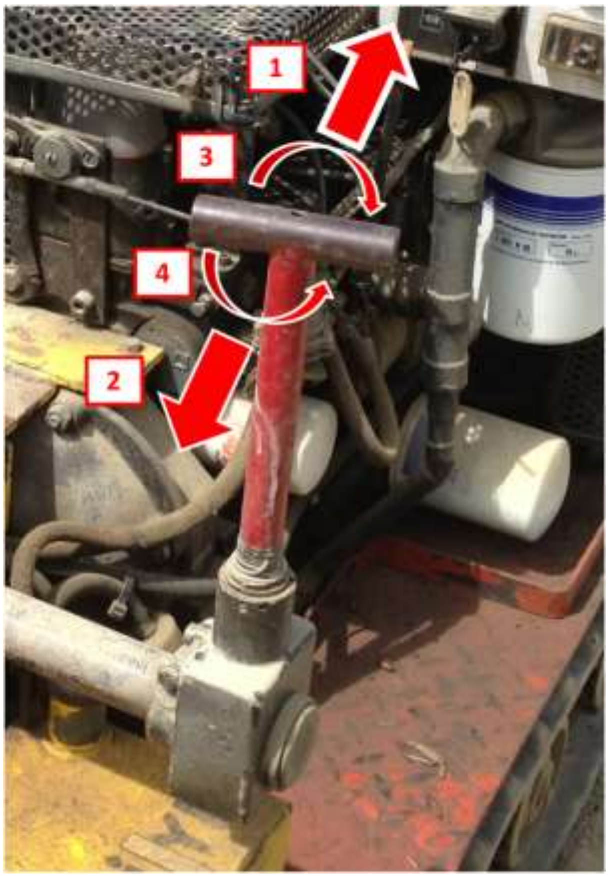


Figure 5.04 – Movement joystick positions

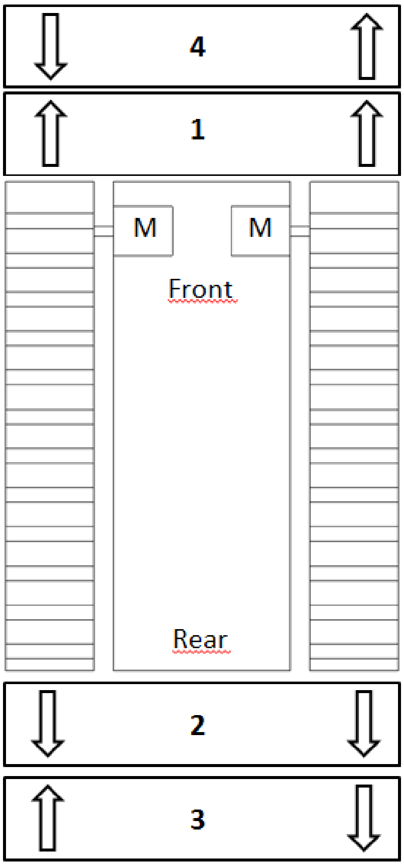


Figure 5.05 – Movement of crawlers according to joystick positions

5.1.4 Hydraulic system

Multijyp movement is performed by a hydraulic system, as described before, powered by the Diesel ICE. For the use of the machine, this solution has some advantages:

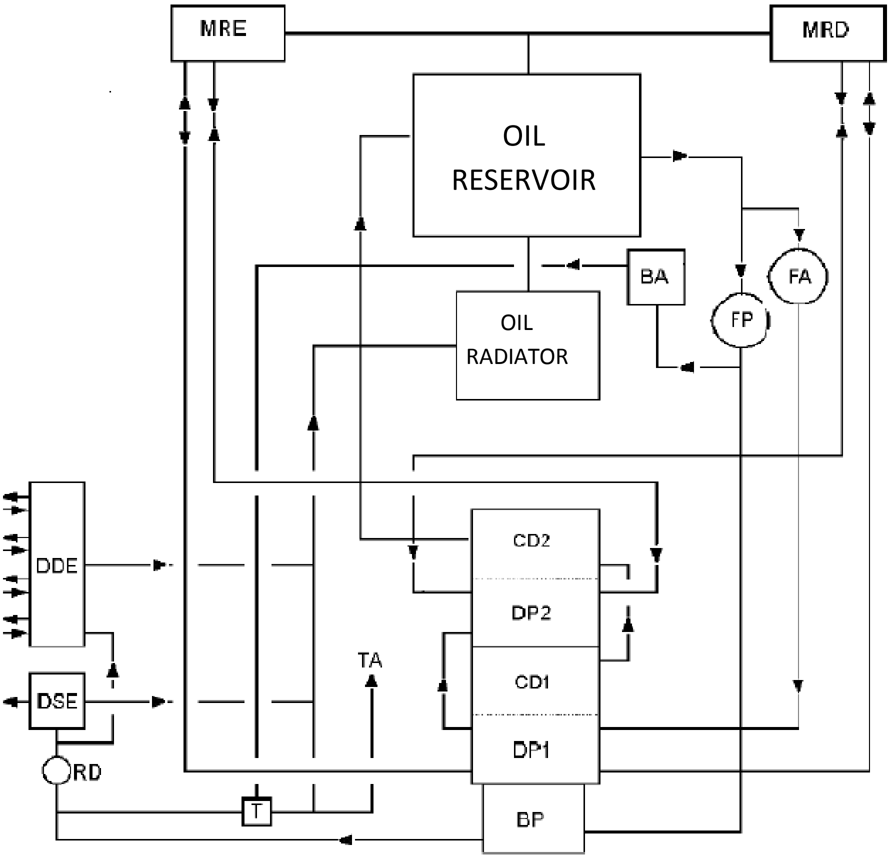
- Speed regulation, once the working speed is low, around 4 km/h, which was possible mechanically with a high transmission ratio, which implied a gearbox and transmission gears.
- Torque – hydraulic motors can work at a low revolution delivering high torque.
- Smoothness – hydraulic drive smooth the engine response, when moving over rough terrains, high slopes.
- Engine life – the absence of a clutch simplifies mechanics and avoids the use of wear parts – clutch discs.

As main disadvantages there are:

- Packaging – there are several tubes around and inside frame.
- Oil leaks – due to several connections, the hazard of oil leaks to the ground is real.
- Noise – Oils pumps emit a very audible noise when they are at the limit of the use.

5.1.4.1 Hydraulic system functioning

The original scheme for the hydraulic system is shown in figure 5.06.



BA	Auxiliary Pump	DDE	Dobble Effect Distributor
BP	Main Pump	DSE	Single Effect Distributor
CD1	Front Distributor Command	MRD	Right Crawler Motor
CD2	Rear Distributor Command	MRE	Left Crawler Motor
DP1	Front Main Distributor	RD	Flow Regulator
DP2	Rear Main Distributor	T	Valve
FA	Auxiliary Filter	TA	Main Oil Intake
FP	Main Filter		

Figure 5.06 – Hydraulic system original scheme

Hydraulic system features

- Closed hydraulic circuit for the movement, with safety system to face pressure drops;
- Closed hydraulic circuit for the equipment actuation;
- Main pump (BP): power the hydraulic motors, aligned with power wheels and the equipment motors though oil intake TA;

- Auxiliary pump (BA): complements the oil flow needed to drive some equipment. Oil flow from the auxiliary pump may be closed at T valve, although the manufacturer recommends to be open when equipment is working;
- Main distributor front pump (BDP1), main distributor rear pump (BDP2), respective commands (CD1 and CD2), to make vary the oil flow to actuate right power wheel (MRD) and left power wheel (MRE);
- Simple effect distributor (DSE): to actuate equipment motors which allow oil flow to intake TA;
- Double effect distributor (DDE): where the oil intakes are connected which allow the relative position of equipment;
- Flow regulator (RD): actuates at oil circuit level, used for the equipment drive which allow vary the equipment functioning level;
- Hydraulic circuit radiator.

The movement circuit oil works in closed circuit, although in the case of over pressure, it also goes to reservoir.

Equipment auxiliary circuit's oil is supplied by the reservoir and then passes through main filter and auxiliary pump, going next to flow regulation valve (T). After that joins the oil coming from main pump. Oil flow returns back to reservoir if T valve is closed.

5.1.4.2 Hydraulic system components specification

Main hydraulic system components specifications are listed as following:

Main pump (BP):

- Manufacturer: Lamborghini
- Part number: MLPD L205
- Displacement: 4.5 cm^3/rot
- Maximum service pressure (P1): 230 bar
- Maximum peak pressure (P3): 270 bar
- Maximum rotation: 3500 rpm (flow: 15.75 l/min)
- Maximum power: 6.04 kW (calculated for pressure of 230 bar and flow of 15.75 l/min)
- Overall dimensions:
- Width: 83 mm
- Height: 100 mm
- Length: 92 mm

Auxiliary pump (BA) [80]**:**

- Manufacturer: VIVOIL BOLOGNA
- Part number: XV-2P/09
- Displacement: 8.4 cm^3/rot
- Maximum service pressure (P1): 260 bar
- Maximum peak pressure (P3): 300 bar
- Weight: 2.4 kg
- Minimum rotation: 700 rpm (flow:6.3 l/min)
- Maximum rotation: 3500 rpm (flow: 31.5 l/min)
- Maximum power: 13.65 kW (calculated for pressure of 260 bar and flow of 31.5 l/min)

Power wheel hydraulic motor [81]**:**

- Manufacturer: Danfoss Part number: OMS 315
- Displacement: 314.9 cm^3
- Maximum rotation (continuously): 240 rpm
- Maximum rotation (peak): 285 rpm
- Maximum torque (continuously): 825 N.m
- Maximum torque (peak): 1000 N.m
- Maximum power (continuously): 15 kW
- Maximum power (peak): 17 kW
- Maximum service pressure: 200 bar
- Maximum peak pressure: 260 bar
- Maximum flow (continuously): 75 l/min
- Maximum flow (peak): 90 l/min

Main rear and front distributor pump (BDP1 and BDP2)

- Manufacturer: Axial Pump Modena Italy
- Part number: APVCT 13-13

5.1.5 Multijyp dimensions

The main dimensions of 36 hp Multijyp are in table 5.02:

Table 5.02 – 36 hp Multijyp main dimensions

Item	Measure
Length (mm)	2 100
Width (mm)	800
Crawler width (mm)	200
Mass, no extra weight (kg)	760
Wheelbase (mm)	1 200
Height (mm)	1 800
Equipment platform height (mm)	400
Ground clearance (mm)	60
Seat’s height (mm)	1 000
Weight (kg)	760

5.2 User’s needs

For the generation of concepts to implement the battery-electric motor powertrain, it is important to identify what are the user’s needs or customer attributes [1] [82]. Due to the specific use of these types of machines, their users have an experience that no other person can easily understand or replicate.

To determine user’s need it was followed the 5 steps method proposed by Ulrich and Eppinger [1]:

- Gather raw data from users
- Interpret raw data in terms of users’ needs
- Organize hierarchically user needs
- Establish relative importance of the needs
- Reflect on results

5.2.1 Gather raw data from users

Raw data was collected during the visits performed at Quintas das Carvalhas and Quinta do Noval by direct conversation with users, managers; taking notes from assisting to presentations; direct observation of working conditions.

Users traditionally don’t want changes in what they consider that it is right and demand changes in what they recognize as a problem or disadvantage of a product. Quinta do Noval user’s asked to maintain:

- Seat reversibility
- Ease of use of main control
- Easy adaptation of existing tools
- Range
- Power

and asked to improve:

- Side stability
- Reliability
- Comfort/ergonomics
- Purchase cost
- Equipment cost
- Equipment functionality
- Reversing direction
- Reduce time to exit/enter vine’s lines

5.2.2 Interpret raw data in terms of users’ needs

Taking these inputs from users, bearing in mind the conditions that the tasks have to be performed and considering also some targets for this project, the identified user´s needs are translated into statements. Need statements from users are:

- Vehicle has a reversal seat
- Vehicle is easy to control
- Vehicle allows to attach existing equipment
- Vehicle allows equipment control
- Vehicle has one working day range
- Vehicle has power to perform work
- Vehicle stays stopped in any position
- Vehicle allows a good visibility
- Vehicle is reliable
- Vehicle is comfortable
- Vehicle has a competitive price
- Vehicle has tools with a competitive price
- Vehicle allows equipment good visibility
- Vehicle is fast to change to another line

Considering the project’s targets, the following user needs were added:

- Vehicle emits low emissions
- Vehicle allows to work in narrow vineyards
- Vehicle allows to work in top-down vineyards
- Vehicle operates with high temperatures

- Vehicle operates in dust environments
- Vehicle operates in cold weather
- Vehicle operates with rain
- Vehicle operates with mud
- Vehicle is robust
- Vehicle has good manufacturing quality
- Vehicle has easy maintenance
- Vehicle has low use cost
- Vehicle is silent
- Vehicle is ergonomic
- Vehicle has a good after-sales service

5.2.3 Organize hierarchically user needs

After the identification of the statement needs, it is important to hierarchize customers need for simplification and easiness to understand what are the most critical and important aspects to focus in the design process.

Table 5.03 – Hierarchy of needs

	(Safety)
***	Vehicle stays stopped in any position
*	Vehicle allows a good visibility
**	**Vehicle is comfortable**
*	Vehicle is silent
*	Vehicle is ergonomic
**	Vehicle has a reversal seat
*	Vehicle is easy to control
***	**Vehicle allows to perform tasks**
***	Vehicle has power to perform work
***	Vehicle allows attaching existing equipment
**	Vehicle allows equipment control
**	Vehicle allows equipment good visibility
**	Vehicle has one working day range
**	Vehicle is fast to change to another line
	(Costs)
*	Vehicle has a competitive price
*	Vehicle has low use cost
*	Vehicle has tools with a competitive price
	(Operation)
*	Vehicle operates in cold weather
**	Vehicle operates with high temperatures
*	Vehicle operates with rain
*	Vehicle operates with mud
**	Vehicle operates in dust environments
***	Vehicle allows working in top-down vineyards
***	Vehicle allows working in narrow vineyards
**	**Vehicle is robust**
**	Vehicle is reliable
*	Vehicle has good manufacturing quality
**	Vehicle has easy maintenance
**!	Vehicle has a good after-sales service
!	**Vehicle emits low emissions**

To do that, statements are grouped according to its proximity with others and gathered bellow a label, which can be a statement that generalizes the needs of a group. Table 5.03 presents the arrangement of needs into primary, the label of the group and secondary that are related to the label's group. Each need was evaluated about its level of critical impact, by the number of asterisks (*), from none, being the lowest level to 3, being a critically important. Also some latent needs were identified with a (!).

Safety, costs and operation were added as group titles. They are identified as important needs overall but alone they do not are easily measured, so other identified needs were grouped under them.

The most critical needs identified were the ones related to safety, capacity of performing tasks and operation under tough conditions, which are quite obvious, once the reason to buy one of these vehicles is to perform tasks in harsh conditions. Safety is critical not only due to the user's integrity but also if an accident occurs, vines can be destroyed if the vehicle rolls down the steeped hills.

Two latent needs were identified, one related to after sales service and low emissions. The first is related to the fact that Multyjip machine is an old machine and parts availability and manufacturer's service is not easily accessed. The second is related to the project's goal, to design a vehicle that produces a low quantity of pollutant gases.

5.2.4 Establish relative importance of the needs

After ranking the needs, the next step is to determine the importance of them by attributing a classification that establishes which ones are more important than others. This is very important because latter on the design process, main attention must focus on the most important needs.

Table 5.04 lists all 30 needs with the classification of the importance, in a scale from 1 to 5, being 1 the least important and 5 a critical one.

Classification follows the same rationale as in the previous point. Needs related to safety, tasks performing and conditions of work are the ones with highest classification.

Table 5.04 – Importance of needs

No.	Need	Importance
1	Vehicle stays stopped in any position	5
2	Vehicle allows a good visibility	3
3	Vehicle is comfortable	3
4	Vehicle is silent	2
5	Vehicle is ergonomic	3
6	Vehicle has a reversal seat	5
7	Vehicle is easy to control	5
8	Vehicle allows to perform tasks	5
9	Vehicle has power to perform work	5
10	Vehicle allows attaching existing equipment	5
11	Vehicle allows equipment control	4
12	Vehicle allows equipment good visibility	3
13	Vehicle has one working day range	4
14	Vehicle is fast to change to another line	4
15	Vehicle has a competitive price	3
16	Vehicle has low use cost	3
17	Vehicle has tools with a competitive price	3
18	Vehicle operates in cold weather	1
19	Vehicle operates with high temperatures	4
20	Vehicle operates with rain	3
21	Vehicle operates with mud	3
22	Vehicle operates in dust environments	4
23	Vehicle allows working in top-down vineyards	5
24	Vehicle allows working in narrow vineyards	5
25	Vehicle is robust	5
26	Vehicle is reliable	5
27	Vehicle has good manufacturing quality	1
28	Vehicle has easy maintenance	4
29	Vehicle has a good after-sales service	4
30	Vehicle emits low emissions	4

5.2.5 Reflect on results

The method followed for determine, hierarchize and classify needs is very straight forward and allows development teams to identify users' needs and to focus later on the most important and critical ones. The result on the identified needs and classification is quite obvious on this case, once it is a vehicle destined to perform work on the hard conditions of Douro vineyards.

5.3 Target specifications

Following Ulrich and Eppinger [1] method, next step is to establish target specifications. These specifications are the translation of user's needs into to measurable details that shows what the vehicle has to do.

Target specifications are established previously to the product concepts, which are later described in point 5.6. The process is composed by four steps:

- Prepare the list of metrics
- Collect competitive benchmarking
- Set ideal and marginally target values
- Reflect on the results

5.3.1 Prepare the list of metrics

Ulrich and Eppinger state that most useful metrics are the ones that reflect as directly as possible the level of which product satisfies user's needs. To achieve this, a set of metrics must be established to allow translation from the set of user's needs to measurable specifications, that once satisfied, will lead to satisfy user's needs. Table 5.05 shows the metrics and the needs that are related to.

Table 5.05 – Metrics and relation with needs

Metric No.	Item	Need	Imp.	Units
1	Maximum height (without roll bar)	1	5	mm
2	European directive rollover test	1,23,24	5	Binary
3	Side maximum slope	1,24	5	°
4	Longitudinal maximum slope	1,23	5	°
5	Mass	1	5	Kg
6	Angle of vision	2,12	3	°
7	Damped seat	3	3	Binary
8	Noise at top speed, without equipment	4	2	db
9	Comfort angles	5	2	List
10	Reverse seat	6	5	Binary
11	Joystick control	7,11	5	Binary
12	Hydraulic connections	8,10	5	List
13	PTO torque	9,10	5	Nm
14	Maximum power	9	4	KW
15	Top speed	9	5	Km/h
16	Working range	13	4	h
17	Reverse direction	14	5	s
18	Tractor acquisition cost	15	3	Euros
19	Use hourly cost	16	3	Euros
20	Tools acquisition cost	17	3	Euros
21	Temperature use range	18,19,25	4	°C
22	Tightness	20,21,22,25	4	Test IPx
23	Total width	24	5	mm
24	Hours without repair's intervention	25,26,27	5	h
25	Each maintenance time	28	4	h
26	Maintenance intervals	28	4	h
27	Assistance arrival time	29	4	h
28	CO2 emissions	30	4	g/h

On the third column of table 5.05 the needs are identified for each metric. This allows building a needs-metrics matrix, table 5.06w, a graphical representation of the relations between needs and metrics. This is a technique used in Quality Function Deployment (QFD), described by Hauser and Clausing [82]

Table 5.06 – Needs-metrics matrix

	Metric Need	Maximum height (without roll bar)	European directive rollover test	Side maximum slope	Longitudinal maximum slope	Mass	Angle of vision	Damped seat	Noise at top speed, without equipment	Comfort angles	Reverse seat	Joystick control	Hydraulic connections	PTO torque	Maximum power	Top speed	Working range	Reverse direction	Tractor aquisition cost	Use hourly cost	Tools aquisition cost	Temperature use range	Tightness	Total width	Hours without maintance intervention	Each maintenance time	Maintenance intervals	Assistance arrival time	CO2 emissions
1	Vehicle stays stopped in any position	x	x	x	x	x																							
2	Vehicle allows a good visibility						x																						
3	Vehicle is comfortable							x																					
4	Vehicle is silent								x																				
5	Vehicle is ergonomic									x																			
6	Vehicle has a reversal seat										x																		
7	Vehicle is easy to control											x																	
8	Vehicle allows to perform tasks												x																
9	Vehicle has power to perform work													x	x	x													
10	Vehicle allows attaching existing equipment												x	x															
11	Vehicle allows equipment control											x																	
12	Vehicle allows equipment good visibility						x																						
13	Vehicle has one working day range																x												
14	Vehicle is fast to change to another line																	x											
15	Vehicle has a competitive price																		x										
16	Vehicle has low use cost																			x									
17	Vehicle has tools with a competitive price																				x								
18	Vehicle operates in cold weather																					x							
19	Vehicle operates with high temperatures																					x							
20	Vehicle operates with rain																						x						
21	Vehicle operates with mud																						x						
22	Vehicle operates in dust environments																						x						
23	Vehicle allows working in top-down vineyards		x		x																								
24	Vehicle allows working in narrow vineyards		x	x																				x					
25	Vehicle is robust																					x	x		x				
26	Vehicle is reliable																								x				
27	Vehicle has good manufacturing quality																								x				
28	Vehicle has easy maintenance																									x	x		
29	Vehicle has a good after-sales service																											x	
30	Vehicle emits low emissions																												x

5.3.2 Collect competitive benchmarking

To achieve success on the market, it is very important to know exactly what competitors are offering to customers. Therefore is it of major relevance to identify the value of competition translated to the new product metrics. In this particular case, of special vehicles for narrow and steep vineyards, competition is limited to special vehicles like Multyjip. In this case, only Multyjip values were used to include competitor's data, table 5.01.

5.3.3 Set ideal and marginally target values

In this step target specifications are established. This is achieved by adding two columns to table 5.05 to define marginal and ideal specifications. Ideal specifications are the best result expected for a particular metrics and target specifications are the least that the vehicle must comply. In table 5.07 both specifications are listed along the Multyjip data from previous point.

Table 5.07 – Target specifications

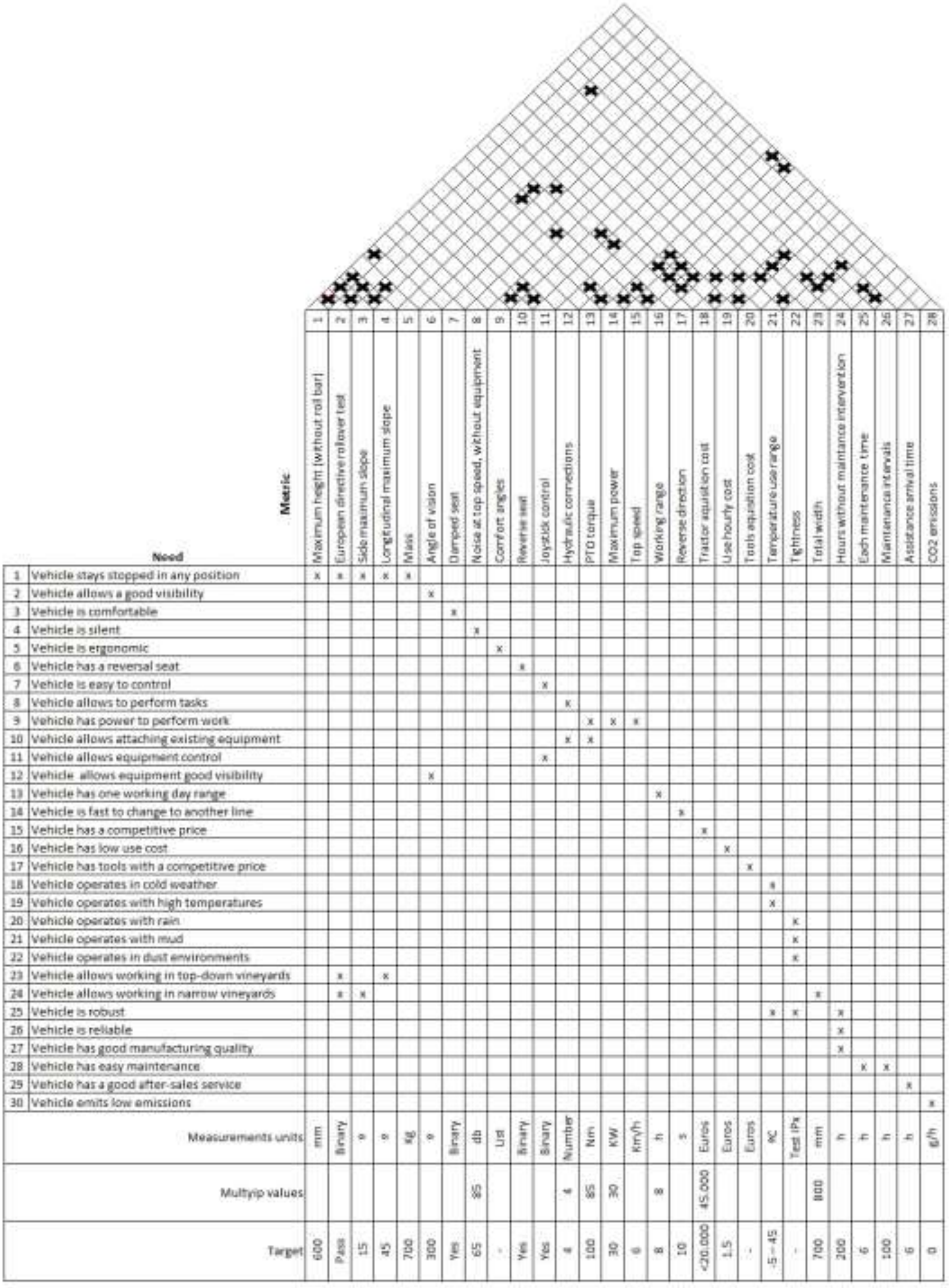
Metric No.	Item	Need	Imp	Units	Multyjip	Marginal	Target
1	Maximum height (without roll bar)	1	5	mm		<800	600
2	European directive rollover test	1,23,24	5	Binary		Pass	Pass
3	Side maximum slope	1,24	5	°		>10	15
4	Longitudinal maximum slope	1,23	5	°		>40	45
5	Mass	1	5	kg		800	700
6	Angle of vision	2,12	3	°		>240	300
7	Damped seat	3	3	Binary		Yes	Yes
8	Noise at top speed, without equipment	4	2	db	85	<70	65
9	Comfort angles	5	2	List		-	-
10	Reverse seat	6	5	Binary		Yes	Yes
11	Joystick control	7,11	5	Binary		Yes	Yes
12	Hydraulic connections	8,10	5	List	4	>4	4
13	PTO torque	9,10	5	Nm	85	>80	100
14	Maximum power	9	4	kW	30	>25	30
15	Top speed	9	5	km/h		4	6
16	Working range	13	4	h	8	6	8
17	Reverse direction	14	5	s		15	10
18	Tractor acquisition cost	15	3	Euro	45.000	<25.000	<20.000
19	Use hourly cost	16	3	Euro		<2	1.5
20	Tools acquisition cost	17	3	Euro		-	-
21	Temperature use range	18,19,25	4	°C		0 – 40	-5 – 45
22	Tightness	20,21,22,	4	Test IPx		-	-
23	Total width	24	5	mm	800	800	700
24	Hours without repair's intervention	25,26,27	5	h		160	200
25	Each maintenance time	28	4	h		< 12	6
26	Maintenance intervals	28	4	h		80	100
27	Assistance arrival time	29	4	h		24	6
28	CO_2 emissions	30	4	g/h		2000	0

Marginal and ideal specifications actuate like lower and upper boundaries for the several metrics.

In this step, a House of Quality was built, figure 5.07, based on the data of table 5.06 and 5.07. Following Hauser and Clausing [82] method, to the needs-metrics matrix a roof was added, which relates the how metrics related with each other and in the bottom information was added with the measurement units, competitors' measures and target values for each metric.

In the roof, it is possible to observe some close relations:

- slope capacity is related to height and the ability to pass safety tests
- comfort angles, reversibility of seat and joystick control are related to ergonomics
- maximum power is related to several other metrics like PTO torque, top speed, working range, tractor acquisition cost and also CO_2 emissions
- use hourly cost is the one with more relations, some very strong like maximum power, top speed, tractor acquisition cost and others like temperature use range and tightness, which affects cost due to limitations on use.

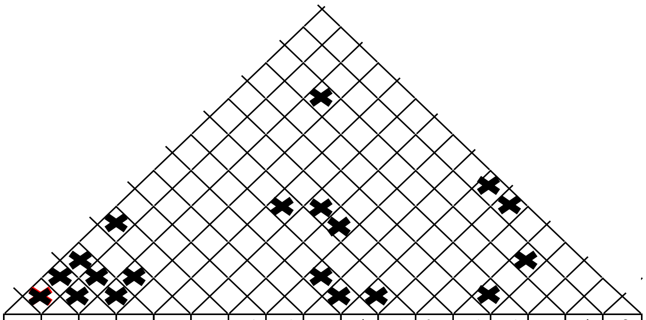


	Need	1 Maximum height (without roll bar)	2 European directive rollover test	3 Side maximum slope	4 Longitudinal maximum slope	5 Mass	6 Angle of vision	7 Damped seat	8 Noise at top speed, without equipment	9 Comfort angles	10 Reverse seat	11 Joystick control	12 Hydraulic connections	13 PTO torque	14 Maximum power	15 Top speed	16 Working range	17 Reverse direction	18 Trastor aquistion cost	19 Use hourly cost	20 Tools aquistion cost	21 Temperature use range	22 Tightness	23 Total width	24 Hours without maintance intervention	25 Each maintenance time	26 Maintenance intervals	27 Assistance arrival time	28 CO2 emissions
1	Vehicle stays stopped in any position	x	x	x	x	x																							
2	Vehicle allows a good visibility						x																						
3	Vehicle is comfortable							x																					
4	Vehicle is silent								x																				
5	Vehicle is ergonomic									x																			
6	Vehicle has a reversal seat										x																		
7	Vehicle is easy to control											x																	
8	Vehicle allows to perform tasks												x																
9	Vehicle has power to perform work													x	x	x													
10	Vehicle allows attaching existing equipment												x	x															
11	Vehicle allows equipment control											x																	
12	Vehicle allows equipment good visibility						x																						
13	Vehicle has one working day range																x												
14	Vehicle is fast to change to another line																	x											
15	Vehicle has a competitive price																		x										
16	Vehicle has low use cost																			x									
17	Vehicle has tools with a competitive price																				x								
18	Vehicle operates in cold weather																					x							
19	Vehicle operates with high temperatures																					x							
20	Vehicle operates with rain																						x						
21	Vehicle operates with mud																						x						
22	Vehicle operates in dust environments																						x						
23	Vehicle allows working in top-down vineyards		x		x																								
24	Vehicle allows working in narrow vineyards		x	x																				x					
25	Vehicle is robust																					x	x		x				
26	Vehicle is reliable																								x				
27	Vehicle has good manufacturing quality																								x				
28	Vehicle has easy maintenance																									x	x		
29	Vehicle has a good after-sales service																											x	
30	Vehicle emits low emissions																												x
	Measurements units	mm	Binary	º	º	Kg	º	Binary	db	List	Binary	Binary	Number	Nm	KW	Km/h	h	s	Euros	Euros	Euros	ºC	Test IPx	mm	h	h	h	h	g/h
	Multyip values								85				4	85	30		8		45.000					800					
	Target	600	Pass	15	45	700	300	Yes	65	-	Yes	Yes	4	100	30	6	8	10	<20.000	1.5	-	-5 – 45	-	700	200	6	100	6	0

Figure 5.07 – House of Quality

5.3.4 Reflect on the results

The definition of specifications is crucial for the following steps of development and a good determination of metrics and its relation to user's needs is essential to ensure it. In this case, specifications were determined as if a new vehicle was designed. For this specific study, some needs won't be considered, once it is not a final product that is being developed but a prototype to assess its functionality. For this study, the considered needs/metrics are shown in figure 5.08.



	Metric **Need**	1 Maximum height (without roll bar)	2 European directive rollover test	3 Side maximum slope	4 Longitudinal maximum slope	5 Mass	6 Angle of vision	11 Damped seat	12 Noise at top speed, without equipment	13 PTO torque	14 Comfort angles	15 Top speed	17 Working range	21 Temperature use range	22 Tightness	23 Reverse seat	24 Joystick control	28 CO2 emissions
1	Vehicle stays stopped in any position	x	x	x	x	x												
2	Vehicle allows a good visibility						x											
7	Vehicle is easy to control							x										
8	Vehicle allows to perform tasks								x									
9	Vehicle has power to perform work									x	x	x						
10	Vehicle allows attaching existing equipment								x	x								
11	Vehicle allows equipment control							x										
12	Vehicle allows equipment good visibility						x											
14	Vehicle is fast to change to another line												x					
23	Vehicle allows working in top-down vineyards		x		x													
24	Vehicle allows working in narrow vineyards		x	x												x		
25	Vehicle is robust													x	x		x	
30	Vehicle emits low emissions																	x
	Measurements units	mm	Binary	º	º	Kg	º	Binary	db	Nm	List	Km/h	s	ºC	Test IPx	Binary	Binary	g/h
	Multyip values								85	85	0					0		
	Target	600	Pass	15	45	700	300	Yes	65	100	-	6	8	-5 – 45	-	Yes	Yes	0

Figure 5.08 – House of Quality for Prototype

5.4 Assess the Multijyp architecture

Multyjip is a Chappot product to perform agriculture tasks in narrow spaces, lines. Its architecture tries to combine the use of a Diesel ICE, hydraulic system, safety roll bar, equipment platform, seat and controls, radiators, crawlers. Each of these main functions is identified in figure 5.09.

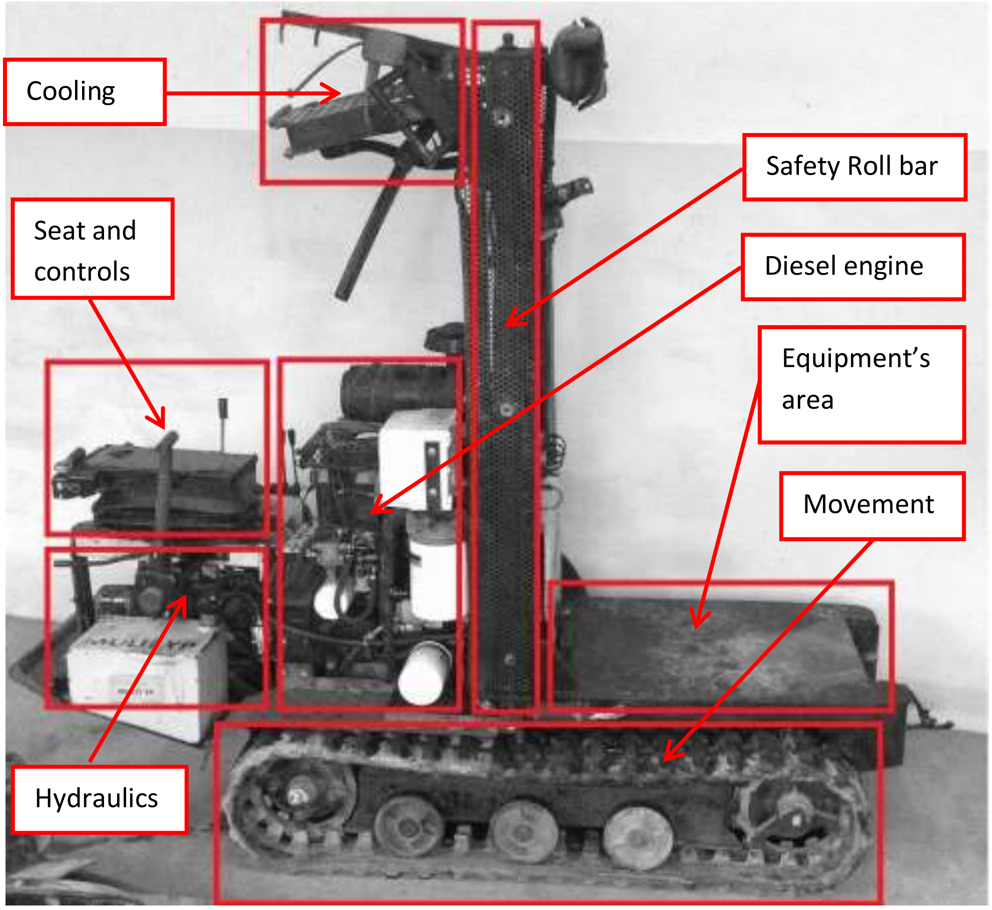


Figure 5.09 – 36 hp Multyjip main functions layout

The design of the conversion to a Battery-Electric Vehicle (BEV) must consider the functions that the ICE Multijyp performs, without changing its main architecture. Also for economic and time constraints, the least changes performed in the main components, would result in less cost and faster application of changes.

Regarding the main functions some considerations were done:

- Movement: this function is a basic function for this machine, so changes must be carefully thought. For the purpose of this study, it was considered to keep as much as possible the original solution, using as drivers the hydraulic motors.
- Equipment's area: Multijyp has specific equipment designed by the manufacturer, although it is possible to adapt other equipment, Pellenc for example. To avoid making new or changing existing equipment, it was considered to keep this area unchanged. Even the PTO shaft position must be kept where it was, if a hydraulic motor was thought to be used.

- Diesel engine: this is the function that was to remove completely. To perform the object of this study, not only the diesel engine but all its directly related components are to remove, like fuel tanks, exhaust pipe and muffler.
- Safety roll bar: some changes might be necessary, not due to improve safety but to improve transportability in a van. Its height does not allow placing it easily in a standard van.
- Cooling: depending on the electric motor to be selected, water cooling could be removed. The hydraulics cooling is essential for the correct functioning of hydraulics
- Seat and controls: to avoid add complexity to the hydraulics piping, it should remain as it was, only with small adaptations
- Hydraulics: depending on the condition of the hydraulic components, it may be needed to replace or change some components. However, the functions should remain.

5.4.1 Disassemble Multijyp to separate all the major components apart

Due to the non-existence of Multijyp's drawings, schemes, user manual or parts list, it was impossible to understand how some components were designed, manufactured and assembled. Also the need to remove the diesel engine and related components required to remove some other components so the decision was taken to disassemble Multijyp.

At the beginning the task was very tough, basically because it was very dirt, with a mixture of mud, oil, rocks, leaves, branches, especially on the frame and hydraulic tubes.

Before disassembly, it was verified that the oil's reservoir, which top surface is the platform for the equipment's support, was welded to the safety roll bar and they must be removed as a whole. During disassembly, two things were verified: this reservoir/roll bar was also originally welded to the frame; reservoir's shape brought a lot of trouble to remove it from the frame.

5.4.2 Remove engine and related components

Engine removal was quite easy to perform, however the weight of the engine itself is considerable to perform with no workshop tools.

By removing the engine from the machine, the two fuel tanks located on the rear on each side were removed; the 12 V battery located in the front of the machine was also removed. Exhaust pipe from the engine to the safety roll bar and muffler were also removed. One of the safety roll bar tubes had also the function of exhaust tube and was kept in place, to avoid change the roll bar.

Three important issues risen up in result of engine removal:

- Power connection to the triple pumps – Triple pumps module was fixed to the engine cover by two bolts and to the seat frame, figures 5.10 and 5.11. By removing the engine, not only the fixation points disappear but also the power transmission had to be considered. To transmit power from crankcase to triple pumps, the end of the crankcase had a ring with two pins. Those two pins were connected to the triple pump's shaft. Once engine is started, the three pumps start to pump system's oil, meaning that even in idle, there is pressure inside the oil's circuit.

Figure 5.10 – Triple pump module attached to engine

Figure 5.11 – Loose tubes after triple pumps module removal

- PTO output – power connection to the equipment is performed by a centrifugal clutch PTO. It is attached to the front end of the crankcase and has a splined shaft to connect to the equipment power shaft, figure 5.12.

Figure 5.12 – Front view of engine with PTO

- Auxiliary hydraulic pump – this pump, located on the right side of the engine is part of the hydraulic system and has a function to add volume of oil when the main pump's flow is not enough, figure 5.13. From observation it was noticed that its rotation direction was clockwise.

Figure 5.13 – Auxiliary oil pump

After removing the previously described components and engine it was possible to see the hydraulic motors tubes path, passing below the oil reservoir and engine, to connect to the bi directional pumps – figures 5.14 and 5.15. It was also possible to see the engine mountings and how the wheels were designed to allow crawler set-up. Both driven wheels were connected between them by a transversal plate. This plate's position could be adjusted by one bolt on each side that allowed to stretch the rubber track for normal use or to relieve when there was a need to remove the rubber track for replacement.

Figure 5.14 – 36 hp Multijyp without engine, side view

Figure 5.15 – 36 hp Multijyp without engine, top view

5.4.3 Oil reservoir removal

Removal of oil reservoir was very difficult and required a lot of arm's strength, not only due to its weight but also to its shape. It had a part that was below the engine mountings, so its removal was not simply lifting it up vertically, it required to lift up first the front, pull it forward, until the end below the engine's mountings was out and then remove it from the frame.

It was verified that the welding that connected frame and reservoir was broken, meaning that the safety conditions of the machine were not right, once the reservoir/roll bar had lost two fixations. The 4 front screws were correctly tightened but its access was very hard and it was very difficult to untighten them. To access these screws, battery support was removed.

After reservoir removal it was the first time it was possible to see and understand how the Multijyp's frame has designed and manufactured, figure 5.16:

- two main longitudinal tubes (1), where there are six pins (2) in each to attach guiding rolls for the crawlers
- a transverse tube on the front (3) where the hydraulic motors(4) mountings (5) are welded
- a plate (6) almost on the middle where the oil reservoir mountings (7) and the engine mountings (8) are welded
- there was a transverse (9) tube to close the longitudinal tubes and to support the engine mountings
- at the rear, two small longitudinal tubes (10) connected to tube (9), support a rear plate (11), which had two rear mountings (12) for the engine.
- Rear wheels shaft adjusters were done by two screws (13) placed on a block (14).

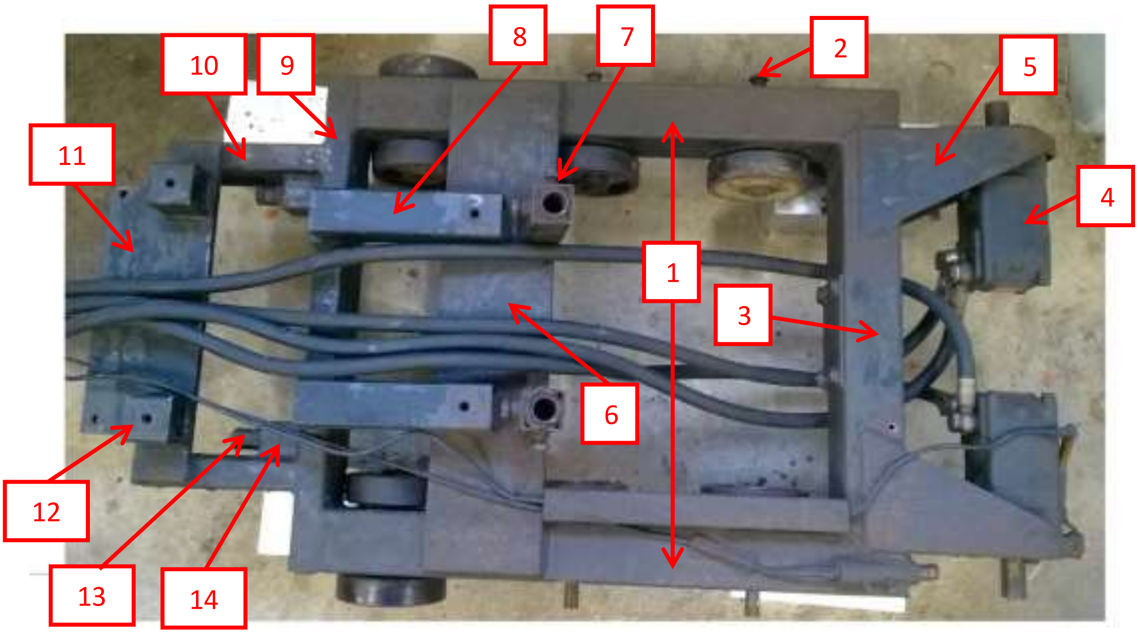


Figure 5.16 – 36 hp Multijyp frame, top view

One evidence after disassembly was that Multijyp was designed and build to be strong and robust but maintenance tasks were not a concern. Tube dimensions, number and quality of welding, thickness of plates, all show that robustness was a priority.

But if for some reason there was a need to replace a component, especially one of those related to frame, accessibility was poor or even impossible, once some components were welded to the frame. The oil reservoir is a good example. In the front there were 4 screws to fix it but in the rear there were two round tubes welded to the reservoir that entered in the reservoir mountings, with an outside square tube and an inner round tube. There were three bolts to fix the reservoir round tubes inside the mounting round tube but these round tubes were welded each other, so it was impossible to take the reservoir out, figure 5.17.

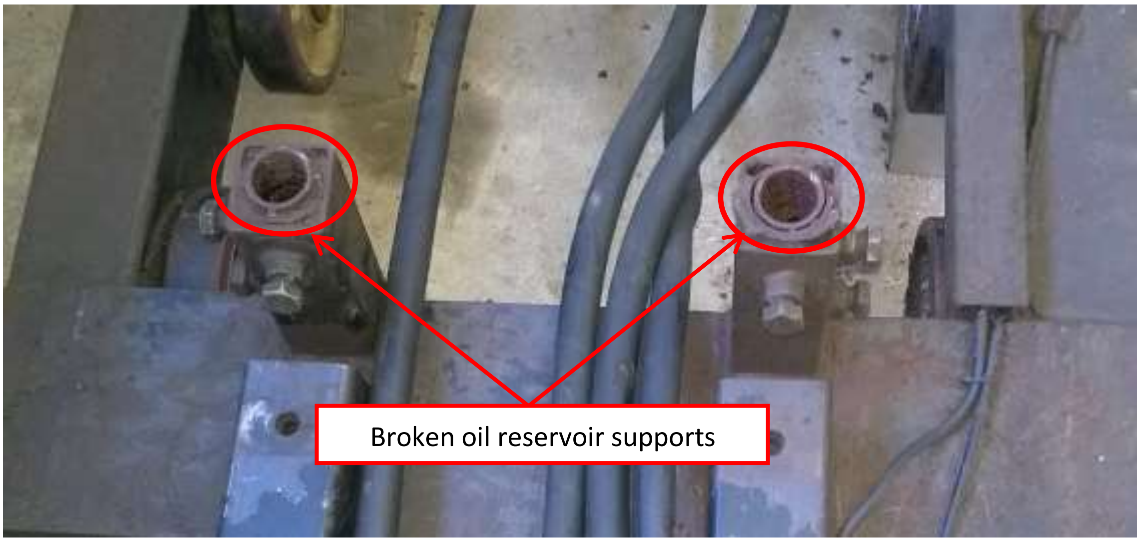


Figure 5.17 – Broken oil reservoir supports

With all components out of the machine and a perfect picture of frame's design, next step was the study of how to convert the machine to receive a battery-electric motor powertrain.

5.5 Source Batteries, Electric Motor, Controller and electric components

With all components removed and access to the machine's frame, next step was to study the way how to convert the machine from an ICE to BEV powertrain.

The main components needed to the conversion are: batteries, electric motor, controller, battery charger, throttle and cables.

5.5.1 Battery sourcing

For the conversion to the BEV machine, batteries are one of the most important components to address, not only because they are the energy accumulators but also due to the dimensions, cost and accessibility when placed in the machine.

There are currently four types of batteries available:

- Lead-acid
- Nickel Cadmium (Ni-Cd)
- Nickel Metal Hydride (Ni-MH)
- Lithium Ion (Li-ion)

In the previous study performed by Canedo [83], the range of batteries considered was reduced only to the lead-acid and lithium ones. The reason was to compare only the solutions in the end of the range, once nickel batteries present intermediate characteristics when compared to lead-acid and lithium.

Batteries for this application have to comply with some requirements:

- Dimensions must fit inside the available space
- Weight must not be so high that might change dramatically the machine’s balance
- Cost must be affordable
- Robustness and ability to work under harsh conditions.

Once the conversion was done over an existing machine, there were important dimensions constraints because one of the goals was to keep the original functionality of the machine and its equipment. So the space available for the batteries was limited to the rear part of the machine, mainly to the space where the ICE was located. This constraint limits the options for the batteries.

Taking the constraints and requirements into account, sourcing was performed and some options were found:

- Trojan Battery – Lead-acid / Traction, figure 5.18a [84]
- Autosil Battery – Lead-acid / Traction, figure 5.18b [85]
- Celectric battery – Lead-acid / Traction, figure 5.18c [86]
- GEB battery – Lithium-Ion, figure 5.18d [87]

(a) (b)

(c) (d)

Figure 5.18 – (a)Trojan Battery, model 150T [83]; (b) Pack of Autosil EA3 batteries [84]; (c) Pack of Celectric 2PzB200 batteries [85] (d) GEB battery – Lithium-Ion. Model: GEB10059156 [86]

For the lead-acid batteries, only traction ones were considered due to the capacity of these batteries to delivery current continuously. Besides being traction batteries there was also a need to use the most of the available energy stored. This means that in each cycle, battery must be able to discharge completely. This can be performed by deep cycle batteries [88].

Table 5.08 comparing the main features of each battery is shown below.

Table 5.08 – Batteries main features comparative

Manufacturer	**Model**	**Voltage [V]**	**Capacity [Ah]**	**Type**	**Dimensions [mm]**		**Weight [kg]**	**Unit cost[€]**
TROJAN	150T	12	150	Lead-acid	Length	327	37	258.5
					Width	180		
					Height	275		
AUTOSIL	EA3	2	150	Lead-acid	Length	198	9.6	65.5
					Width	63		
					Height	282		
CELECTRIC	2PzB200	2	200	Lead-acid	Length	158	13.1	64.5
					Width	45		
					Height	628		
GEB	GEB10059156	3.7	11	Lithium-Ion	Length	59	0.20	14.1
					Width	10		
					Height	158		

A study was performed to determine the pack of batteries needed to output 36 or 72 V. The result is shown in table 5.09:

Table 5.09 – Batteries needed for 36V or 72V solution

Manufacturer	**Model**	**Pack 36V**				**Pack 72V**			
		Element nr.	**Energy [kWh]**	**Total Weight [kg]**	**Total cost [€]**	**Element nr.**	**Energy [kWh]**	**Total Weight [kg]**	**Total cost [€]**
TROJAN	150T	3	5.4	111.0	776	6	10.8	222.0	1 551
AUTOSIL	EA3	18	5.4	347.0	1180	36	10.8	345.6	2 361
CELECTRIC	2PzB200	18	7.2	545.0	2325	36	14.4	471.6	4 650
GEB	GEB10059156	140	5.7	28.2	1977	280	11.4	56.4	3 954

5.5.2 Electric motor sourcing

If batteries are the energy supplier for the machine, electric motor is the heart of the system. Its function is to convert electric energy stored and delivered by the batteries into rotation movement. It has to replace the ICE using Diesel fuel that powers the hydraulic system pumps.

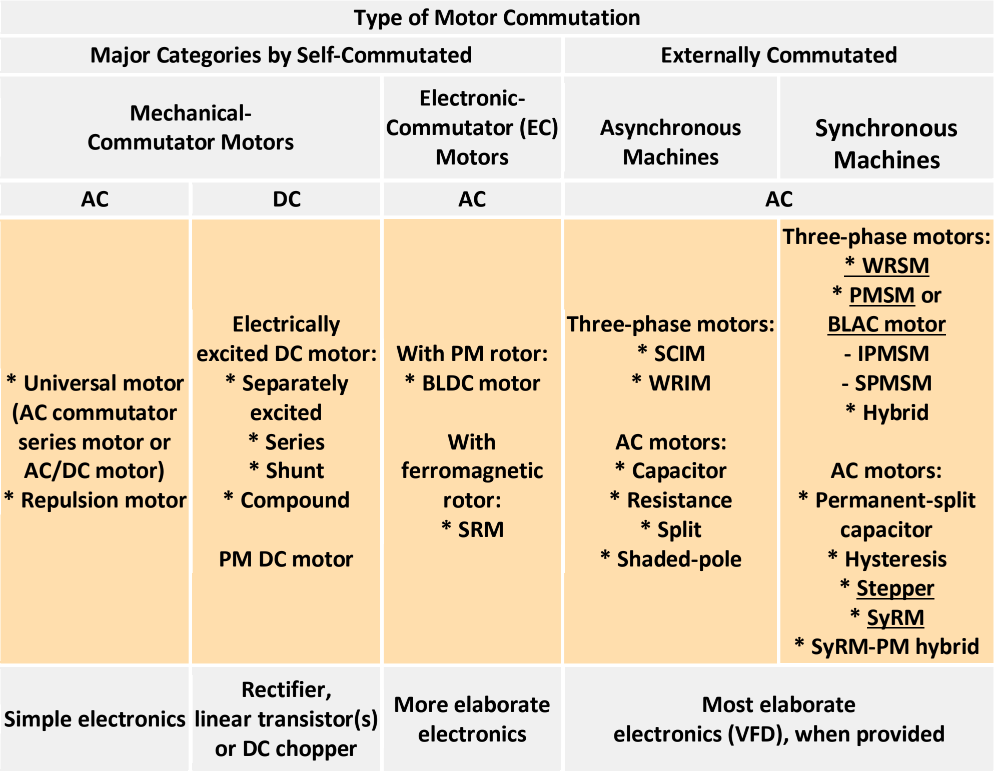
Engine sourcing depends on some requirements, listed below:

- Dimensions must fit inside the available space
- Output power and rpm in the same range of replaced ICE
- High efficiency in the working range
- Cost must be affordable
- Robustness and ability to work under harsh conditions.

Electric motors have a wide range of solutions, types of construction, for general and specific applications. The types of electric motors that might be considered are [89]:

- Conventional Direct Current Motor
- Permanent Magnet Direct Current Motor
- Coreless Direct Current Motor
- Brushless Direct Current Motor
- Mono-phase Induction Motor
- Three-phase Induction Motor
- Mono-phase Synchronous Motor
- Three-phase Synchronous Motor
- Switched Reluctance Motor
- Synchronous Reluctance Motor

Figure 5.19 shows the various types of electric motors by type of motor commutation [90].



Type of Motor Commutation				
Major Categories by Self-Commutated			Externally Commutated	
Mechanical-Commutator Motors		Electronic-Commutator (EC) Motors	Asynchronous Machines	Synchronous Machines
AC	DC	AC	AC	
* Universal motor (AC commutator series motor or AC/DC motor) * Repulsion motor	Electrically excited DC motor: * Separately excited * Series * Shunt * Compound PM DC motor	With PM rotor: * BLDC motor With ferromagnetic rotor: * SRM	Three-phase motors: * SCIM * WRIM AC motors: * Capacitor * Resistance * Split * Shaded-pole	Three-phase motors: * WRSM * PMSM or BLAC motor - IPMSM - SPMSM * Hybrid AC motors: * Permanent-split capacitor * Hysteresis * Stepper * SyRM * SyRM-PM hybrid
Simple electronics	Rectifier, linear transistor(s) or DC chopper	More elaborate electronics	Most elaborate electronics (VFD), when provided	

Abbreviations:

BLAC	Brushless AC	SPMSM	Surface permanent magnet synchronous motor
BLDC	Brushless DC	SCIM	Squirrel-cage induction motor
BLDM	Brushless DC motor	SRM	Switched reluctance motor
EC	Electronic commutator	SyRM	Synchronous reluctance motor
PM	Permanent magnet	VFD	Variable-frequency drive
IPMSM	Interior permanent magnet synchronous motor	WRIM	Wound-rotor induction motor
PMSM	Permanent magnet synchronous motor	WRSM	Wound-rotor synchronous motor

Figure 5.19 - various types of electric motors by type of motor commutation [89]

To perform the sourcing, the requirements listed before were considered and after market research, the selected motors were:

- HPEVS AC-50, figure 5.20(a) [91];
- AGNI 155R, figure 5.20(b) [92];
- ENSTROJ EMRAX 207, figure 5.20(c) [93];
- Golden Motor HPM20KW, figure 5.20(d) [94].

Figure 5.20 – (a) HPEVS AC-50 motor plus controller [91]; (b) AGNI 155R motor [92]; (c) ENSTROJ EMRAX 207 motor [93]; (d) Golden Motor HPM20KW motor [94]

The comparison between selected motors is shown in table 5.10.

Table 5.10 – Main specifications of electric motors

Manufacturer	Model	Type	Voltage [V]	Rated Power [kW]	Dimensions [mm]		Weight [kg]	Unit Cost
Agni	155R	DC brushed motor, air cooled	12 – 108	33	Diameter Length	270 225.5	20	2 103 €
Enstroj	EMRAX 207 (air cooled)	Brushless synchronous three phase AC	24 - 95	20-30	Diameter Length	207 85	9.1	2 490 €
Enstroj	EMRAX 207 (liquid cooled)		24 - 95	22-35	Diameter Length	207 85	9.3	3 390 €
Golden Motor	HPM20KW	Brushless DC motor, liquid cooling	72 - 120	20-25	Length Width Height	300 250 300	39	3 029 €
HPEVS	AC-50	AC brushless induction	72 - 108	20	Diameter Length	216 393	52.2	3 114 €

5.5.3 Controller sourcing

The choice of the controller is directly related to the electric motor. For the 4 electric motors considered, 2 were already delivered with a specific controller and for the other 2 the supplier suggested a controller that fitted the motor they sell.
HPEVS and Golden Motor motors were already supplied with a specific controller. For the Agni motor, supplier suggested an Alltrax controller and for Enstroj motors, manufacturer suggested a Unitek controller.

Table 5.11 shows for the considered motors the suggested controller, its cost and the aggregate cost of electric motor and controller.

Table 5.11 – Costs for the electric motor/controller package

Electric Motors			Controller	Controller Cost	Electric motor + Controller Cost
Manufacturer	**Model**	**Unit Cost**			
Agni	155R	2 103 €	Alltrax SPM72650	975 €	3 078 €
Enstroj	EMRAX 207 (air cooled)	2 490 €	UNITEK Bamocar D3-400-400-RS	3641 €	6 131 €
Enstroj	EMRAX 207 (liquid cooled)	3 390 €	UNITEK Bamocar D3-400-400-RS	3641 €	7 031 €
Golden Motor	HPM20KW	3 029 €	Delivered with electric motor	-	3 029 €
HPEVS	AC-50	3 114 €	Delivered with electric motor	-	3 114 €

In terms of total cost, Agni, Golden Motor and HPEVS solutions have a very similar cost, slightly above 3.000 Euro. Enstroj presents the most expensive solution, the controller cost is even higher than the motor itself, both solutions are above 6 000 Euro.

5.5.4 Sourcing decision

For the choice of the battery-electric motor-controller pack, some issues were considered:

- Energy is supplied by Direct Current (DC) batteries; the use of three-phase or Alternating Current (AC) motors would imply the use of converters between batteries and the controller of the electric motor, raising complexity, cost and loss of efficiency.
- Lithium-Ion batteries are very sensitive to high temperatures, vibrations. They require an expensive Battery Management System (BMS), although they are the second most expensive solution, both for 36 and 72 V applications.
- For the initial application, the aim was to use the simplest system as possible, to allow a quick learning of how to implement it and to make it work.

Considering these issues, the decision was to:

- Choose the Trojan batteries: they offered the lowest cost, reasonable weight – around 111 kg in a pack of three – and were deep cycle.
- The decision to purchase Trojan Batteries implied the purchase of a battery charger.
- Choose the Agni – Alltrax controller pack: Agni motor was a DC, its dimensions were aligned with the other alternatives, and its peak power with 36 V was expected to be around 10 kW. Alltrax controller could control a motor from 12 to 72 V and deliver a peak current of 650 A, more than the Agni Motor could support. Also a reason to select this package was that the distributor was located in UK and the lead time to receive the package was 2/3 weeks after order confirmation.

For a 36 V application, considering the Agni performance data [94], the expected maximum output was around 10 kW, with motor supplied with 300 A – figure 5.21.

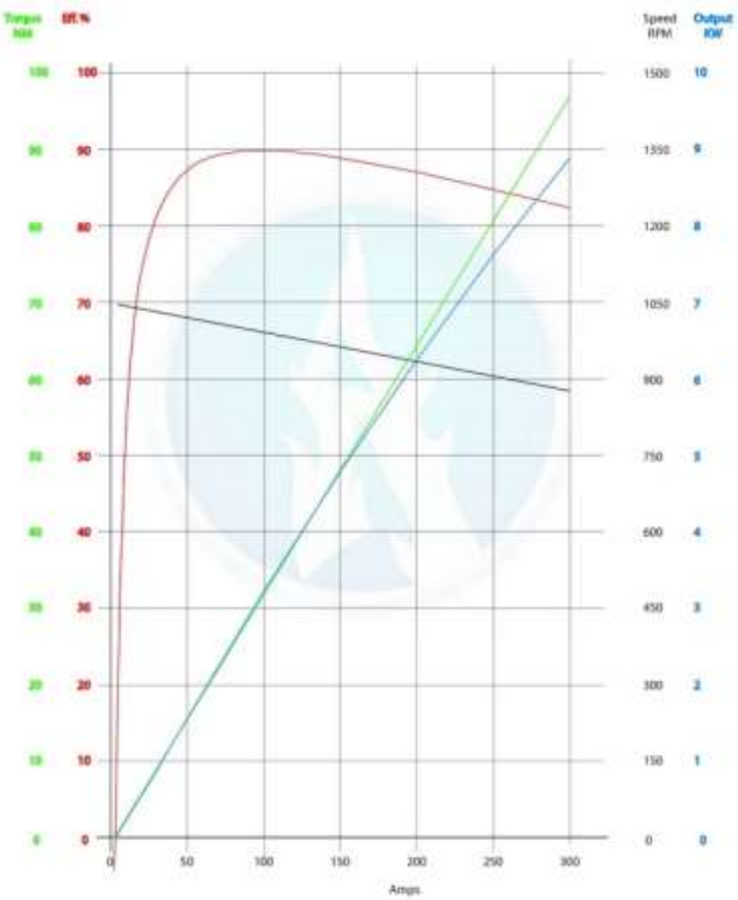


Figure 5.21 - Agni 155R performance graphs, 36V [94]

5.6 Components layout

Along with the disassemble tasks, described in 5.3, the 3D model of the removed parts was designed in 3D software. The used software was Siemens NX 7.5. First version was only with the major components which would remain in the converted prototype: frame, oil reservoir, crawlers and related components, hydraulic motors, roll bar. The assembly model is shown in figure 5.22.

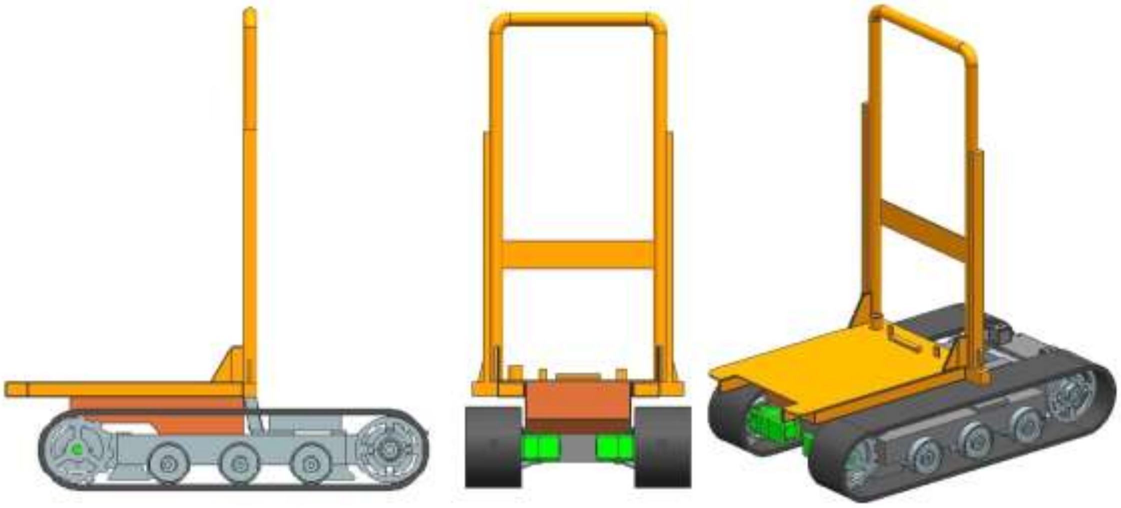


Figure 5.22 – Prototype 3D base model start

The original width of the prototype was 810 mm and it was reproduced in the 3D assembly, signaled in the top view, figure 5.23.

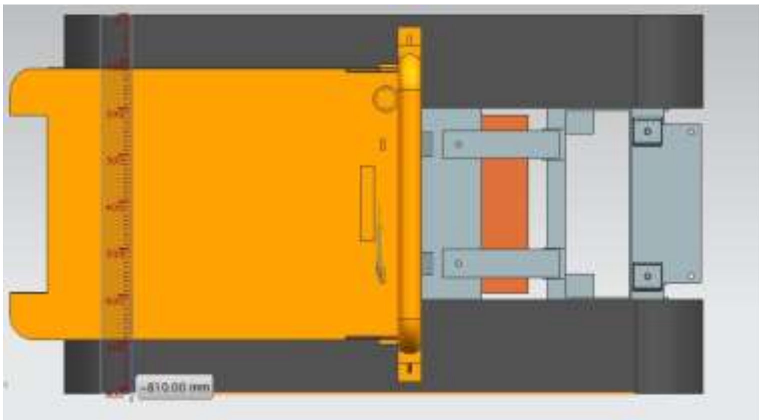


Figure 5.23 – Prototype 3D top view

With this 3D model, it was possible to study several alternatives for the location and packaging of the several components that needed to be kept and new ones that were to be added, like batteries and electric motor. It was designed a solution of 3 batteries as well for 6 batteries.

5.6.1 Three batteries solution

Along with sourcing of components, some alternative solutions were being designed to check the possibility of place to load it on into the prototype. The most critical component were the batteries, not only to its volume but also because of the need to pack a few of them, the access to the positive and negative terminals, access to fill the electrolyte, fixation, etc. Also the electric motor was one critical component, because its axle had to be aligned with the triple pumps axle, in order to drive them in the most favorable conditions.

Considering the Trojan Batteries dimensions, it was studied the possibility of placing them between the crawlers, in the lowest position. If the original frame was maintained, the height location of the batteries would push all the others components up, making the prototype as unstable as it was with the original ICE.

So it was thought to make a change in the frame in order to allow the batteries to fill the space between the crawlers as low as possible. That idea was implemented in the 3D model and the result is in figures 5.24 and 5.25:

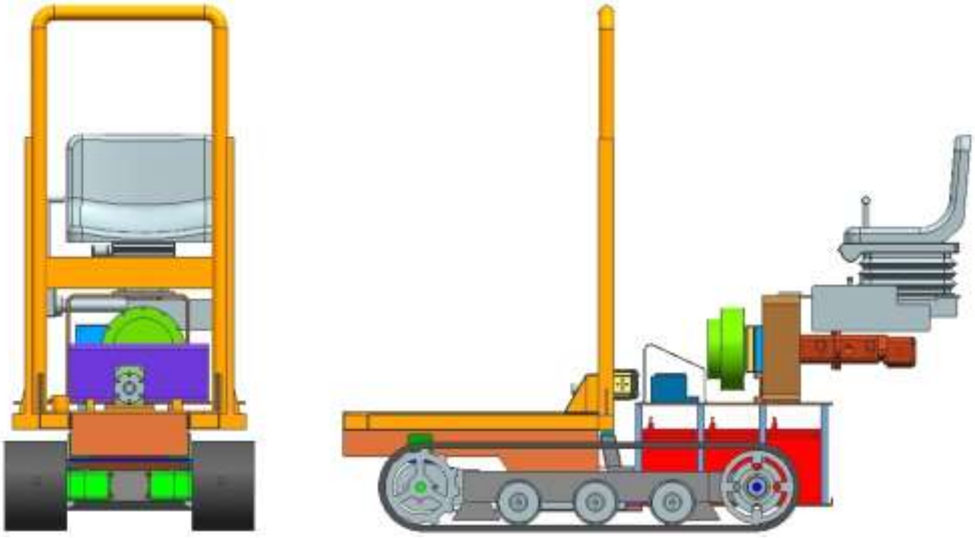


Figure 5.24 – Three batteries solution front and side views

Figure 5.25 – Three batteries solution isometric view

In the side view, it is easily to identify the 3 batteries in a very low position. This helped to lower the Center of Gravity (CoG) and in terms of longitudinal gravity center, the difference for the original ICE was not considerable. The Agni electric motor – in green - was also in position, supported by a box with gears. Triple pumps were aligned with the electric motor and also supported by the box. Above the batteries, it was designed a steel plate were all the others components would be supported, including the controller, protected by a steel cover.

This solution implied a total length, measured from the front end of reservoir to the end of the seat support of 2 000 mm.

In the trimetric view – figure 5.25 - it is possible to identify the hydraulic motor that would replace the original PTO. Once it was attached to the ICE, there was a need to replace it and a hydraulic motor was considered. In this first attempt, the cabling and piping were not represented, as well the distribution valves.

5.6.2 Six batteries solution – Version 1

Keeping some solutions from the 3 batteries pack of 5.5.1, it was considered a first version with a six pack batteries. Three would be in the same position as for the three batteries solution but the remaining three posed some problems. While for the previous solution, batteries were positioned in a way that even with steep ways, the electrolyte inside would not easily spill over, if the batteries were positioned along the prototype, when facing those steep ways, it was most likely that batteries would spill. This was not good for two reasons: without electrolyte, batteries may overheat and even explode; electrolyte is corrosive and may destroy some vines or even hurt persons.

The solution was to implement a storey packaging: three batteries on the bottom, two above them in a second floor and one on the top, on a third floor, figure 5.26.

Electric motor, transmission box and triple pumps would be located in the second floor. Controller was placed in the third floor. The storey solution implied a tubular frame, with steel plates in all floors, to support all the components.

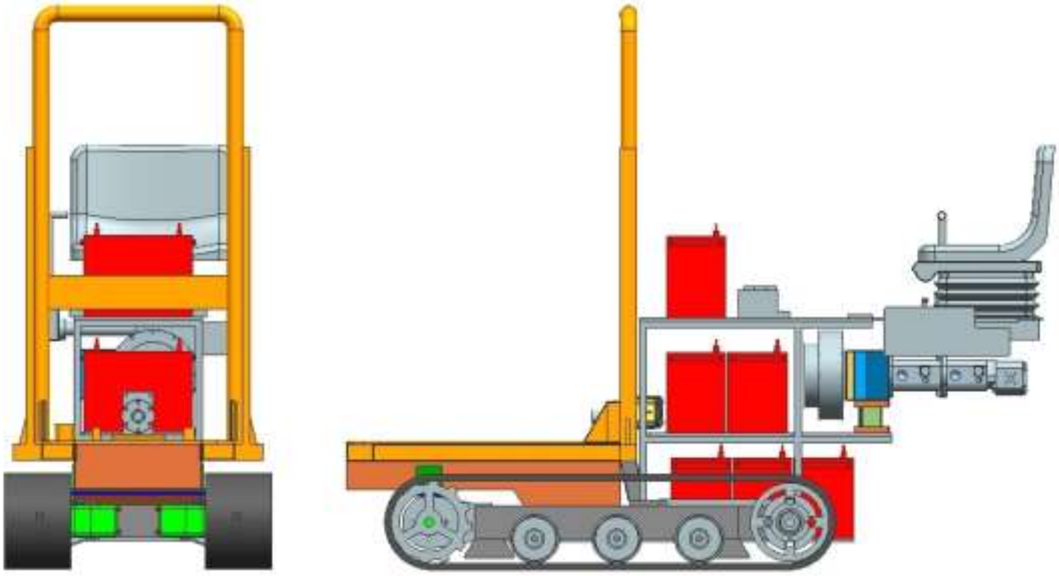


Figure 5.26 – Six batteries solution, version 1 front and side views

The overall length was 2.100 mm, 100 mm longer than the three pack solution. With this solution, the gravity center was pulled up, due to the three additional batteries placed above the three on the lower floor. Driver's seat was pushed to the rear and it may be a cause of instability, not only to the weight of the driver but also to the placement of the electric motor/triple pumps module.

As for the previous solution, the hydraulic motor replacing PTO was in its position.

In terms of ergonomics, this solution is not as good as previous one, once the legs of the driver may collide with the frame, obliging him to have the legs in a non-comfortable position, figure 5.27.

Figure 5.27 – Six batteries solution, version 1 isometric view

5.6.3 Six batteries solution – Version 2

Once the first attempt to place six batteries extended the length of prototype to an instable use, it was designed another solution, similar, but with one difference in the second floor: the batteries instead of being placed one after the other, they were placed side by side, figure 5.28.

With this solution, the overall length was of 2.040 mm, only 40 mm longer than the three pack solution.

Due to the batteries length, it was possible to place two side by side and still be inside the width of the prototype. I would require a larger plate for the second floor support but it wouldn't bring any problem.

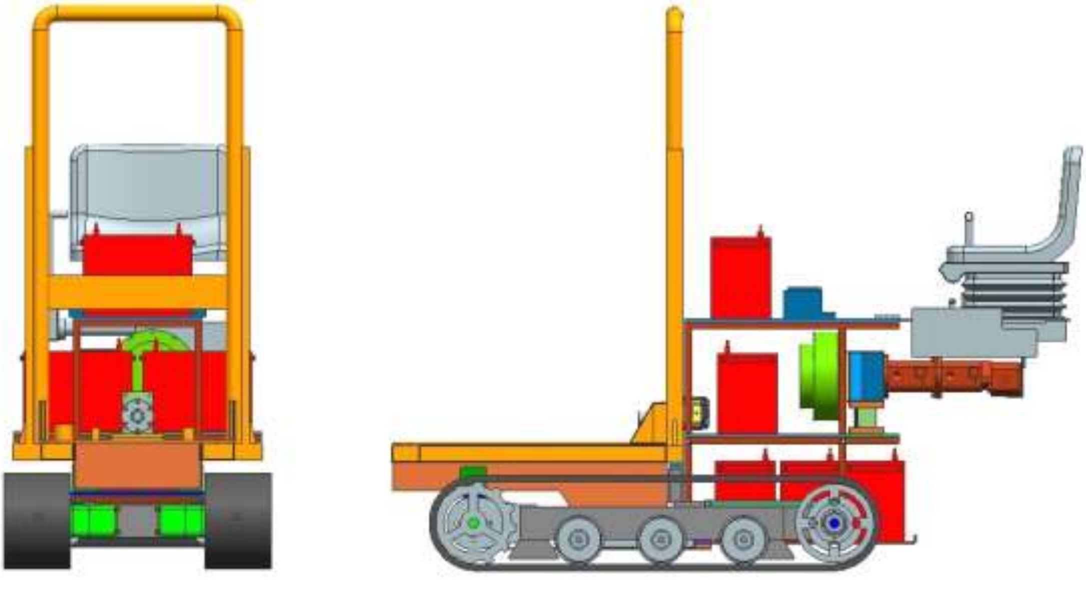


Figure 5.28 – Six batteries solution, version 2 front and side views

Ergonomically it would be at the same level as six batteries pack version 1 and in terms of stability it would be slightly better, once the second floor batteries allow the electric motor / triple pumps to move frontwards, improving the prototype's balance, figures 5.28 and 5.29.

Figure 5.29 – Six batteries solution, version 2 isometric view

The shown solutions were not the only designed ones but were the ones that benefit from previous versions and were the ones that were considered for the building of the prototype. In total, around 20 versions were designed and evaluated.

5.6.4 Concept selection

To evaluate the concept to be selected for the prototype, the Ulrich and Eppinger [1] method of concept selection was followed, using concept scoring. To perform this, the needs selected in 5.3.4 were used, with an additional need related to prototyping cost. In this phase the cost of building the prototype was considered and added to the list. Scoring of the concepts was from 1 to 5 – table 5.12.

Table 5.12 – Concept scoring criteria

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

Using these criteria and considering the importance of each need as a weighting factor, the result of concept scoring is show in table 5.13

Table 5.13 – Concept scoring

		Concepts			
Need	Description	Importance/ Weight	3 Batteries pack	6 Batteries pack Version 1	6 Batteries pack Version 2
1	Vehicle stays stopped in any position	5	3	3	3
2	Vehicle allows a good visibility	3	4	3	3
7	Vehicle is easy to control	5	3	3	3
8	Vehicle allows to perform tasks	5	2	2	2
9	Vehicle has power to perform work	5	1	2	2
10	Vehicle allows attaching existing equipment	5	3	3	3
11	Vehicle allows equipment control	4	3	3	3
12	Vehicle allows equipment good visibility	3	4	3	3
14	Vehicle is fast to change to another line	4	2	3	3
23	Vehicle allows working in top-down vineyards	5	3	3	3
24	Vehicle allows working in narrow vineyards	5	3	3	3
25	Vehicle is robust	5	3	3	3
30	Vehicle emits low emissions	4	5	5	5
	Prototyping cost	5	5	3	3
Total		-	220	210	210

From table 5.13, the highest score was achieved by the 3 batteries pack, with the two versions of 6 batteries tied. The factor that untied the result was prototype cost. It is easy to understand that from the table, solutions scoring did not move much from the reference score, once all concepts use the base Multyjip, with no relevant changes in its functionality. Maybe different criteria should be used to better differentiate concepts.

This decision was taken in December 2014. It was also decided that the conversion would carry on in two phases:

- First phase: Implement the 36 V solution; design, prototype, assemble and test.
- Second phase: Implement a 72 V solution; with the results, comments and updated calculations, redesign, make new prototypes, assemble and test.

A schedule was defined for these two phases: the first one would start in January 2015 and end in May, while second phase would start in June and end in November 2015, figure 5.30.

Schedule had some critical tasks: the components reception, the definition of the prototype parts and its manufacturing and the prototype assembly. If one of these tasks took more time than it was scheduled, the end of each phase would not be granted.

Phase #	Detailed task	1Q2015			2Q2015			3Q2015			4Q2015		
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Phase 1	Components order	■											
	Components receipt	■	■										
	3D development	■	■	■									
	Prototype parts 3Dmodels, drawings		■	■									
	Prototype parts manufacturing		■	■									
	Prototype assembly			■	■								
	Workshop test				■								
	Field test				■	■							
	Results analysis					■							
Phase 2	Assessment of the project						■						
	Components order						■						
	Components receipt						■	■					
	3D development						■	■	■				
	Prototype parts 3D models, drawings							■	■				
	Prototype parts manufacturing							■	■				
	Prototype assembly								■	■	■		
	Workshop test										■		
	Field test										■	■	
	Results analysis											■	

Figure 5.30 –Tasks planning for the development of the prototype

5.7 Components design

According to schedule, in January 2015 3D development models started, following the three batteries pack solution. The 3D models from electric motor, battery, hydraulic components were asked to suppliers but only some were available. Battery and electric motor were designed according to the drawings and specifications sent by suppliers. For the main hydraulic components, only auxiliary pump 3D model was available and there was a need to design the rest.

For the components manufactured and assembled in Multijyp’s factory, like the frame, roll bar, oil reservoir, all of them were measured and the components design was made under those measurements.

There were two main design changes to be performed in frame and in oil reservoir, along with new components, as transmission box, steel plates, seat support, controller cover and other small ones. Also some original components needed to be changed, like the connection shaft from ICE to triple pumps and also the auxiliary pump shaft.

5.7.1 Frame modification

To place the three batteries between crawlers as low as possible, the frame had to be changed in order to allow batteries inside of it. According to the 3D model, it was established were it needed to be cut. The original frame and where it would be cut is shown in figure 5.31.

Figure 5.31 – Frame modification cutting lines

The cut will remove from frame front and rear engine mountings, support rear plate, rear wheels shaft regulators and its blocks. The plate that supports the oil reservoir had to be cut close to the oil reservoir mountings and in a width of approximate 400 mm.

The cut was performed by Oxisol, located in V.N. Gaia which used flame cutting to remove the components and cut the plate – figure 5.32.

Figure 5.32 – Frame after modification

This solution however origins another problem: rear wheels were connected each other by a rear shaft which was adjusted by the rear wheel adjusters. These adjusters function was to keep the crawlers with a certain level of tension, to avoid them to deform too much or get off the guides.

5.7.2 Oil reservoir modification

It was mentioned in 5.3.2 the difficulty to remove the oil reservoir, due to its bottom's shape. Unfortunately, there are no pictures of the original shape. Measures form original reservoir allowed reproducing it in 3D model, figure 5.33.

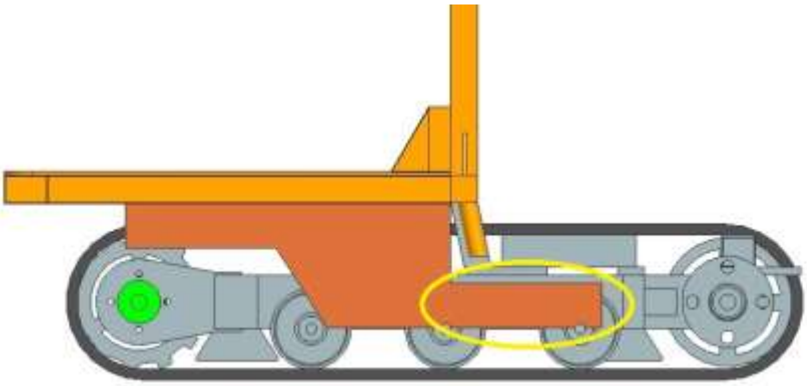


Figure 5.33 – Oil reservoir shape, side view. In yellow area, removed

It is seen in the 3D assembly that the oil reservoir bottom's extension was below the plate that supports reservoir's and ICE's mountings, making it difficult to remove and even to access. That extension had around 280 mm, figure 5.34.

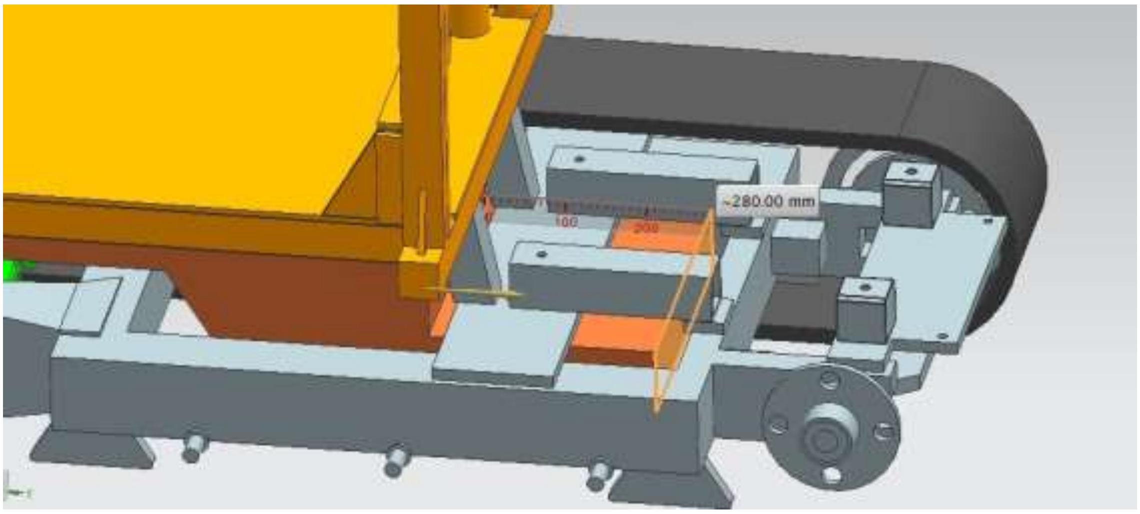


Figure 5.34 – Oil reservoir shape, under engine mountings

For the conversion, the space occupied by that extension was colliding with the batteries. So it was decided to remove that extension. The removal raised one issue: it would reduce the capacity of the oil reservoir in 7.3 liters. Reducing oil reservoir's capacity is negative for the hydraulic system's performance, once the reservoir capacity has a function of reducing the oil's temperature, a critical parameter for the hydraulics system's performance. Original capacity was around 50 liters.

Fortunately, there was a chance to replace the removed capacity, using the volume left from the 12 V battery that started Diesel ICE. That volume was available, with no other application on sight.

New shape was designed and compared with the original one, figure 5.35. The change allowed not only to restore but even to increase the oil reservoir's capacity in 3.5 liters. Total capacity would be around 53.5 liters, more 7% when compared to the original.

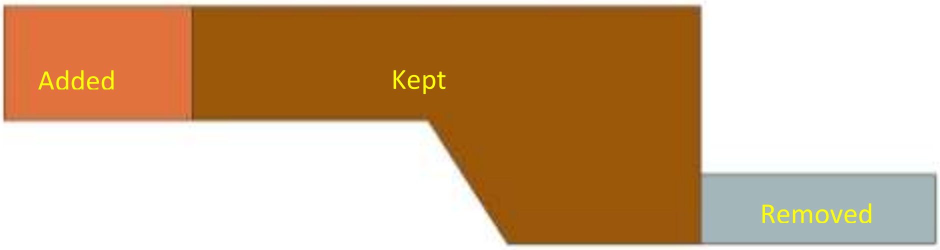


Figure 5.35 – Oil reservoir shape changes

To perform the change, the extension was removed and a plate was welded aligned with the vertical wall. In the front, a rectangular cut was done and some plates were welded to extend the wall to the end of the platform, figures 5.36 and 5.37.

Figure 5.36 – Oil reservoir rear cut

Figure 5.37 – Oil reservoir front cut

In the front end, after welding the plates, final result is shown in figures 5.38 and 5.39.

Figure 5.38 – Oil reservoir front view after change, left view

Figure 5.39 – Oil reservoir front view after change, right view

5.7.3 Transmission box

Original ICE had two pumps modules attached to it: triple pumps and auxiliary pump. Removing the ICE and replacing it by an electric motor brought one problem up that was how to connect both modules to the motor.

Agni's electric motor had only one output shaft and it was not a possibility to ask a diverse shaft's end, once it would delay the delivery of the motor. It was found in Lombardini's literature [69] that the side output on the engine was rotating at the same speed as the crankshaft.

Considering this, a solution needed to be found that allowed both modules to be driven at the same speed and in the same rotation direction.

After some discussion, the solution found was an assembly that had some functions:

- Support the electric motor
- Support the pumps modules
- Transmit power and rotation from electric motor to pumps modules.

While the power transmission from electric motor to triple pumps was direct, the electric motor's output shaft was directly connected to the triple pumps input shaft; the auxiliary pump had to be placed beside the triple pumps. The power transmission was performed by three gears: two with the same size, in the left and right and a different gear in the middle. To support these three gears, a two parts aluminium housing was designed. For the gear connected to the pumps, there was a bearing placed in the housing in the side of the electric motor. The gear in the middle rotate over a shaft, with two bearings, that was hold by two steel parts attached to both housings. The main parts of this assembly were:

- 1 gear connected to electric motor/triple pumps: Z 40; m 1,5; thickness 17 mm
- 1 gear connected to auxiliary pump: Z 40; m 1,5; thickness 17 mm
- 1 gear in the middle, Z 47; m 1,5; thickness 17 mm
- 2 bearings 6008 2RSR
- 2 bearings 6202 2RSR
- 1 triple pump ring
- 1 triple pump bushing
- 2 square steel inserts
- 1 steel shaft for the middle gear
- 1 aluminum housing for the electric motor side
- 1 aluminum housing for the pumps side
- 1 aluminum spacer
- 2 aluminum holders

The solution in 3D is shown below in figure 5.40.

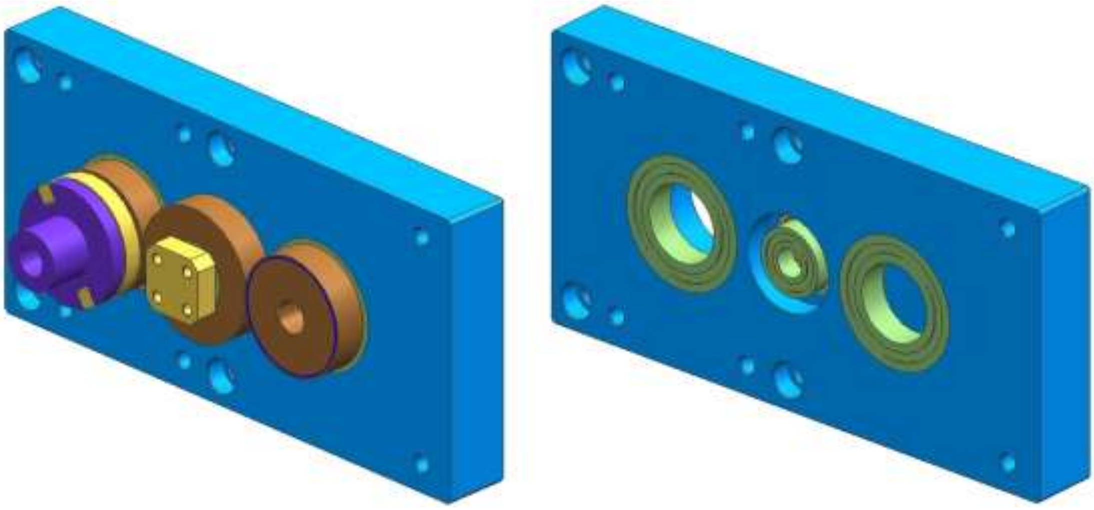


Figure 5.40 – Transmission box design, front and rear views

Brown parts are the gears, purple part was the same used in ICE, the yellow ring was a new part designed to be attached to the electric motor gear, to drive the purple part. In the right picture, it is possible to see the bearings, in the middle position, only one of two is represented.

The look of this assembly is shown in figure 5.41, with pump modules, electric motor and the holders of the transmission box. There was a need to insert a spacer plate between the electric motor and the housing of its side, to avoid making a thicker housing, to reduce weight. In the housing that holds the pumps, there was a need to make a big cut for the auxiliary pump. The reason was that the shaft of this pump was very short and to avoid making a new one or adapt an intermediate part, to allow the original shaft to attach its gear, the thickness of the part where this pump was located was very thin.

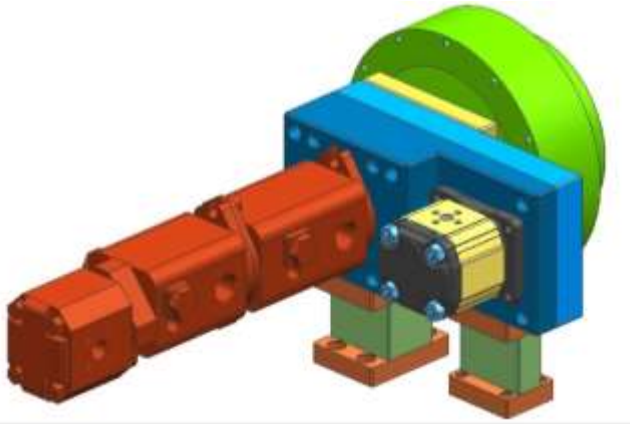


Figure 5.41 – Assembly with electric motor, transmission box, triple pump and auxiliary pump.

Final parts of transmission box are shown in figure 5.42.

Figure 5.42 – Final parts of transmission box

Aluminum and steel parts were machined in Engenhotec, ring and middle gear shaft were sub contracted. Gears were bought in a supplier and its material was mild steel – CK 45 – with no surface or thermal treatment.

5.7.4 Sheet metal parts

Some new parts were designed to be made in sheet metal. Due to the laser cutting and bending processes, it is quite easy to obtain flat or bended parts from simple geometries. The most important sheet metal parts designed were: bottom shield, platform, controller cover and seat holder.

Bottom shield and platform were designed in steel sheet metal with 4 and 5 mm thick respectively. Both are flat parts, only bottom shield has a bend in one end, to avoid dirt to enter into the shield.

Bottom shield was fixed to the frame with nine holes. Its main function is to support the three battery pack and all the components that will be placed over the platform, figures 5.43 and 5.44.

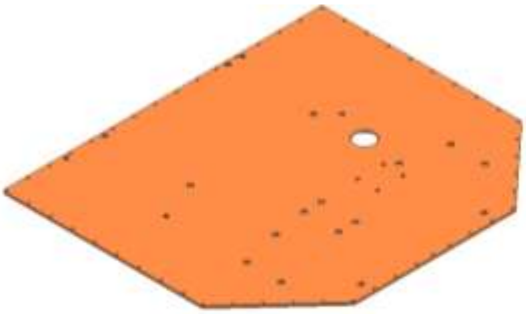


Figure 5.43 – Platform 3D model

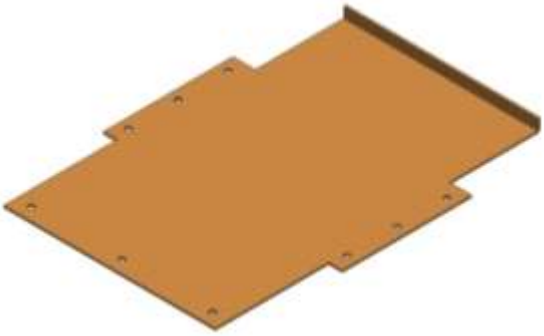


Figure 5.44 – Bottom shield 3D model

Platform will support the electric motor/transmission box/pump modules, controller, seat holder and other accessories.

Seat holder was designed in 10 mm steel sheet metal, once it will support the driver's seat and due to the distance from driver's seat to the fixation in seat holder, torque is around 600 N.m, considering an 80 kg driver, figure 5.45.

Controller cover is to protect controller of damage and also can be used as a foot rest for the driver. It has 2 mm thick which is enough because it has no structural purposes, figure 5.46.

Figure 5.45 – Seat holder 3D model

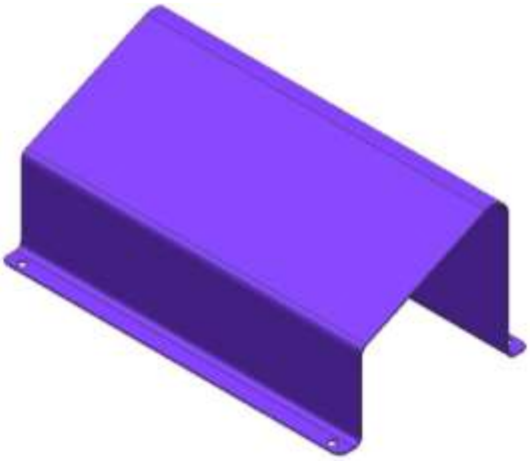


Figure 5.46 – Controller cover 3D model

5.7.5 Rear wheels adjusters

It was mentioned in 5.6.1 that the frame modification brought up a problem concerning the fixation and alignment of the rear wheels. Once the part that connects both rear wheels was cut, only the ends that connect to the wheels were used but the square steel block was not enough to guarantee that the wheels were aligned with the crawlers. If the alignment was not correct, crawlers may jump off the wheels and stop the prototype or damage crawlers and led to a premature wear.

To avoid these problems and have guarantee that the wheel will work correctly a solution was designed that consisted in adding two U shaped plates with 15mm thick on each side along the square area, at a distance equal to the width of the tube in the frame where this part fits. The result is shown in figure 5.47 and how it stands it the prototype in picture 5.48.

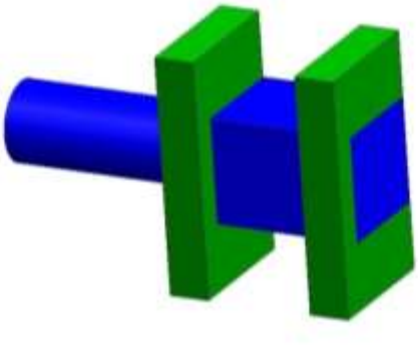


Figure 5.47 – Rear wheels adjuster 3D model

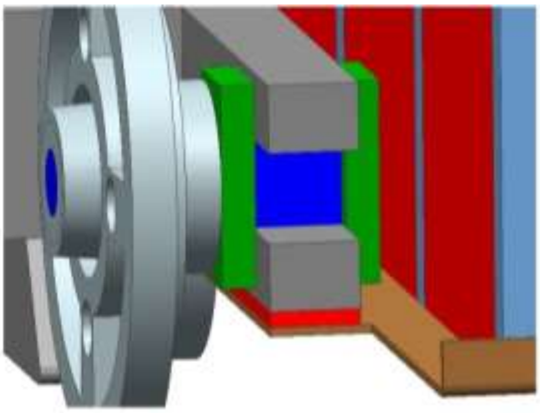


Figure 5.48 – Rear wheels adjuster assembled with wheel

The U shaped parts were produced but laser cutting and the material of these parts was ST37-2. They were welded with the rear wheel axle on position on the frame to ensure that the distance was correct. If after welding, it got tight due to contraction, it could be deburred with a grinding wheel until it enters in the frame. It must be not loose otherwise rear wheel would be misaligned, causing the problems already described.

5.7.6 Other parts

At the end, nearly 30 new parts were designed to the purpose of converting the ICE powertrain to a BEV. Besides the ones already described, some other simpler parts were designed or adapted. They are described next, related to figure 5.49:

- Vertical bars that support platform (1): 8 rectangular aluminum parts with section 40x20 mm were used to hold the platform, supported in the bottom shield. They were fixed to both parts with 8 mm bolts.
- Rectangular bars to support bottom shield (2): two bars with 260 x 40 mm, with 7 mm thick were welded to the lower part of the frame to allow bottom shield to be fixed with bolts, for a quick removal if necessary.
- Spacer plates (3): two steel plates with 60 x 50mm with 11 mm thick, welded to the bottom of the frame, used as spacers.
- Transversal bar (4): rectangular steel bar with 650 x 50 mm with 15 mm thick, welded to spacer plates (3) that was used to fix bottom shield with bolts.
- Spacer plates (5): two steel plates with 100 x 40 mm with 8 mm thick, welded to the original oil reservoir mountings.
- Reservoir mounting bar (6): a rectangular steel bar with 365 x 40 mm with 12 mm thick, welded to spacer plates (5), to fix oil reservoir with 4 bolts, instead of welding.
- Front reservoir support plate (7): a rectangular steel bar with 550 x 80 mm with 10 mm thick welded at the top of the hydraulic motors mounting.
- Front reservoir corners (8): two bended steel parts with 8 mm thick, welded to the side of oil reservoir to allow its fixation by bolts.

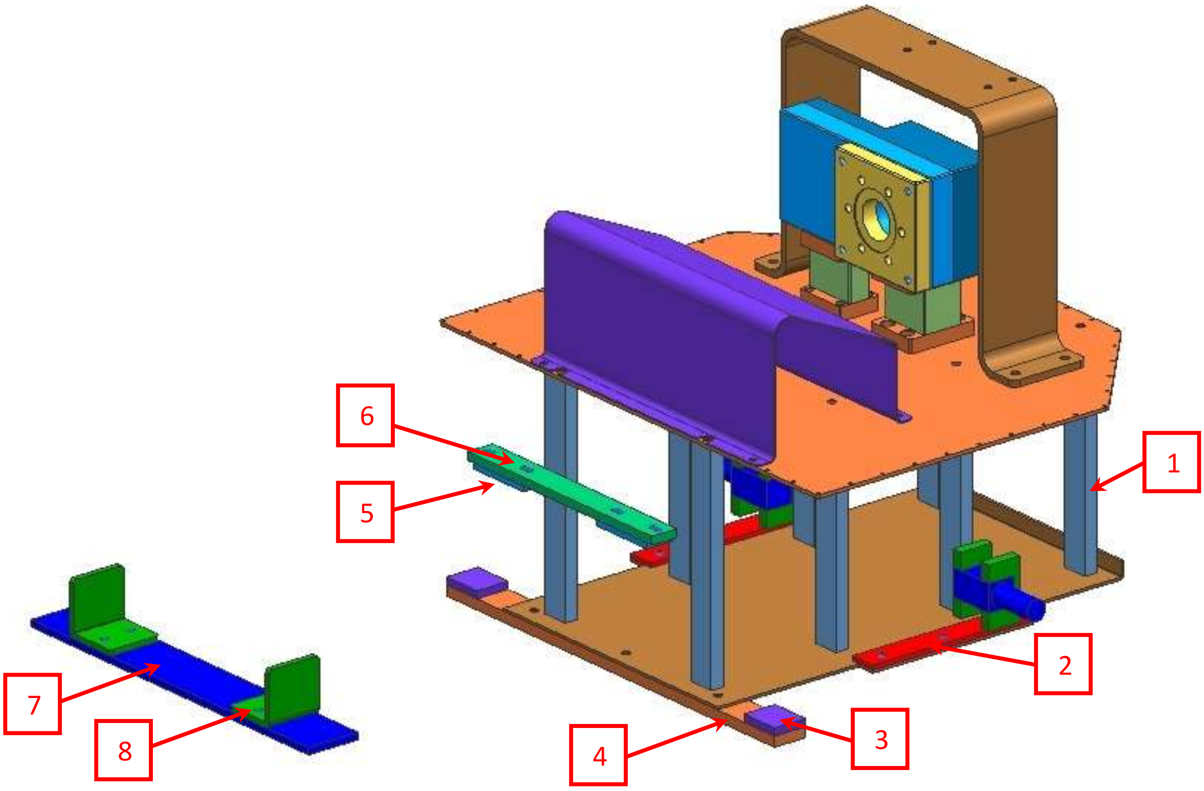


Figure 5.49 – 3D view of all new designed parts

Only the vertical aluminum bars were manufactured in Engenhotec. All the others were produced by laser cutting and bending and were sub contracted to V-Laser On.

5.8 Assembling, control and adjustments

According to the planning of point 5.4.4, the selected components for the electric system were ordered in January 2015 and the development of the new parts started at the same time. As soon the design of each component was frozen, they were either manufactured in Engenhotec or contracted to suppliers.

The manufacturing of the parts was done close to the planning and between February and March almost all the parts were available to start assembling the prototype.

However, there were two big setbacks with one of the most important components - electric motor:

- The initial lead time presented by the English distributors was that the motor was available for shipping 2/3 weeks after order confirmation, meaning that the motor should arrive in Engenhotec 1 month after ordering. When order was placed and paid, distributor gave the information that there were no motors in stock and most likely the delivery would occur late April. If electric motor would be available in that date, it would imply one month delay.
- Electric motor arrival was on April 24th, according to the last plan. When it arrived, it was taken out of the box and surprisingly, the look of the motor was like it was a used motor, with rust in the bearing and paint coming off, see figures 5.50 and 5.51.

Figure 5.50 – Agni 155R motor overall look

Figure 5.51 – Rust detected in the bearings and shaft

Even worse, when the inside was checked, one found out that the brush holder was cracked and cracks were filled with glue, figures 5.52 and 5.53. An immediate complaint was sent to the distributor and they agreed that the motor was not new. Agni was stating that motor was new and there were no reasons to complain.

Figure 5.52 – Brush holder center cracked

Figure 5.53 – Individual brush holder with cracks

After some emails exchange with distributor, hardly complaining about the situation, Agni agreed to send a new brush holder to replace the cracked one immediately and as soon it could send a new motor, replacement would be made.

If one had to wait for the new motor to be used in the prototype, it would delay even more the final assembling and test starting so it was communicated to Agni that as soon new brush holder arrived, it would replace the cracked one and the motor was to be used as it was.

New brush holder arrived May 18th and apparently in good conditions, figures 5.54 and 5.55.

Figure 5.54 – New brush holder, inside view

Figure 5.55 – New brush holder, outside view

It was necessary to remove brushes and rear plate from the cracked brush holder to the new one. Installation had to be done carefully once carbon brushes are fragile and its position must follow the original one. After the replacement, new brush holder assembly was with a bright look, figures 5.56 and 5.57.

Figure 5.56 – Agni 155R motor with replaced brush holder

Figure 5.57 – Detail of Agni 155R motor with replaced brush holder

After this replacement it was possible to put the electric system together and prepare it for the first test. Electric system should respect the scheme provided by Alltrax, figure 5.58.

Besides batteries, electric motor and controller, is was necessary to add to the system a Kilovac EV200 Contactor, a 600 A fuse, a 5 A fuse (125 V), a pre-charge resistor 1 kΩ and a throttle. The Kilovac contactor was bought in Jozztek, throttle was bought in Aquário and the other sourced in E-Bay. The optional interlock was not used, once it was not absolutely necessary.

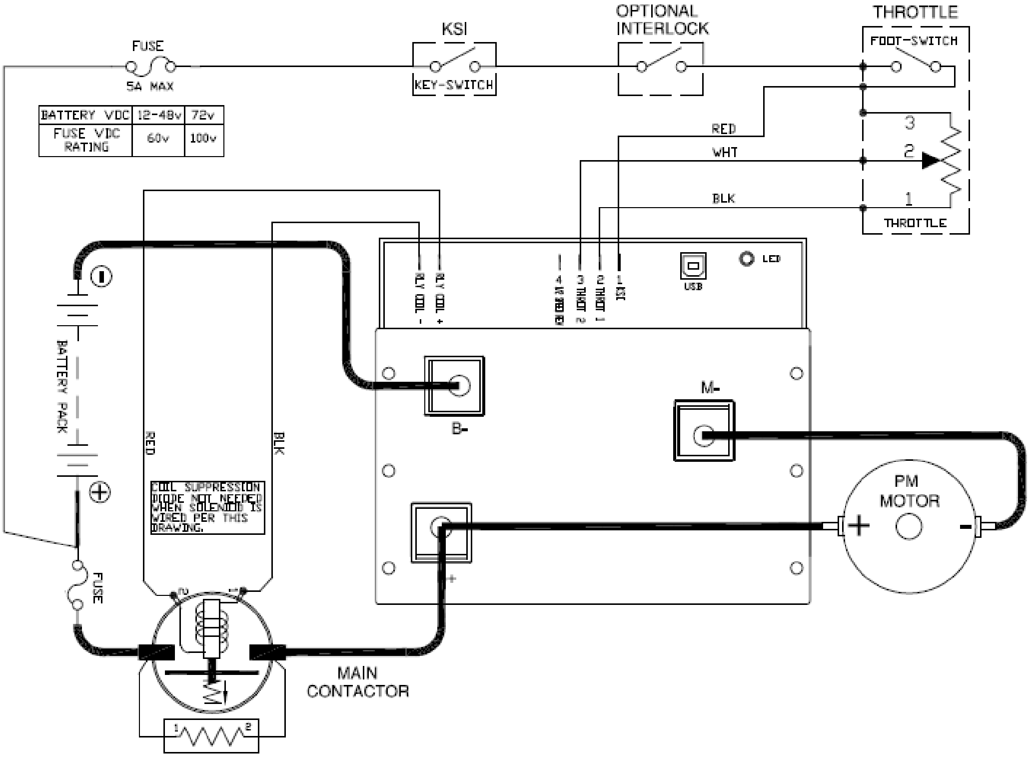


Figure 5.58 – Electric scheme for the implementation of the batteries / electric motor solution

5.8.1 Electric system first test

All the needed components were available when new brush holder arrived and the system was connected shortly after. In May 27th it was possible to perform the first test to the complete system, figure 5.59. Auxiliary pump was placed in its position and to avoid damaging it, the test only took a few minutes, with the electric motor working at very low rpm. In this test the Kilovac contactor was not used, once it can only be used in a 72 V system. It was replaced by a switch: brand Comar, model 500010.

Figure 5.59 – Assembly for the first electrical test, May 2015

The control of the electric motor output is done by two ways: controller set-up and throttle opening.

Alltrax controller has a specific application – Alltrax Toolkit V2.0.8 - that allows set-up the output characteristics which can be installed in a common desktop or laptop. The set-up is divided in three tabs: controller settings; throttle settings and monitor. Each of the tabs is shown in figures 5.60, 5.61 and 5.62.

Controller was programmed with the following settings:

Voltage Settings

- Under Voltage: 30 V DC
- Over Voltage: 50 V DC
- KSI On Voltage: 20 V DC

Current Settings

- Max Motor Amps: 149.5 A
- Max Battery Amps: 149.5 A

Maximum throttle opening allowed by controller is 95%. When opening passes 95%, controller shuts down the output for safety reasons.

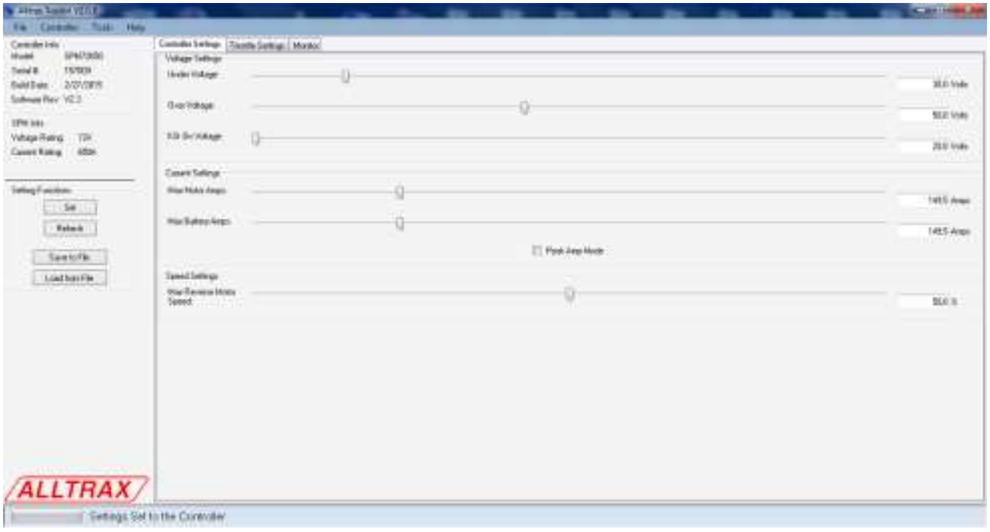


Figure 5.60 – Alltrax controller settings tab

In controller settings tab, it is possible to set under and over voltage thresholds, current settings as the maximum current from batteries and sent to motor and the maximum reverse motor speed. For the first test the set-up was the one of figure 5.59.

In throttle settings tab, it is possible to see the expected output of the electric motor: in a graphic window, a green column shows the throttle position in percentage (%) and two lines representing expected speed – in red – and expected torque – in dash blue. For the first test, the maximum throttle opening was 43% - figure 5.60.

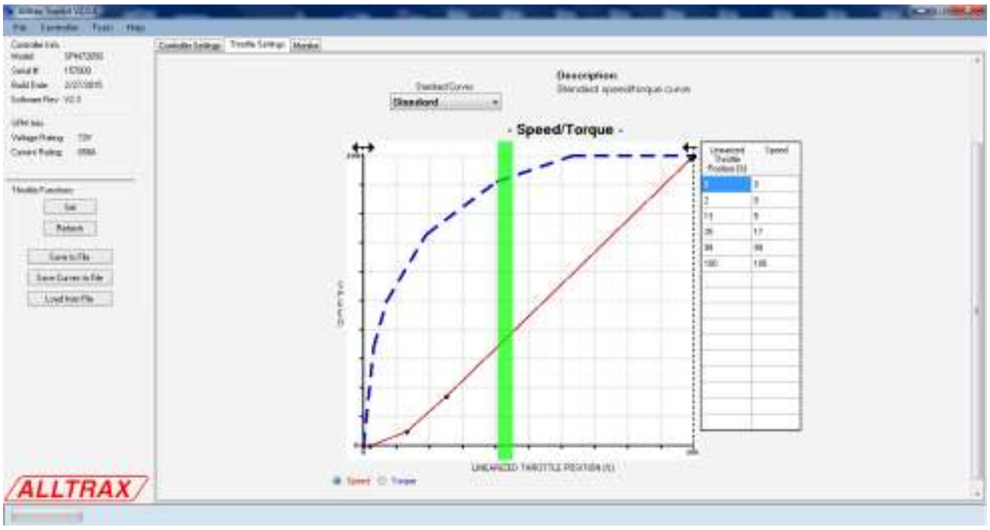


Figure 5.61 – Alltrax throttle settings tab

In monitor tab, it is possible to identify two areas: errors flags and gauges values. Errors flags show if there is any problem in the system for 13 causes. If an error occurs, a black dot appears in the screen, figure 5.61.

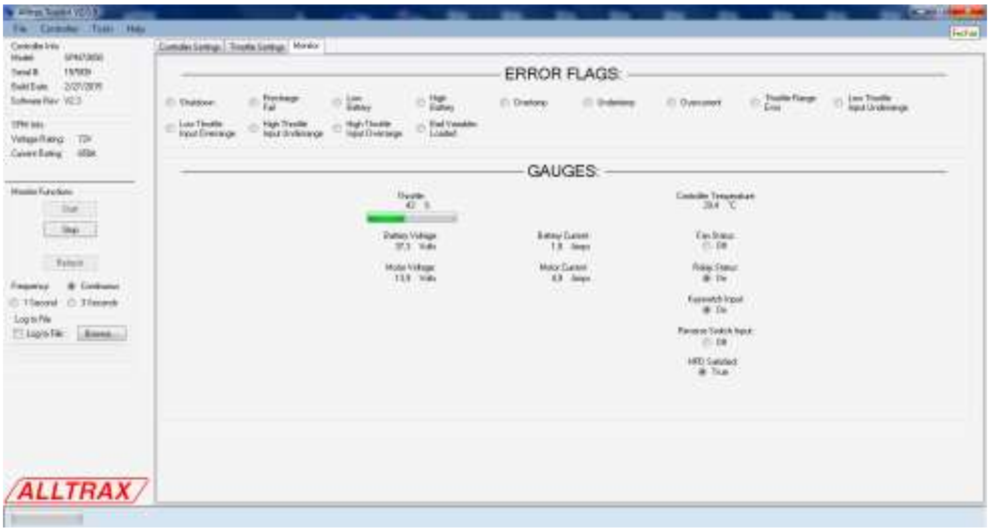


Figure 5.62 – Alltrax monitor tab

In the gauges area, it is shown the throttle opening, battery voltage and current, motor voltage and current, controller temperature and some flags. These values are very important once they give the picture how system is working and performing. In picture 5.62, for a throttle opening of 43%, with no load, batteries output was of 37.3 V and 1.8 A and motor input was of 13.9 V and 4.9 A. Controller "plays" with the voltage and current available and delivers voltage and current to the motor to achieve the best performance.

Throttle opening depends on the opening of the shaft. This throttle has a fine setting; from close to full open it is necessary to turn it 10 times. Rotating clockwise decreases opening, rotating counter clockwise, increases opening, figure 5.63.

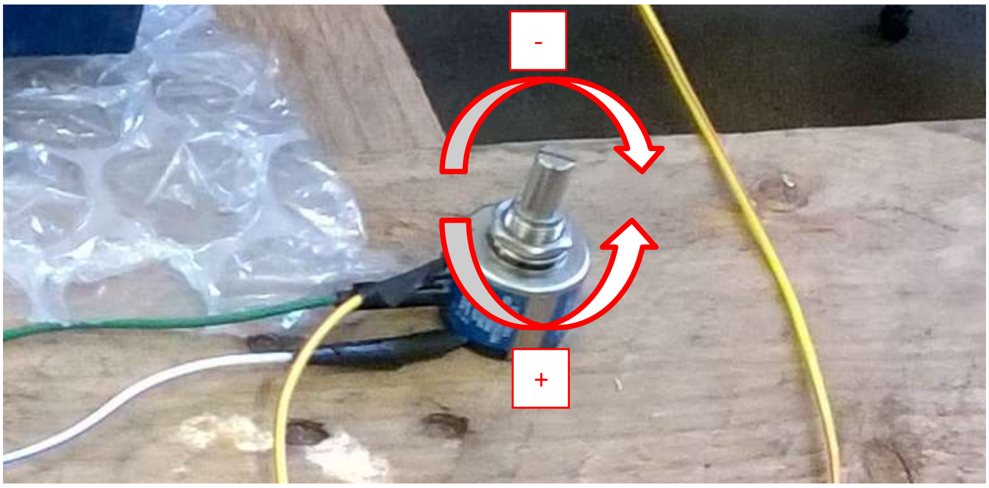


Figure 5.63 – Throttle control

5.8.2 Transmission box first test

Immediately after the first electric test, the transmission box was tested. Using the same layout, triple pump module was added and using the same controller set-up, the test of the whole assembly was made, figure 5.64.

Figure 5.64 – Transmission box first test, May 2015

During this test a problem occurred: even with the throttle fully opened, the electric motor was not rotating. It was not expected, once in the test of the electric system, auxiliary pump was in place and it worked and by adding the triple pump module it was expected more resistance, meaning more throttle opening but even at the maximum position there was no movement.

It was thought that maybe the triple pumps module was stuck, due to lack of oil caused by almost a one year with no use. Another cause could be the transmission box itself, due to some kind of interference preventing the system to work. It was tried to relief the tightening of the bolts that fix the two housings one to another and it was enough to allow the electric motor to work.

After the test, the transmission box was disassembled and it was verified that there were markings in the side face of the cuts were the gears are placed, figure 5.65, showing clearly that it was the cause preventing electric motor motion.

To solve this problem, the cuts in the housing were reworked, by raising the depth in both cuts by 2 mm. After rework, transmission box was assembled again and with all bolts tightened correctly, gears moved smoothly, with no constraints.

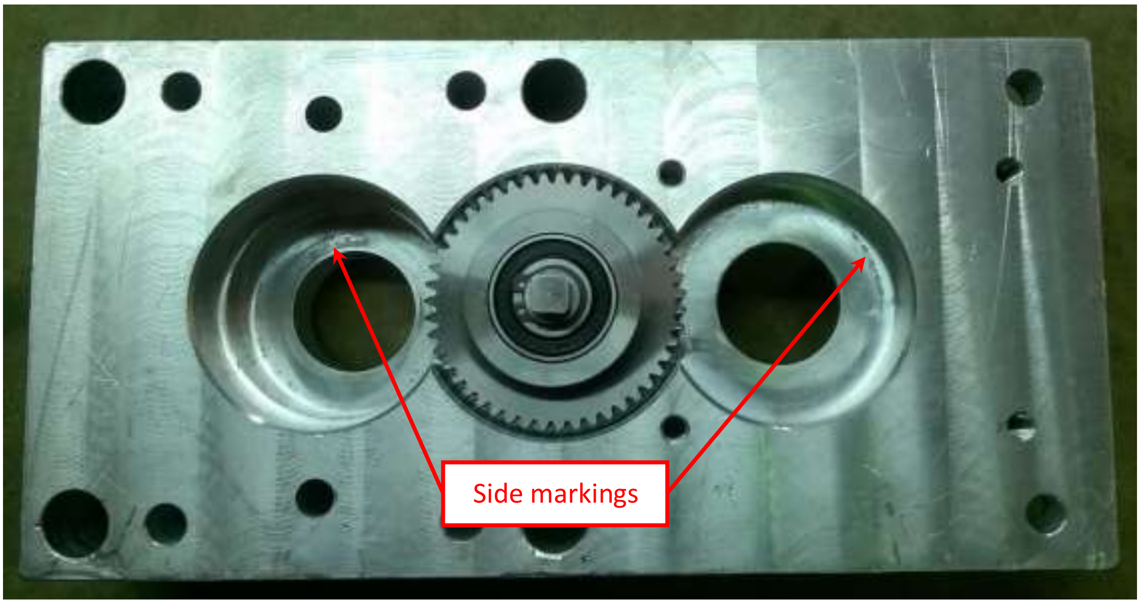


Figure 5.65 – Transmission box side markings after first test

5.8.3 Prototype assembly

After the first electric test and with the main components already available, the assembling of the prototype started early June 2015.

First the bottom shield was fixed to frame and the batteries where spread along the space, according to the layout shown in 5.5.1. Vertical supports were fixed to bottom shield which also fixed batteries to its position. All the cables connecting batteries were prepared to their appropriate length and terminals crimped to cables. After this batteries floor ready, the platform was placed and fixed to vertical supports. Controller, transmission box and seat holder were fixed to platform with bolts. It had to be made some new holes because the designed original ones had some mistakes, once it was not possible to fix transmission box and seat holder together. After this correction, all these components were finally fixed.

Then the oil reservoir was placed in its position and fixed by bolts in front and rear mountings. It was very easy to place it and fix it, only a pair of bolts in rear mountings were not tight correctly due to difficult access to the key.

Next step was the hydraulic system. Once prototype movement is done by hydraulic motors fed by the bi-directional pumps, all the hydraulic system was placed as it was originally. However some problems showed up:

- Some tube lengths did not allow attaching one of the ends at the right place. For example, hydraulic motor tubes that connect to bi-directional valves did not have enough length to allow connection;
- Due to reposition of auxiliary pump, some old tubes were not possible to use at all;
- Placement of oil filters had to be repositioned and even its orientation changed, to a new vertical one;
- Some tubes were worn and did not shown guarantees that they would not leak;
- Some connections and elbows had some cracks and were deteriorated that would suggest possible cause for leaks;

- Even the original hydraulic scheme was under question, once there were some doubts if it was designed for the maximum efficiency.

With almost the prototype assembled, the problems and questions regarding the hydraulic system did not allow to make a test to the prototype. We were in middle July when prototype assembly reach this level and with no internal expertise in Engenhotec that could make the changes to the hydraulic system, an external company was contacted and asked to perform such tasks. Contacts were made with Zanancho, a company located in Maia, Portugal, that sells hydraulic components and have a workshop where it is possible perform operations needed to such task. After the task were assigned to Zanancho, a technician made a visit to Engenhotec to assess what were the changes needed. Initially was considered that the necessary changes to be made with the prototype will take place in Engenhotec, with the components being prepared in Zanancho's facilities. However, after the first two working days with the prototype in Engenhotec, the technician realized that it was more productive if the prototype was available directly in Zanancho facilities.

Prototype was transported to Zanancho's facilities early August. Due to the summer vacations, Zanancho's technicians were not available to work in August in the prototype, so it led to a period of 3 weeks with no work done over the prototype.

In early September, with the return of the technicians after vacations, figure 5.66, prototype was ready one week later. There was only one issue: when maneuvering the movement's joystick, the rotation of the hydraulic motors did not match with the ones described in 5.1.3. It was due to the connection of the tubes to the bidirectional pumps and after some trial and error, the right match was achieved.

Figure 5.66 – Hydraulic system repair

When Zanancho's tasks were finished, the prototype returned to Engenhotec.

Some components were still missing in their positions. The rear wheel adjusters were placed, crawlers guides fixed and crawlers came back to their position. It was not possible to put the bolts that would allow adjusting the crawler’s tension, because it was too much difficult to place crawlers back. In one side there was the need to remove the drive wheel connected to hydraulic motor to help to place crawlers in the right position, even applying a lot of “arms” strength to do it.

In September 11th, all was ready and in place to perform the first test to the whole prototype. Figures 5.67, 5.68, 5.69 and 5.70 show prototype’s final look. Comparing with the original prototype it is easy to recognize the space released in front of driver’s seat caused by the removal of ICE. Movement’s joystick and hydraulic system commands were also very close to the original position. Batteries are “hidden” below platform, electric motor is in a position with good venting access for cooling and controller is easily accessed for connecting cable to laptop.

Figure 5.67 – Final look of prototype, rear view

Figure 5.68 – Final look of prototype, front view

Figure 5.69 – Final look of prototype, rear side view

Figure 5.70 – Final look of prototype, detail of electric motor, batteries and controller

6 Testing and improving

Along with the steps for a development process, Ulrich and Eppinger [1] present the need to build and test models and prototypes.

After the building of the BEV prototype, a set of tests was performed to assess the technologic solution and the new design of the prototype.

According to the planning of 5.6.4, the tests were divided in 2 phases: the first for a 36 V solution and a second for a 72 V solution.

6.1 Phase I - First tests - Engenhotec

After the assembly of all components, finished in September 11th, a functional test was performed to check if the prototype worked after all the changes made.

In this first test the movement of the prototyped was checked, if it moved accordingly with the movements of joystick. The result was positive, the prototype moved frontward and backward, following the movements done by the control joystick.

4 days after, September 15th, a new test was made. It lasted 7 minutes and 35 seconds – 455 seconds. Test consisted in moving prototype front and backward, rotating left and right, in a plain concrete floor.

In this test data was collected from controller. It was possible to save a log file in the laptop at the same time controller is on. Controller outputs a csv file that can be converted to an Excel file. In Excel it was possible to create graphics with the available parameters. For the first test five graphics were created: voltage, current, controller temperature, electric motor input power and controller efficiency.

Voltage graphic is shown in Figure 6.01. It has three parameters: throttle opening, battery voltage and motor voltage. This test last for 455 s which is represented in the horizontal axis. Left vertical axis scale is for throttle opening and right vertical axis is for voltage.

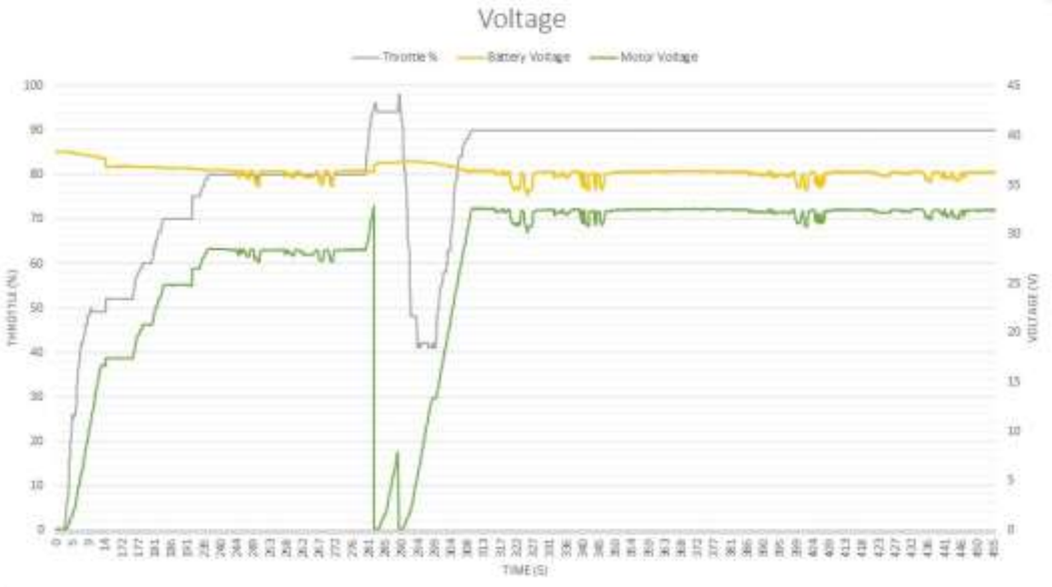


Figure 6.01 – Voltage graphic for the 15th September test

In the voltage graphic is easily identified controller shutting down voltage output for the motor when throttle opening was over 95%, at second 282. From the beginning until the end of the test battery voltage drop from 38.3 V to 36.3 V.

Current graphic shows only the current input from batteries and current output for electric motor – Figure 6.02. Left vertical axis scale is for current and the horizontal axis is the time scale, as for all graphics shown.

Figure 6.02 – Current graphic for the 15th September test

Peaks on the current's graphics correspond to the moments where prototype was turning left or right. On those moments the power required by the hydraulic system demands more power of the electric motor, causing those current peaks. Maximum current occurred at second 325 with 121 A.

Another output is controller temperature, measured in the motor M(-) and battery B(+) terminals. Initial temperature was 23°C, in the end M(-) was 28.7°C and B(+) was 32°C, Figure 6.03.

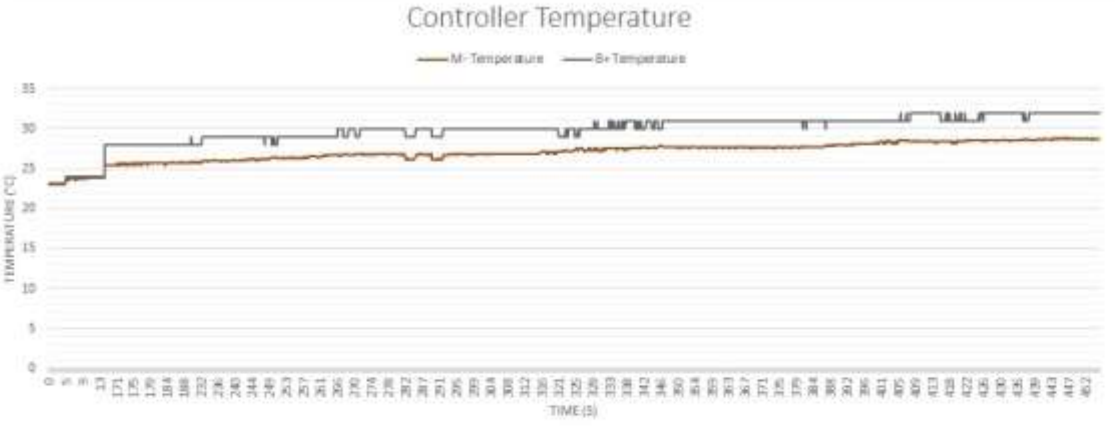


Figure 6.03 – Controller temperature graphic for the 15th September test

Motor power graphic correspond to the value of voltage times current supplied by controller at each instant. It matches the current graphic and the peak was also at second 325, with an output of 3.6 kW, Figure 6.04.

Figure 6.04 – Motor power graphic for the 15th September test

A new graphic was made to understand the level of efficiency of the controller. Calculation was made using the following expression:

$$\mu = \frac{V_m \times A_m}{V_b \times A_b} \quad (6.1)$$

Where µ is the efficiency, V_m is the voltage input in the motor, A_m is the current input in the motor, V_b is the voltage output of batteries and A_b is the current output of batteries.

In graphic 6.05 controller's efficiency is displayed. Except when controller shut down output to motor due to the throttle opening, overall efficiency is close to 100%.

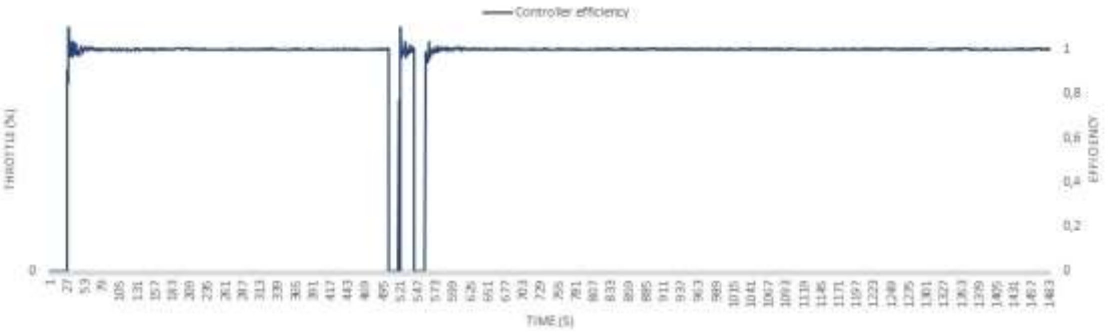


Figure 6.05 – Controller efficiency graphic for the 15th September test

Besides values taken from the controller, in this test it was possible to realize that direction changes are quite difficult. It can be caused by the friction of the rubber tracks in the concrete, once the grip in this condition is higher when compared to gravel soil.

Also it is noticed a high noise coming from the triple pumps module when a rotation to left or right is done. When moving only front and backward, that noise does not happen.

Another issue is a high noise coming from the transmission box. When throttle opening passes around 30%, there is a high level of noise caused by the gears.

Some days later another test was performed. Before it started, batteries were charged to full load and the purpose was to use the prototype until batteries were completely down.

This test was divided in two parts, one in the morning and the other in the afternoon. It was performed in September 26th. It was done outdoors, outside Engenhotec facility.

Data collected in the morning had a problem: the period between minute 3 and 27 was not recorded. It was only noticed when data was analyzed and the cause was not determined.

Figures 6.06 to 6.08 show voltage, current and power for the morning test.

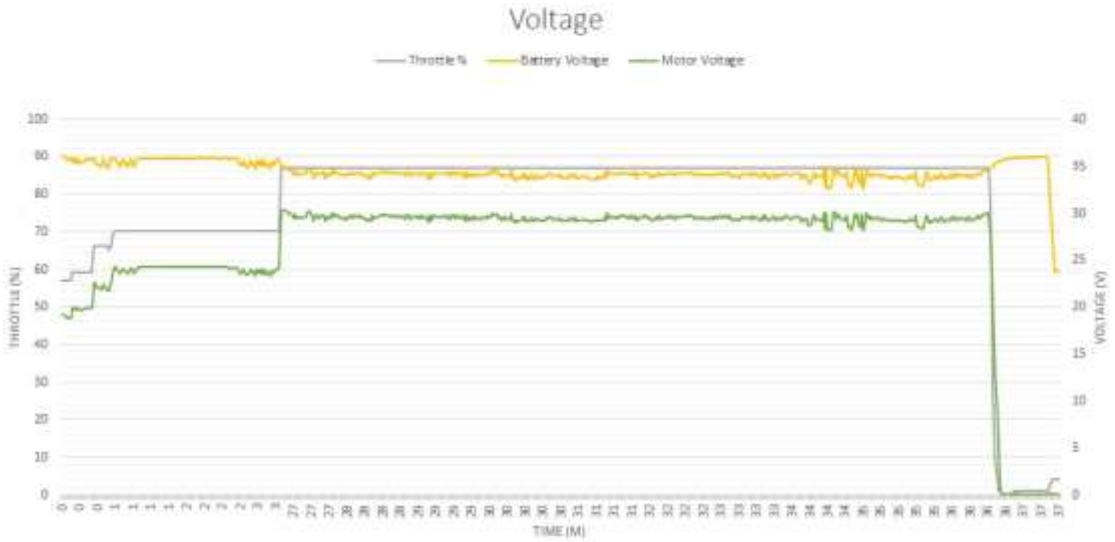


Figure 6.06 – Voltage graphic for the 26th September test - morning

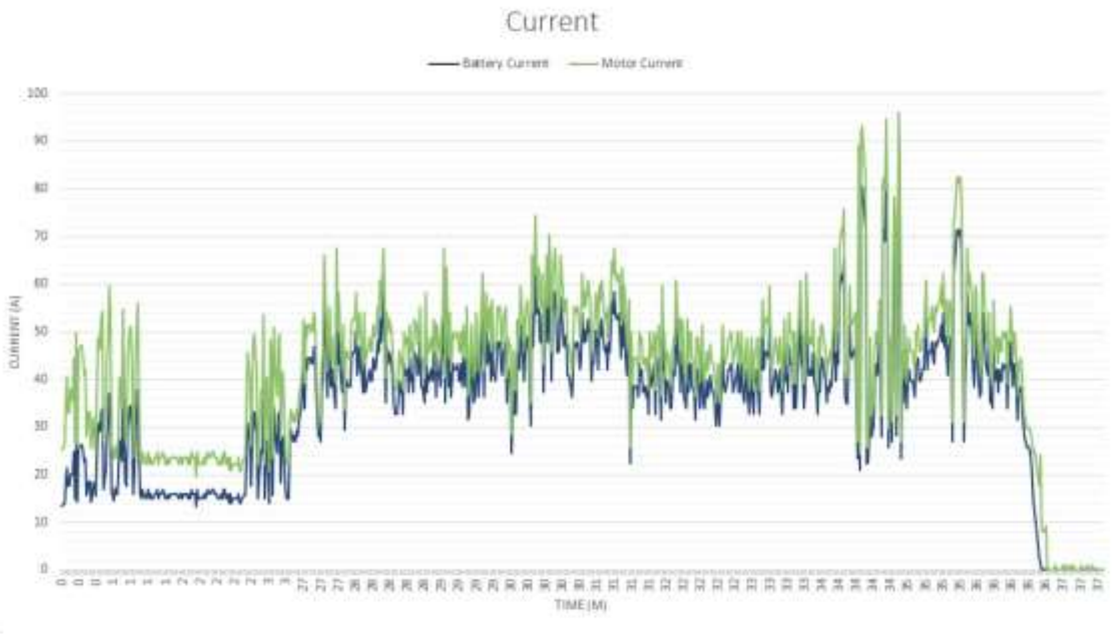


Figure 6.07 – Current graphic for the 26th September test - morning

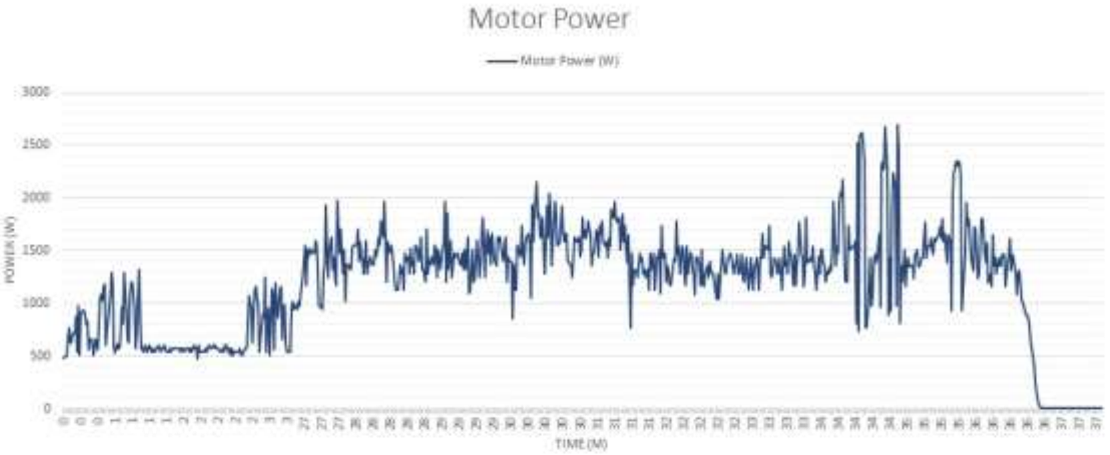


Figure 6.08 – Motor power graphic for the 26th September test - morning

During this test the issues detected in the first indoor test revealed again: difficulty in changing direction together with the high noise from the triple pumps and the constant noise coming from the transmission box.

Changing direction was really hard; it needed to make repeated maneuvers front and backward while rotating joystick left and right, trying to make the prototype turning. In each turn of 180°, it was needed to move front and back around 5 or 6 times. Ground in this case was made of rock bricks which grip with rubber tracks is also quite high. Even without a direct comparison with a standard ICE Multijyp, the direction turning was taking around 2 minutes which reveals how slow it was.

Afternoon test was done in the same place, under the same conditions. Batteries were not charged so their charge was at the same level when morning test finished.

Test only finished when batteries were out of charge. In Figures 6.09 to 6.11 it is possible to see the evolution of main parameters during the test.

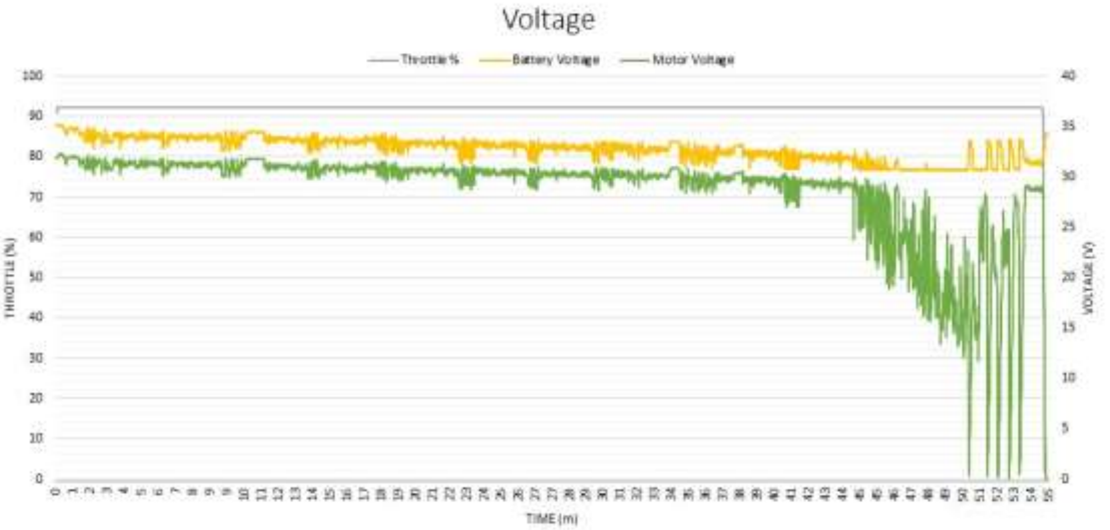


Figure 6.09 – Voltage graphic for the 26th September test - afternoon

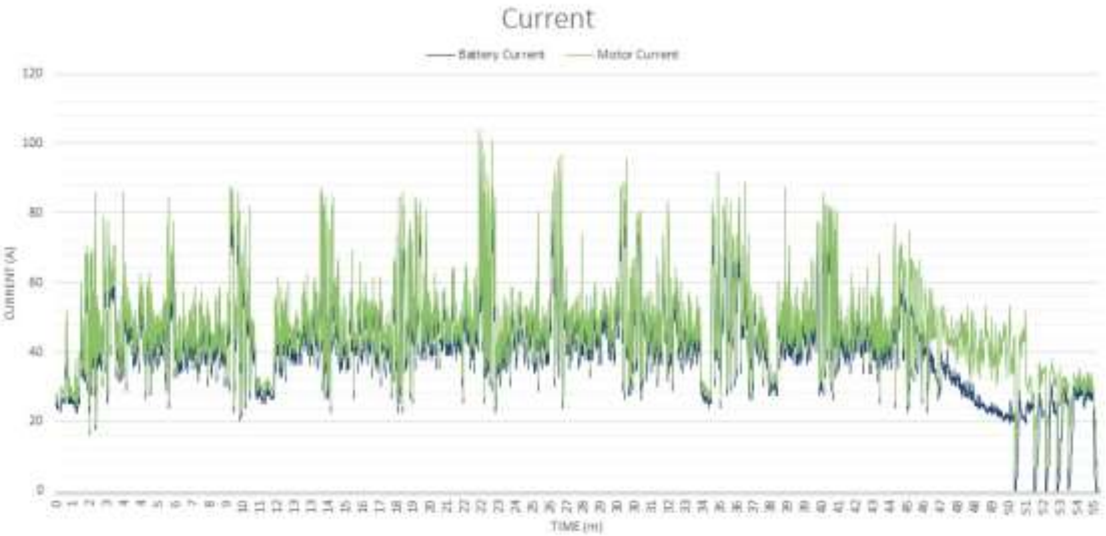


Figure 6.10 – Current graphic for the 26th September test - afternoon

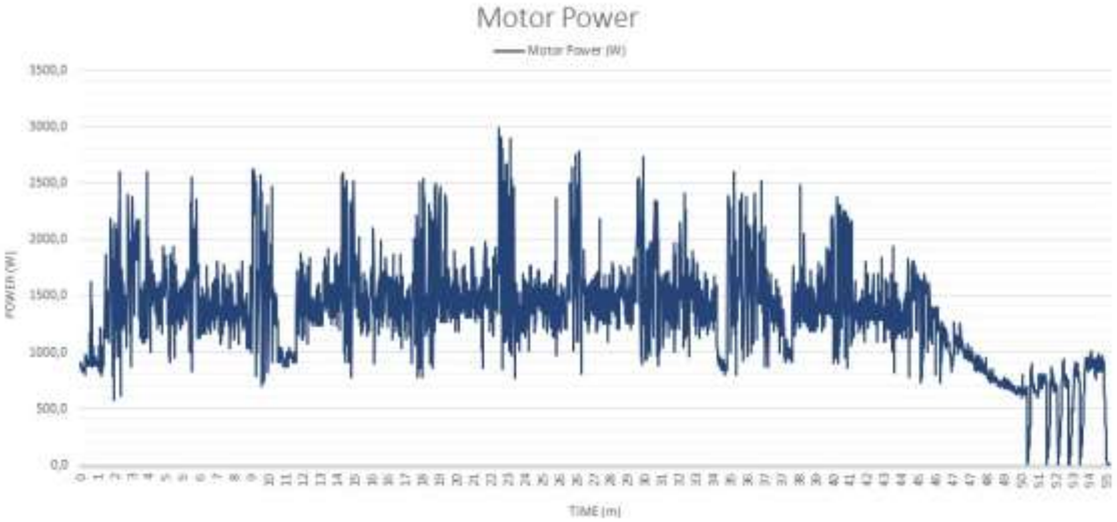


Figure 6.11 – Motor power graphic for the 26th September test - afternoon

Test last for 55 minutes but from minute 45 it was noticeable the drop of performance of electric motor, once it stopped to allow turning. In the afternoon the issues found in the morning were the same and in minute 45, when another 180° turning was in course, electric motor was not able to supply power enough to hydraulic system and it was not possible to perform the turn.

In the last 10 minutes of the test, prototype only traveled around 15 meters, from the outside of Engenhotec to its door. It is possible to see in all graphics that power was down for 5 times in the last 5 minutes, when batteries were completely depleted and not able to supply enough energy to the system.

Counting with the 37 minutes in the morning and more 45 minutes in the afternoon, total range was 82 minutes but only moving, not making any kind of operation.

6.2 Phase I - Transmission box improvement

After the September 26th test, it was decided to make an improvement in transmission box. The high noise may suggest that there is a certain level of friction which is an energy waste. Gears chosen were of untreated steel, so it was expected that after some time, they might be worn.

The designed alternative was to replace the 3 gears by 2 pulleys and a belt. From the available pulleys in the market, two equal pulleys were selected with the following characteristics:

- Number of teeth: 22
- Module: 8 mm
- Width: 28

Belt was selected accordingly the pulleys. There are standard lengths and the closest that would fit better in the existing transmission box was of 424 mm.

To perform such improvement, it was considered to make the changes in the existing transmission box to avoid make new components. In 3D model the changes were implemented and in fact the original transmission box could be used with the needed changes.

All changes were performed are shown from Figures 6.12 to 6.16. Their correspondence to changes is detailed below:

- An electric motor pulley (1)
- An auxiliary pump pulley (2)
- A belt (3)
- Both housings inside cuts were changed to allow the pulley to pass (4);
- Pumps side housing received a new cut to allow an adjuster part to play inside (5);
- Pumps side housing bolts holes that fix auxiliary pump were opened to allow belt adjustment (6);
- An adjuster part in aluminum where the pulley connected to auxiliary pump is attached (7);
- Four bushings were placed between electric motor housing and spacer plate (8). The pulley implied a different connection to the electric motor shaft and forced electric motor move outward.

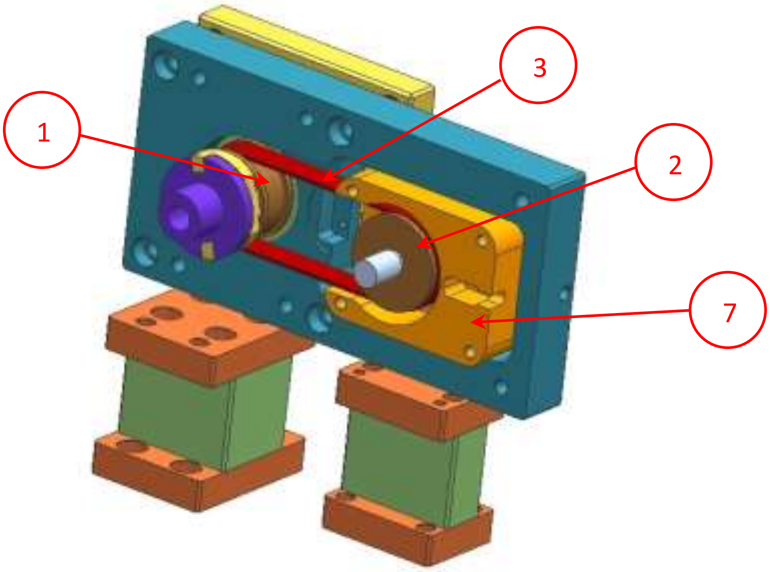


Figure 6.12 – View of new transmission box

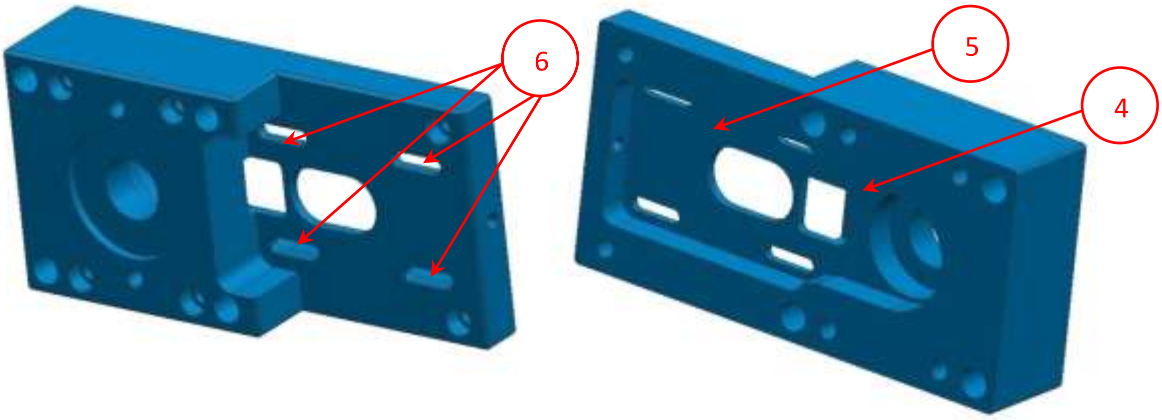


Figure 6.13 – Outside view of pumps housing

Figure 6.14 – Inside view of pumps housing

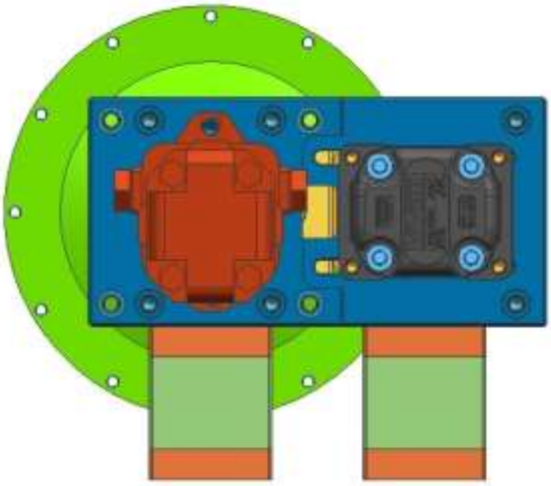


Figure 6.15 – View from pumps side of new transmission box

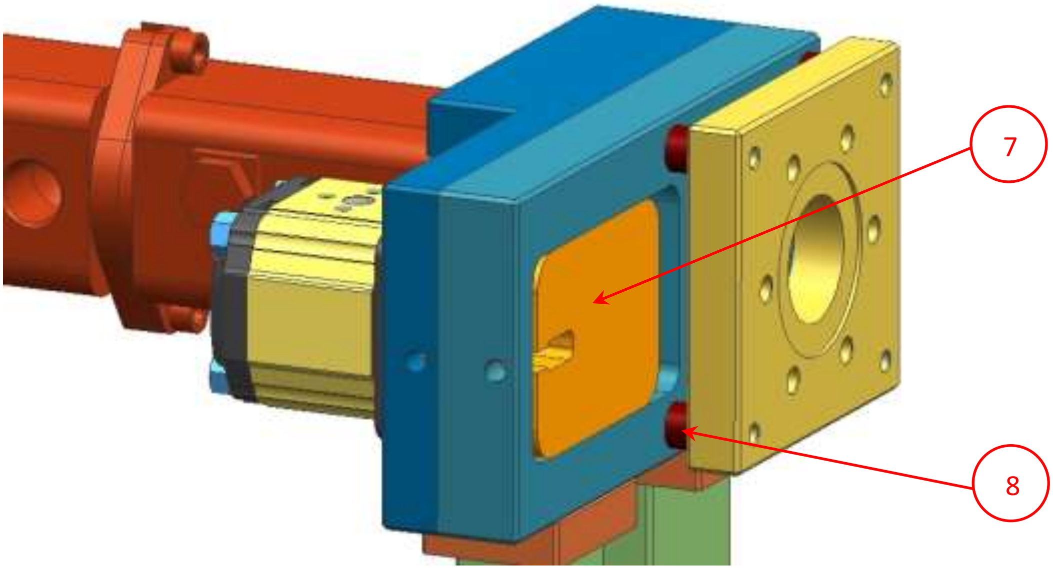


Figure 6.16 – Outside view of new transmission box

After carrying out these changes, a new test in Engenhotec was made to check functioning of the system.

Batteries were completely charged and test started with batteries fully loaded.

Output data was collected from controller and the results are shown in Figures 6.17, 6.18 and 6.19.

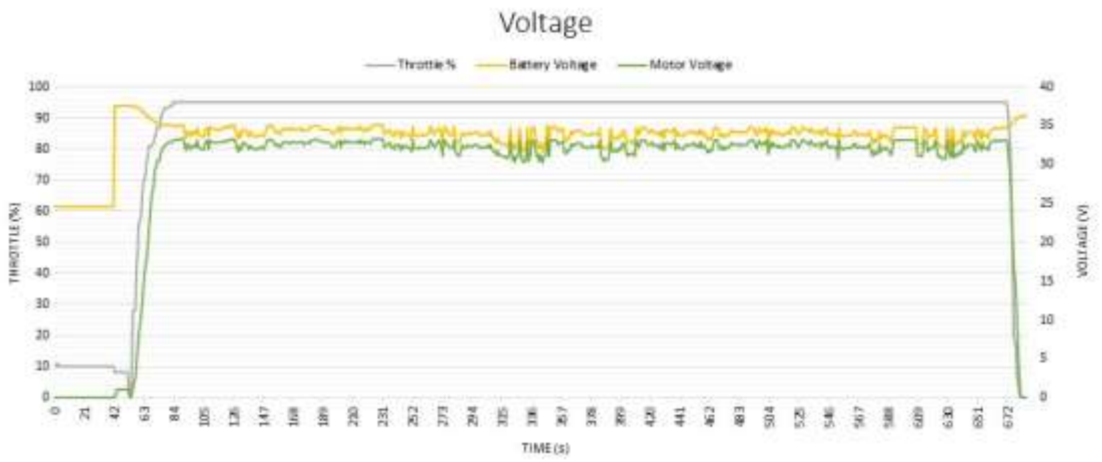


Figure 6.17 – Voltage graphic for the November 26th test

Figure 6.18 – Current graphic for the November 26th test

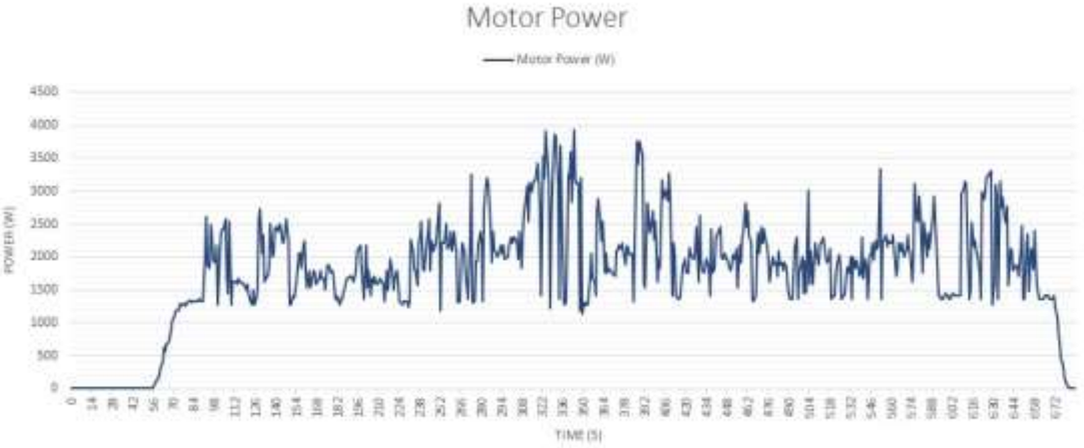


Figure 6.19 – Motor power graphic for the November 26th test

The most evident result of the improvement is the noise level reduction from transmission box. With electric motor moving at higher speed, the loudest noise heard no longer comes from gears but from electric motor itself. Only the bi directional pumps noise exceeds the electric motor noise when turning.

Comparing the graphics, the look is similar, with current peaks when prototype had to turn left or right, with maximum value of 124.2 A at 343 seconds. Motor input power topped 3.9 kW at the same instant.

6.3 Phase I - Quinta do Noval test

In September 23rd a preliminary visit to Quinta do Noval was done, to show the final version of the prototype. By then, no test was performed, just a small demonstration of how it was working and a description of the changes done.

A new test was schedule for mid-November but the agenda of Noval responsible was quite tight, once after the grape harvest that finished in late October, the season of olive harvest started immediately after. It was only possible to schedule the new test for the beginning of December.

In December 3rd, prototype was carried back to Quinta do Noval to make a test in the field. It was asked to have available the 45hp Multijyp belonging to Quinta do Noval to make some comparisons.

Noval responsible also gathered a group of experts in the use of tractors in general and Multijyp in particular: besides José Eduardo Costa (Quinta do Noval), there were Adelino Teixeira (Quinta da Romaneira), Bruno Caseiro and José Henrique (da Quinta do Noval) and Joaquim Fernandes.

Some trials were done: 180° turning, speed, noise and climbing. For the 180° turning it was compared with the 45 hp Multijyp. Prototype made the turning in 25 seconds, while 45 hp Multijyp did in in less than 10 seconds, Figures 6.20 and 6.21.

Figure 6.20 – Prototype 180° turning test

Figure 6.21 – 45 hp Multijyp 180° turning test

Speed test was performed just by comparison if the apparent top speed of each machine. 45 hp Multijyp is faster when compared with prototype, at least two times. Also it was noticed that prototype had different speed when moving frontward and backward, being faster moving backward – Figure 6.22.

Figure 6.22 – Prototype speed test

Noise test was made with a sound meter and results were:

45 hp Multijyp:
- Idle: 82.5 dB
- 50% throttle: 84 dB
- 100% throttle: 97.5 dB

BEV prototype:
- idle: 70 dB
- in turning movement: 85 dB

In this point prototype has a clear advantage over Multijyp, once it is much more quite.

Last test was a climbing test. In one of the accesses to a vine level, a test was made to check if prototype was able to climb it. In the first attempt, prototype was not able to pass it and it had to move back. In a second attempt, throttle was opened to the maximum and then prototype was able to climb it – Figure 6.23. It was not possible to measure the slope directly but some photos were taken to make the calculation later.

Figure 6.23 – Prototype climb test

In Figure 6.24, a horizontal and a slanted line were drawn to correspond to the horizontal level and the inclination of the slanted access. It is an approximate calculation but is enough to have an estimated value of the slope. The measured angle between the two lines is around 25° or 46 %.

Figure 6.24 – Prototype climb test result

In the end all participants expressed their comments:

- Prototype must output enough power to operate the equipment to work on the vineyards, namely the sprayer;
- Needed range of 7 hours a day, that can be divided by 3.5 hours in the morning and 3.5 hours in the afternoon;
- Adjust joystick position, to eliminate difference from front and backward speed;

- To increase range, it was suggested to use the load area to place more batteries and elevate the load area 300 mm;
- If the previous point was to be done, the supports that hold sprayer must be replicated.

6.4 Phase I - Tests conclusions

Considering the tests performed and comments gathered, there was one requirement that was not possible to achieve which is range. With this solution of lead-acid batteries, it would be necessary to apply a large number of batteries to comply with the 3.5 hours operation shift.

For the other requirement, power output, there may be a chance to do it and there were some options:

- Apply a total of 12 batteries as used in the 3 batteries pack, with two pairs of 6 batteries. Each pair of 6 batteries would be connected in serial, for a voltage output of 72 V and then these two pairs may be connected in parallel, to have a current output near to 300 A. Checking Agni's motor performance graphic at 72 V, with 300 A, power output would be nearly 20 kW. This solution however has three main issues:
    - Weight: it would increase prototype total weight at least 333 kg;
    - Packaging: the available space for additional 9 batteries is the load platform, implying to raise the platform for equipment 300 mm;
    - Cost: 9 extra batteries would cost nearly 2.500€, plus adaptations.
- Apply 6 six batteries as used in the 3 batteries pack and a super capacitor. Six batteries connected in serial would raise voltage to 72 V and then a super capacitor would supply the extra current needed to reach 300 A. This solution also has three main issues:
    - Availability – there are only a few solutions for a super capacitor with the required features;
    - Cost – minimum cost of a super capacitor would be 2.500 Euros;
    - Complexity – adding a super capacitor to the system would require an electronic controller, to manage and balance electric flows of components.
- Apply 6 batteries as used in the 3 batteries pack and another 6 automotive batteries. All batteries are 12 V batteries but the automotive batteries function is only to provide 300 A in a short period of time, one or two minutes.

6.5 Phase II - Implementation

All the options listed in 6.4 required additional investments, placed extra difficulties in packaging and make the system too complex. Considering all these constraints, it was decided to apply an extra pack of 3 batteries as the ones that were already in the prototype. With this solution, the investment was below 1.000 €, considering the 3 batteries, additional cables and connectors and also the parts to support the 3 new batteries. The 3 extra batteries were to be connected in serial along with the existing 3, to give an output of 72 V, keeping the current at around 125 A. With this solution it was expected a total output on the electric motor of 9 kW.

There was also a point that led to the solution: with the 36 V batteries pack, electric motor speed was only around 950 rpm – Figure 5.20, which is a speed that is below the minimum recommend speed for the hydraulic pumps which is around 1 500 rpm. With the increase to 72 V, maintaining the same current of 125 A, the expected motor speed is more than 2 000 rpm – Figure 6.25 [95] - above the minimum recommend speed for the pumps.

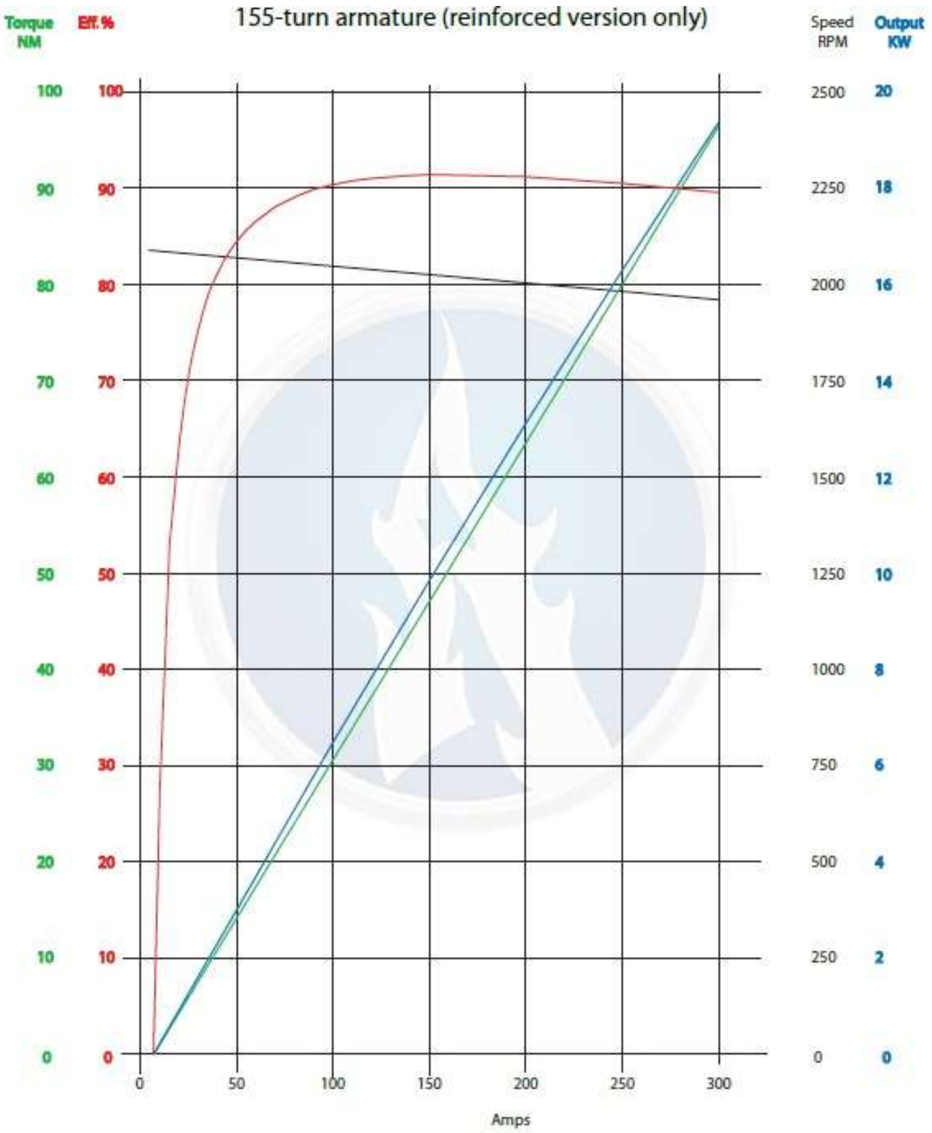


Figure 6.25 - Agni 155R performance graph, 72 V

The purchase of the 3 extra batteries was done in December 2015 along with the design of the new parts. Once the parts were essentially sheet metal parts, their production took place in a short period and they were available in the beginning of January 2016.

With all the parts and new batteries in place, the prototype look is shown in Figure 6.26.

Figure 6.26 – Prototype with 6 batteries pack

The space between the electric motor and the frame and above electric motor was filled with the extra 3 batteries. This solution eliminates any chance for a driver to have a minimum comfortable position but it not a concern by this stage of the project, once the main target was to verify the differences between the 3 and 6 batteries pack solutions.

With this upgrade, phase II of the project's planning was already running and the functioning tests could start.

6.6 Phase II - First tests - Engenhotec

To check the upgrades differences, first some tests were performed in Engenhotec to assess the change.

Between January and February 2016 the system was tested with the 6 batteries pack to check if the electrical connections were correct, if the movements of the prototype were still working properly and if the hydraulic system showed some issues due to the increase of power.

All the functionality tests were passed and the prototype was able to be tested in the field.

6.7 Phase II – Maria Alice test

By the end of this function test, along with the experience of the Phase I tests, it was clear that for the mountain vines application the BEV solution would not be a practical solution, once power and mainly range were very difficult to compete with the ICE solution. It was considered to make a test in another field of application – greenhouses. Due to the lower need of power, flat surface, soft terrain and easier availability of electric power the BEV solution may look more suitable for this softer application. As described in Chapter 4, a visit was made to a greenhouse belonging to Maria Alice Company, a dairy vegetables producer. A contact was made with the responsible and a test was schedule for February 18th 2016.

The test in one of Maria Alice's greenhouse had one goal to understand if the BEV prototype could move between the lines of crops. In the greenhouse where the test was performed there was a plantation of tomatoes. They were quite small, once they were planted only a pair of weeks before and their height was around 15 cm. In each line of tomatoes there were 2 lines of plants, distanced around 25 cm. In the middle of this 25 cm there is no path but between each line of 2 tomatoes lines there is one path with 1 meter. The maximum distance between tomatoes lines is around 1.2 meters, Figure 6.27.

Figure 6.27 – Tomatoes plantation at Maria Alice greenhouse

Test started by moving the prototype along one path, turning 180º at the end of the line and then return by the adjacent path, Figures 6.28 and 6.29. It was repeated several times to assess the behavior in straight line and also during the turns.

Figure 6.28 – Prototype test in a greenhouse

Figure 6.29 – Prototype turning direction in a greenhouse

With the 72 V solution the prototype moved faster when compared to the 36 V and the turns are made more easily. Nevertheless it is noticeable that the turn could be quicker, once there a need to move back and forward a few times before the turn is completed. Also another note is regarding the width of the prototype. In Figure 6.30 it is possible to see that the plastic film that is protecting tomatoes is not straight and in some points the rubber tracks touched it. It means that for this application the prototype needed to be slightly narrower to avoid damaging the plastic film.

Figure 6.30 – Prototype in a straight line

This test took around 30 minutes and there were no signs of batteries running out of charge. It was the first time that such type of machine was tested in this greenhouse so there were only a few comments regarding range and the capacity to perform some tasks. The main tasks related to tomatoes crop is spraying, once there is a need to apply 12/14 treatments during each crop.

6.8 Phase II – Quinta do Noval test

A new test in Quinta do Noval was planned to compare the behavior of the 2 batteries pack solutions.

For this test, it was arranged with the Quinta do Noval responsible to attach the spray tank to the prototype and to have available the 45 hp Multijyp for comparison.

To run the test with the spray tank attached, it was needed to apply to the prototype a replacement for the original PTO. The way found to perform that was to apply a hydraulic motor, similar that may rotate at a similar speed when compared with the PTO connected to the ICE.

The hydraulic motor selected had the following specifications:

- Make: GALTECH
- Model: 2SM11R10N
- Displacement: 11 cm^3/rot.
- Maximum Pressure: 230 bar
- Maximum speed: 3 500 rpm

The motor was connected to the main hydraulic output on the hydraulics output bar and controlled by the lever shown in Figure 6.31.

Figure 6.31 – Hydraulic motor control lever

The application of the hydraulic motor is shown in Figure 6.32.

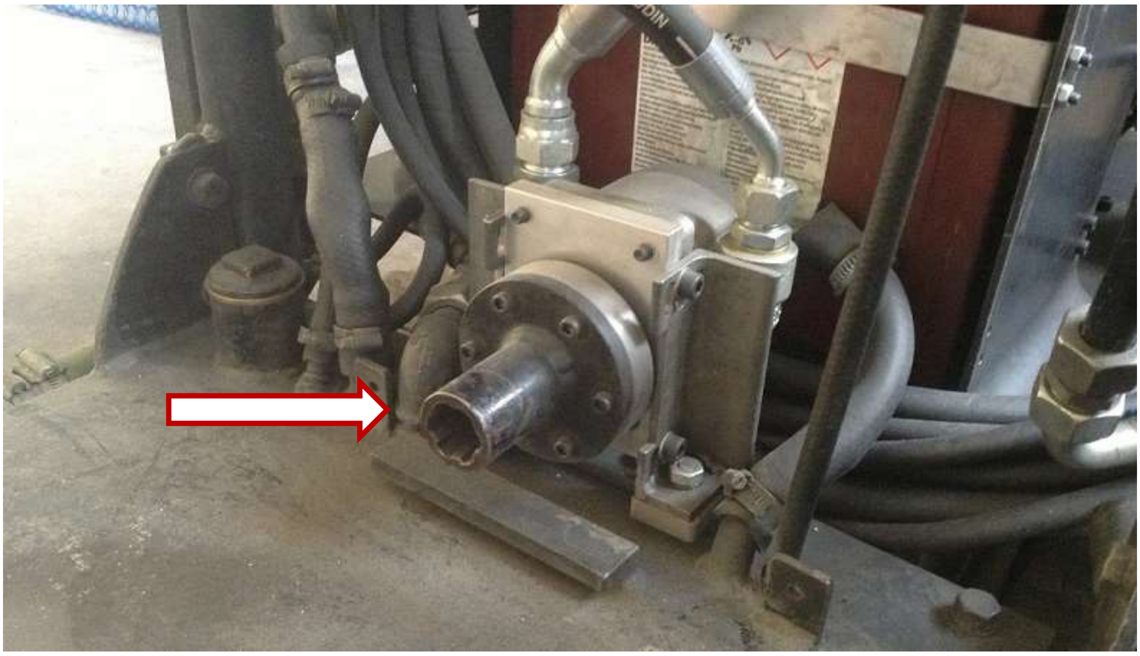


Figure 6.32 – PTO hydraulic motor position

The end of the hydraulic PTO was taken from the original ICE and it was performed an adaptation, to fix to the hydraulic motor flange. The brackets to support the hydraulic motor were performed by hand, taking standard bars and profiles. The positioning was at the center of the platform but there was a doubt about the longitudinal position.

The last test was performed only in June 30th 2016 due not only to agenda constraints but also to favorable weather conditions and availability of the regular user of Quinta do Noval Multijyp.

When the spray tank was being applied to the prototype to perform the test, it was verified that the spray tank pins were not entering in the platform holes, with a deviation of around 50 mm, Figure 6.33.

Figure 6.33 – Spray tank position gap

This was due to the hydraulic motor position that was in fact 50 mm deviated to the front of the prototype. Once there was no chance to make a change on the field, it was decided to fix the spray tank with belts and only to fill a small amount of water into the tank to keep the weight as low as possible, Figure 6.34.

Figure 6.34 – Spray tank and laptop fixation

Also to allow data collection, a laptop was installed over a battery protection, connected to the controller. This way it was possible to check the behavior of the electric system, under working conditions.

After checking that all was operational the test started with spraying only water, Figure 6.35.

Figure 6.35 – Prototype test with spraying

The test was divided in 2 parts once it was necessary to fill the tank with more water. The first part lasted for 55 minutes and the second lasted for 19 minutes. In the last minutes of the second part it was noticeable a bigger difficulty of the prototype just to perform movement and when the prototype was loaded into the van it was necessary to push it, once batteries were almost discharged.

In Figures 6.36, 6.37 and 6.38, graphics of voltage, current and power are shown for the 1st part of the test.

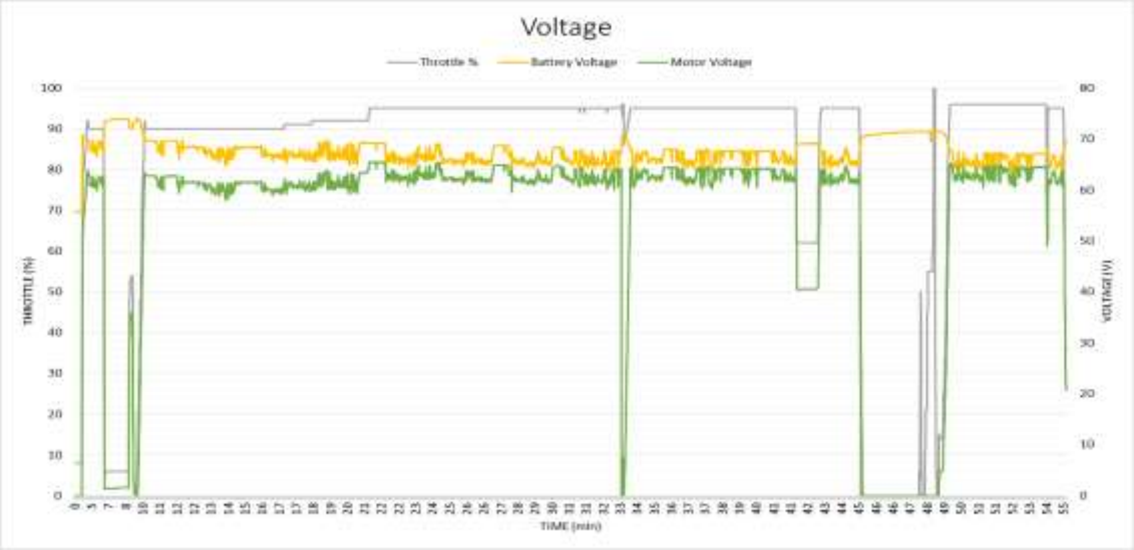


Figure 6.36 – Voltage graphic for the 1st part of 30th June test

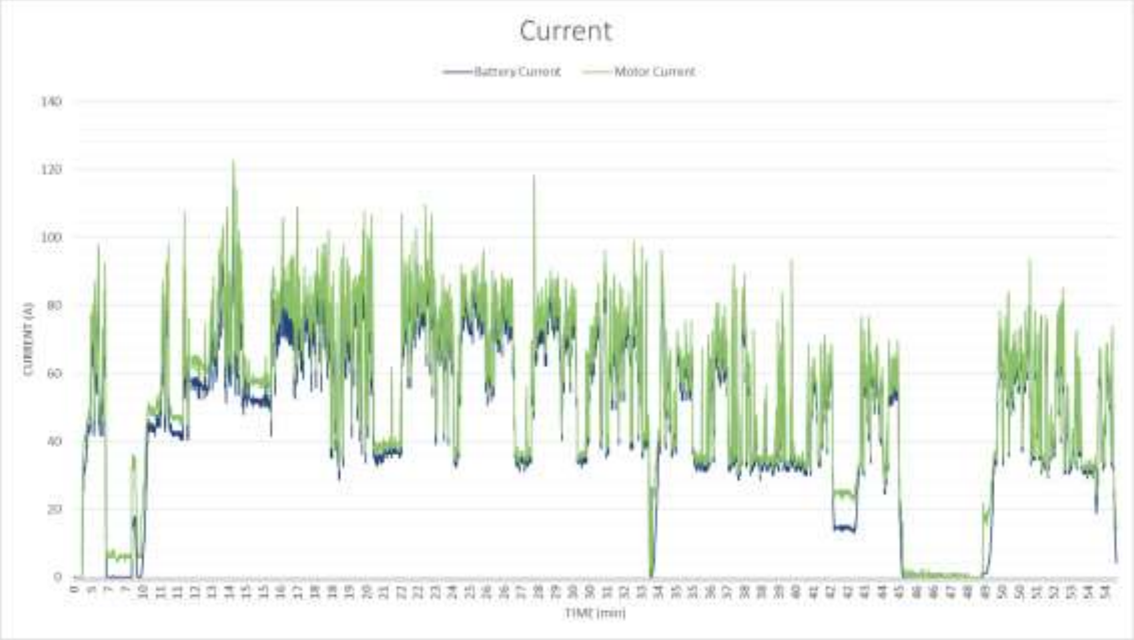


Figure 6.37 – Current graphic for the 1st part of 30th June test

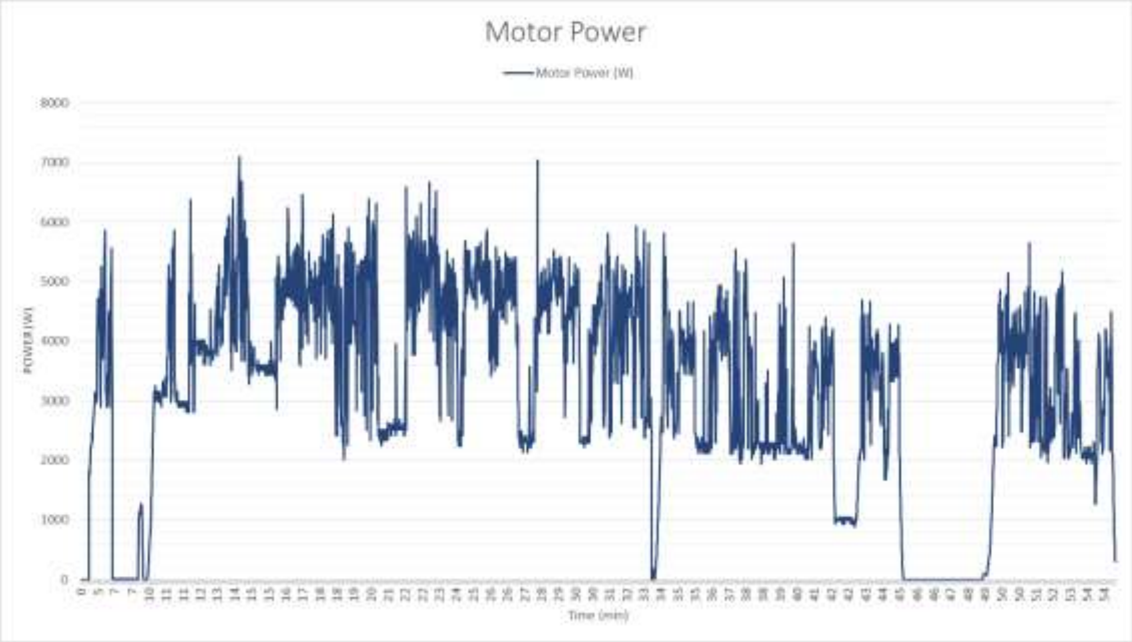


Figure 6.38 – Power graphic for the 1st part of 30th June test

From the 3 graphics above and by comparison with Figures 6.17, 6.18 and 6.19 it is noticeable same differences:

- Batteries voltage, near 35 V in the previous test and around 65 V in this one;
- Maximum current output is very similar in both tests, around 120 A;
- Power output peak is 7 kW in the last test, almost the double when compared with the previous, close to 4 kW.

For the last 19 minutes the graphics are shown in Figures 6.39, 6.40 and 6.41.

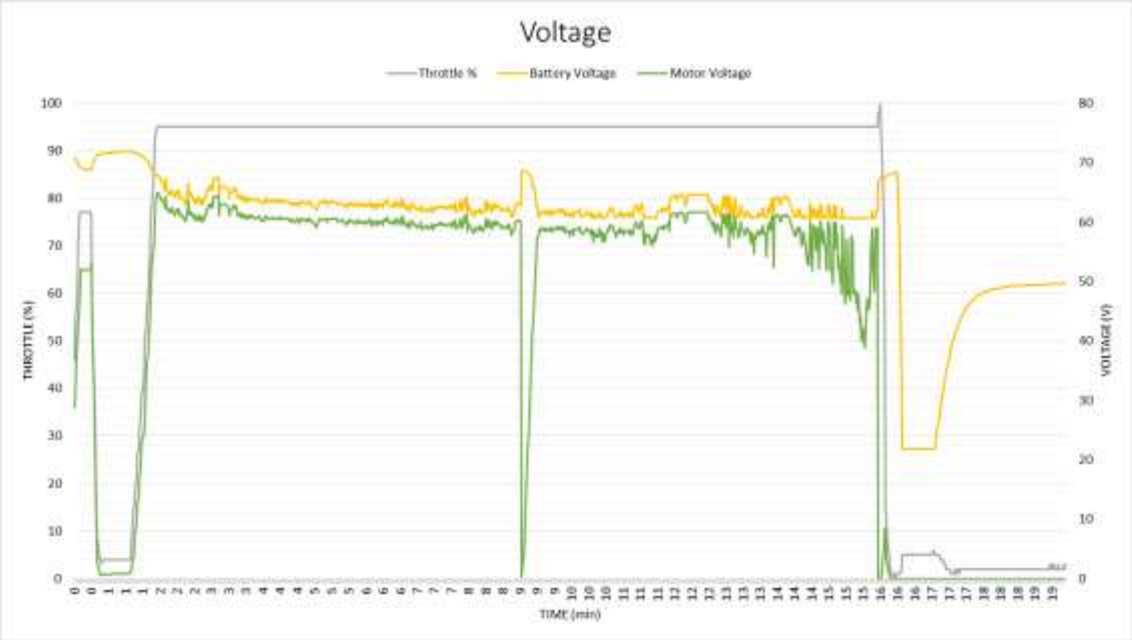


Figure 6.39 – Voltage graphic for the 2nd part of 30th June test

Figure 6.40 – Current graphic for the 2nd part of 30th June test

Figure 6.41 – Power graphic for the 2nd part of 30th June test

Comparing second part graphics to the ones of first part, we can observe:

- Voltage dropped slightly;
- Current did not passed 100 A;
- Power peal was below 6 kW.

These values show that batteries were quite uncharged and in the last 4 minutes they were completely “dead”, with no energy to allow moving the prototype.

In total, the prototype was able to perform spraying around 70 minutes.

Like mentioned before, the 45 hp Multijyp was also available for comparison and if in moving back and forward there were no differences in terms of speed, when it was needed to make a turn the other way around, there is still quite visible the difficulty that the prototype still had when it is need to change for one line to other.

Comments performed by the regular user and the responsible were in a way that the functionality could be comparable with the original but the most critical points are range and the lack of power to perform turns and moving in higher slopes.

Consumption of electric energy was not measured directly but it is possible to make an estimated consumption of the electricity spent during this test. Batteries were fully loaded, so they were charged with around 10.8 kWh. Test lasted for 70 minutes, around 1.17 hours.

For the consumption per hour, we have:

10.8 kWh / 1.17 hour = 9.23 kWh/hour (6.1)

For the cost per hour, considering a cost of 0.1641€/kWh, see 4.5.4.6, we have:

9.23 kWh/hour x 0.1641 €/kWh = 1.514 €/hour (6.2)

If an off peak charging was considered, with a cost of 0.101 €/kWh, we have:

9.23 kWh/hour x 0.101 €/kWh = 0.932 €/hour (6.3)

Compared with the average 3 liter/hour consumption of the ICE Multijyp and considering an agricultural diesel cost of around 0.83 €/liter, we have:

3 liter/ hour x 0.93 € / liter = 2.49 €/hour (6.4)

If charging occurred in peak period reduction was only 39.2% but if it occurred during off peak period then it reduction was 62.7%

Even being estimated, it gives a good outlook of the potential energy cost savings, when BEV is used instead of one with ICE.

It is possible to make an estimate for the Multijyp's emissions. CO_2 emissions from ICE running on Diesel are around 22.38 pounds each gallon of Diesel fuel [96]. Converting pounds to grams and gallons to liters the result is 2 681 g per liter.

Considering an average consumption of 3 liters/hour, we have:

3 liter/ hour x 2 681 g / liter = 8 045 g/hour

6.9 Phase II – conclusions

With the test of June 30th at Quinta do Noval the tests of the prototype were concluded.

From results, comments and experience some conclusions were drawn:

- The adaptation was correctly performed, the hydraulic system was working as in the original vehicle, allowing the prototype to move and to perform operations;
- The 72 V battery pack output was higher than the 36 V battery pack but still underperforming when compared with the original vehicle;
- Range is one of the major disadvantages of the BEV solution, unable to guarantee a minimum of 3.5 hours corresponding to a work's shift;
- Prototype is a heavy vehicle and that reflects on the demand of power to the hydraulic system and therefore to the electric powertrain. A lighter vehicle would consume less energy to move and perform the turns;
- The hydraulic system is a complex, expensive, heavy, with a potential hazard of leaking lubricant to the ground; in the prototype it generates a lot of noise and the pump or the hydraulic motor of the left side was not working properly;
- The operation in mountainous vine yards is very demanding in terms of power and energy and the lead-acid batteries do not provide enough energy for such conditions;
- Rubber tracks are needed to guarantee traction in high slopes and rocky grounds but also contribute for higher energy losses and higher consumption.
- The overall efficiency of the prototype could be higher but the hydraulic system was not in the best conditions. The performance of the hydraulic motors was different, especially noticed in turns, when the left side motor did not move as the right side motor. Besides the service performed to the hydraulic system, pumps and motors where not checked and their performance may reduce the system's performance.

From the conclusions above, the prototype was too heavy, underpowered and with a lack of range to operate in mountainous vine yards. Hydraulic system for the movement has some advantages, mainly low speed control and high torque but it is a complex system and in the prototype it was not working properly, even after the maintenance performed before the tests.

Main conclusions were that made no sense to keep working in the prototype, once it had constraints due to the original design and that the focus on the BEV should be in application not so demanding as the mountainous vineyards but rather in greenhouses, where conditions are much more adequate for a BEV.

7 New concept

In result of the tests performed and experiences gained during this project, it was concluded that there may some other applications where the alternative energy source for agriculture vehicles may be applied. Douro region vineyards are a very hard environment for machines, due to soil, slopes and extreme temperatures.

The test performed in February 2016 in a vegetables greenhouse was enlightening to see that a BEV could be used in other applications.

For this kind of machines for narrow lines we can identify three possible types of applications:

- Outdoor applications / hard conditions – this type is the one we found in Douro vineyards that we can identify as mountain farming.
- Outdoor applications / light conditions – this type is like horticulture, flower culture and orchards. Ground is leveled, no slopes, soft soil.
- Indoor applications / light conditions – this type is the one found in greenhouses. Ground is leveled, soft soil, no exposure to environment changes.

Each one of these applications has its specific requirements. Once the study was focused on the harshest conditions, for the other applications some requirements may be softened like the power output, traction ability and use of special equipment.

For the light conditions applications the use of crawlers is not necessary. From Canedo [83] calculations, a machine equipped with rubber tires may be used in inclinations up to 30%, a machine with rubber tracks can go up to 60%.

Also the potential market for greenhouse vehicles was expected to be considerably bigger when compared to mountainous vineyards, a very special application in the world of wine production.

Taking this onto account a new concept for a BEV was considered, to be used in greenhouse dedicated to the production of dairy vegetables.

In this chapter observations that resulted from 2 visits performed between April and May 2016 are described, some data about vegetables production is shown and a new proposal for the design of a BEV dedicated to work on greenhouses.

7.1 Visits to Maria Alice Company

In April 11th and May 10th 2016, 2 visits were done to 2 different production greenhouses. In April, the visited greenhouse was the same were the test was performed with the prototype. By then, the tomatoes crop was much more developed and it was possible to assist a water spraying demonstration with a vehicle used for such operation, figure 7.01.

Figure 7.01 – Greenhouse spraying operation

The spraying operation is performed several times during a tomatoes crop and could reach 14 rounds for crop. Spraying is mainly for application of phyto treatments but also to nurture the soil and the plants. The machine used in this operation is a Bertolini small tractor that was adapted to apply a spraying tank. Information gathered during the visit about the spraying operation was:

- Tank capacity: 200 liters
- Time to perform spraying in the greenhouse: 3 hours
- Fuel consumption: 1.5 liter / hour
- Cost of the machine: around 4 500 Euros

The Bertolini small tractor model is BTR 550 and has the following main specifications [97]:

- Engine: Robin EH 17 gasoline;
- Maximum output: 5.0 hp / 3 600 rpm
- Speed: 3 forward + 2 reverse;
- Clutch: By belt, with automatic disengagement by releasing command lever;
- Start: Manual;
- Transmission: Gears in oil bath;
- Brakes: with jaws with automatic engagement by releasing command lever;
- PTO: Independent with 2 100 rpm;
- Traction: rubber tracks;
- Weight: 215 kg
- Length / wide / height: 1 575 / 622 / 900 mm
- Load capacity: 550 kg;

- Cost of purchase: around 5 500 Euros.

Engine is supplied by Robin, a company connected to Subaru and it is a very small and compact one, especially designed to be used in small vehicles, figure 7.02. The driving of the pump that pressurizes the water is mechanic. A belt connected to engine crankshaft actuates an axle that drives the pump.

Figure 7.02 – Bertolini BTR 550 Powertrain

This vehicle is clearly much more adapted for the use in greenhouses. Not only by the smaller dimensions, mainly in terms of width, but also its total weight, slightly above 215 kg. Rubber tracks guarantee more than enough traction for compact soil but on terrains with sand, their use is recommendable. Maria Alice greenhouse is very close to the Atlantic Ocean shore and the ground is some places in not so compact, so rubber tracks are needed.

The control of the vehicle is rather complicated and requires the use of both hands to control direction. If there is a need to perform other command, like turn on or off the spraying, the driver must stop the vehicle, perform the command and then resume the moving.

But the biggest difference is found in the powertrain. Quinta do Noval is using a vehicle with 45 hp, while Maria Alice is using one with 5 hp, almost 10 times less. This is quite remarkable, once in both places the main operation that is necessary to do in the vines or in the vegetable plants is spraying. Even considering that an outdoor spraying operation have the interference of wind, that requires more spraying pressure to ensure a good dispersion on the plants, the difference in power cannot be explained by the spraying needs or to another more demanding operation.

One explanation is the need in the mountainous vines to climb very steep vine yards, which needs power to be possible to perform such climbing. Also the weight of the base vehicle is very important; the BEV prototype weights 830 kg with no tools against 215 kg of Bertolini in the same situation. Almost 4 times more weight to perform similar tasks, although terrain and slope conditions are different.

This led to a conclusion that weight is a very important parameter to consider in a future development of a new vehicle, especially if it is going to work on mountainous vines or similar applications.

In May another greenhouse was visited and the goal was to observe a harvest operation with lettuces. In this case there were no vehicles operating in the lettuce field. Operators collected the plants and placed them on racks. These racks were piled and then moved by hand to a fork lift applied on a tractor. Finally they were loaded into a truck to be carried to the customer logistics center. Apparently there was no need to use a vehicle to support this operation but there was a point that was not controlled during the operation which was the weight of the racks. There was a minimum weight to be loaded in each rack and it is not controlled during the harvest. If a vehicle equipped with a libra was supporting the operation, it was possible to control the load of each rack and immediately after the harvest ends, the total load of lettuces may be calculated.

From observation, it was noticed that there were paths along the lettuces field that were covered with weeds, figure 7.03.

Figure 7.03 – Weeds on greenhouse lettuce crop

It was commented by the greenhouse responsible that from time to time these weeds are removed. Even though, some lettuces that are in the line where weeds grow at the side, are smaller than the other that are in the other lines, meaning that weeds affect productivity and the quality of those lettuces. The path is very narrow, around 40 cm, so even the Bertolini vehicle cannot pass there but it is an opportunity to a special vehicle/machine to perform such operation.

The conclusions from the visits to the greenhouse were:

- The power required to a vehicle to operate in a greenhouse is around 10 times smaller when compared to one operate in mountainous vine yards;

- Ground conditions and flatness may not require the use of rubber tracks;
- Control of the vehicle may be more ergonomic;
- A new vehicle based in batteries – electric motor powertrain may have the power and enough range to be used in greenhouses.

7.2 Greenhouse vehicles potential market

In order to have a perception of what might be the potential market for vehicles for greenhouses, some data of the production of vegetables that are mostly produced in greenhouses was gathered.

From FAO 2013 [98], the cultivation of vegetables in the world covered a total of 58 000 000 ha which represents only 1.18 % of agriculture area. Tomato is the main crop, representing 14.4% of vegetables production, followed by cabbages and cucumbers both with 6.3 %.

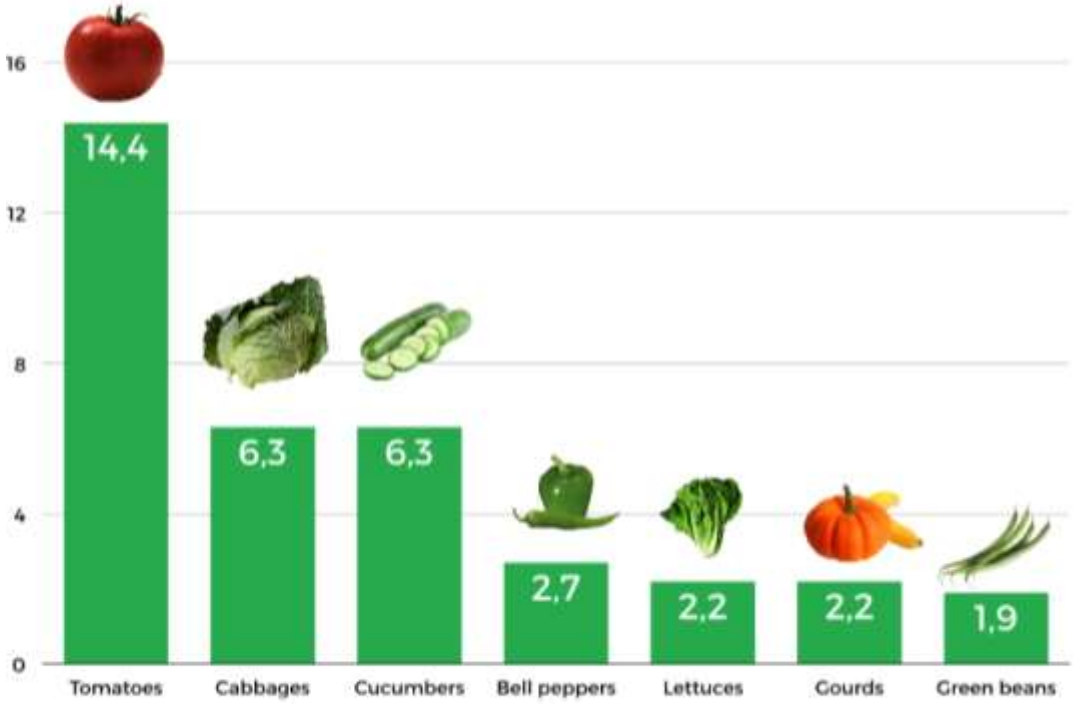


Figure 7.04 – Main vegetables produced in the World 2013

Using the vegetables cultivated area, one assumption was considered to calculate what might be the total market for greenhouses vehicles. If each vehicle has a 10 years lifetime and for each 10 ha there is one vehicle, each year the number of needed vehicles would be 580 000 units, a very interesting number considering a niche market.

Considering the price of Bertolini vehicle, the value involved in this market would be 3 190 M Euros, around 3.5 % of World agriculture machinery sales in 2015 [21].

7.3 Design of the new concept

After conclusion of the field tests, the visits to greenhouses and having the perception of the potential market for greenhouse vehicles, it was discussed the chance to apply a battery – electric motor solution to power a vehicle to operate in greenhouses.

It presents a lighter challenge when compared to a mountainous vine yards vehicle and a broader market. Also it would be a chance to design a solution that relied only in electrical motors, by eliminating all the hydraulic circuits and mechanical connections that take volume, increase weight and have power losses due to friction.

There is also another potential benefit of using electrical vehicles in greenhouses which is the chance to charge the batteries recurring to Photo-Voltaic (PV) solar panels. Once vehicles operate in a limited area it is quite easy to install charge stations where the vehicles may stop to load their batteries. Cost of solar panels has being falling in the recent years which reduces the investment in a PV system and brings the cost of self-generated electricity down.

For the vehicle itself, a new set of specifications had to be defined, different from the one presented in 5.5.3.

From comments collected and observation a new table was filled, table 7.01, keeping the same metrics used for the first prototype.

Table 7.01 – Target specifications comparison – mountainous prototype versus greenhouse prototype

Metric No.	Item	Imp	Units	Mountainous prototype	Greenhouse prototype
1	Maximum height (without roll bar)	5	mm	600	600
2	European directive rollover test	5	Binary	Pass	Pass
3	Side maximum slope	5	°	15	10
4	Longitudinal maximum slope	5	°	45	20
5	Mass	5	kg	700	200
6	Angle of vision	3	°	300	300
7	Damped seat	3	Binary	Yes	Yes
8	Noise at top speed, without equipment	2	db	65	65
9	Comfort angles	2	List	-	-
10	Reverse seat	5	Binary	Yes	Yes
11	Joystick control	5	Binary	Yes	Yes
12	Hydraulic connections	5	List	4	-
13	PTO torque	5	Nm	100	-
14	Maximum power	4	kW	30	4
15	Top speed	5	km/h	6	8
16	Working range	4	h	8	8
17	Reverse direction	5	s	10	10
18	Tractor acquisition cost	3	Euro	<20 000	7 000
19	Use hourly cost	3	Euro	1.5	1.5
20	Tools acquisition cost	3	Euro	-	-
21	Temperature use range	4	°C	-5 – 45	5 – 35
22	Tightness	4	Test IPx	-	-
23	Total width	5	mm	700	700
24	Hours without repair's intervention	5	h	200	200
25	Each maintenance time	4	h	6	3
26	Maintenance intervals	4	h	100	200
27	Assistance arrival time	4	h	6	6
28	CO_2 emissions	4	g/h	0	0

Some specifications are the same, related to comfort, easiness of use, maintenance and obviously CO_2 emissions but in what concerns to the operation of the vehicle, the differences are huge, namely for power, weight and no need of hydraulic connections and PTO for the greenhouse prototype.

Considering this specifications, it was started a design for a new prototype for greenhouses application. In this case there were more degrees of freedom when compared to the first prototype: the frame can be designed from scratch, movement of the machine can be made by tires instead of rubber tracks, there is freedom to find a different layout for the batteries and electric motor, no need to place a large tank for hydraulic fluid, no hydraulic components, no need for PTO.

Besides that, main constraints are dimensions, weight, need to have a 8 hours range and a final cost to the potential customer limited to 7 000 Euros, in order to be competitive when compared to Bertolini, for example.

There was an important issue related to the movement of the new vehicle. In the previous prototype movement was performed by the hydraulic motors connected to each rubber track, controlled by a joystick. For the new prototype the movement should follow the same principles with the need of a steering wheel and rotating wheels. For the turns in the end of the lines, the use of a traditional steering would make the vehicle more complex by using moving wheels.

One of the ideas for the new vehicle was to have the option of having rubber tracks or tires, depending on the choice of the potential customer. To achieve this, the design must offer a solution in which it was possible to apply a pair of rubber tracks or four wheels with tires.

Along with this issue there was another one related to the transmission of power from the electric motor to the tires or rubber tracks. The small existing vehicles for greenhouses like the Bertolini have a single ICE running on gasoline. The rotational movement of the crankshaft is transmitted to a differential. From the differential one axle connects to left side and another axle to the right side. Movement for the left or right is performed by releasing the hand levers; if the driver releases the right lever, the vehicle moves to the right; if releases the left lever, it moves to the left. Levers actuate brakes on each side’s axle, for example, releasing right lever, it will actuate the brake on the right axle and therefore the right rubber track has no power and the vehicle moves to the right, once only the left rubber track has power. Not only the control of the vehicle is not comfortable, the system to control movement requires some mechanical parts that are subject to wear.

One possible solution was to consider the use of one electric motor for each side of the vehicle and this solution may fit both for tires and rubber tracks. Compared with the traditional solution it has the following issues:

- Removal of mechanical parts, some subject to wear like brake pads;
- Less weight, mainly to the removal of mechanical differential;
- Higher cost, once it demand the use of 2 electric motors instead of 1;
- Electronic control more complex, once it is necessary to balance the 2 motors to rotate at the same speed when the vehicle moves front and backward.

To make a better assessment of the 2 possible alternatives, it was performed an economic study to compare the costs of both. An initial 3D model was created to design an architecture that could use only 1 central electric motor or 1 on each side of the vehicle and also to offer tires or rubber tracks, figure 7.05. With this initial model it was possible to design a frame for the vehicle, place and check the number of batteries that could be used, availability of space for the electric motors and the dimensions of tires and rubber tracks. With these inputs, suppliers of the main components were contacted and asked to send proposals for parts supply.

Figure 7.05 – Initial 3D model for the greenhouse prototype

On the 3D model, presented with the tire version, it is possible to see a solution for the turning of the vehicle, by connecting both wheels on the same side with a chain or a belt, to ensure that both wheels are rotating at the same time, simulating a rubber track.

When the initial design was frozen, it was possible to place a 4 battery pack with the same batteries used in the first prototype. With this solution, a 48 V output was possible and then a search for a DC motor running on 48 V with 2kW output started. It was identified an electric motor that GEM Motors was developing, with an output of 4 kW [99]. This motor was considered for both for 1 or 2 electric motors solution.

7.4 New concept costs

After receiving feedback from some suppliers, a spreadsheet was created to compare the costs of the 2 solutions. Once the base vehicle is the same, independently of the solution, some parcels have the same cost, for both solutions. Only what is related to the number of motors, the cost of the differential for the 1 electric motor and the more complex electric system for the 2 electric motors, makes the difference in terms of costs. Table 7.02 shows the costs per main components and the total cost.

Table 7.02 – Cost comparison between solutions with 1 or 2 electric motors (Values in Euros)

	2 electric motors		1 electric motor	
	Qty	Cost	Qty	Cost
Chassis Module	1	105	1	105
Batteries Module	1	1 190	1	1 190
Motor Module	1	1 630	1	815
Transmission	1	311	1	311
Differential + axles	-	-	1	500
Rubber track Module	2	1 122	2	1 122
Electric	1	320	1	270
Seat	1	250	1	250
Total		4 928		4 653

The total cost difference is 275 Euros, meaning that the 2 electric motor solution is 5.9% more expensive when compared to the 1 electric motor solution. It is not a large difference and the advantages of the 2 electric motor solution may overtake the higher cost.

With this information about costs and the initial 3D model for the greenhouse vehicle prototype, there is a base to implement the Ulrich and Eppinger method [1] for a new product. A whole new development process may start and in this case not subjected to the constraints of starting over an existing base, therefore with more freedom to find new design solutions.

From the visits feedback there is an interest for vehicles with higher performance, less impact on environment and at the same time with operational costs that can compete with the traditional vehicles.

8 Conclusions

Along the study, there were some changes made to the initial idea, due to the opportunities that occurred, mainly the shift of the type of vehicle to be object of the study. Instead of a regular tractor, the object of the study was a special machine for a very special application in the vineyards of Douro

The theme of the study itself found acceptance not only on the MIT-Portugal committee but also on 2 important kinds of stakeholders: potential customers and users.

The theme also led to go forward with an initial query conducted at the Portuguese National Agriculture Fair, where tractor user's and owner supply important data about the use of tractors.

Some other contacts were made with dedicated agricultural associations like ADVID, from Douro vineyards region and Horpozim, from horticulture farms in the North shore of Portugal. Their inputs were important to have a broader horizon for application of the study.

This study was the start of what it is intended to be a bigger study, having in sight the offer to farmer, agricultural vehicles with a new solution for the energy source, instead of the use of fossil fuels. It is a trend that was already introduced in light motorcycles, it is nowadays a major target for the investment of car manufacturers and it will spread all over other vehicles and machines that depend on fossil fuels and ICE for the energy source and powertrain technologic solution.

Being mainly an experimental study, the application of a battery-electric motor solution on an existing vehicle with an ICE, was possible to have a big insight of the major issues that a conversion may bring up and forced to find the most practical, economical and feasible solutions to, in the first stage, put the vehicle moving, and in a second stage, prepare it to be tested in real conditions, performing real operations in its application.

Some of the planned tasks were performed later than expected and even others weren't performed. This doesn't mean that those tasks weren't important or were simply forgotten but economical and time constraints played an important role in the execution of this study, by limiting components purchase and availability to prepare and perform some tasks, mainly the field tests.

8.1 Results of the study

It is important to summarize the main results of the study and especially the more objective oriented ones. The study and design of the BEV prototype give good results in terms of functionality, once it was possible to prove it during the field tests and especially in the last one in Quinta do Noval.

In table 8.01 there is a summary of the main outputs of the prototypes, both in the 36 V and 72 V versions and the original 36 hp Multijyp.

Table 8.01 – Comparison between original 36 hp Multijyp, 36 V BEV and 72 V BEV prototypes

Item	36 hp Multijyp	36 V BEV prototype	72 V BEV prototype
Power (kW)	26.4	4	7
Consumption per hour	3 l / hour	-	9.23 kWh
Range	8 hours operating	82 minutes (only movement)	70 minutes spraying
Weight (kg)	760	720	830
Cost per hour (€)	2.49	-	0.93
CO_2 Emissions (g/h)	8 045	0	0

There is a huge gap in what concerns to power output. Even in the 72 V version, the calculated output is around 4 times smaller when compared to the original vehicle. For the movement of the vehicle, the difference is felt mainly when it is needed to make a U turn, where both prototype perform worse than the original.

Consumption was calculated for the BEV when it performed a spraying operation but more tests were need to make a mapping of consumption versus operations and ground conditions.

Range is a critical issue once to perform agriculture operations, there are some times where availability of the vehicle is fundamental. In this parameter, the original vehicle has a tremendous advantage: fuel tank can carry enough fuel to perform 8 hours in a row; if necessary it is easily refilled and can continue operating another 8 hours and so on. For the BEV versions, testing results gave the same range but in different conditions: 70 minutes for both versions but while 36 V prototype was only moving on hard ground, the 72 V prototype lasted same time but performing spraying, in the mountainous vineyard. Also recharging is a very slow operation, especially with the charging equipment available, which charges one battery in 8 hours.

During the tests, weight showed to be an important issue, once the less powered BEV has more difficulties in moving due to the amount of mass. The 72 V BEV prototype weight is 830 kg, more 110 kg when compared to 36 V BEV due to the extra 3 batteries and supports.

Cost per hour was calculated after the last test at Quinta do Noval and showed that if the batteries of prototype were charged during off-peak period the electricity cost would be 62.7 % below the cost of agriculture diesel. This was a very encouraging result and confirmed the validity of the search for alternative energies to reduce or eliminate fossil fuels consumption.

The last item on the table is CO_2 emissions. The measurement of the original vehicle was not done but considering the average diesel consumption, it was possible to estimate average CO_2 emissions. For the BEV prototype there are no tailpipe emissions, so in this parameter, the BEV prototype proofed emit zero emissions, not only CO_2 but also other pollutant gases.

8.2 Answers to research questions

In introduction one main and three sub research questions were presented. Now they will be answered.

Main Research Question was: “Is it possible to use an alternative energy source for agricultural machines?”
The answer is positive. Even if at the current stage of this study is not possible to ensure without any doubt that other energy sources could be used, it was possible to perform the conversion from an ICE power train using diesel to an electric motor using electricity provided by batteries.

From the main research question, three associated sub research questions were placed. The answers to each are:

- SRQ1 – “With the present technology, is it possible to adapt or design agricultural machines with alternative energy sources?” The answer is positive. The study was based in current and available components and technology, meaning that with the current state of the art is it possible to find other solutions to agriculture vehicles rather than the established ICE running with diesel.

- SRQ2 – “Can an agricultural or farm machine equipped with an alternative energy source perform the same operations as one running on fossil fuels? The answer is positive. With the initial pack of 3 batteries, it was not possible, due to the low value of output power of the system. With the 6 batteries pack, it was possible to perform a spraying operation with a tank installed in the prototype, actuated by a replacement PTO.

- SRQ3 – “What are the economic and environmental impact of the conversion from fossil fuels to alternative energies?” In chapter 4, where the analysis of the impact on consumption, cost of use and emissions is shown, it is quite clear to see the benefits of the use of alternative energy sources, mainly the use of electricity produced recurring to renewable energies, like sun, wind, hydric. Although it is not possible to reduce to zero the impact of renewable energies, once the production of the equipment, installation and energy transport implies production of CO_2, its impact is considerably lower when compared to others. Considering the estimated cost per hour of the 72 V BEV and the original vehicle, the BEV solution represents a cost reduction of 62.7 %.

Although the original vehicle implied some constraints to the application of the batteries pack and electric motor, the result shows that it is possible to overcome those constraints even recurring to existing components as the batteries, electric motor and controller, just to mention the most important ones. If those components were specially design for this application, for sure power output and range could be bigger and be more in line with the end-users expectations.

8.3 Future work

The main tasks and goals of this study were performed and achieved. There were still some tasks that needed to be done or done several times, like the consumption measurement, perform of other agriculture tasks with other equipment to verify the behavior of the prototype under different demands, test in different types of grounds, test in different temperature ranges, test with different types of crops. All these tasks may be part of future works than can be carried out by the existing prototype. Gathering more data and collecting feedback for other farmers of different crops would enlarge the potential use of vehicles using an electric powertrain.

In a medium/long term the possible work to be performed in this area may be:

- Development of a machine for outdoor applications, under hard or light conditions, considering that for hard conditions, a crawler machine is mandatory
- Development of a machine for indoor applications, also presented in chapter 7, a lighter frame and the use of tires, once slopes are small and ground is soft
- The study of a system for a quick battery pack swap. Once range of batteries hardly ensures the use for the standard 8 hours use, it may be of great importance to study a system that could allow a quick replace of a battery with low charge for another fully loaded
- Study of a range extender. Lead acid batteries energy storage is low when compared with Li-ion batteries so it could be very useful if a range extender was installed in the machine or easily connected to it. It is a very sensitive subject if such a machine gets low on the batteries and it is on the middle of a field or in the middle of a vineyard, far away from the garage or an electricity plug.
- Study of application of other alternative energy sources like hydrogen and its use in fuel cell powertrains. In the car industry there are already some prototypes and a small number of units running experimental tests with this technology.
- Study of alternative energy solutions for the most powerful agriculture machines. There are machines with power output over 200 HP, in which a possible solution for the replacement of the ICE running on diesel seams quite difficult to do. The battery-electric motor solution may not be adequate for such applications, due to the considerable volume and weight of the batteries. Even if the number of machines with high power is not considerable, the impact of those machines is important; once they perform the most demanding operations and may run several hours continuously.
- Study of equipment. For the case of Multyjip machines, some equipment are designed to be applied only in the Multyjip, so special equipment may be needed for this type of special machines. Also another chance is to stop using hydraulic power supplied by the machine that drives hydraulic tools to perform the movements and replace it by direct drive electric motors. One of the issues of the conversion was the oil tubes position, volume and leak hazards.

At the beginning of this study some questions rose up, like if the study end results would be in line with the expectations or if it could be applied in practice. In the end, the results showed that the solution found worked and on the other hand, the interest showed by the Quinta do Noval and Maria Alice responsible means that the application of such a solution raise interest in potential users.

It can be the start of a new generation of agricultural vehicles, with less impact on environment, more economical, reducing the dependence on fossil fuel that is extracted many kilometers away of its end use and a small contribution to mitigate climate changes.

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ANNEX 1

USER IDENTIFICATION

Name: ____________________

Age: ____________________

Address: ____________________

Phone: ____________________

Email: ____________________

Employee ☐ Individual business ☐ Share holder / owner ☐

Company: ____________________

Are you affiliated in any farmer association : Yes ☐ No ☐

Which: ____________________

TRACTOR IDENTIFICATION

Manufacturer: ____________________

Model: ____________________

Age: 0-5 ☐ 6-10 ☐ 11-15 ☐ 16-20 ☐ 21-25 ☐ >25 ☐

Years of possession: 0-5 ☐ 6-10 ☐ 11-15 ☐ 16-20 ☐ 21-25 ☐ >25 ☐

Power (hp): <15 ☐ 16-25 ☐ 26-40 ☐ 41-60 ☐ 61-80 ☐ 81-100 ☐ 101-150 ☐ 151-200 ☐ >200 ☐

Buy new? Yes ☐ No ☐

Where was bought: Private ☐ Tractor store ☐ Brand dealer ☐

TRACTOR USE

Yearly hours tractor use:		
Perform subcontract services?	Yes ☐ No ☐	
Sub-contractor percentage (%):		
3 most demanding time tasks		
Consumption:	Road l/km	At work l/hour

Yearly fuel cost (€)	
Yearly maintenance cost (€)	
Average distance from parking to work spot (km)	
Average distance to fuel tractor (km)	
Right to Agriculture Diesel	Yes ☐ No ☐

PURCHASE OPTIONS

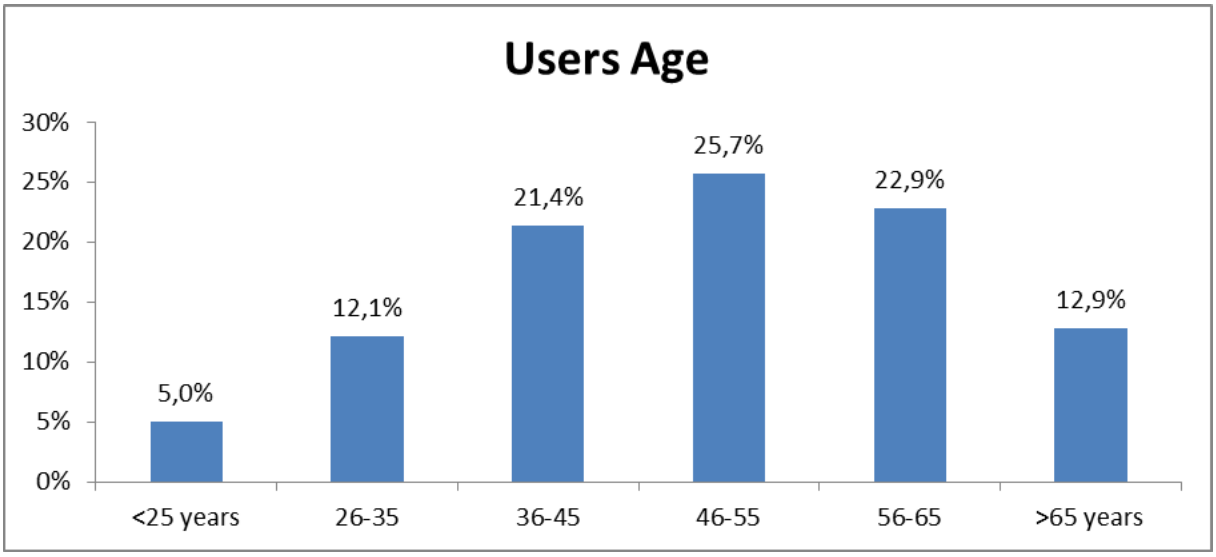
Are you considering to buy a new tractor?		Yes ☐ No ☐	
If yes:	New ☐ Used ☐	When?	
Would you buy from same manufacturer?		Yes ☐ No ☐	
Would you buy with same power?		Yes ☐ No ☐	

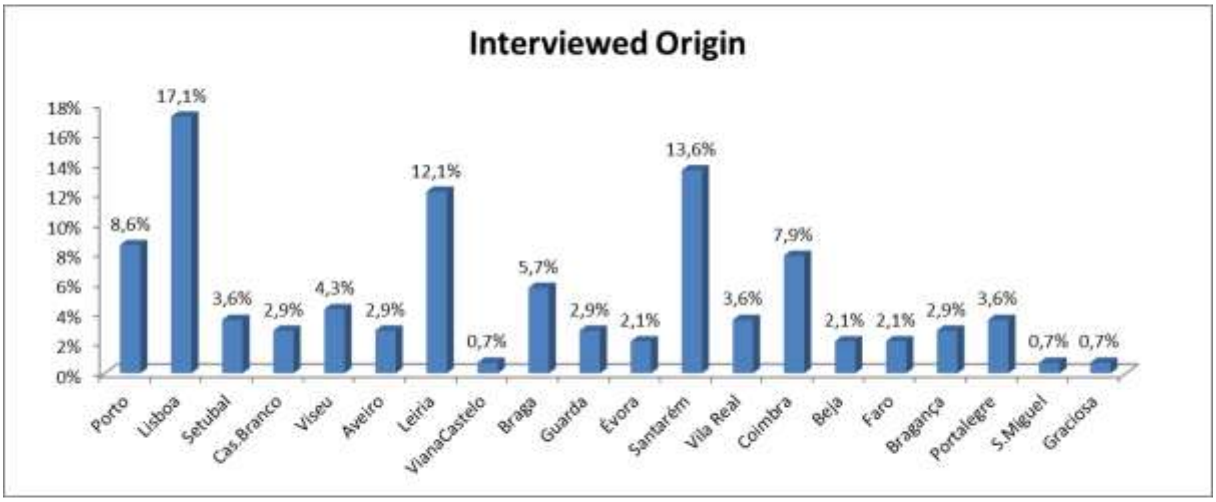
In a range 1-6 (1 – Irrelevant, 6 – Undoubtable) classify the following items on a tractor purchase

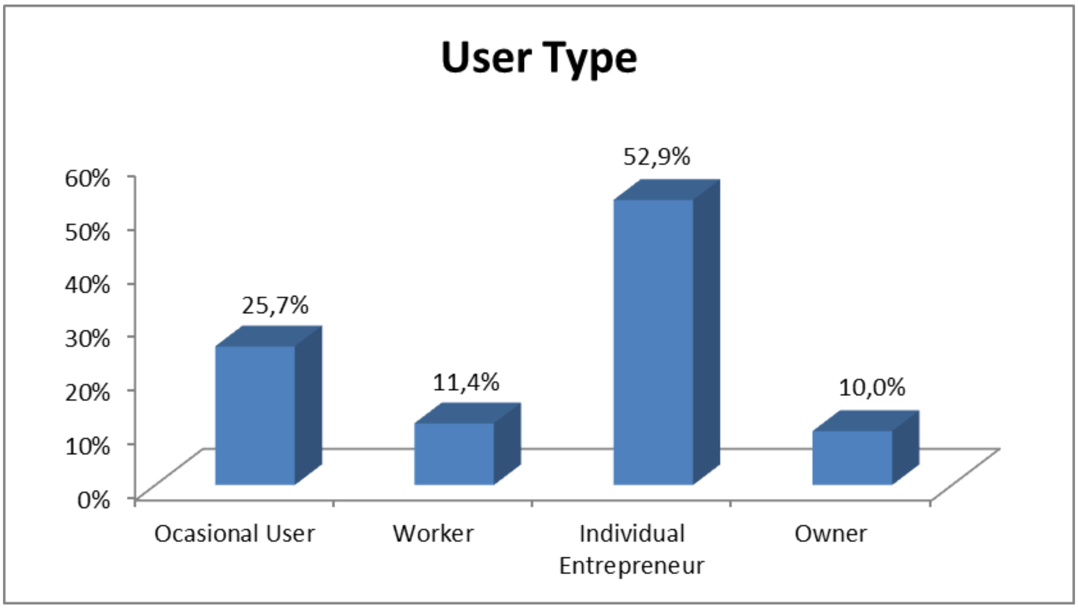
ITEM	1 Irrelevant	2 Does not matter	3 Indifferent	4 Important	5 Very Important	6 Undoubtable
Robustness	☐	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐	☐
Maintenance cost	☐	☐	☐	☐	☐	☐
After sales service	☐	☐	☐	☐	☐	☐
Power	☐	☐	☐	☐	☐	☐
Consumption	☐	☐	☐	☐	☐	☐
Size	☐	☐	☐	☐	☐	☐
Comfort	☐	☐	☐	☐	☐	☐
Quality	☐	☐	☐	☐	☐	☐
Equipament	☐	☐	☐	☐	☐	☐
Hydraulic output	☐	☐	☐	☐	☐	☐
Price	☐	☐	☐	☐	☐	☐

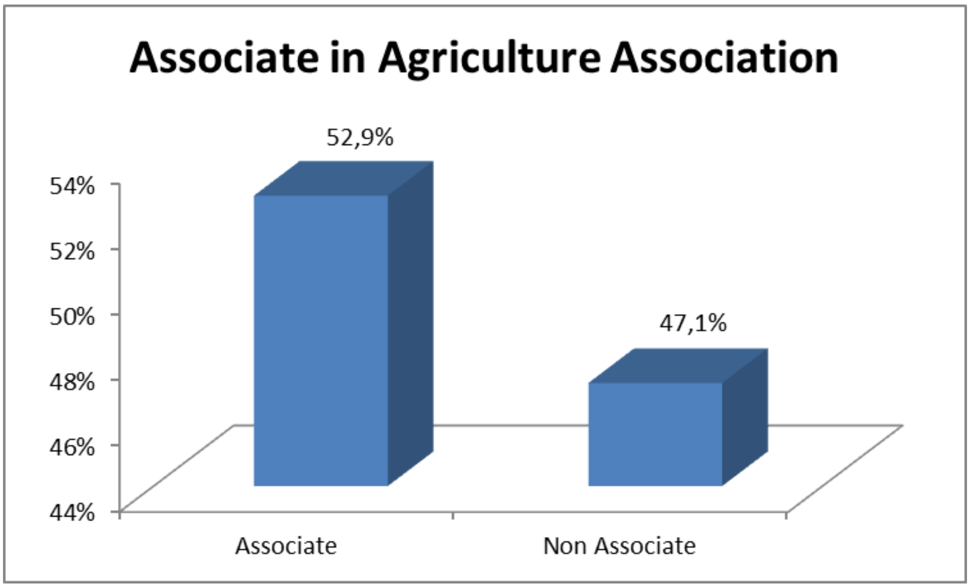
ANNEX 2

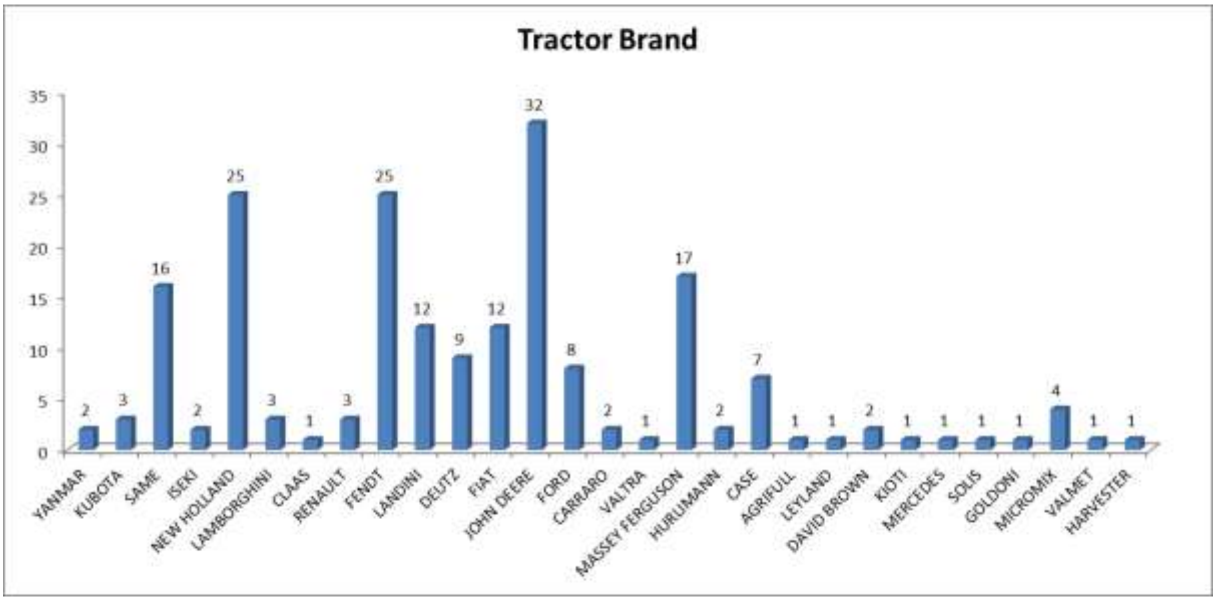
Agriculture National Fair Survey Results – June 2013

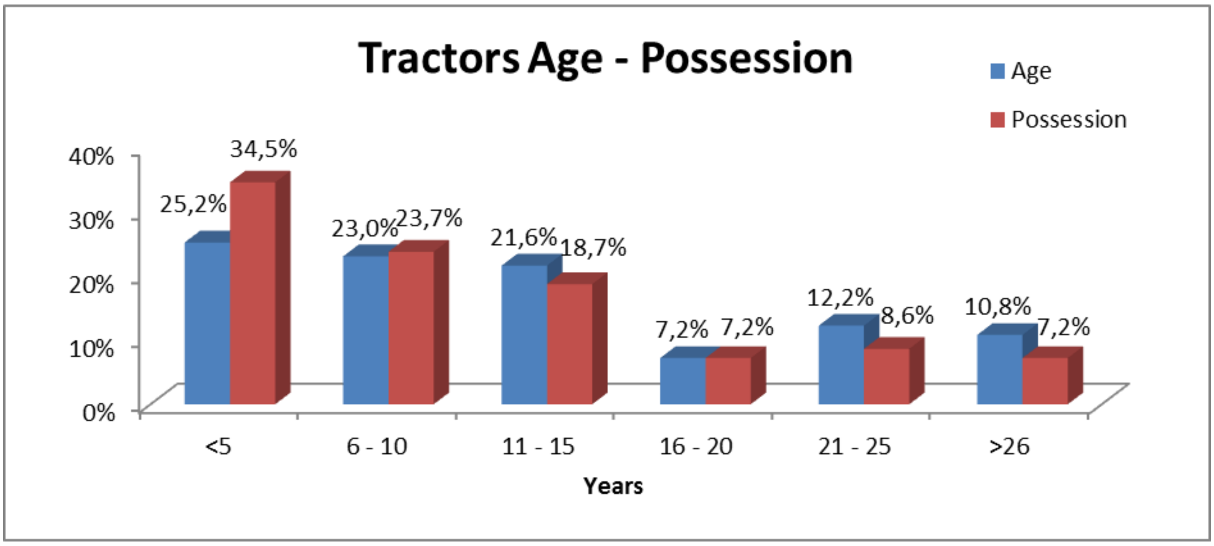


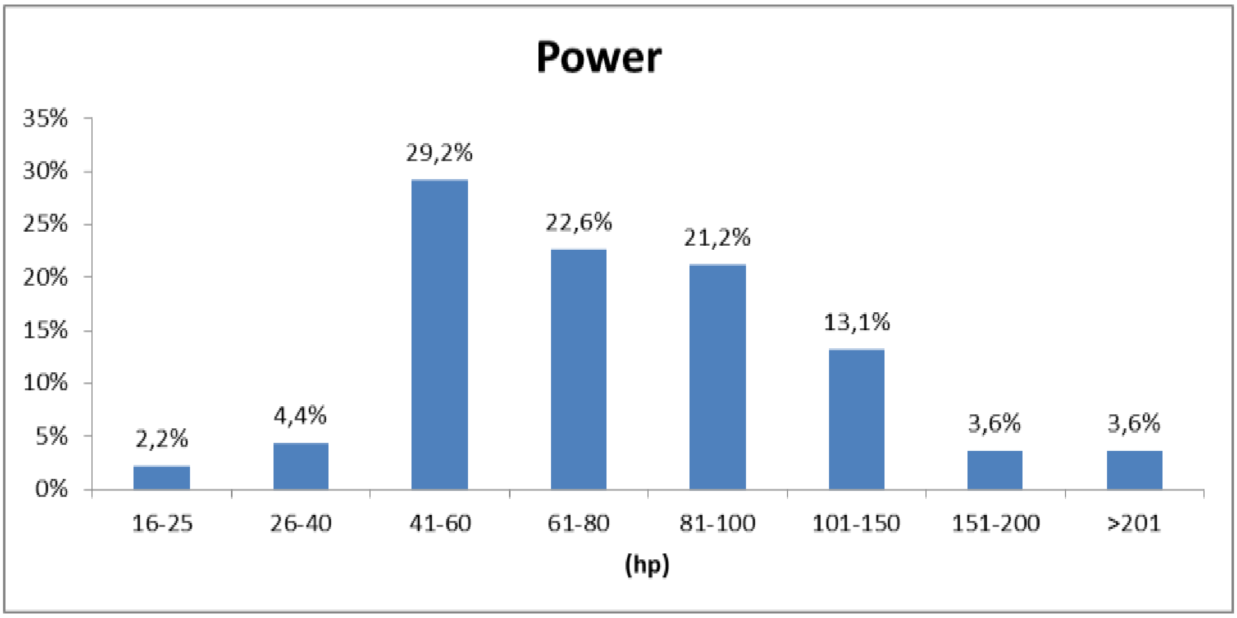


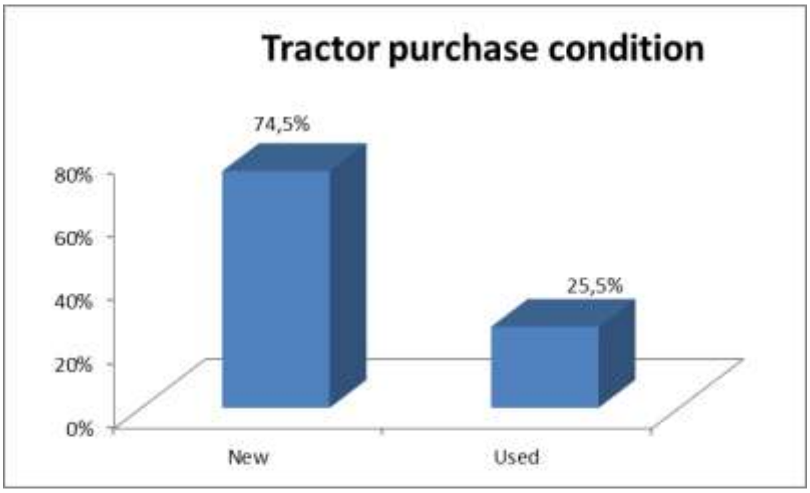


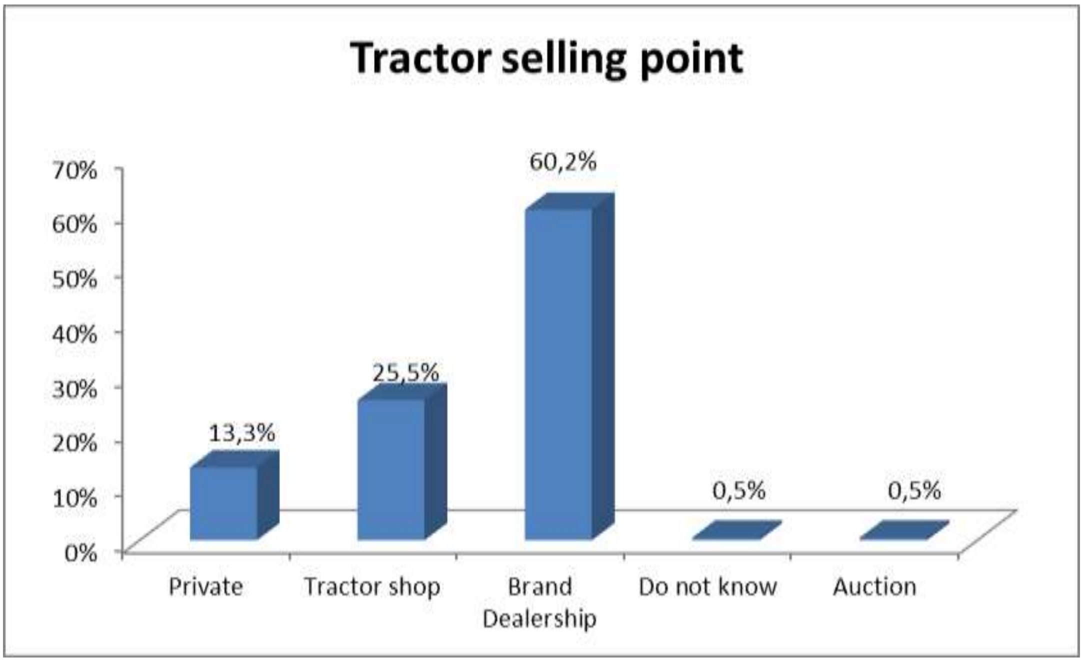

Associate in Agriculture Association
52,9%
47,1%
54%
52%
50%
48%
46%
44%
Associate
Non Associate

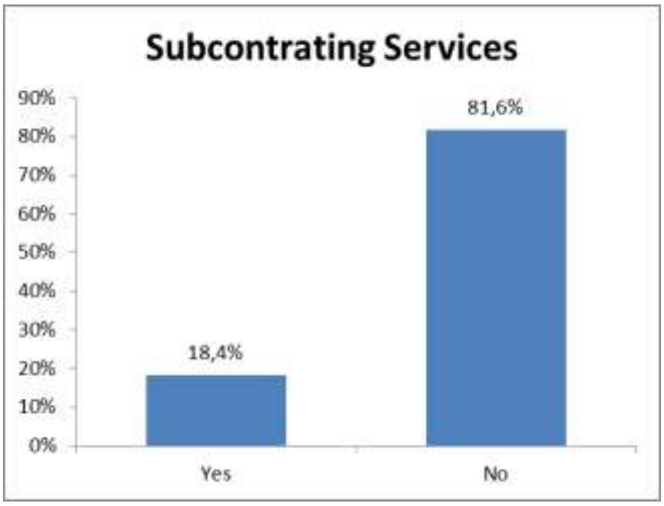

Tractor Brand
35
30
25
20
15
10
5
0
2
3
16
2
25
3
1
3
25
12
9
12
32
8
2
1
17
2
7
1
1
2
1
1
1
1
4
1
1
YANMAR
KUBOTA
SAME
ISEKI
NEW HOLLAND
LAMBORGHINI
CLAAS
RENAULT
FENDT
LANDINI
DEUTZ
FIAT
JOHN DEERE
FORD
CARRARO
VALTRA
MASSEY FERGUSON
HURLIMANN
CASE
AGRIFULL
LEYLAND
DAVID BROWN
KIOTI
MERCEDES
SOLIS
GOLDONI
MICROMIX
VALMET
HARVESTER

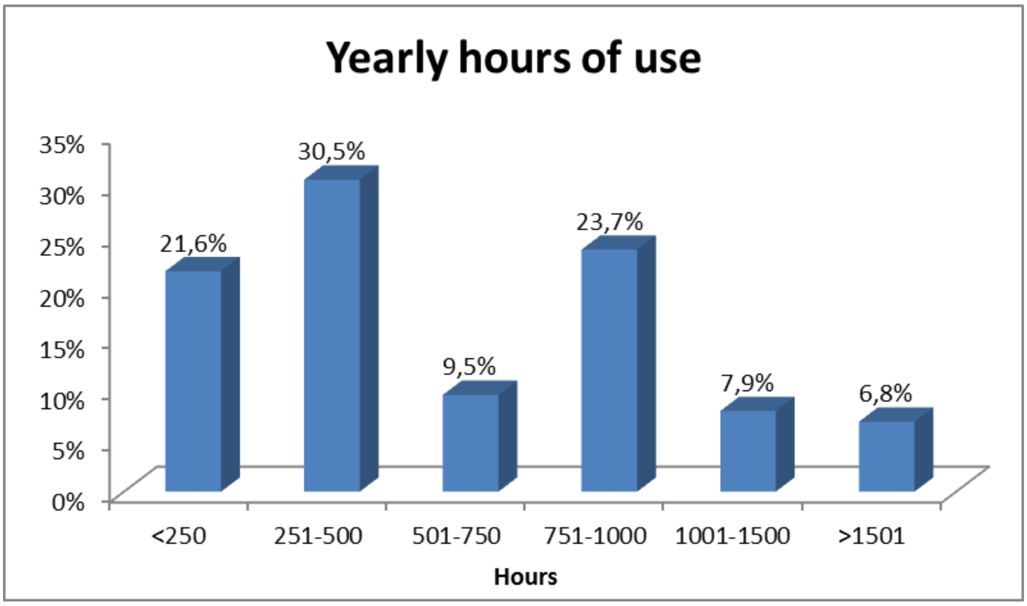

Tractors Age - Possession
Age
Possession
40%
30%
20%
10%
0%
25,2%
34,5%
23,0%
23,7%
21,6%
18,7%
7,2%
7,2%
12,2%
8,6%
10,8%
7,2%
<5
6 - 10
11 - 15
16 - 20
21 - 25
>26
Years

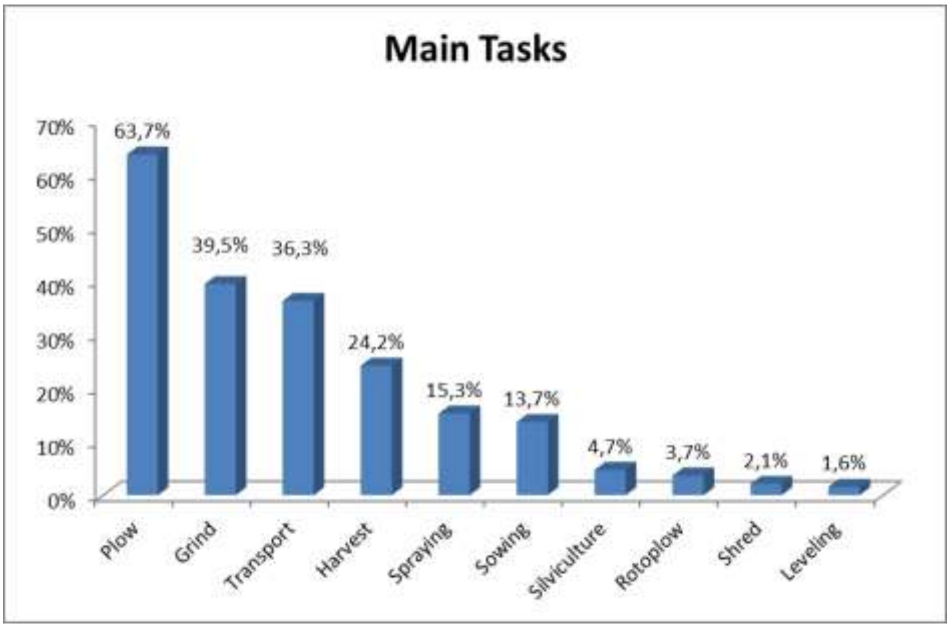

Power
35%
30%
25%
20%
15%
10%
5%
0%
2,2%
4,4%
29,2%
22,6%
21,2%
13,1%
3,6%
3,6%
16-25
26-40
41-60
61-80
81-100
101-150
151-200
>201
(hp)

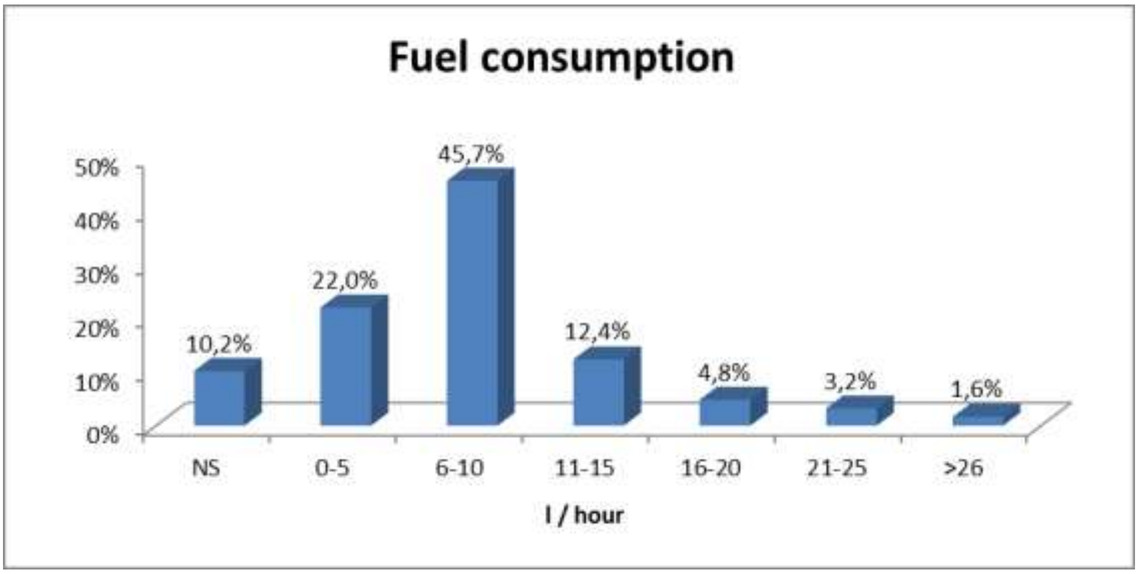

Tractor purchase condition
80%
60%
40%
20%
0%
74,5%
25,5%
New
Used

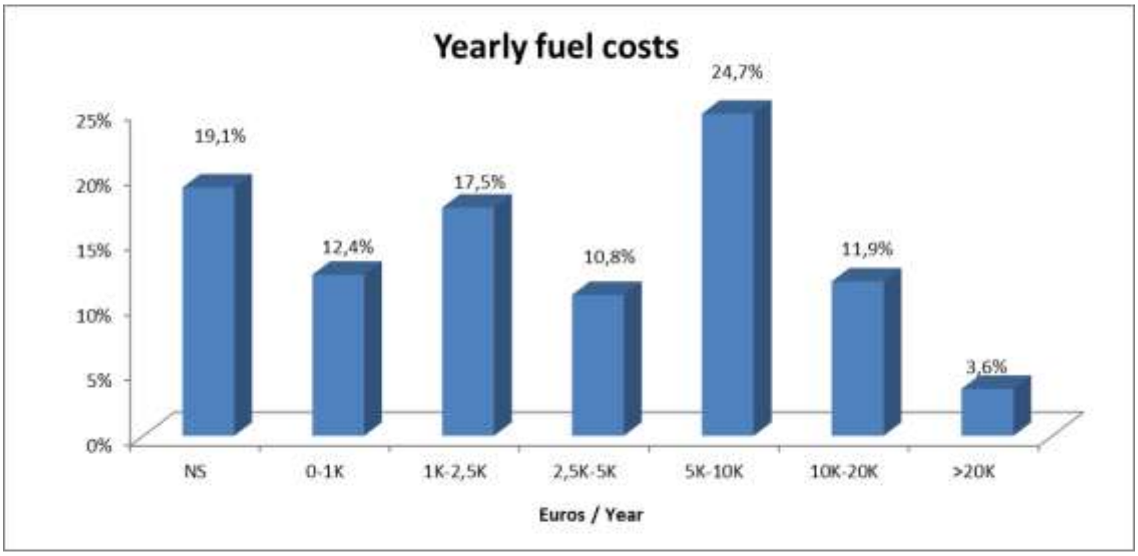

Tractor selling point
70%
60%
50%
40%
30%
20%
10%
0%
13,3%
25,5%
60,2%
0,5%
0,5%
Private
Tractor shop
Brand Dealership
Do not know
Auction

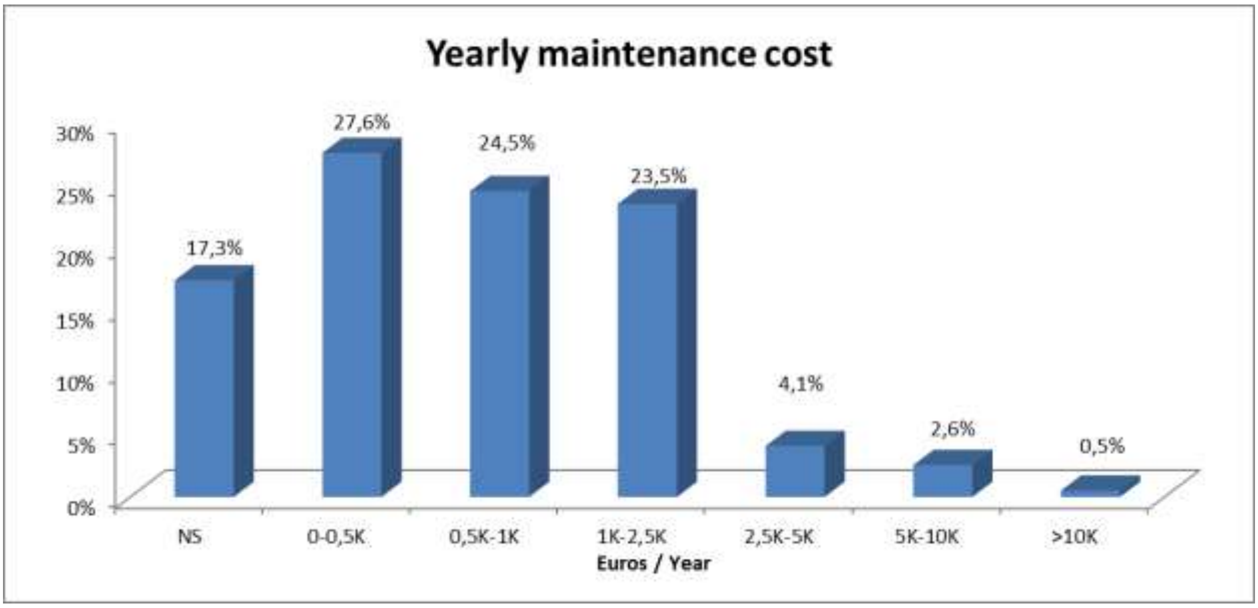

Subcontrating Services
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
18,4%
81,6%
Yes
No

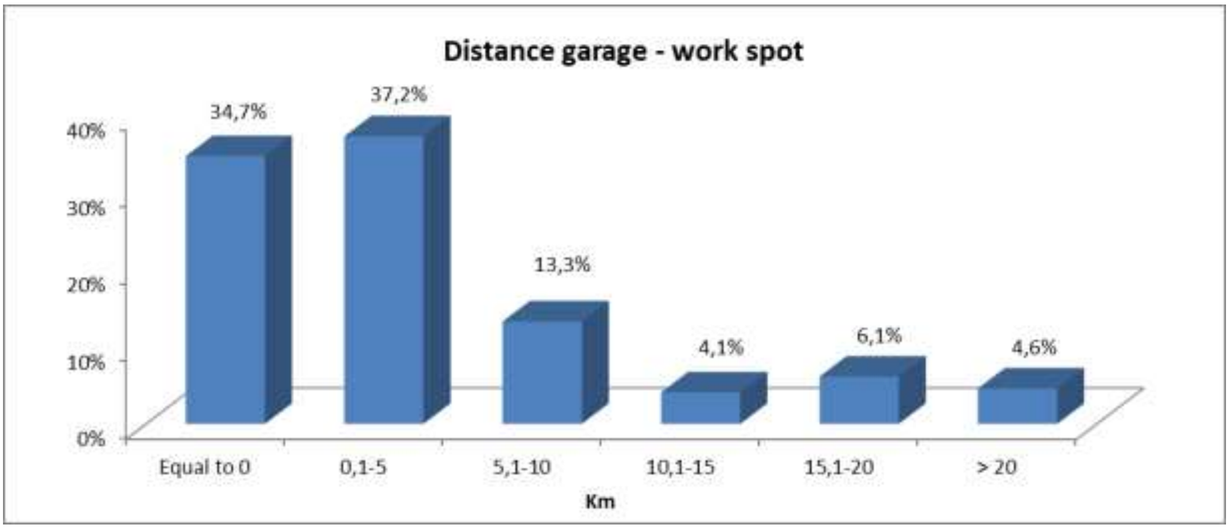

Yearly hours of use
35%
30%
25%
20%
15%
10%
5%
0%
21,6%
30,5%
9,5%
23,7%
7,9%
6,8%
<250
251-500
501-750
751-1000
1001-1500
>1501
Hours

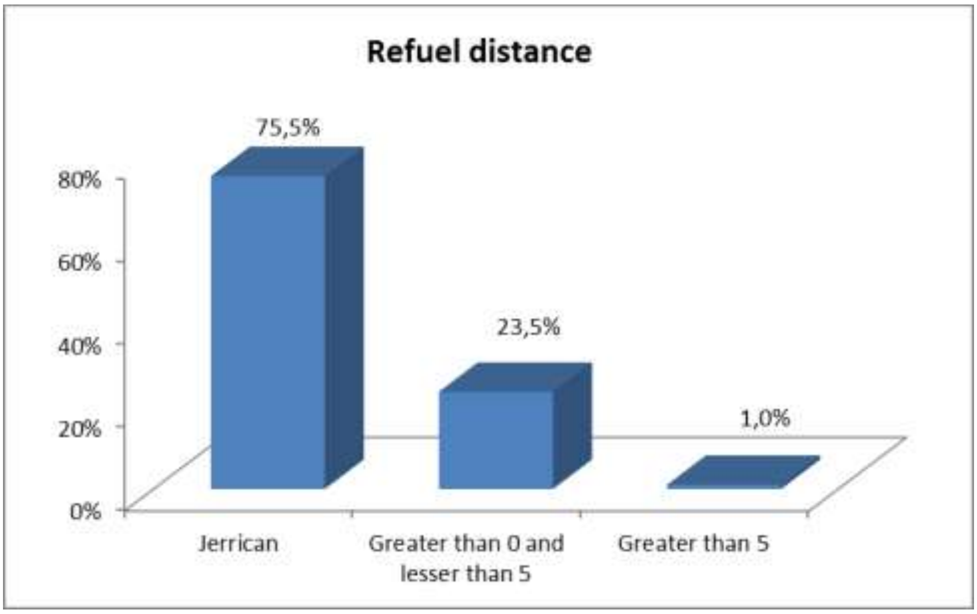

Main Tasks
70%
60%
50%
40%
30%
20%
10%
0%
63,7%
39,5%
36,3%
24,2%
15,3%
13,7%
4,7%
3,7%
2,1%
1,6%
Plow
Grind
Transport
Harvest
Spraying
Sowing
Silviculture
Rotoplow
Shred
Leveling

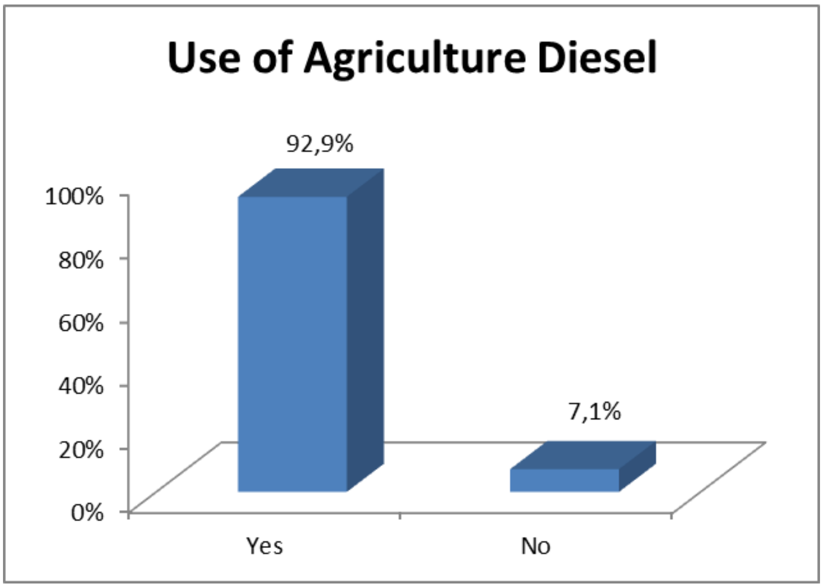

Fuel consumption
50%
40%
30%
20%
10%
0%
10,2%
22,0%
45,7%
12,4%
4,8%
3,2%
1,6%
NS
0-5
6-10
11-15
16-20
21-25
>26
l / hour

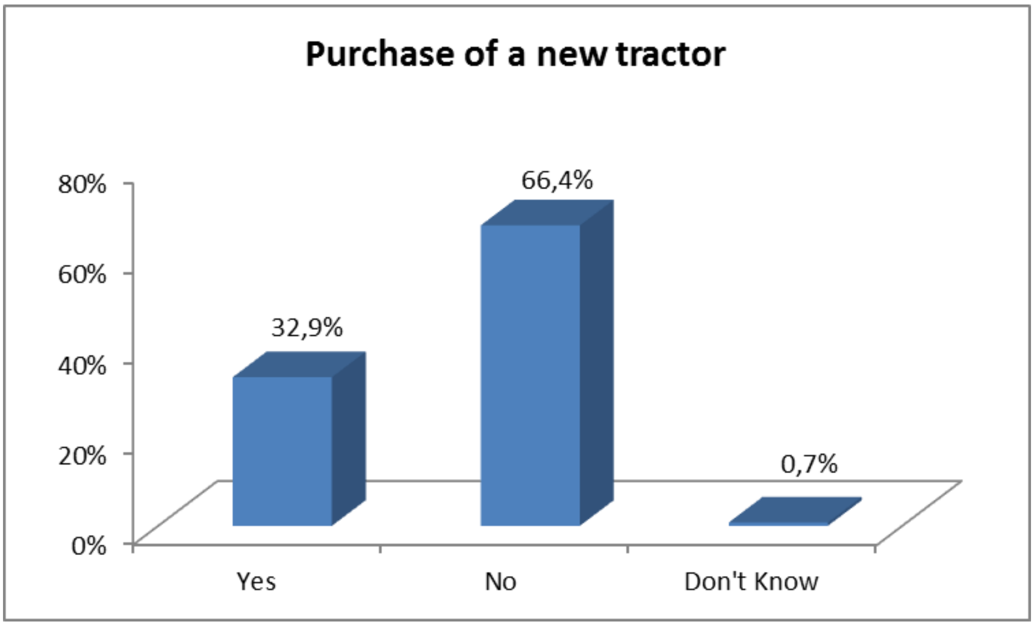

Yearly fuel costs
25%
20%
15%
10%
5%
0%
19,1%
12,4%
17,5%
10,8%
24,7%
11,9%
3,6%
NS
0-1K
1K-2,5K
2,5K-5K
5K-10K
10K-20K
>20K
Euros / Year

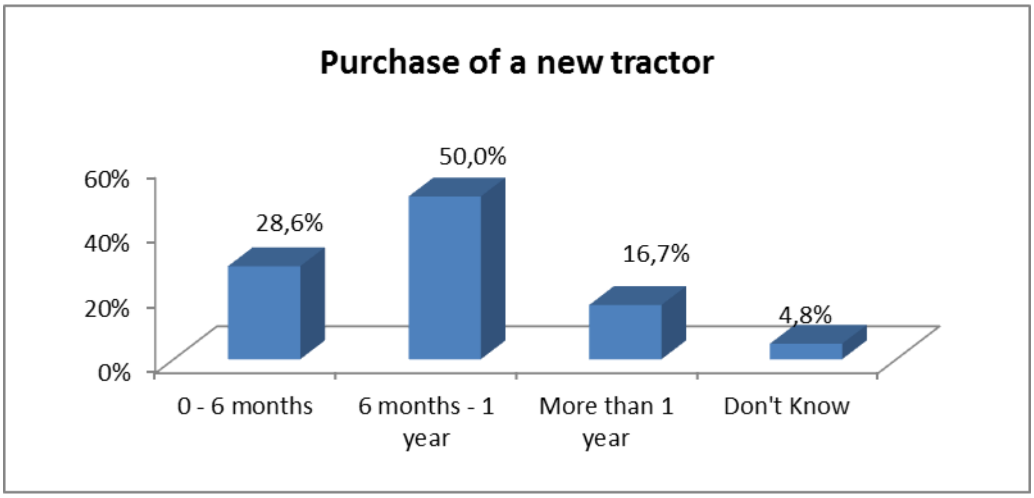

Yearly maintenance cost
30%
25%
20%
15%
10%
5%
0%
17,3%
27,6%
24,5%
23,5%
4,1%
2,6%
0,5%
NS
0-0,5K
0,5K-1K
1K-2,5K
2,5K-5K
5K-10K
>10K
Euros / Year

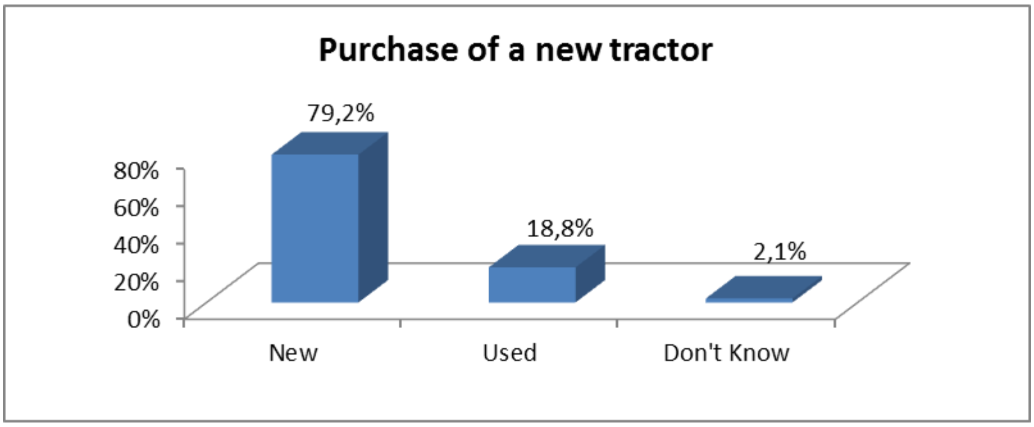

Distance garage - work spot
40%
30%
20%
10%
0%
34,7%
37,2%
13,3%
4,1%
6,1%
4,6%
Equal to 0
0,1-5
5,1-10
10,1-15
15,1-20
> 20
Km

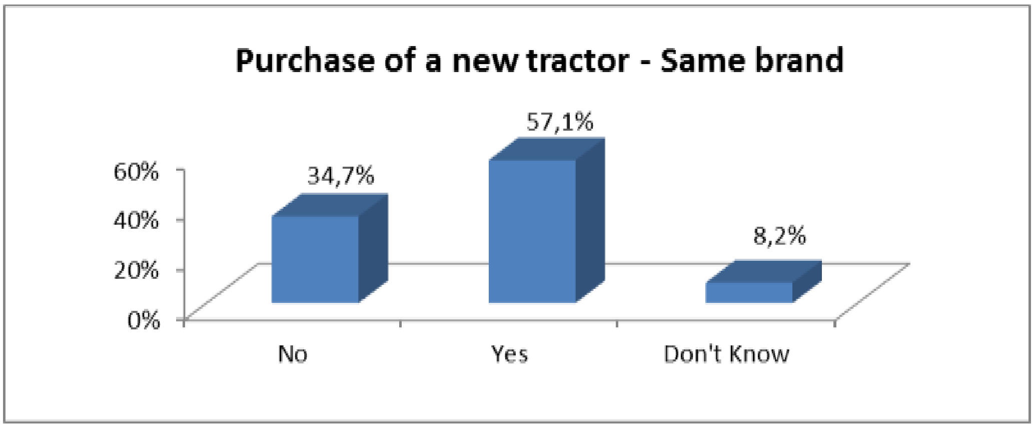

Refuel distance
80%
60%
40%
20%
0%
75,5%
23,5%
1,0%
Jerrican
Greater than 0 and lesser than 5
Greater than 5

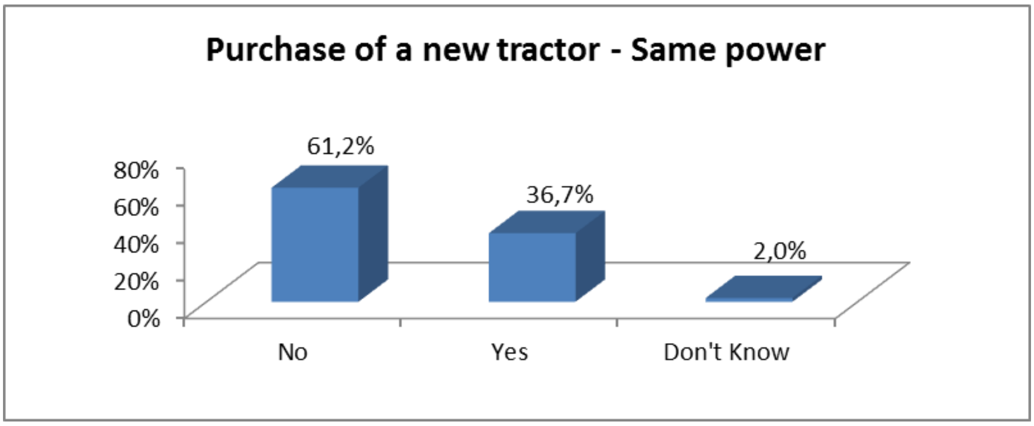

Use of Agriculture Diesel
100%
80%
60%
40%
20%
0%
92,9%
7,1%
Yes
No

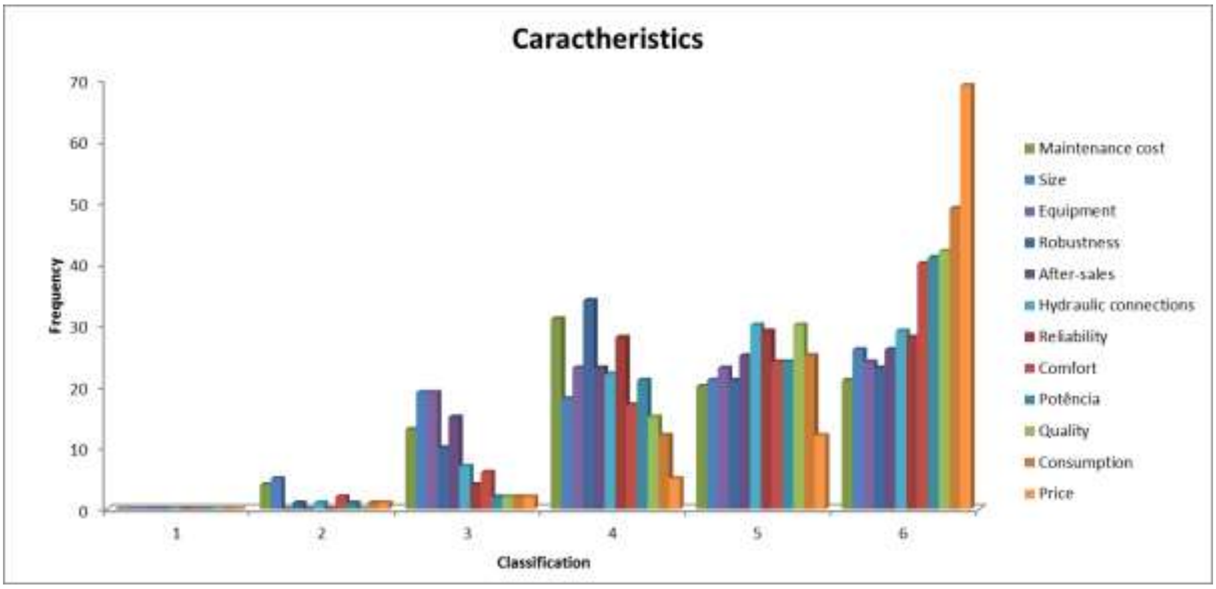

Purchase of a new tractor
80%
60%
40%
20%
0%
32,9%
66,4%
0,7%
Yes
No
Don't Know


Purchase of a new tractor
60%
40%
20%
0%
28,6%
50,0%
16,7%
4,8%
0 - 6 months
6 months - 1 year
More than 1 year
Don't Know


Purchase of a new tractor
80%
60%
40%
20%
0%
79,2%
18,8%
2,1%
New
Used
Don't Know


Purchase of a new tractor - Same brand
60%
40%
20%
0%
34,7%
57,1%
8,2%
No
Yes
Don't Know


Purchase of a new tractor - Same power
80%
60%
40%
20%
0%
61,2%
36,7%
2,0%
No
Yes
Don't Know


Caractheristics
Frequency
70
60
50
40
30
20
10
0
1
2
3
4
5
6
Classification
Maintenance cost
Size
Equipment
Robustness
After-sales
Hydraulic connections
Reliability
Comfort
Potência
Quality
Consumption
Price