



Report on current energy use status in EU agriculture

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Abstract

According to Eurostat, current direct (on-farm) energy use accounts for 3.2% of the EU's total energy consumption and is dominated by energy from fossil sources. Based on data from available studies and provided by the AgroFossilFree partners, our findings suggest that if indirect energy inputs are included, which are predominantly produced using fossil energy, this figure would be 62% higher. For the open-field crops covered in this study, the energy embedded in fertilizers is the largest input, accounting for around 50% of all energy inputs, followed by on-farm diesel use at 31%. In livestock systems, animal feed is generally the main energy input, accounting for around three quarters of all energy inputs, while on-farm energy use is concentrated in housing and manure management. For greenhouses, energy inputs vary considerably between advanced, high-energy intensity greenhouses, which are dominated by energy inputs for heating/cooling, and basic, low-energy intensity greenhouses for which energy inputs are split between direct and indirect inputs. An acceleration of the development, adoption and scaling of Fossil Energy Free Strategies and Technologies, such as conservation agriculture, will improve energy efficiency, reduce agriculture's reliance on fossil energy and support the attainment of the goals outlined in the EU's Green Deal and Farm to Fork Strategy.

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Abbreviations

AFF	-	AgroFossilFree
AGENSO	-	Agricultural & Environmental Solutions
AU	-	Aarhus Universitet
AUA	-	Geoponiko Panepistimion Athinon
CAP	-	Common agricultural policy
CEMA	-	Comite Europeen Des Groupements De Constructeurs Du
Machinisme Agricole		
CERTH	-	Ethniko Kentro Erevnas kai Technologikis Anaptyxis
CONFAGRICOLTURA	-	Confederazione Generale Dell Agricoltura Italiana
DELPHY	-	DELPHY
ECAF	-	European Conservation Agriculture Federation
ETS	-	Emissions Trading System
FEAT	-	Farm energy analysis tool
FEFTS	-	Fossil-energy-free strategies and technologies
GHG	-	Greenhouse gas emissions
INI	-	Iniciativas Innovadoras Sal
IPPC	-	Intergovernmental Panel on Climate Change (IPCC)
IUNG-PIB	-	Instytut Uprawy Nawożenia I Gleboznawstwa, Panstwowy Instytut Badawczy
L&F	-	Landbrug & Fodevarer F.M.B.A.
LCA	-	Life cycle assessment
LODR	-	Lubelski Osrodek Doradztwa Rolniczego W Konskowoli
PV	-	Photovoltaic
RES	-	Renewable energy sources
RESCOOP	-	RESCOOP EU ASBL
SOC	-	Soil Organic Carbon (SOC)
SOM	-	Soil Organic Matter
TEAGASC	-	the Agriculture and Food Development Authority
TTA	-	Trama Tecnoambiental S.L.
UAA	-	Utilised agricultural area
WIP	-	Wirtschaft Und Infrastruktur Gmbh & Co Planungs Kg

Units and Conversion table

MJ	-	Megajoules
GJ	-	Gigajoules
PJ	-	Petajoules
Ha	-	Hectare
kg	-	Kilogram
Toe	-	Tonne of oil equivalent
kWh	-	Kilowatt-hour
LSU	-	Livestock unit
ECM	-	Energy corrected milk
FPCM	-	Fat and protein corrected milk
m ³	-	Cubic metre
m ²	-	Square metre
Tg	-	Teragram
Gg	-	Gigagram
Pg	-	Petagram
Mg	-	Megagram
CO ₂	-	Carbon dioxide
CH ₄	-	Methane

Extended Summary

This study investigates the energy use status in the agricultural sector of the EU, providing an overview of the energy use and identifying the sectors and activities in which energy use is concentrated. Our results indicate that energy use throughout EU agriculture is significant and fossil dependent. Consequently, in order for the EU to reach the targets outlined in the Green Deal and the Farm to Fork strategy, energy use in European agriculture needs to move away from its dependency on fossil fuels. This transition can be supported by a range of fossil-energy-free strategies and technologies that improve energy efficiency, increase the penetration of renewable energy in agriculture and transition to more sustainable agricultural practices and farming systems.

According to Eurostat, agriculture accounts for 3.2% of the total energy consumption in EU countries, 56% of which derives directly from oil and petroleum products, 17% from electricity, 14% from gas and 9% from renewables and biofuels. However, our results suggest that if the energy use associated with the production and transport of fertilizers and pesticides is included, then the proportion of final energy use for agriculture in the EU-27 would be 62% higher than the current estimates. Nitrogen fertilizers production and transportation is the most significant factor (78% of all the energy associated with fertilizers and pesticides in the EU). Our research indicates that reductions in the energy use associated with fertilizer and pesticide use can be driven by more precise and reduced use, the development of alternatives and a shift to sustainable practices.

Table 1 provides an overview of the share of direct and indirect energy inputs in the production systems covered in this study. Notably, indirect energy constitutes over half of total energy inputs in open-field and livestock systems, while our findings, presented in the greenhouse section, indicate that direct energy inputs are dominant in greenhouse systems.

Table 1. Energy inputs in EU agricultural systems (%)

Agricultural System ¹		Indirect ²		Direct		Other/unclassified		Total	
Open field	Arable	63%	(769)	31%	(380)	6%	(78)	100%	(1227)
	Orchards and vineyards	51%	(106)	31%	(64)	18%	(38)	100%	(208)
Livestock	Meat	56%	(282)	44%	(218)			100%	(501)
	Dairy	74%	(400)	15%	(82)			100%	(543)
Greenhouse ³	High intensity	1%		99%				100%	
	Low Intensity	23%		27%		50%		100%	
¹ Only crops and systems covered in this study are included									
² Data in brackets are total energy consumption figures in PJ									
³ The data for greenhouses are simple averages based on studies that provided data on tomatoes, cucumbers and peppers and therefore should solely be seen as indicative									

Energy use, its concentrations and breakdown vary significantly across production systems - open-field, livestock, greenhouses - in the EU. The total energy consumption, both direct and indirect, in the selected open-field crops covered in this study is equivalent to 3.6% of final energy consumption in the EU. For open-field agriculture, our study finds that the energy embedded in fertilizers is the largest energy consuming activity in EU agriculture, accounting for around 50% of all energy inputs. On-farm diesel use accounts for 31% of all energy use and is mainly associated with field operations (in particular soil tillage), other uses mainly referring to irrigation, storage or drying, account for 8%, while seeds account for 6% and pesticides for 5% of the total energy inputs (see Table 2).

In arable agriculture, tillage activities generally consume the most direct on-farm energy, accounting for between 24-61% of total on-farm energy consumption depending on the crop, followed by

harvesting and sowing operations. Similarly, in orchard systems, the highest energy use is associated with harvesting operations, followed by irrigation, soil cultivation and pruning.

Table 2. Total energy inputs for selected open-field crops EU-27, (PJ)

Crop	Seeds	Fertilizers	Pesticides	Diesel use	Other	Total
Wheat	18	251	21	138	7	434
Maize	14	217	14	94	40	379
Barley	38	61	0	51		150
Potatoes	7	15	3	12	13	49
Sugar beet	0	15	2	11		27
Rapeseed	0	50	4	30	7	91
Sunflower seed	1	30	3	35	9	78
Soybean	2	5	1	8	3	18
Apples		3	3	7	1	14
Citrus		10	3	9	5	26
Olives		46	13	24	30	113
Vineyards		14	11	24	2	50
EU Total	79	716	75	444	116	1431
EU Total (%)	6	50	5	31	8	100

In all livestock systems, except for beef production systems, animal feed is the main energy input, accounting for around three quarters of all energy requirements (see Figure 1). The production and use of animal feed is energy-intensive as its main feedstock are crops (mainly cereals), it is estimated that animal feed consumes around 60% of the cereal production in the EU. In addition, a large amount of high-protein animal feed is imported from outside the EU, further increasing the energy intensity of animal feed. In this regard, the study discusses a number of pathways to reduce the fossil energy associated with feed use, such as switching to locally produced feedstocks and developing alternative feed sources, like wheat middlings, cottonseed and soybean hulls.

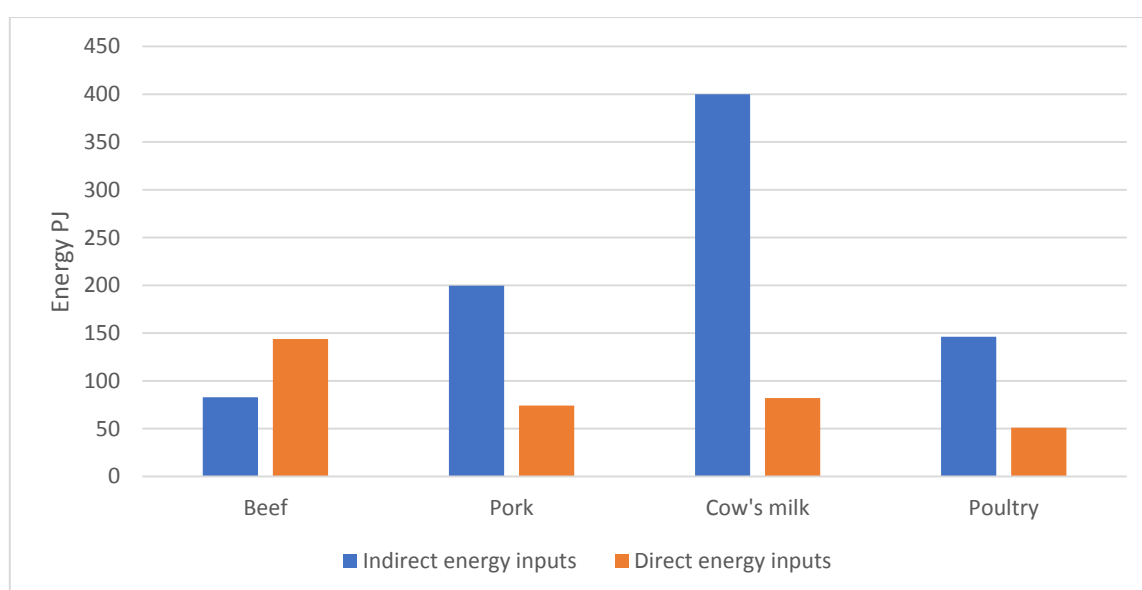


Figure 1. Total direct and indirect energy inputs for selected livestock systems EU-27 (PJ)

Figure 1 illustrates that on-farm energy use varies significantly depending on the type of livestock covered. The main direct energy consuming uses for beef production are diesel use for manure management (71%), electricity used in stables (17%) and electricity used in crop processing (11%); for pork production these are electricity used in housing (50%), diesel use for manure management (22%), fuels used for heating (17%) and electricity used for manure pumping and stirring (10%); for poultry production, its heating (92%), ventilation (5%) and lighting (3%); for dairy, around a third is diesel use associated with manure management, while two third is electricity for milk cooling (36%), milk harvesting (32%), water heating (23%) and water pumping (9%).

For greenhouses, energy inputs vary considerably between advanced high-energy intensity greenhouses and basic low-energy intensity greenhouses. Our research suggests that high-energy intensity greenhouses are more dominant in Northern and Central Europe and low energy intensity greenhouses more dominant in Southern Europe, though certain areas in Southern Europe have high concentrations of energy-intensive greenhouses. In high yielding and high-energy intensive greenhouses energy use is dominated by heating and cooling with other inputs accounting for a minor amount of energy use. In contrast, lower yielding and less energy-intensive systems use little to no heating/cooling and instead energy use is mainly split between fertilizers, diesel use for machinery, and electricity for irrigation, lighting and other activities.

Over the past decades, energy use in European agricultural systems has evolved, and in recent years there is an increasing shift towards more sustainable systems, which impacts the energy concentrations in agricultural systems. Nevertheless, all production systems are still highly dependent on fossil fuels; direct fossil fuel use is mainly associated with diesel use for machinery (e.g. tractors, generators) or heating fuels. In the long run, alternatives to these fossil fuels, more efficient use of these machinery within agricultural operations and processes and increased use of renewable energy sources, can reduce this dependence. Furthermore, although a large share of electricity use in EU agriculture (generally associated with irrigation, storage, drying, livestock housing and greenhouses) still depends on fossil fuels, the production of electricity in the EU is currently experiencing a shift towards renewable sources which will have implication for long term energy use.

The adoption of agricultural practices (such as conservation agriculture) that have been proven to reduce energy use through minimizing fuel consumption and inputs and sequester carbon into the soil will also have large implications on energy use and the carbon emissions associated with agriculture. To illustrate this, this report includes a section on the potential of conservation agriculture in the EU, it has been estimated that the practice of Conservation Agriculture, at EU level (covering one-third of the current utilized agricultural area), would store around 190 million tons of CO₂ which would account for over 22% of the EU commitments in non-ETS GHG reduction by 2030 (González-Sánchez et al. 2017). Sustainable mechanization through Conservation Agriculture systems reduces the need for fossil energy and balances carbon emissions, thanks to the high capacity of carbon sequestration in the soil.

The study identifies a number of areas for further research. Further research is required into the relationship between energy intensity and the size of farms as there appears to be a rough positive correlation. The study also highlights that significant data gaps in the energy use status for certain crops and agricultural systems on a European level exist, these gaps are identified as areas for further research.

1. Introduction

1.1 Context

Energy use in the global and European agriculture sector is dominated by energy produced from fossil fuels. Multiple studies have developed data on energy use in agriculture in the EU, but a clear overview and agreement of all energy use in the EU agricultural sector does not exist, while existing data is fragmented due to various reasons. Eurostat estimates that 3.2% of the total energy consumed in the EU is used in the agriculture and forestry sectors, however this figure only accounts for direct energy uses, as a consequence, energy use in EU agriculture is underreported (de Visser et al. 2012). In addition, there is no apparent extensive breakdown of how this energy use is assigned within agricultural systems (Eurostat 2020a).

Simultaneously, the agricultural sector is a major emitter of GHG emissions. The EU's Farm to Fork Strategy highlights that agriculture accounts for 10.3% of the EU's greenhouse gas emissions, with the livestock sector alone accounting for around 70% of all GHG emissions related to agriculture (European Commission 2020b). It is important to note that if the emissions of additional activities associated with the food system, such as post-harvest activities as well as the production of fertilizers and pesticides that are used in agriculture, are included the total amount of GHG emissions would be significantly higher. A clear positive correlation between energy use and greenhouse gas emissions currently exists, one of the main reasons is the dependence on fossil fuels. This suggests that a reduction in fossil energy use would also decrease greenhouse gas emissions and that a shift towards renewable sources can decouple energy use from GHGs. Moreover, the dependence of the agricultural sector on fossil fuels also places an array of additional burdens on the environment, including a loss of biodiversity, soil depletion and the pollution of natural ecosystems (Gomiero, Paoletti, and Pimentel 2008) (Pfeiffer 2006).

With the launch of the Green Deal the EU aims to be climate neutral by 2050 and the EU's farm to fork strategy calls for a sustainable agriculture sector, requiring a major shift away from fossil fuels. More specifically, through the 2030 Climate and Energy Framework, the European Union has set targets and policy objectives for the period 2021-2030. In this Framework, it is proposed that GHG emissions should be reduced by at least 40% (from 1990 levels), the share for renewable energy should be at least 32% and that there should also be an energy efficiency improvement by 32.5% (European Council 2014).

In this context, this study provides an overview of the current energy use status within EU agriculture identifying in which sectors and activities energy use is concentrated and the main activities and uses to which this energy is attributed. Such a study is particularly relevant as it allows stakeholders and policymakers to use our findings to design and implement fossil-energy-free strategies and technologies (FEFTS) supporting the energy transition and the EU energy targets for 2030 and beyond. One of the most promising techniques, identified by numerous previous studies (González-Sánchez et al. 2017) (Lal 2004b), for reducing energy use and carbon emissions associated with agriculture and supporting carbon sequestration is conservation agriculture. To illustrate and discuss the workings and potential of such a technology, if scaled, to reach EU climate goals a section of this report is devoted to providing an overview of conservation agriculture.

The report is structured as follows: the rest of section one will provide a general literature review on energy use in agriculture; section two lays out the methodological and conceptual framework of the study; section three provides an overview of energy use in EU agriculture, sections four, five and six

provides an overview of energy use in EU open-field agriculture, greenhouses and the livestock sector respectively; section seven provides an analysis and discussion of our findings, section eight provides an overview of conservation agriculture and to what extent if implemented can reduce energy use and carbon emissions in EU agriculture.

1.2 Literature Review

EUROSTAT publishes data annually on direct energy consumption within the EU based on the ‘agri-environmental indicator on energy use’, these publications include data on the various energy carriers and information on how energy use in agriculture is changing over time within the EU and per Member State (Eurostat 2020b). In addition, Member States and different stakeholders also produce national data on energy use within national systems. The focus of this European and national data, however, is on direct on-farm energy uses and inputs, includes data from the forestry and fishery sectors and does not include data on indirect energy inputs. Several studies have highlighted the importance of including both direct and indirect energy inputs in order to provide a more comprehensive picture on actual energy use in agriculture. Indeed, when indirect energy uses are included, the estimated proportion of energy use in agriculture goes up significantly. For instance, Beckman et al.’s (2013) study on energy consumption in US agriculture estimates that direct energy use accounted for 63% of total energy consumption and indirect energy consumption for 37% (Beckman, Borchers, and Jones 2013).

On an EU level, a limited number of studies combine data from both direct and indirect sources on energy use in the EU. These studies provide a wealth of useful data but are limited to specific geographical areas or specific crops. The ‘State of the Art on Energy Efficiency in Agriculture’, using an LCA-like approach estimates both direct and indirect energy use in agriculture in different sectors in 6 European countries (de Visser et al. 2012). Monforti-Ferrario et al. (2015) provides an overview of energy flows within the entire EU food sector relying mainly on direct energy data from EUROSTAT and a limited number of LCAs (Monforti-Ferrario et al. 2015). Martinho (2016) investigates energy consumption across farms in 12 European countries (Martinho 2016). Kyriakarakos et al. (2020) provide an overview of the current energy status within EU agriculture and discuss strategies and possibilities of reducing fossil energy use (Kyriakarakos et al. 2020). Rega et al. (2020) investigate the spatial energy intensity of EU agriculture (Rega et al. 2020).

By contrast, a large range of studies have been conducted that focus on energy use within specific agricultural sectors and on specific crops at local, national, and regional levels. Regarding the greenhouse sector, Campiotti et al. (2012) investigate some of the energy parameters in the greenhouse sector in 4 European countries (Campiotti C et al. 2012). Mohamed et al. (2017) investigate the energy profile of greenhouses in Cyprus (Mohamed et al. 2017), while Wageningen University releases an annual report monitoring energy use within the Dutch greenhouse sector (van der Velden and Smit 2019). Similarly, for the livestock sector, Veermäe et al. (2012) provides an overview of energy consumption in animal production (Veermäe et al. 2012), and Markou et al. (2017) conduct an energy profile of the Cypriot livestock sector (Markou et al. 2017). This illustrates that there is no comprehensive overview of energy use amongst EU agricultural systems.

A multitude of studies exist that consider energy use for different crops and production systems through Life Cycle Assessments (LCAs). These studies, though fragmented, provide detailed information on a wide variety of energy inputs as well as the different energy carriers used within the agricultural sector. The findings in these studies are published individually but also collated and reviewed. For instance, Pimentel’s (1978) Handbook of Energy Utilization in Agriculture provides a

detailed overview of energy use for the production of a range of agricultural inputs and crops. A number of studies conduct meta-analyses combining results from a range of studies on specific crops in the EU. For instance, Achten & van Acker (2015) compile data from a range of studies on energy consumption in the EU wheat sector (Achten and Van Acker 2016a). Similarly, the Farm Energy Analysis Tool (FEAT) provides a framework for users to calculate energy use and GHG emissions within various agricultural systems (Camargo, Ryan, and Richard 2013).

Studies that focus on the energy used in the production of indirect agricultural inputs have also been conducted. Aguilera et al.'s (2015) paper on the embodied energy in agricultural inputs provides a detailed overview of the findings of a multitude of studies (Aguilera et al. 2015). While a number of studies investigate the energy use required in different fertilizer production processes (Bhat et al. 1994) (Gellings and Parmenter 2004) (Dimitrijević et al. 2020), results presented in these findings vary depending on fertilizer type and origin. In addition, Fertilizer Europe has conducted a number of studies that investigate the relationship between energy and fertilizer production and use (Fertilizers Europe 2014). Similarly, there are numerous publications that focus on the production and use of animal feed, again data is fragmented due to different methodologies and large variations in animal feed composition and geographic origin (Pimentel 1980) (Woods et al. 2010) (Veermäe et al. 2012).

By contrast, only a few studies have compiled data on energy use attributed to pesticides, most existing studies rely heavily on Green's (1987) analysis on energy in pesticide manufacture, distribution and use (Green 1987). Building on Green's work, Audsley et al. (2009) and Bhat et al. (1994) provide a detailed overview of energy consumption within pesticide production and inputs for different crops (Audsley et al. 2009) (Bhat et al. 1994). Similarly, few studies have been conducted that look at the energy profile of the production of seeding materials –such as Pimental's 1978 review of four methods (Pimentel 1980)– and that of off-farm irrigation. A range of studies investigate ways to reduce the agricultural sector's dependence on fossil fuels, both sector-wide and for specific crops. These suggested ways include changing agricultural practices (Alluvione et al. 2011) (Gomiero, Paoletti, and Pimentel 2008) (Balafoutis et al. 2017), increasing renewable energy use, adoption of energy efficient and alternative strategies and technologies (Zhang et al. 2020) (Ahamed, Guo, and Tanino 2019) (Woods et al. 2010) (Monforti-Ferrario et al. 2015), optimal energy management strategies (Monforti et al. 2015). In particular, many studies highlight the potential of using agricultural feedstocks for the use of renewable energy and the production of advanced fuels from a range of feedstocks. Due to the inherent complexity of the EUs agricultural system, it is clear that any approach to reduce reliance on fossil energy will require an extensive array of technological and policy-oriented interventions across the agricultural value chain. This requires an in-depth understanding of energy use and a comprehensive map of where it is concentrated, highlighting the importance and relevance of this study.

2. Methodology / Materials and Methods

2.1 Defining Energy Use in Agriculture

This study uses an operational definition of energy use in agriculture and attempts to include all operational energy use that is covered by agricultural activities and uses, both directly and indirectly. This definition is informed by a range of sources that have previously investigated energy use in agriculture and defines the direct and indirect energy inputs/uses and the activities that fall under these operational categories (Pimentel 1980)(Stout 1990). Conversely, energy use that is related to the creation of agricultural infrastructure, such as energy used in the production of agricultural machinery and agricultural buildings, is not included in our definition. This is because there are significant issues with measuring agricultural infrastructure use accurately and, in most cases, energy use is assigned to sectors other than agriculture. In addition, energy consumption for these categories is relatively minor when taking into account energy use across the agricultural sector. Our approach for defining indirect energy use is in line with approaches adopted by other studies (de Visser et al. 2012). Several previous studies include energy use in the forestry and aquaculture sectors in their definition of agriculture, which our study does not include.

The system boundary of this study is cradle to farm-gate and includes all energy consumption up until the farm gate. Direct energy use refers to all energy inputs used directly in the agricultural production process; activities occurring on farm and up to the farm gate (Kyriakarakos et al. 2020). This generally includes energy consumed for: on farm operations, transportation, heating and cooling, lighting, electrical equipment, machinery, automation processes, farm management and irrigation. While the main direct energy uses vary depending on the production system, in this study it is allocated according to three sectors: open-field agriculture, livestock and greenhouses, as discussed in the conceptual framework. The main energy uses that the study will focus on for each category are:

Open-field agriculture:

- On farm operations (sowing, planting, tillage, application of inputs, harvesting)
- Machinery use
- Irrigation
- On farm post-harvest operations (threshing, storage, grain drying)

Livestock:

- On farm operations, crop processing and feeding, milking processes (milking and milk cooling) manure handling
- Animal housing (heating, cooling, dehumidifying and ventilation)
- Machinery use
- Water heating and pumping
- Lighting

Greenhouses:

- On farm operations
- Heating and cooling
- Lighting
- Irrigation

There are a number of operational agricultural activities in which energy consumption is low and difficult to measure, such as the maintenance of machinery, and therefore these activities will not be included in our definition. It is also important to note that human labour associated with agriculture is not included in our definition. This is in line with other studies due to the difficulties associated with measuring and quantifying energy values for different agricultural tasks (Pimentel 1980).

Indirect energy use refers to all the energy used for the production of agricultural inputs. These inputs account for energy use that can be assigned to the agricultural sector but prior to reaching farms, including energy used in the:

- production of fertilizers (raw materials, manufacturing, transport)
- production of pesticides (raw materials, manufacturing, transport)
- production of animal feed (includes all the energy use to produce animal feed, including its raw materials)¹
- pumping of water to the agricultural holding
- production, storage and transportation of seeding materials

2.2 Energy Carriers and Units

Throughout this study, the different energy carriers used across agricultural sectors are highlighted. The main energy carriers are listed below and, where applicable and available, our analysis discusses which proportions of energy carriers are used within each category of energy use (de Visser et al. 2012):

- Electricity (kWh per unit converted into MJ/GJ per unit)
- Refined petroleum fuels (L per unit converted into MJ /GJ per unit)
 - Diesel
 - Gasoline
 - Propane
 - Liquid petroleum
 - LPG
- Natural Gas
- Solid fuels (including biomass fuels such as wood chips)
- Coal
- RES
 - Solar thermal – Photovoltaic (PV)
 - Biomass
 - Wind
 - Geothermal
 - HydroelectricMarine (Wave and tidal energy)
 - Hydrogen
 - Biofuels

¹ It is important to note that this includes the energy used for the production of crops, both from within and outside the EU, that are used in the production of animal feed. For this reason, the energy use between open-field and livestock systems are separated in this study, and discussed separately, as combining the two would lead to the double-counting of certain energy inputs (once in the production of crops and again as the use as animal feed).

2.3 Conceptual Framework

It is well documented that productivity and energy use in EU agriculture varies significantly depending on various farm characteristics, including farm type and size, geographical location, high input or low input, etc. To provide a reliable and detailed overview of energy use in agriculture, this study conceptually divides agriculture into several categories and sub-categories and investigates energy use in each category and sub-category. Agriculture is divided into three main categories: open-field agriculture, livestock and greenhouses. Each category, except for greenhouses, is further split into sub-categories (Figure 2). Open-field agriculture is split into arable agriculture, orchards and vineyards. Livestock is split into different categories of livestock, namely: cows, pigs, poultry and sheep and goat. The particular choice of these categories and sub-categories allows for an effective analysis of the locations and concentrations of energy use, both direct and indirect, within the agricultural system. Throughout our analysis, other references to specific crops, geographic locations and farm types are also included where appropriate.

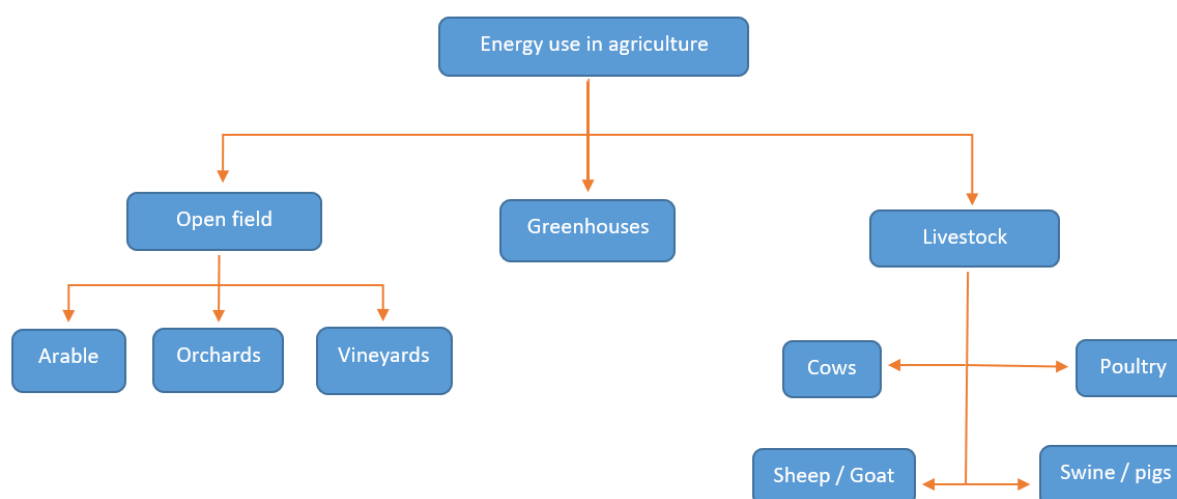


Figure 2. Conceptual Framework

2.4 Estimating energy use

Due to the scale of this study, multiple methodologies are adopted to calculate and illustrate energy use in EU agriculture. Section 3 provides an overview of direct and indirect energy use in EU agriculture as a whole. Data on direct energy use is mainly drawn from Eurostat and national surveys. On the other hand, aggregate figures on indirect energy are calculated by multiplying EU consumption levels of each input drawn from EUROSTAT and national surveys to the energy embodied in each agricultural input presented in the literature and databases.

A meta-analysis, which combines the results from multiple scientific studies, is used to estimate energy use in open-field and livestock systems. Data is presented in a variety of ways depending on the agricultural system but is generally depicted according to the following categories: seed, fertilizers, pesticides, diesel use and other. Data is drawn mostly from LCAs, reports and data provided to us by AFF partners. Depending on the specific crop/livestock system, results are combined which allows us to calculate EU averages in terms of energy per category as well as total energy use per system. We also attempt to provide direct energy use breakdowns per crop, based

on proportions and percentages found in other studies, taken directly from relevant LCAs. This method provides us with estimates of the total amount of energy use per crop and livestock system in EU agriculture as well as of the total amount of direct energy use for each category and sub-category as well as energy use per activity.

For greenhouses, energy use is presented per country and for the three main cultivated crops: tomatoes, cucumber and peppers. This approach was chosen as there is relatively little accurate data available on energy use in greenhouses in the EU as a whole, while there is considerable information available on greenhouses for some countries and variations in energy use between countries. The countries covered are the Netherlands, Spain, Greece, Germany, Italy, Denmark and Ireland.

2.5 Data Sources and Limitations

Data is drawn from a variety of sources including databases, journals and scientific articles, lifecycle assessments, legal agreements and information shared by AFF partners. As existing data on energy use is often fragmented in terms of the type of data and the manner it is presented, this study combines and attempts to unify data from these different sources allowing for an analysis of energy use in EU agriculture as a whole. It is important to note that most data presented are estimates and as such are indicative.

The data used and presented is predominantly focused on the main and conventional agricultural systems that make up most of the agriculture in the EU. Other minor and non-conventional systems, such as organic, hydroponic, aquaculture, permaculture, are not focused on, but are discussed where applicable, as they constitute a relatively small percentage of agriculture in the EU and there is limited accurate data available which would allow for accurate estimations. By doing so, the energy use of some and alternative parts of the EU agricultural system is not accounted for. For instance, the report does include some data on energy use in EU organic European systems, which accounts for 8.5% of the EU UAA (Eurostat 2020h), but this data is not used in our overall energy use estimates due to a lack of data. Similarly, hydroponic and permaculture systems, while interesting agricultural strategies for reducing energy use, are currently practiced on such as small scale that there is not enough reliable data available to be included in energy use overall.

Within the existing literature, energy is mainly presented either as energy used per hectare or energy used per agricultural output. Energy use per hectare is generally used within studies that focus on land use and perennial agriculture, while energy use per output focuses on the production function and activities associated with agriculture (Haas, Wetterich, and Geier 2000). In this study both forms are present where applicable, however, in general energy use per hectare is used for arable crops and energy use per output is used for livestock systems. In some instances, data in both forms is complimentary and highlighted. Similarly, existing studies use a range of energy units to quantify energy use in agriculture, including joules, TOE, calories, etc. In this study, we converted energy units into joules and calculated proportions of energy use per input.

It is important to note that in multiple cases, significant variability exists on energy use in agriculture between different studies. Where applicable, these differences are discussed and data from the most reliable sources are used. In addition, some LCAs have different system boundaries; some look at the agricultural production, while others go further to include post-harvest processing and retail.

Our analysis is limited to the farm level and ends at the farm gate, but included indirect energy uses, and data from post-harvesting processing and retail are not included. In addition, there are numerous ways in which energy use is defined across studies and between LCAs and different approaches are taken in measuring and aggregating energy uses. For instance, some studies combine energy on transportation and farm machinery use, while others separate and measure them as distinct activities. For this study, these activities are specified where possible.

3. Energy use in EU Agriculture

3.1 General overview

According to Eurostat, in 2016, there were 10.5 million agricultural holdings in the EU and over 173 million hectares of land were used for agricultural production. This represents about 39% of the EU's total land area. These farms vary significantly in size, topography, crop type, management structure and soil type. While most agricultural land is concentrated in larger farms, most agricultural holdings are small farms of less than 5 hectares each. For instance, farms larger than 100 hectares account for only 3.3% of total agricultural holdings, but for 52.7% of utilized agricultural area, (UAA) (Figure 3) (Eurostat 2018a). On a country level, most agricultural holdings are located in Romania, accounting for around one third of EU's total agricultural holdings (32.7%), of which 91.8% are smaller than 5 hectares. This is followed by Poland (13.5%), Italy (10.9%) and Spain (9%). Larger farms (50 hectares or more) constitute a majority of farms in Luxembourg (51.8%), France (41.3%) and Denmark (35.3%). By contrast, all other Member States have mostly small farms (less than 5 hectares); the countries with the highest number of small farms are Malta (96.5%), Cyprus (89.6%), Bulgaria (82.6%), Hungary (81.4%), Greece (77.3%), Portugal (71.5%) and Croatia (69.5%) (Eurostat 2018b).

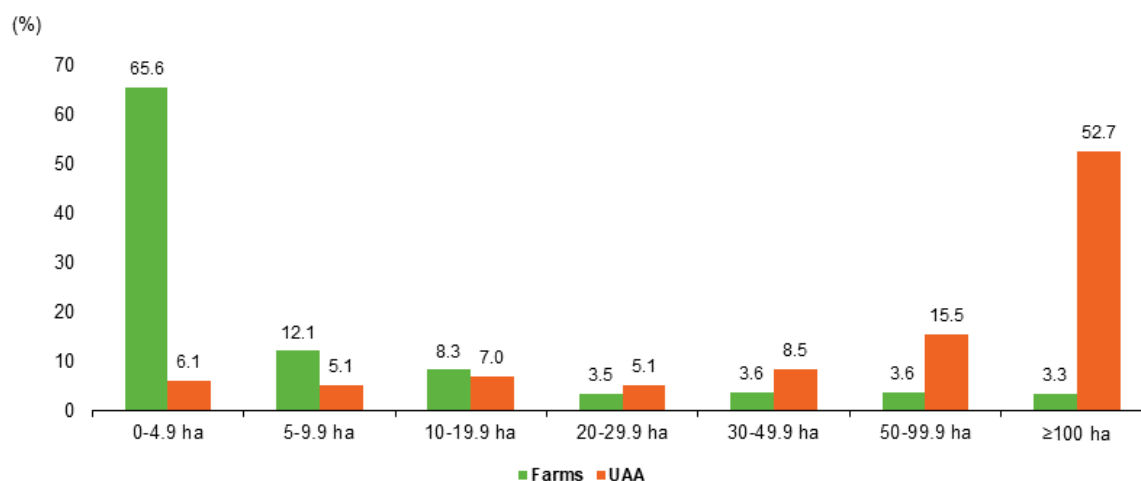


Figure 3. Distribution of EU farms and utilized agricultural area according to farm size, 2016 (source: Eurostat (Eurostat 2018b))

Accordingly, there exists significant variation across EU farms in terms of crop specialization, topographical constraints and cultivation techniques (Eurostat 2018a). EU farms can be categorized into three main groups based on the type of farming operations/ farm types: open-field agriculture, greenhouse installations and livestock production. In 2016, more than half of all farms in the EU (52.5%) were categorized as specialized in crop production, while livestock farms constituted just over one quarter (25.1%), 21.1% were categorized as mixed farms and 1.3% were not classified (Figure 4) (Eurostat 2019b).

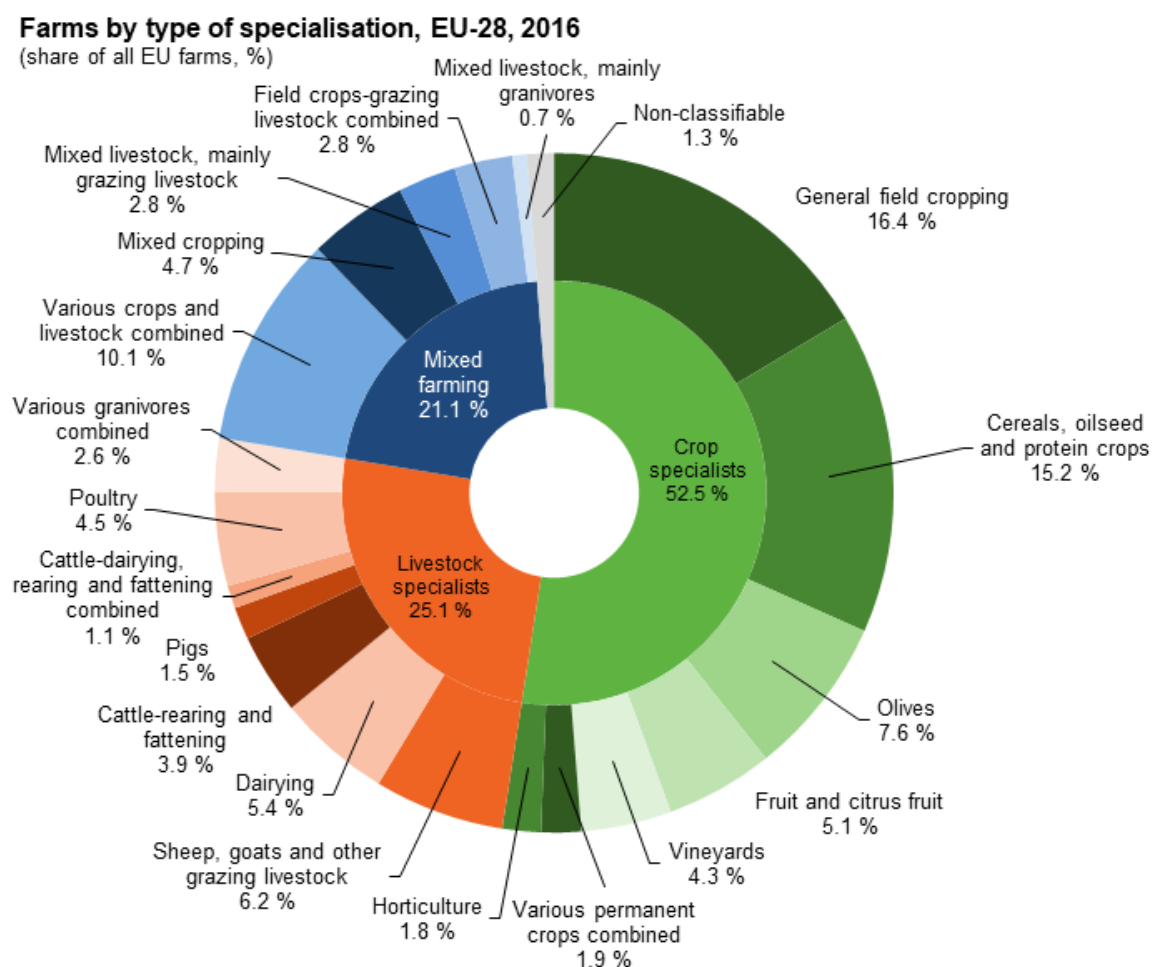


Figure 4. Farms by type of specialization, EU-28 (Eurostat 2019b)

3.2 Direct Energy Use

According to Eurostat, direct energy consumption in the agriculture and forestry sector made up 3.2% of the total energy consumption in 2018. The share of agriculture in final energy consumption was highest in the Netherlands (8.1 %) and Poland (5.6 %) and lowest in Malta and Luxembourg (see Figure 5). Between 1998-2018, energy consumption in agriculture decreased by 10.8% to 24 million TOE (see Figure 6) while agricultural output in terms of volume (growing by around 10% over the past decade) and agricultural labour productivity have shown steady increases (Eurostat 2020j). This transformation (reduced energy use with growth in production and productivity improvements) is supported by a number of trends including improvements in the efficiency of the use of agricultural machinery within the operations and processes, minor improvements in resource efficiency and reductions in fertilizer use in the 1990's and 2000's (European Commission 2019).

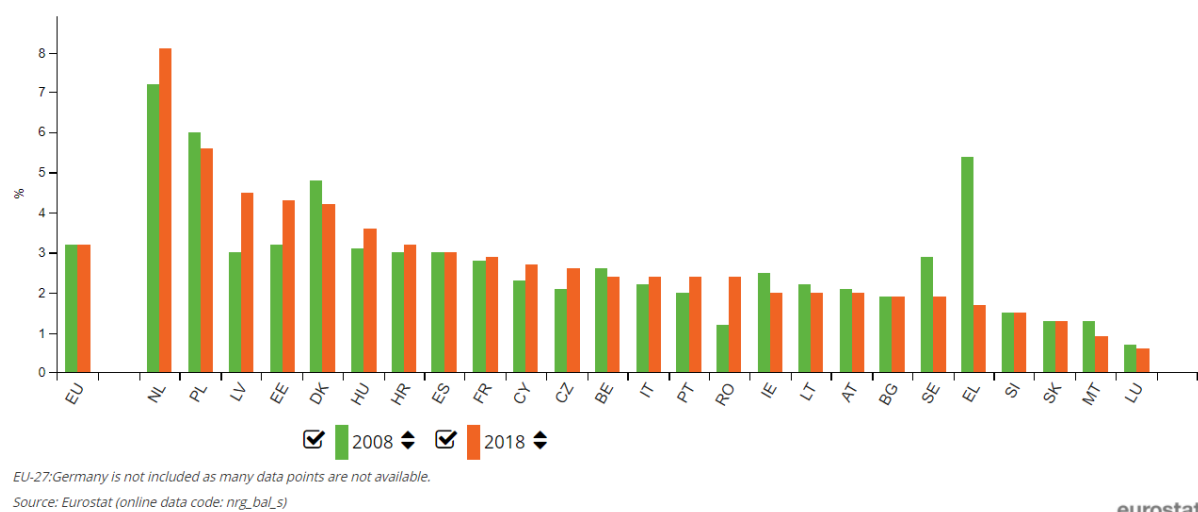


Figure 5. Share of energy consumption by agriculture in final energy consumption, EU-27, 2008 and 2018 (Eurostat 2020b)

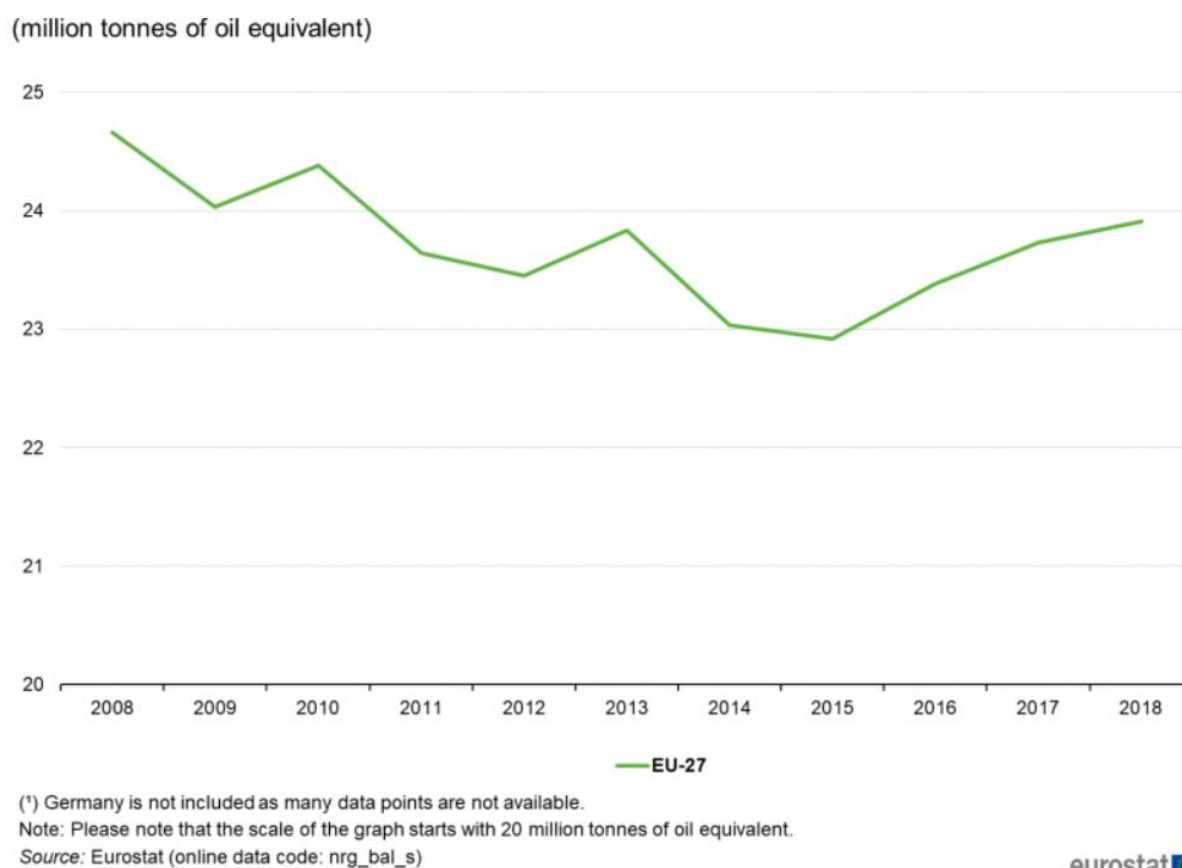


Figure 6. Energy consumption in agriculture, EU-27, years 2008-2018, (million tonnes of oil equivalent) (Eurostat 2020b)

Figure 7 illustrates the share of energy carriers used in on-farm EU agriculture. Overall, 56% of the total direct energy consumption in agriculture is derived from crude oil and petroleum products and is the dominant fuel in the agriculture sector in the majority of EU countries, electricity accounts for 17% of direct energy inputs, 14% from gas and 9% from renewables and biofuels. In the Netherlands,

natural gas was the main energy carrier while in Greece it was electricity (Eurostat 2020b). This anomaly for Greece, can to a certain extent be explained by the effects of the Greek economic crisis whereby petroleum prices increased disproportionately as compared to other EU countries. As such, the price Greek farmers paid for petroleum products increased significantly even though they consumed significantly smaller amounts of energy than before. According to the Hellenic Statistical Authority (ELSTAT) the energy input price index in agriculture went from 77.9 in 2007 to 106.8 in 2017 (ELSTAT 2021). In addition to this, the excise tax on the consumption of agricultural oil was abolished in 2016, resulting in farmers turning to other forms of energy and especially electricity, as it is a cheaper fuel type due to the dependency on lignite production (Labrou 2017; Giannakopoulou 2013). It should be noted that during that period a reduction in the energy consumption occurred for all fuel types (Labrou 2017).

Our research from the open-field and livestock sectors indicate that crude oil and petroleum products mainly come in the form of diesel for tillage, harvesting and sowing operations in open-field agriculture and manure management in livestock systems. Similarly, electricity use, depending on the crop and location, is mainly associated with irrigation, storage and drying in open-field systems and housing and feeding in livestock systems, though significant variations are observed between countries and crops.

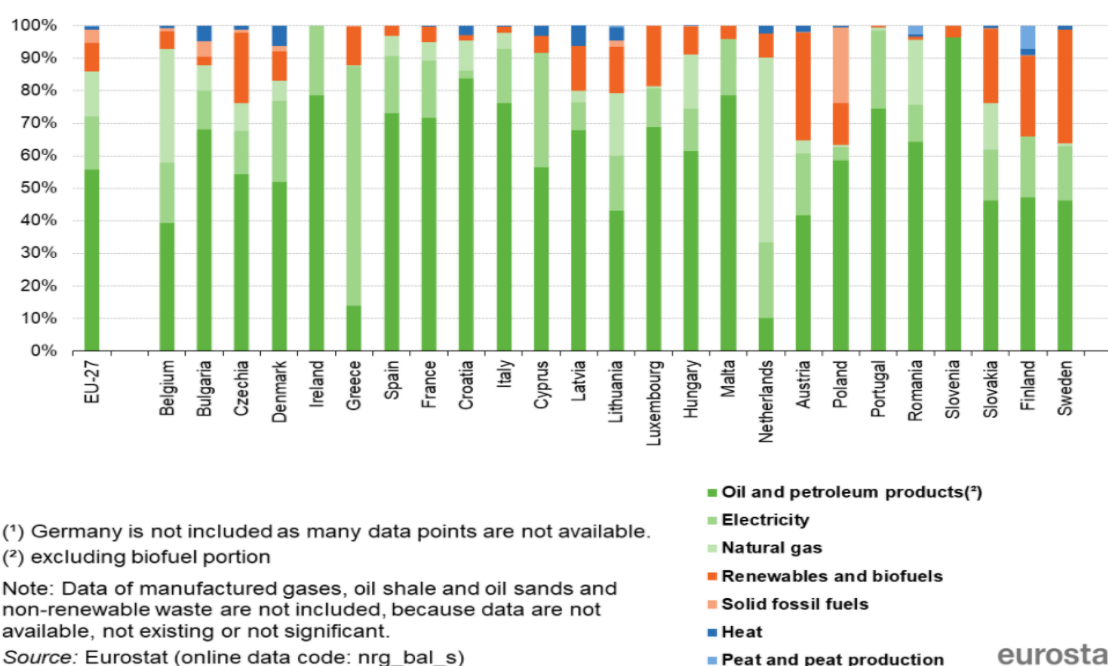


Figure 7. Share of fuel type in energy consumption by agriculture EU27 (Eurostat 2020b)

Figure 8 illustrates that the sources of energy used in EU agriculture are changing gradually, with the share of energy coming from renewables and biofuels increasing from 4% to 9% between 1998 and 2018 and the share of energy from other non-renewable sources decreasing. Figure 8 also illustrates that this transition is occurring at a relatively slow pace, as direct energy use in agriculture is still dominated by crude oil and petroleum products and other fossil fuels; the proportion of oil and petroleum decreased from 61% to 56% and natural gas to 14% in 2018. It is important to note that this data does not include data from Germany, it is likely that if data from Germany was included the rate of transition would appear greater due to its relative speed in the energy transition, especially its dominance in biogas production (Thrän et al. 2020).

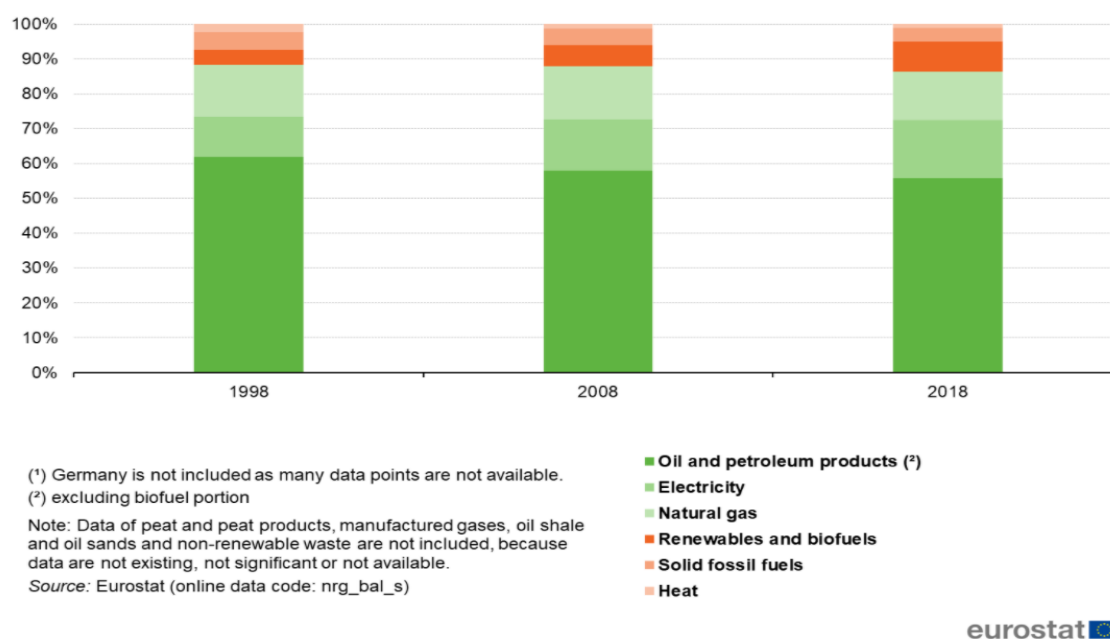


Figure 8. Share of fuel type in energy consumption by agriculture EU-27 1998 2008 2018 (Eurostat 2020b)

Figure 9 shows energy consumption per hectare of utilized agricultural area per country while figure 10 indicates average farm size per region. These two figures indicate a rough, though not universal, correlation between smaller farm size and less intense agricultural energy use, for instance, Lithuania, Bulgaria and Romania, Greece which are dominated by small farms also consume the least energy per UAA. By contrast, countries in northern and Western Europe which have larger farm sizes are more energy intensive.

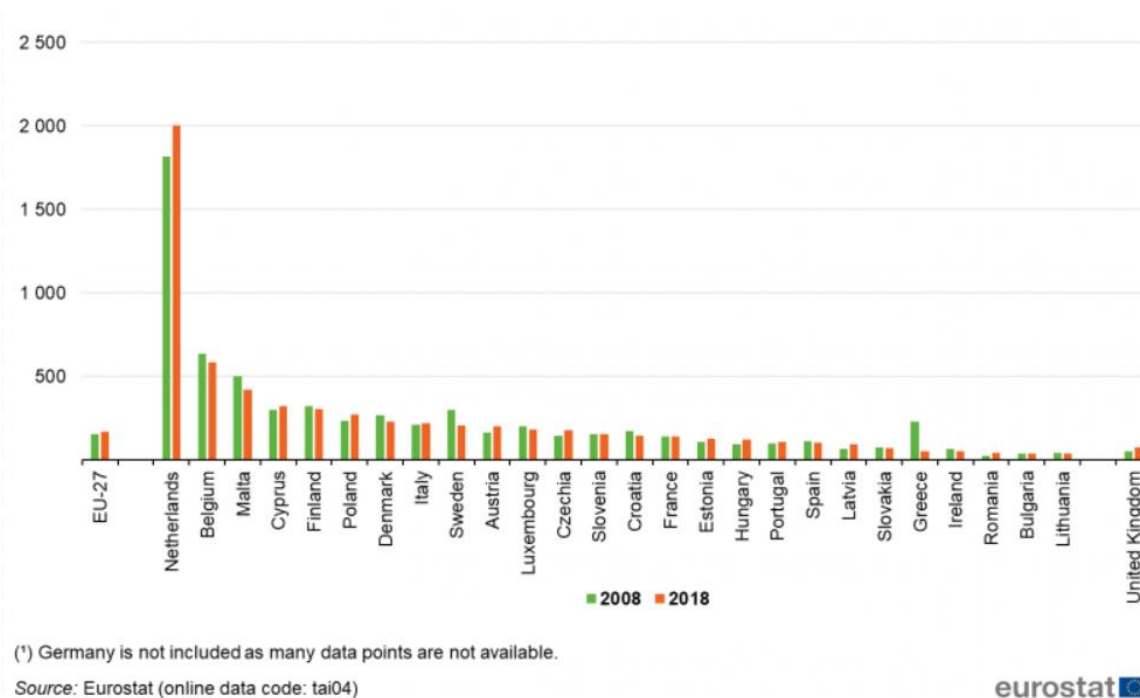


Figure 9. Energy consumption by agriculture EU-27 TOE per hectare UAA (Eurostat 2020b)

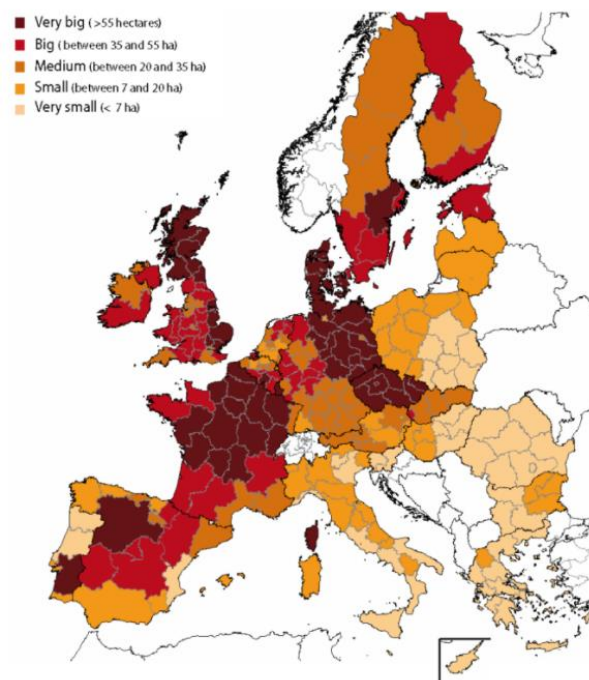


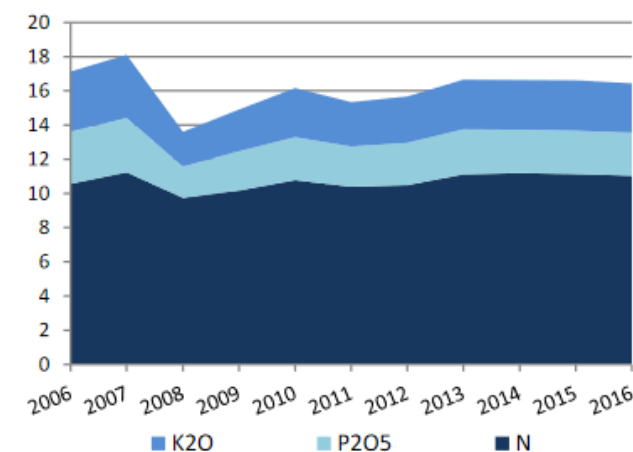
Figure 10. Average farm size by region (EPRS 2013)

3.3 Indirect Energy Use

3.3.1 Fertilizers

3.3.1.1 Overview of fertilizers use in the EU

The EU agricultural sector is fertilizer intensive, using large amounts of organic and manufactured (synthetic/chemical) fertilizers annually. Figure 11 shows that around 10 million tonnes of manufactured nitrogen fertilizer, 2.6 million tonnes of manufactured phosphate fertilizer and 2.1 million tonnes of manufactured potash fertilizer are consumed in the EU annually (Eurostat 2020i).



Source: DG AGRI, based on Eurostat

Figure 11. Consumption estimates of manufactured fertilizers in the EU (million tonnes) (European Commission 2019)

The intensity of fertilizer consumption varies across countries, ranging from 21.8 kg/ha in Portugal to 136 kg/ha in the Netherlands for nitrogen-based fertilizers, 5.2 kg/ha in Denmark to 13 kg/ha in

Poland for phosphorus based fertilizers, and 7.6 kg/ha in Portugal to 28.8 kg/ha in Poland for potassium fertilizers (F. Baptista et al. 2013). Overall, the EU is a net importer of fertilizers with the number of imports increasing in recent years, even though fertilizer use has decreased slightly over the past two decades.

3.3.1.2 Energy use in Fertilizers

We estimate the energy embedded in the sale of nitrogen, phosphate and potash fertilizers in the EU at 596 PJ, which is equivalent to around 52% of the current direct energy consumption in EU agriculture (see table 3) and 1.93% of total energy consumed in the EU. The energy embedded in nitrogen fertilizers is by far the largest of the three main mineral fertilizers, which is equivalent to 48% of the current direct energy consumption in EU agriculture. These findings are roughly in line with the findings of other studies that suggest that fertilizer production and transport account for around 50% of total energy inputs in agricultural systems. In addition, the IFA has found that globally, fertilizer production accounts for 1.2% of final energy consumption (Kyriakarakos et al. 2020) and according to Ramirez & Worrell (2006), over 1% of global energy use is for fertilizer production (Ramírez and Worrell 2006). Data on the annual sales of fertilizer² is taken from EUROSTAT and is referenced against the average energy consumption value per fertilizer presented in the FEATs model (Eurostat 2020i) (Camargo, Ryan, and Richard 2013).

Table 3. Energy embedded in the production of fertilizers consumed in the EU

Type of Fertilizer	Amount sold in the EU (million tonnes) (Eurostat)	Energy Consumed in Production (MJ/kg) (FEAT Model)	Total Energy (PJ)	% of direct energy consumption in agriculture
Nitrogen	10.04	54.8	550	48%
Phosphate	2.55	10.3	26	2%
Potash	2.85	7.0	20	2%
Total			596	52%

Table 4 provides an overview of the proportion of energy used in production, packaging, transportation and application of manufactured fertilizers. This data illustrates that for all three types of fertilizers most of the energy is embedded in the production stage, accounting for around 90% for nitrogen fertilizers and 45% for phosphate and potash. All the stages prior to reaching the farm combined account for over 90% of total energy inputs of fertilizers. By contrast, the on-farm field application stage accounts for relatively little energy (Woods et al. 2010).

Table 4. Energy proportions in the production, transport and use of fertilizers (Gellings and Parmenter 2004)(Fertilizers Europe 2014)

Source	Type of fertilizer	Production	Packaging	Transportation	Application
Fertilizers Europe	Nitrogen	91.0%		2.2%	6.8%
Gellings & Parmenter, 2004	Nitrogen	88.9%	3.3%	5.8%	2.0%
Gellings & Parmenter, 2004	Phosphate	44.0%	14.9%	32.6%	8.6%
Gellings & Parmenter, 2004	Potash	46.4%	13.0%	33.3%	7.2%

² EUROSTAT data on the sales of fertilizers is used instead of EUROSTAT data on consumption of fertilizers as the data in the former is more up to date and includes more detailed information on fertilizer use, the differences between the two sources are minor.

Overall, the production of nitrogen fertilizers is energy intensive and largely dependent on fossil energy; it is estimated that the production of 1 tonne of nitrogen fertilizer consumes 1-1.5 TOE (Fertilizers Europe 2014). In the EU, natural gas is the main feedstock and energy source for the production of manufactured nitrogen fertilizers (Woods et al. 2010). The proportions generally presented in the literature estimate that 60-80% of natural gas is used as feedstock while 20-40% for energy production, whereas the European Commission market brief states that roughly 65% is used as a feedstock and 35% for energy production. (Fertilizers Europe 2014). Similarly, the production of phosphate and potash fertilizers are also energy intensive and dependent on fossil energy. This is because the raw materials for phosphate and potash are mostly mined and imported from outside the EU (Gellings and Parmenter 2004).

3.3.2 Pesticides

Over the past decade, the sale of manufactured pesticides in the EU has remained stable at around 0.35 million tons per year (Eurostat 2021). Pesticides³ use can be split into a number of categories, including: fungicides and bactericides; herbicides, haulm destructors and moss killers; insecticides and acaricides, and; plant growth regulators.

Table 5 below provides an estimate on the energy required to produce the total amount of pesticides consumed in the EU agricultural sector annually. Our estimates find that the energy embedded in the sale of pesticides in the EU is equivalent to around 10% of the current direct energy consumption in agriculture in the EU. Data on the annual sales of pesticides is taken from Eurostat and is referenced against the average energy consumption value per pesticide presented in the FEATs model.

Table 5. Energy Use for the production of pesticides in the EU

Type of Pesticide	Sale of Pesticide in the EU (m tonnes)	Energy Consumed in Production (MJ/kg)	Total Energy (PJ)	% of direct energy consumption in agriculture
Fungicides and bactericides	0.16	376	61.81	5%
Herbicides, haulm destructors and moss killers	0.12	293	35.10	3%
Insecticides and acaricides	0.04	312	12.28	1%
Other plant protection products	0.02	NA		
Plant growth regulators	0.01	NA		
	0.35	Total	109.19	10%

The production of pesticides is extremely fossil intensive, mainly because petroleum products (oil and natural gas) are the main inputs in their production. The energy embedded in producing each pesticide is estimated at 215 MJ/kg for herbicides, 245 MJ/kg for insecticides and 356 MJ/kg for fungicides. Depending on the final pesticide form, it is estimated that manufacturing the pesticides consumes another 10-30 MJ/kg (Audsley et al. 2009).

3.3.3 Animal Feed

Within the EU, about a third of total animal feed is compound feed; other ingredients are forages (approximately 50%) and direct-fed raw materials (approximately 20%) [9]. According to the EU, 77% of total feed consumption in the EU is produced domestically and feed production accounts for

³ The sale of pesticides is used as an indicator of the amount of pesticides consumed in the EU. Direct data on the amount of pesticides consumed in the EU is not available.

around 60% of total wheat, maize and barley consumption in the EU and a significant share of feed also comes from pasture estimated at around 940 million tonnes (DG Agriculture and Rural Development 2020). Despite this, the EU livestock sector is dependent on imported protein sources for livestock feed. It is estimated that the EU has a deficit of about 70% high-protein materials of which 87% is met by imported soybean and soymeal [10]. The EU imports 18.5 million tonnes of soybean meal every year, of which 95% goes towards feeding animals (European Commission 2020a).

Our estimates, which are collated from our livestock analysis and depicted in table 6, indicate that the total energy embedded in animal feed for beef, pork, poultry and cow milk⁴ production is 828.69 PJ. Energy inputs in the production of animal feed are dominated by the production of fodder crops and the associated indirect energy inputs including fertilizers, pesticides, seeds and feed supplements [8]. Many existing studies provide figures on the energy use associated with the production of animal feed, these however, show significant variation depending on origin, raw material use and livestock system (Woods et al. 2010). The production, processing and transportation of these feeds require significant amount of energy inputs, which are mostly dependent on fossil sources, and represent a large proportion of the total energy consumed in livestock production. From the data covered in the livestock section of this report, the proportion of feed (concentrates, conserved forage or grazing) makes up more than 50%, and in many cases 75% or more, of the total energy consumption within livestock sectors.

Table 6. Total energy requirements for feed production and transport for selected livestock systems in the EU-27 (PJ)

Production System	Total energy embedded in feed and transport
Beef	82.90
Pork	199.58
Cow's milk	400.04
Poultry	146.18
Total	828.69

3.3.4 Pumping water to the agricultural holding

It is estimated that 40% of water abstraction in the EU is for agriculture (Rossi 2019). In most EU Member States, most of this is on farm groundwater and therefore its energy use would be included in current direct on farm statistics. However, in Italy, Cyprus, and Greece, water supply networks are the predominant source of water used in agriculture (Rossi 2019). This is important as, according to Eurostat, together these countries account for 81% of the total volume of water used for irrigation in EU (Figure 12) (Eurostat 2020f), and the energy used for supplying these farms with water would not be included in direct energy use statistics as the energy consumption happens off-farm. Overall, water supply networks are powered by electricity and it is estimated that they account for around 3.5% of total electricity consumption in the EU (IEA). This suggests that a significant amount of the electricity in these countries is consumed for providing water to agricultural holdings and is an important area for further research.

⁴ Other livestock categories were not included due to a lack of accurate data on feed consumption and composition for the EU as a whole

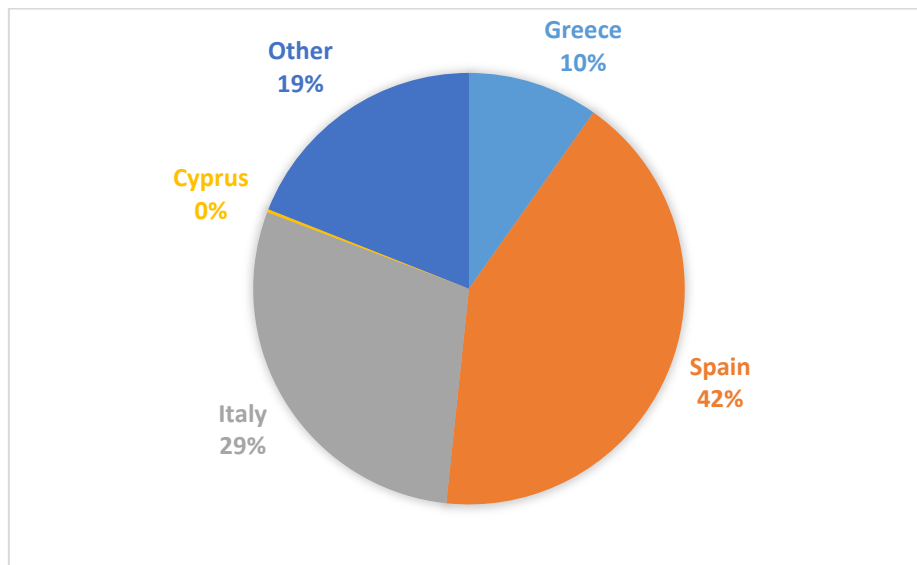


Figure 12. Breakdown of water use for irrigation in the EU -27 (Eurostat 2020f)

4. Energy use in open-field agriculture

Table 7 provides an overview of the total energy inputs for the open-field crops covered in this study in the EU-27. The three main cereals cultivated in the EU account for the majority of energy consumed in open-field agriculture. Despite the variation between crops, some generalizations in energy use are apparent across the entire open-field sector; our findings clearly illustrate that for all crops, except for sunflower and soya, fertilizer production and use is the largest energy consuming activity in EU agriculture accounting for around 50% of all energy inputs overall. This is followed by on-farm diesel use representing 31% of total energy inputs. The category other represents 8% of total energy inputs, which, depending on the production system, refers to on-farm irrigation, storage or drying and generally powered by electricity. Pesticides and seeds account for 5% and 6%, respectively, of total energy inputs.

Table 7. Total energy inputs for selected open-field crops EU-27 (PJ)

Crop	Seeds	Fertilizers	Pesticides	Diesel use	Other	Total
Wheat	18	251	21	138	7	434
Maize	14	217	14	94	40	379
Barley	38	61	0	51		150
Potatoes	7	15	3	12	13	49
Sugar beet	0	15	2	11		27
Rapeseed	0	50	4	30	7	91
Sunflower seed	1	30	3	35	9	78
Soybean	2	5	1	8	3	18
Apples		3	3	7	1	14
Citrus		10	3	9	5	26
Olives		46	13	24	30	113
Vineyards		14	11	24	2	50
EU Total	79	716	75	444	116	1431
EU Total %	6%	50%	5%	31%	8%	100%

Overall, on-farm operations are generally dominated by diesel use, which, depending on the production system, crop and geographical location, consists mainly of tillage, harvesting and sowing operations. Table 8 illustrates that for cereals and oilseeds, tillage operations account for the largest proportion of energy use. For cereals, harvesting operations are the next biggest consumer, followed by sowing, while for oilseeds sowing operations are the second most energy intensive activity followed by harvesting. Table 9 illustrates that in citrus and olive systems, except for traditional olive systems, harvesting is the most energy consuming on-farm activity, followed by irrigation, soil cultivation and pruning.

Table 8. % of energy inputs in selected arable crops according to on-farm operations (Achten and Van Acker 2016b; Felten et al. 2013; Venturi and Venturi 2003)

Source	Crop	Tillage	Harvest	Sowing	Fertilizer application	Pesticide application	Other
Achten & Acker, 2015	Wheat	43%	31%	12%	NA	NA	8%
Felten et al., 2013	Maize	57%	32%	9%	1%	1%	NA
Felten et al., 2013	Rapeseed	35%	23%	32%	2%	7%	NA
Venturi & Venturi, 2003	Sunflower	61%	14%	25%	NA	NA	NA
Venturi & Venturi, 2003	Soybean	61%	16%	23%	NA	NA	NA

Table 9. % of energy inputs in selected orchards according to on-farm operations (Pergola et al. 2013; Cappelletti et al. 2014)

Source	Crop	Soil Cultivation	Harvesting	Pruning	Irrigation
Pergola, et al., 2013	Oranges	9%	74%	2%	15%
Pergola, et al., 2013	Lemons	17%	63%	2%	18%
Cappelletti et al., 2014	Olives -Traditional	73%	0%	27%	0%
Cappelletti et al., 2014	Olives - Intensive	15%	17%	3%	65%
Cappelletti et al., 2014	Olives - Super intensive	12%	34%	2%	51%

4.1 Arable Crops

4.1.1 Cereals

This section provides data on the energy use for the three largest cereals (wheat, maize and barley) cultivated in the EU. The cultivation of oats and rye are also discussed in this section but due to a lack of EU wide data, they are not included in aggregate figures for the EU as a whole. In 2018, 295.1 million tonnes of cereals were produced in the EU, accounting for 11% of world cereal production. The leading producer was France, accounting for 62.6 million tonnes, followed by Germany with 38 million tonnes, Romania with 31.5 million tonnes and Poland with 26.8 million tonnes. The three main cereals produced in the EU are wheat (43.7%), maize (23.4%) and barley (19.2%). Other cereals, including rye and oats, make up relatively small percentages of the entire cereal harvest (see Figure 13). It is important to note that there is some notable variation in cereal production per year but that overall production has remained stable in the long run (Eurostat 2020c).

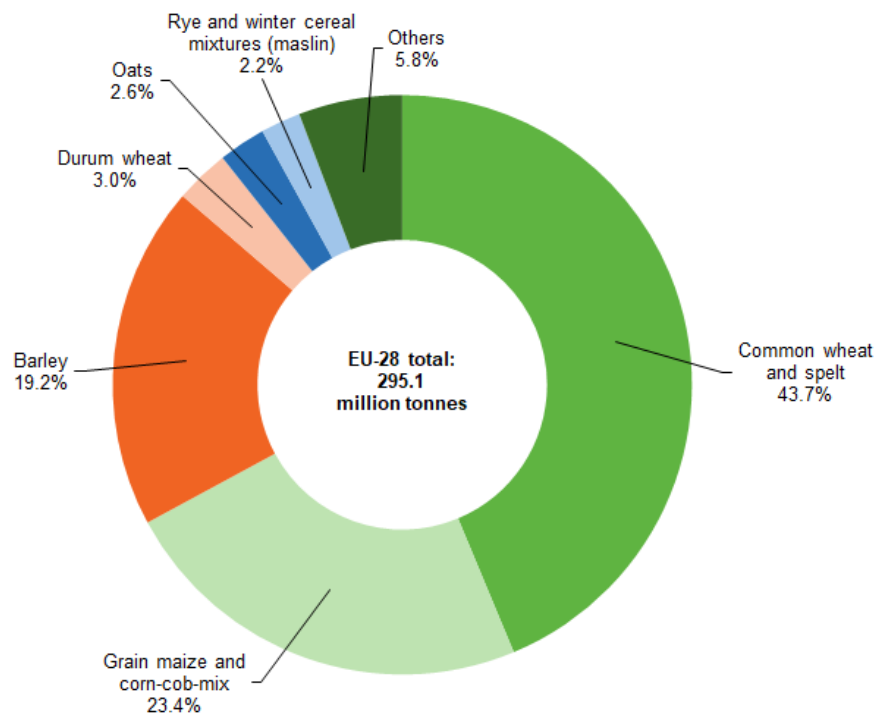


Figure 13. Share of main cereals in the EU, 2018 (Eurostat 2020c)

Figures 14 and 15 illustrate the energy inputs in the cereal sector in the EU as whole. Overall, our results show that for all cereals, fertilizers account for 56% of total energy inputs, followed by diesel use at 29%.

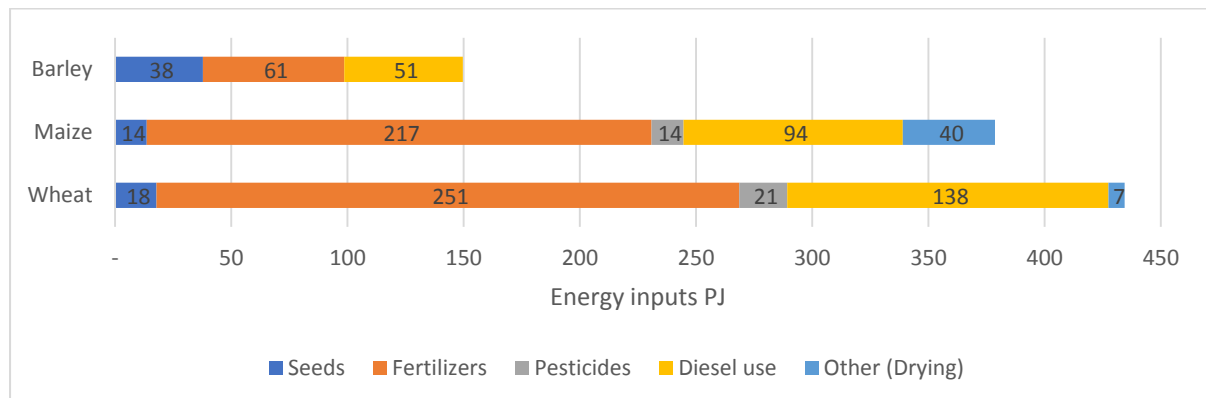


Figure 14. Energy inputs for cereals EU-27 (PJ)

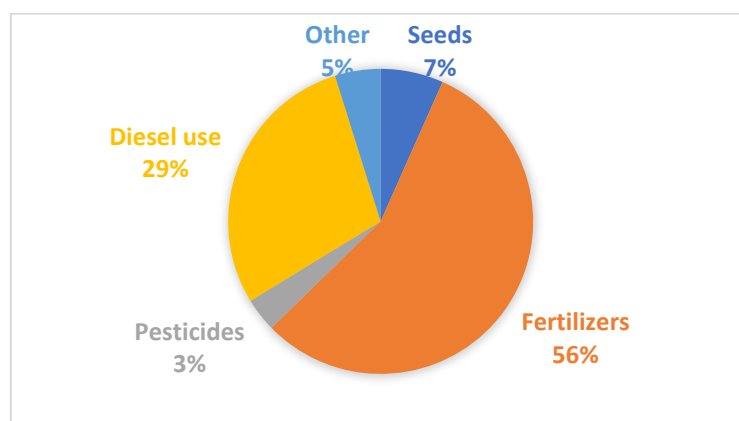


Figure 15. Energy inputs for cereals EU-27

4.1.1.1 Wheat

Compared to all the open-field crops covered, the available data on wheat is the most comprehensive and data is available both in terms of MJ per kg and GJ per hectare. Our findings illustrate that on average 3.37 MJ is required to produce 1 kg of wheat in the EU, or 15.08 GJ is required to cultivate one hectare. The main energy consuming input is allocated to the production and use of fertilizers, accounting for 58-59% of total energy consumption, followed by diesel use at 30-32%, seeds at 3-4%, pesticides at 4-5% and drying at 2-4%. As expected, energy use varies considerably between studies ranging from 2 MJ/kg to 6.43 MJ/kg. On a country level, our results show considerable variations, with Greece, Italy and Spain showing energy requirements close to or over 4 MJ per kg, while most other studies indicate energy requirements between 2-3 MJ per kg.

Table 10. Energy inputs in wheat production EU MJ/kg (de Visser et al. 2012; Achten and Van Acker 2016a)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Drying)	Total
de Visser et al. 2012	Portugal	0.15	2.12	0.13	1.89	0.00	4.29
de Visser et al. 2012	Poland	0.10	1.70	0.08	0.72	0.00	2.60
de Visser et al. 2012	Netherlands	0.05	1.16	0.12	0.70	0.03	2.06
de Visser et al. 2012	Greece	0.09	1.76	0.14	2.01	0.00	3.99
de Visser et al. 2012	Germany	0.06	1.46	0.08	0.52	0.30	2.42
de Visser et al. 2012	Finland	0.14	1.52	0.12	0.38	0.50	2.66
Achten & Acker, 2016	Belgium	0.05	1.68	0.16	0.73	0.00	2.62
Achten & Acker, 2016	Greece	0.27	2.92	0.32	1.89	0.00	5.41
Achten & Acker, 2016	Italy	0.15	1.84	0.12	0.91	0.00	3.02
Achten & Acker, 2016	Netherlands	0.11	1.53	0.36	0.78	0.00	2.79
Achten & Acker, 2016	France	0.14	2.47	0.29	0.68	0.00	3.58
Achten & Acker, 2016	Spain	0.32	3.99	0.13	1.99	0.00	6.43
Achten & Acker, 2016	Denmark	0.09	1.79	0.06	0.95	0.03	2.91
Achten & Acker, 2016	Germany	0.17	2.03	0.17	1.00	0.00	3.35
Achten & Acker, 2016	Sweden	0.14	1.50	0.14	0.96	0.00	2.73
Achten & Acker, 2016	Switzerland	0.18	1.64	0.15	1.05	0.00	3.02
	EU Average	0.14	1.94	0.16	1.07	0.05	3.37
	EU Average (%)	4%	58%	5%	32%	2%	100%

Table 11. Energy inputs in wheat production (GJ/ha) (de Visser et al. 2012; Lin et al. 2017; Klepper and Rainer 2011; Pugesgaard et al. 2015)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Drying)	Total
de Visser et al. 2012	Portugal	0.40	6.30	0.40	5.70	0.00	12.80
de Visser et al. 2012	Poland	0.60	9.90	0.45	4.10	0.00	15.05
de Visser et al. 2012	Netherlands	0.40	10.10	1.10	6.10	0.00	17.70
de Visser et al. 2012	Greece	0.40	8.80	0.70	10.00	0.00	19.90
de Visser et al. 2012	Germany	0.40	11.20	0.60	4.00	2.30	18.50
de Visser et al. 2012	Finland	0.70	6.80	0.50	1.70	2.30	12.00
Lin et al., 2017	Germany	1.00	6.85	0.55	1.85	0.00	10.25
Klepper, 2011	Germany						26.52
Pugesgaard et al., 2014	Denmark	0.50	9.50	0.50	2.30	0.00	12.80
Dobek & Dobek, 2010	Poland	28.10			4.20	0.00	32.30
	EU Average	0.49	8.94	0.61	4.47	0.58	15.08
	EU Average (%)	3%	59%	4%	30%	4%	100%

We estimate the total energy consumption, both direct and indirect, for wheat production in the EU at 434.38 PJ, which is the largest total energy consumption for all crops covered in this study. According to Achten and Acker's (2016), around 90% of all energy consumed in wheat production in the EU comes from non-renewable fossil sources (Achten and Van Acker 2016a).

Table 12. Total energy use for wheat production in the EU-27 (PJ)

Total Wheat Production EU 2018 (m tonnes)	Seeds	Fertilizers	Pesticides	Diesel use	Other (Drying)	Total
129	17.79	250.80	20.66	138.20	6.93	434.38

Table 13. Direct energy % according to agricultural activity (Achten and Van Acker 2016b)

Country	Seed and Sowing	Tillage	Harvesting	Transport
Belgium	7%	53%	37%	3%
Greece	13%	50%	35%	3%
Italy	14%	46%	31%	9%
Netherlands	13%	50%	34%	3%
France	17%	39%	43%	0%
Spain	14%	50%	36%	0%
Denmark	8%	33%	22%	36%
Germany	14%	51%	31%	3%
Sweden	13%	50%	35%	3%
EU average	12%	47%	34%	7%

Table 13 provides an overview of the breakdown of energy inputs regarding on-farm activities. This table illustrates that on average around 47% of all on-farm energy (predominantly diesel) is related to tillage operations, followed by harvesting at 34%, seed and sowing at 12% and transport at 7%. In some studies, on-farm grain drying was also mentioned as a significant energy input.

4.1.1.2 Maize

Our findings illustrate that on average around 24.84 GJ are consumed per hectare of maize cultivated in the EU. The main energy consuming input is allocated to the production and use of fertilizers, accounting for around 57% of total energy consumption, followed by diesel use at 25%, other (mainly irrigation) at 10%, seeds at 4% and pesticides at 4%. It is important to note that irrigation is limited to Southern European countries. In cases where irrigation is used, it constitutes a significant part of the total energy consumption. Significant variations are observed between different countries, ranging from 11.25 GJ per hectare in certain cases in Germany to 36-41 GJ per hectare in Italy.

Table 14. Energy inputs in maize production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
Ceccon et al. 2002	Italy	0.21	21.54	0.88	8.09	5.40	36.11
Goglio et al. 2012	Italy	0.09	13.92	2.07	10.54	9.53	36.15
Borin et al., 1997	Italy	1.78	21.62	1.41	7.67	8.50	40.97
Šarauskis et al. 2014	Lithuania	0.46	12.62	0.63	2.66	0.00	16.38
Felten et al., 2013	Germany	0.21	6.41	0.12	6.06	0.00	12.80
	Germany	1.60	6.60	0.60	2.45	0.00	11.25
Klepper, 2011	Germany						39.90
Jankowski et al. 2016	Poland	1.90	17.06	0.63	5.72	0.00	25.31
Gorzelany et al., 2011	Poland		13.68		5.66	0.00	19.33
Gorzelany et al., 2011	Poland		13.68		6.86	0.00	20.54
	EU Average	0.89	14.25	0.91	6.19	2.60	24.84
	EU Average (%)	4%	57%	4%	25%	10%	100%

Table 15. Total energy use for maize production in the EU-27 (PJ)

Total Maize Cultivation EU 2018 (millions ha)	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
15.24	13.61	217.20	13.79	94.33	39.67	378.61
EU Average (%)	4%	57%	4%	25%	10%	100%

Regarding direct energy breakdown in maize systems, Felten et al. (2013) provides a breakdown of on-farm diesel use without irrigation. Based on the results presented, we calculate that 57% is associated with tillage operations (ploughing, harrowing and tillage), 32% with harvesting operations, 9% with sowing operations and 1% each with diesel use in fertilizer and pesticide application (Felten et al. 2013).

4.1.1.3 Barley

From the data covered in our analysis, we estimate that on average around 13.21 GJ are consumed per hectare of barley cultivated in the EU. The main energy consuming input is allocated to the production and use of fertilizers, accounting for around 41% of total energy consumption, followed by diesel use with 34% and seeds with 25%. Our calculations suggest that the entire barley sector consumes around 149.89 PJ annually in the EU.

Table 16. Energy inputs in barley production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Total
Borin et al., 1997	Italy	4.42	1.18		4.70	10.30
Klepper, 2011	Germany					21.21
Czarnocki et al. 2013	Poland	1.36	11.60	0.01	3.42	16.39
Alonso & Guzman, 2010	Spain average	4.20	3.30	0.03	5.38	12.91
	EU Average	3.33	5.36	0.02	4.50	13.21
	EU Average (%)	25%	41%	0%	34%	100%

Table 17. Total energy use for barley production in the EU-27 (PJ)

Total barley cultivation EU 2019 (millions of ha)	Seeds	Fertilizers	Pesticides	Diesel use	Total
11.35	37.76	60.83	0.25	51.06	149.89
EU Average (%)	25%	41%	0%	34%	100%

4.1.1.4 Oats and Rye

Oats and Rye account for a relatively minor proportion of the total cereal production in the EU. No studies were located that provide an accurate overview of their overall energy requirements. As they are cereals it can be assumed that their energy use is similar to that of other cereals (Rajaniemi, Mikkola, and Ahokas 2011).

4.1.2 Potatoes and sugar beet

Potatoes and sugar beet are the two main root crops grown in the EU. In 2018, there were 1.7 million hectares dedicated to the growth of sugar beet and the same amount to potatoes. The EU accounts for half of the world production of sugar beet, while in 2018 119.6 million tonnes of sugar beet were harvested, with France accounting for 33.4% of the total production and Germany for 21.9%. Similarly, the EU produced 51.8 million tonnes of potatoes in 2018, presenting a decrease as compared to 2017 due to poor weather conditions. For both potatoes and sugar beet, France, Germany and Poland were the main producers (see Figure 16) (Eurostat 2020c).

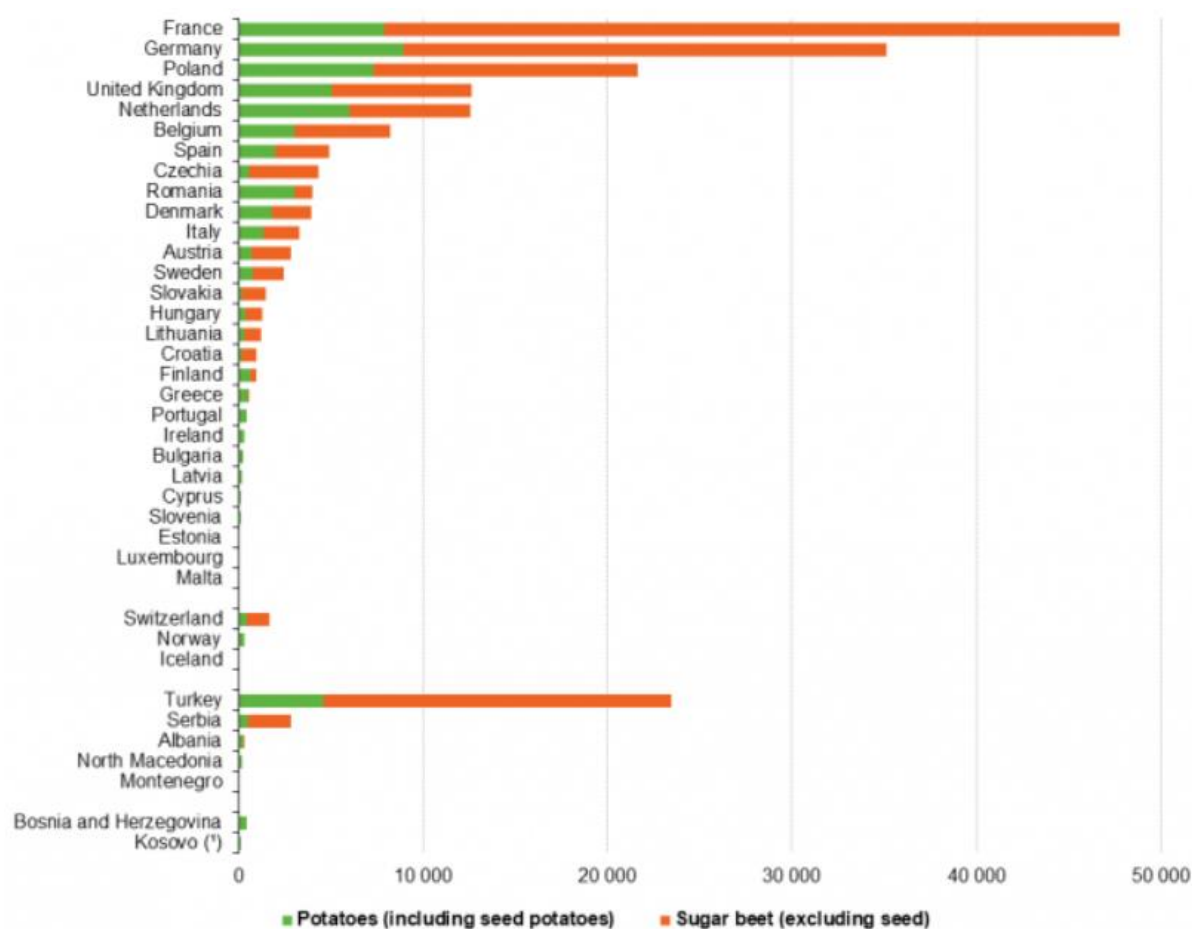


Figure 16. Production of potatoes and sugar beet (thousand tonnes) (Eurostat 2020c)

We estimate that in the EU the entire potato sector consumes around 50.57 PJ and the sugar beet sector around 27.4 PJ annually (see Figure 17).

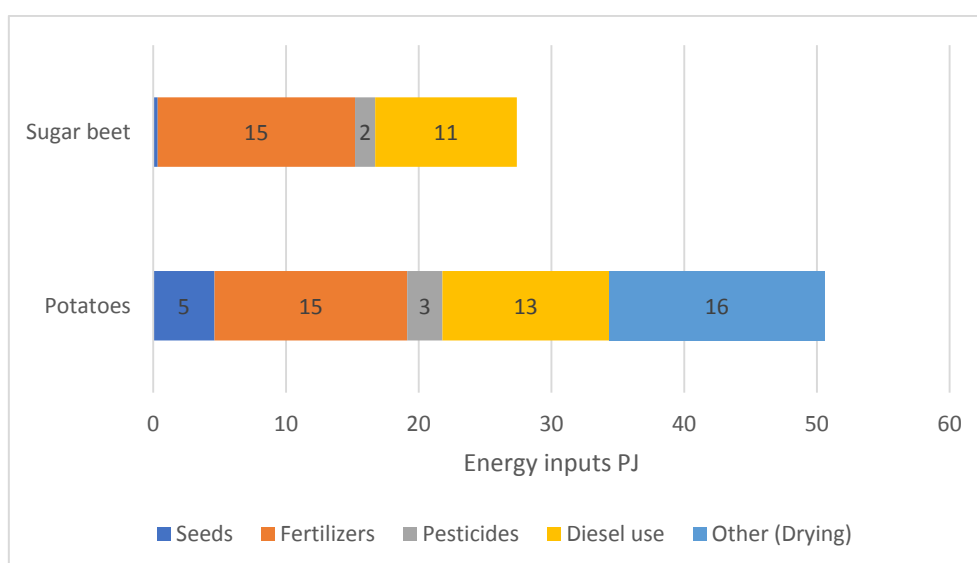


Figure 17. Energy inputs for sugar beet and potatoes EU-27 (PJ)

4.1.2.1 Potatoes

From the data covered in our analysis, we estimate that on average around 29.61 GJ are consumed per hectare of potatoes cultivated in the EU. The main energy consuming input is allocated to fertilizers at 29%, followed by other (which mainly accounts for on-farm storage) at 26%, diesel use at 25% (sowing, tillage, harvesting), seeds at 15%, and pesticides at 5%.

Table 18. Energy inputs in potato production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Storage)	Total
Lin et al., 2017	Germany	3.8	4.6	1	4.2		13.6
Klepper, 2011	Germany						73.15
Stawinski, 2011	Poland		10.9		6.5	3.2	20.50
de Visser et al. 2012	Germany	1.5	10.5	1.6	7.2	6.1	26.9
de Visser et al. 2012	Poland	3.1	6.7	0.2	6.8		16.8
de Visser et al. 2012	Netherlands	2.7	13.1	3.6	12	13.4	44.8
	EU Average	4.39	8.73	1.60	7.33	7.55	29.61
	EU Average (%)	15%	29%	5%	25%	26%	100%

Table 19. Total energy use for potato production in the EU-27 (PJ)

Total Potato Cultivation EU 2018 (millions of ha)	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
1.66	7.31	14.51	2.66	12.20	12.56	49.25
EU Average (%)	15%	29%	5%	25%	26%	100%

4.1.2.2 Sugar beet

Our findings illustrate that on average around 18.61 GJ are consumed per hectare of sugar beet cultivated in the EU without irrigation. Within these studies, the main energy consuming input is allocated to the production and use of fertilizers, accounting for around 54% of total energy consumption, followed by diesel use at 39%, pesticides at 6% and seeds at 1%. Two studies were conducted on farms that were irrigated, which show significant variation, with a study in Italy showing that irrigation accounted for 18% and a study in Greece showing that irrigation accounted for 62% of total energy consumption. Due to these variations, these studies were not included in the EU averages presented in Table 20 and suggest that further research is needed on the total energy use of irrigation in sugar beet cultivation.

Table 20. Energy inputs in sugar beet production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
de Visser et al. 2012	Poland	0.20	10.90	1.40	7.10		19.60
de Visser et al. 2012	Poland	0.20	9.90	1.00	6.00		17.10
de Visser et al. 2012	Poland	0.20	9.00	0.90	5.10		15.20
de Visser et al. 2012	Netherlands	0.10	7.20	1.20	5.20		13.70
de Visser et al. 2012	Germany	0.20	9.00	0.00	4.90		14.10
de Visser et al. 2012	Germany	0.20	9.00	0.00	4.80		14.00
de Visser et al. 2012	Germany	0.20	9.00	0.30	4.70		14.20
Kuesters and Lammel	Germany						8-16

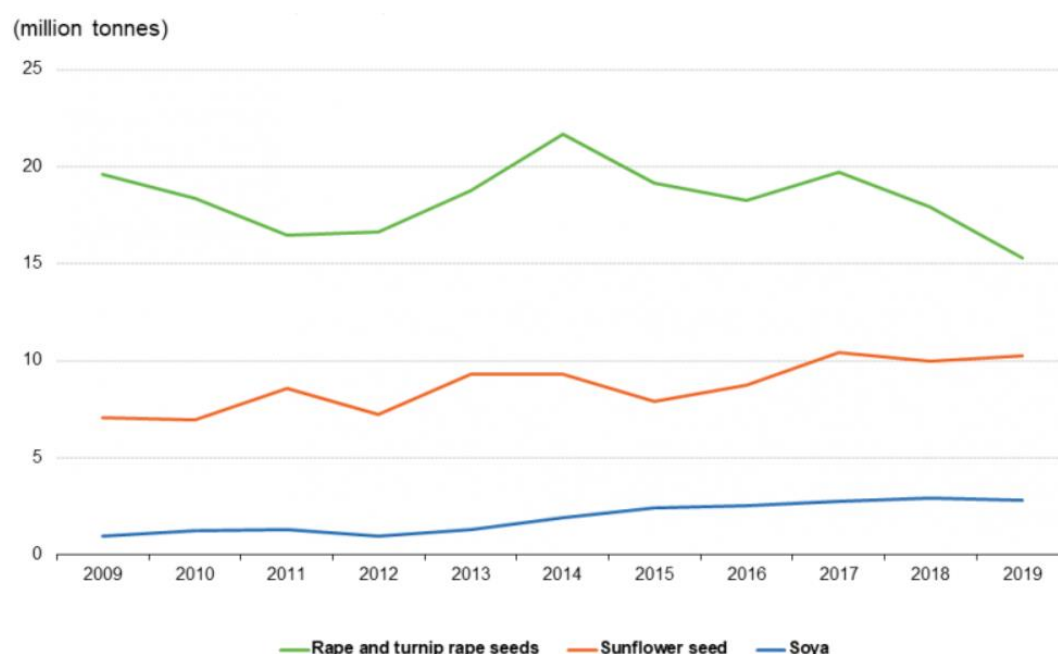
1999							
Klepper, 2011	Germany						24.19
Venturi & Venturi, 2011	Italy average	0.30	14.30	1.10	14.10	0.00	29.80
Ceccon et al., 2002	Italy	0.04	10.76	0.54	12.50	5.40	29.235*
	Greece	0.67	11.91	3.89	8.13	40.92	65.511*
	EU Average	0.23	10.10	1.03	7.25		18.61
	EU Average (%)	1%	54%	6%	39%		100%

Table 21. Total energy use for sugar beet production in the EU-27 (PJ)

Total sugar beet Cultivation EU 2018 (millions of ha)	Seeds	Fertilizers	Pesticides	Diesel Use	Total
1.47	0.34	14.86	1.52	10.67	27.40
EU Average (%)	1%	54%	6%	39%	100%

4.1.3 Oilseeds

In the EU three main oilseed crops are grown, rapeseed, sunflower and soya (see Figure 18). Figures 19 and 20 illustrate the energy inputs associated with the three main oilseeds cultivated in the EU. As expected rapeseed production is the most energy intensive, followed by sunflower seed and soybean. On average, fertilizers (46%) and diesel use (39%) are the main energy consuming inputs while seeds and pesticides constitute relatively small proportions of energy inputs.



Source: Eurostat (online data code: apro_cpn1)

eurostat

Figure 18. Production of oilseeds, EU-27, 2009-2019 (Eurostat 2020c)

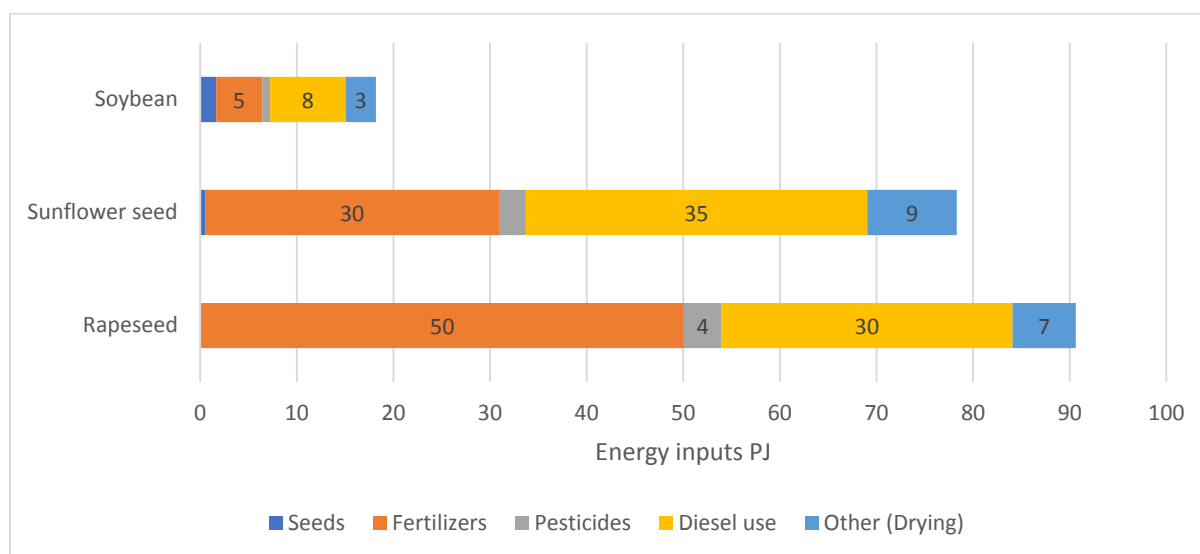


Figure 19. Energy inputs for oilseeds EU-27 (PJ)

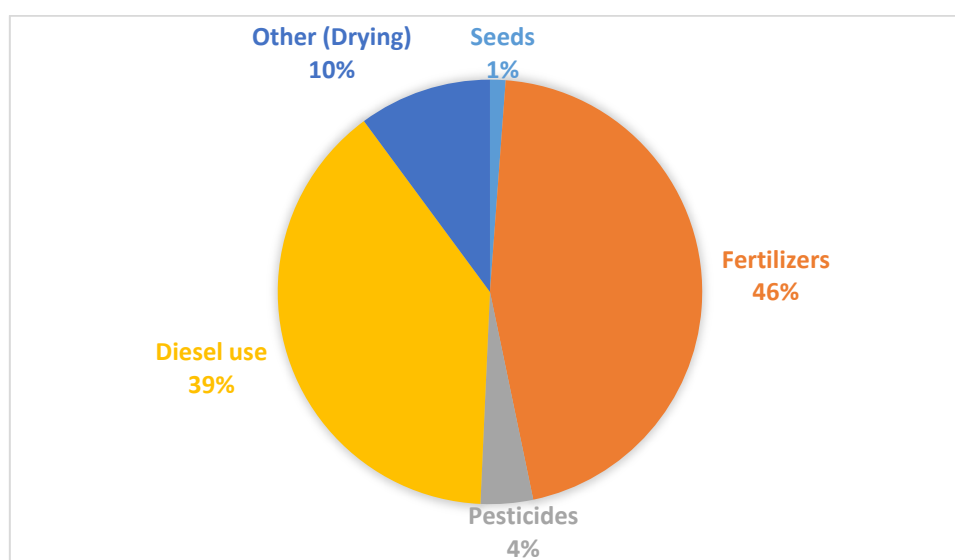


Figure 20. Energy inputs for oilseeds EU-27 (%)

4.1.3.1 Rapeseed

Our research shows that on average around 17.10 GJ are consumed per hectare of rapeseed cultivated in the EU. Within these studies, the main energy consuming input is allocated to the production and use of fertilizers, accounting for around 55% of total energy consumption, followed by diesel use at 33%, irrigation at 7% and pesticides at 4%. Our calculations suggest that the rapeseed sector consumes around 90.63 PJ annually in the EU.

Table 22. Energy inputs in rapeseed production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
Klepper, 2011	Germany						19.94
Felten et al., 2013	Germany	0.02	5.58	0.36	2.68	0.00	8.64
Venturi & Venturi, 2003	Italy Low		5.60	0.20	5.00	2.20	13.00
Venturi & Venturi, 2003	Italy High		11.90	0.90	19.00	5.20	37.00
Dobek & Dobek, 2010	Poland		21.47		3.68	0.00	25.15
Firrisa 2011	Poland	0.00	13.24	1.33	2.08	0.00	16.65
Firrisa, 2011	Netherlands	0.00	10.86	0.88	1.68	0.00	13.42
	EU Average	0.01	9.44	0.73	5.69	1.23	17.10
	EU Average (%)	0%	55%	4%	33%	7%	100%

Table 23. Total energy use for rapeseed production in the EU-27 (PJ)

Total rapeseed cultivation EU 2018 (millions of ha)	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
5.30	0.05	50.02	3.89	30.14	6.54	90.63
EU Average (%)	0%	55%	4%	33%	7%	100%

Regarding direct energy breakdown in rapeseed systems, Felten et al. (2013) provides a breakdown of on-farm diesel use. Based on the results presented, we calculate that 26% is associated with tillage operations, 24% with harvesting operations, 17% with sowing operations, 5% with pesticide application and 2% with fertilizer application (Felten et al. 2013).

4.1.3.2 Sunflower

Our results show that on average around 17.54 GJ are consumed per hectare of sunflower seed cultivated in the EU. Within these studies, the main energy consuming input is allocated to on-farm diesel use at 45%, followed by fertilizers at 39%, irrigation at 12%, pesticides at 4% and seeds at 1%

Table 24. Energy inputs in sunflower production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
Kallivroussis et al. 2002	Greece	0.18	4.88	0.43	3.56	0.00	9.05
Spugnoli et al., 2012	Italy	0.05	6.01	0.14	6.18		12.38
Venturi & Venturi, 2003	Italy		9.55	1.30	14.00	4.15	29.00
Klepper, 2011	Germany						22.91
	EU Average	0.12	6.81	0.62	7.91	2.08	17.54
	EU Average (%)	1%	39%	4%	45%	12%	100%

Table 25. Total energy use for sunflower production in the EU-27 (PJ)

Total sunflower cultivation EU 2018 (millions of ha)	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
4.46	0.52	30.41	2.78	35.33	9.26	78.31
EU Average (%)	1%	39%	4%	45%	12%	100%

Regarding direct energy breakdown in sunflower systems, Venturi & Venturi (2003) provides a breakdown of on-farm diesel use. Based on the results presented, we calculate that 61% is associated with tillage operations, 14% with harvesting operations and 25% with sowing operations (Venturi and Venturi 2003).

4.1.3.3 Soybean

Our results show that on average around 19.34 GJ are consumed per hectare of soybean cultivated in the EU. Within these studies, the main energy consuming input is allocated to on-farm diesel use at 43%, followed by fertilizers at 26%, irrigation at 17%, pesticides at 4% and seeds at 9%.

Table 26. Energy inputs in soybean production (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
Ceccon et al. 2002	Italy	0.71	3.951	0.411	6.227	5.4	16.699
Venturi & Venturi, 2003	Italy Average		5.35	1.5	13.05	4.6	24.5
Borin et al., 1997	Italy	2.791	5.995	0.626	5.66	0	15.072
Klepper, 2011	Germany						15.423
	EU Average	1.75	5.10	0.85	8.31	3.33	19.34
	EU Average (%)	9%	26%	4%	43%	17%	100%

Table 27. Total energy use for soybean production in the EU-27 (PJ)

Total soybean cultivation EU 2018 (millions of ha)	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
0.94	1.65	4.79	0.79	7.81	3.13	18.18
EU Average (%)	9%	26%	4%	43%	17%	100%

Regarding direct energy breakdown in soybean systems, Venturi & Venturi (2003) provides a breakdown of on-farm diesel use. Based on the results presented, we calculate that 61% is associated with tillage operations, 16% with harvesting operations and 23% with sowing operations (Venturi and Venturi 2003).

4.1.4 Orchards

Orchards (excluding vines and olives) cover 1.295 million hectares in the EU. Over one third of the total fruit plantations are apple orchards (36.6%), one fifth are orange groves (19.7%) and the remaining percentages are of peach and nectarine orchards (14.7%), small citrus fruit trees (10.8%), as well as pear trees, and apricots (see Figure 21). The Member States with the most fruit plantations in 2017 were Spain (32.6%), Italy (21.6%) and Poland (12.9%).

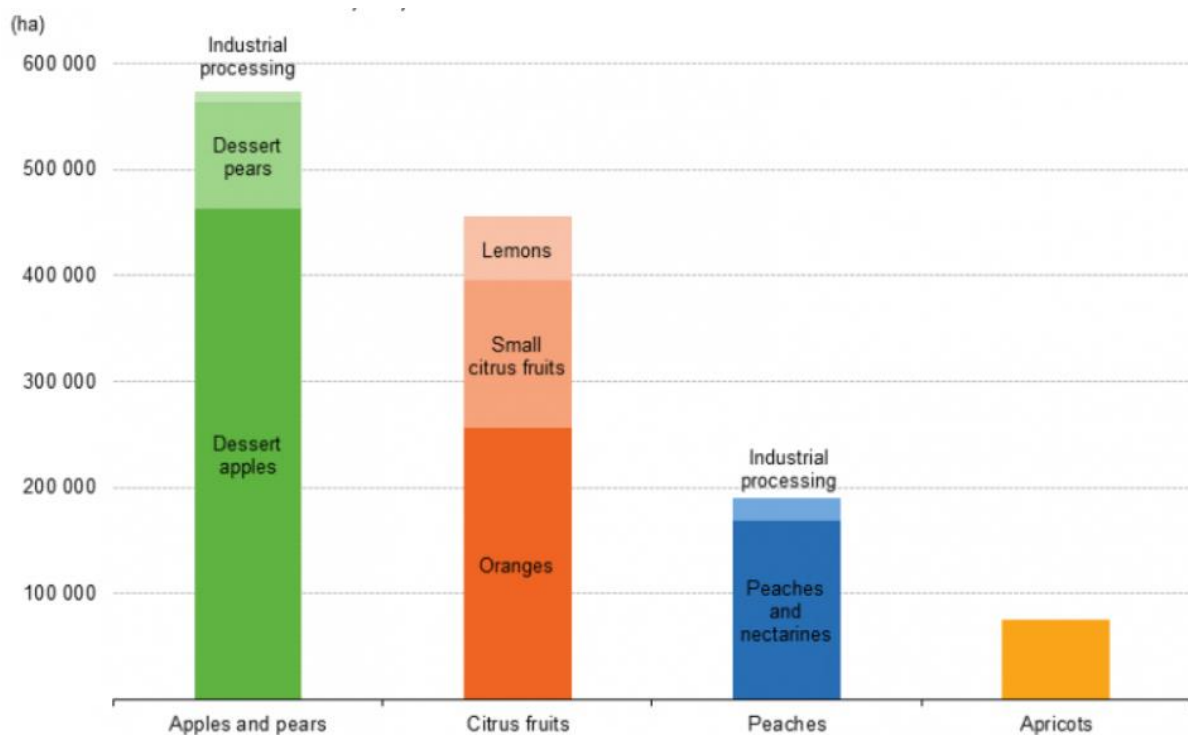


Figure 21. Production area of fruit trees EU (Eurostat 2020e)

Few studies focus on energy use within fruit orchards in the EU. Our findings suggest that the cultivation of olive groves consumes considerably more energy as a whole as compared to vineyards, citrus and apple producing systems. In all fruit growing systems, our research shows that direct on-farm energy consumption is mostly associated with diesel use for harvesting, soil cultivation and pruning, and with electricity for irrigation (Figure 22).

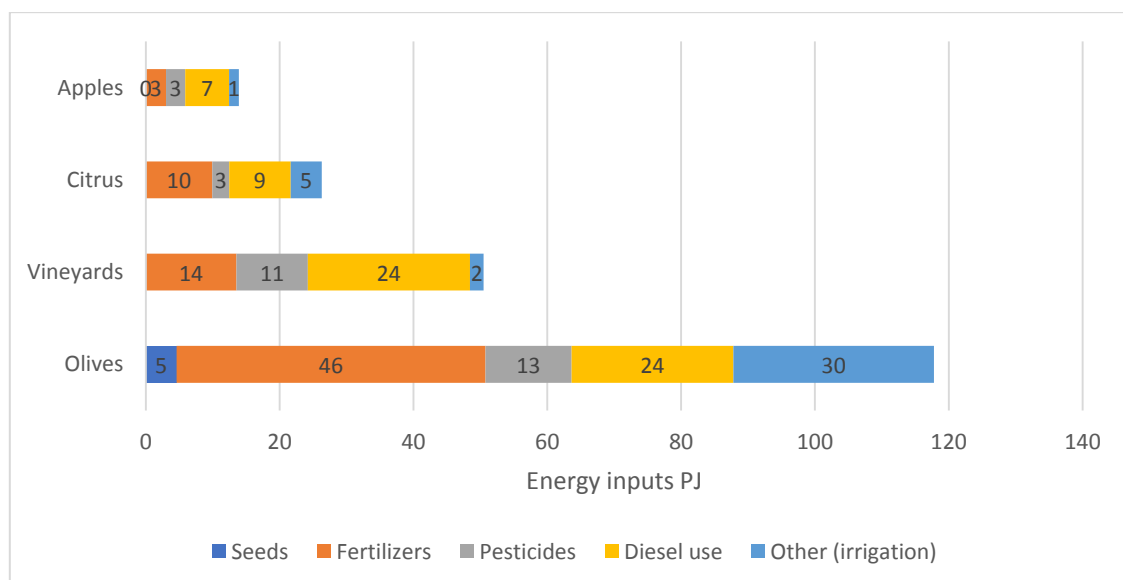


Figure 22. Energy inputs for orchards EU-27 (PJ)

Table 28. % of energy inputs in selected orchards according to on-farm operations

Source	Crop	Soil Cultivation	Harvesting	Pruning	Irrigation
Pergola, et al., 2013	Oranges	9%	74%	2%	15%
Pergola, et al., 2013	Lemons	17%	63%	2%	18%
Cappelletti et al., 2014	Olives -Traditional	73%	0%	27%	0%
Cappelletti et al., 2014	Olives - Intensive	15%	17%	3%	65%
Cappelletti et al., 2014	Olives - Super intensive	12%	34%	2%	51%

4.1.4.1 Apple orchards

3.2.3.1 Apple Orchards

Apple trees are the dominant type of orchard in the EU, covering around 473,500 hectares. Poland accounts for 34% of the total area, followed by Italy and Romania who each held 12% of the total (Figure 23).

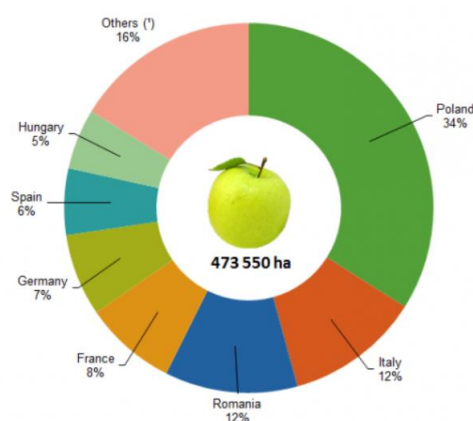


Figure 23. Area under apple trees (Eurostat 2020e)

The energy data presented in Table 29 is a combination of the findings of two studies. On the one hand, Canals et al. (2007) find that the range of MJ per kg of apple produced in the EU ranges from 0.4-2 MJ with a mean of 1.2 MJ. This is in line with other studies from around the world which find 0.9-1.1 MJ/kg for the US (Canals et al. 2007) and 1.2 MJ/kg for Switzerland. As Canals et al. (2007) does not provide a breakdown of on-farm energy use, we complement this data by drawing from another study conducted in Greece by Strapatsa et al. (2006) which finds that fertilizers, pesticides, diesel use and storage account for around 22%, 21%, 47% and 11% respectively and estimates energy consumption at 35.2 GJ/ha (Strapatsa et al. 2006). Again, this is in line with other studies (the Swiss study estimates 37.6 GJ/ha). Based on this, we roughly estimate that diesel use is the largest energy consumer in apple production in the EU at 47%, followed by fertilizers at 22%, pesticides at 21% and other at 11%. Our findings suggest that the entire apple production in the EU consumes around 13.9 PJ of energy.

Table 29. Energy inputs in apple production MJ/kg

Source	Country	Fertilizers	Pesticides	Diesel use	Other (Storage)	Total
Canals et al., 2007; Strapatsa et al., 2006	EU Average	0.26	0.25	0.57	0.13	1.2
	EU Average (%)	22%	21%	47%	11%	100%

Table 30. Total energy use for apple production in the EU-27 (PJ)

Total Apple Production EU 2018 (m tonnes)	Fertilizers	Pesticides	Diesel use	Other (Storage)	Total
11.59	3.00	2.88	6.56	1.46	13.91
EU Average (%)	22%	21%	47%	11%	100%

4.1.4.2 Citrus orchards

The total area under citrus fruit plantations across the EU amounts to around 455,000 hectares, of this total orange production account for around 56% of the total area, followed by small citrus fruits at 31% and lemons at 13%. (Eurostat 2019c). Geographically, around 60% of total citrus plantations are located in Spain, followed by Italy with 27% and Greece with 9%. Most data that we located were based on studies located in Spain. Overall, our research suggests that the entire EU citrus production consumes around 26.48 PJ energy inputs annually. The most energy consuming inputs are fertilizers at 37%, followed by diesel use at 35%, irrigation at 17% and pesticides at 10%.

Table 31. Energy inputs in orange production (GJ/ha)

Source	Country	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
Pergola et al., 2013	Italy	32.21	7.98	31.32	5.58	77.09
Alonso & Guzman, 2010	Spain average	13.91	5.32	7.28	11.76	38.27
	EU Average	23.06	6.65	19.30	8.67	58
	EU Average (%)	40%	12%	33%	15%	100%

Table 32. Energy inputs in clementine and tangerine production (GJ/ha)

Source	Country	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
Di Vita et al., 2018	Italy	19.44	5.97	14.04	19.65	59.09
Alonso & Guzman, 2010	Spain average	12.81	2.62	12.81	10.18	38.42
	EU Average	16.12	4.29	13.43	14.91	48.75
	EU Average (%)	33%	9%	28%	31%	100%

Table 33. Energy inputs in Lemon production (GJ/ha)

Source	Country	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
Pergola et al., 2013	Italy	30.66	4.35	40.56	6.60	82.17
	Average (%)	37%	5%	49%	8%	100%

Table 34. Total energy use for citrus production in the EU-27 (PJ)

Crop	Total Area Under Cultivation EU 2018 (millions of ha)	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
Oranges	0.26	5.89	1.70	4.93	2.22	14.74
Small citrus (clementine and tangerine)	0.14	2.19	0.58	1.82	2.02	6.75
Lemon	0.06	1.84	0.26	2.44	0.40	5.00
Total Citrus	0.45	9.92	2.54	9.19	4.63	26.48
	EU Average (%)	37%	10%	35%	17%	100%

Table 35. % energy use according to on farm activity Pergola et al., 2013

Country	Soil Cultivation	Harvesting	Pruning	Irrigation
Lemon	9%	74%	2%	15%
Orange	17%	63%	2%	18%

Pergola et al. (2013) investigates energy use in orange and lemon production systems in Sicily over a 50-year period. This study finds that within orange production systems fertilizers are the most energy consuming input, followed by diesel use, pesticides and irrigation, while in lemon production systems diesel use is the most energy intensive input, followed by fertilizers, irrigation and pesticides. Regarding direct energy breakdown over the reference period, Pergola et al. (2013) highlights that the highest energy consumption is related to harvesting (63-74%), followed by irrigation (15-18%), soil cultivation (9-17%) and pruning (2%).

4.1.4.3 Olive groves

Olive trees are mainly grown in the area around the Mediterranean, covering around 4.6 million hectares. In 8 Member States, the area under olive cultivation exceeds 1,000 hectares; Spain accounts for 55%, Italy for 23%, Greece for 15% and Portugal for 7% of the total area under olive trees (Eurostat 2019c). By contrast, France, Croatia, Cyprus and Slovenia combined account for around 1% of the area under olive trees (Figure 24). Notably, most olive trees in the EU are quite old, with only 281,000 hectares holding olive trees younger than 5 years old.

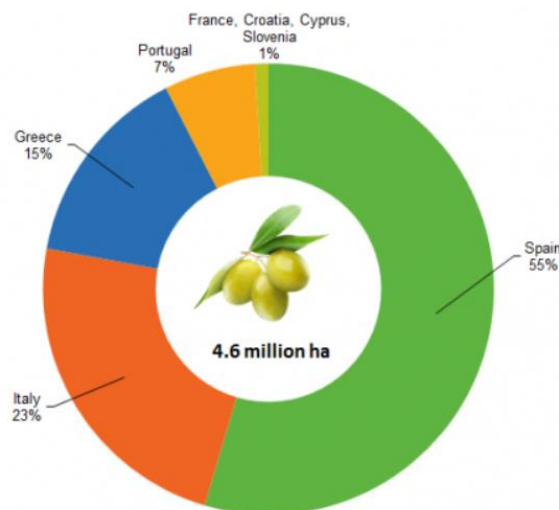


Figure 24. Area under olive trees EU (Eurostat 2020e)

The intensity of olive cultivation varies significantly based on the variety of olives grown, the agricultural systems and the cultivation techniques used. Indeed, the studies that were located show considerable variation in terms of energy use, with those including irrigation showing considerably higher overall energy inputs. For those studies that do not include irrigation and are as such less energy intensive, we find that on average 12.58 GJ is required to cultivate one hectare of olives, with fertilizers accounting for 45% of the final energy consumption, followed by diesel use at 40% and

pesticides at 15% (Table 36). For those studies that do include irrigation and are more energy intensive, our results find that on average 35.71 GJ is required to cultivate one hectare of olives, with fertilizers accounting for 39% of the final energy consumption, followed by irrigation at 35%, diesel use at 15% and pesticides at 10% (Table 37).

Table 36. Energy inputs in olive groves (GJ/ha) - without irrigation

Source	Country	Fertilizers	Pesticides	Diesel use	Total
Guzmán & Alonso, 2008	Spain dryland	15.53	3.45	3.58	22.56
Guzman & Alonso, 2008	Spain dryland	8.36	1.71	7.10	17.17
de Visser et al. 2012	Greece	4.30	0.50	1.10	5.90
Taxidis et al., 2015	Greece	0.29	2.08	4.73	7.10
Taxidis et al., 2015	Greece	0.00	1.54	8.63	10.17
	EU Average	5.70	1.86	5.03	12.58
	EU Average (%)	45%	15%	40%	100%

Table 37. Energy inputs in olive groves (GJ/ha) - with irrigation

Source	Country	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
Guzman & Alonso, 2008	Spain Irrigated	29.14	3.62	4.21	19.18	56.15
Guzman & Alonso, 2008	Spain Irrigated	10.68	4.77	8.39	17.53	41.37
de Visser et al. 2012	Portugal average	2.30	2.60	3.80	0.90	9.60
	EU Average	14.04	3.66	5.47	12.54	35.71
	EU Average (%)	39%	10%	15%	35%	100%

Russo et al. (2016) divide olive groves into three categories: traditional (low inputs and less than 140 trees per hectare), semi-intensive (medium inputs and between 140-399 trees per hectare) and super-intensive (high inputs and over 400 trees per hectare). In the EU, it is estimated that 48% of all olive farming systems are categorized as traditional, 47% as semi-intensive and 5% as super-intensive (Russo et al. 2016). In order to estimate the total energy use within the EU, we attribute all the traditional olive farms to our results for no irrigation and all the semi-intensive and super-intensive to our results with irrigation. Based on this, we estimate that 113PJ are required for all olive cultivation in the EU (Table 37).

Table 38. Total energy use in olive groves in the EU-27 (PJ)

Type of Olive System	Area (ha)	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
Traditional	2.21	12.58	4.10	11.10	0.00	27.78
Semi and super intensive	2.39	33.58	8.76	13.08	29.99	85.41
EU Total	4.60	46.16	12.86	24.18	29.99	113.19

Regarding direct energy breakdown in olive groves, Cappelletti et al. (2014) provides a breakdown of on-farm energy use according to different systems (Table 39). This illustrates that on-farm energy use is split between soil cultivation 12-73%, harvesting 0-33.7%, pruning 2.2-27% and irrigation 0-

65%. Irrigation in the vast majority of olive systems is electric powered, while the rest of the activities are powered by diesel (Cappelletti et al. 2014).

Table 39. % energy use according to on-farm activity Cappelletti et al. 2014

Country	Soil Cultivation	Harvesting	Pruning	Irrigation
Italy - Traditional	73%	0%	27%	0%
Italy - Intensive	15%	17%	3%	65%
Italy- Super intensive	12%	34%	2%	51%

4.1.4.4 Vineyards

Around 3.2 million hectares of vineyards are cultivated in the EU by 2.5 million holdings, representing around 1.8% of UAA and accounting for around 45% of the world's total area under vines. Spain, France and Italy are the main vine growing countries, covering 74.1% of the total area under vines. Figure 25 illustrates the total area under vines per country (Eurostat 2017). Between 1999-2015, the area under vines in the EU declined by 5%. Overall, the average size per holding is 1.3 hectares but there is significant variation between countries. France had the largest holdings (76,453) with an average size of 10.5 ha, followed by Luxembourg at 3.97 ha. On the other hand, countries with the smallest average vineyard area per holding were Romania (0.21 ha/holding), Croatia (0.4 ha), Slovenia (0.5 ha), Greece (0.6 ha) and Cyprus (0.6 ha). Overall, over 500 different vine varieties are cultivated in the EU, with the red and white vine varieties occupying around 52.7% and 42.7% respectively of the total area under vines, with the remaining 4.6% regarding other grape colour varieties.

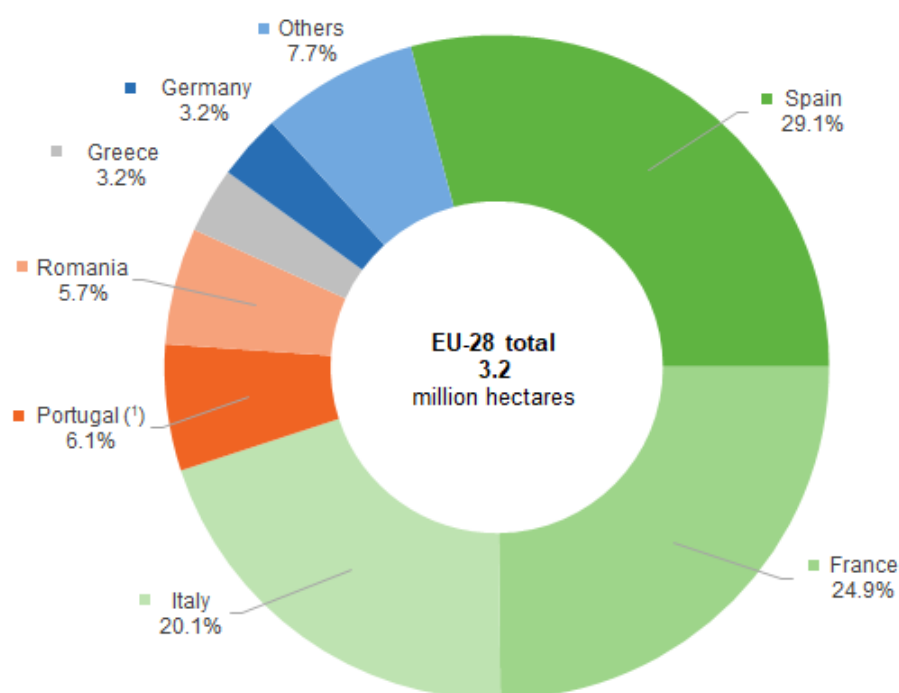


Figure 25. Area under vines EU (Eurostat 2017)

Our results show that on average around 15.78 GJ are consumed per hectare of vineyards cultivated in the EU. The main energy consuming input is allocated to on-farm diesel use accounting for 48% of total energy consumption, followed by fertilizers at 27%, pesticides at 21% and irrigation at 4% (Table 40).

Table 40. Energy inputs in vineyards (GJ/ha)

Source	Country	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
de Visser et al. 2012	Portugal average	1.20	4.40	5.10	0.13	10.83
de Visser et al. 2012	Greece average	9.10	3.20	2.20	1.80	16.30
de Visser et al. 2012	Germany Average	2.40	2.40	15.40	0.00	20.20
Alonso & Guzman, 2010	Spain average	11.27	1.63	1.34	1.50	15.74
	EU Average	4.23	3.33	7.57	0.64	15.78
	EU Average (%)	27%	21%	48%	4%	100%

Table 41. Total energy use in vineyards in the EU-27 (PJ)

Total area under vineyards EU 2019 (millions of ha)	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
3.20	13.55	10.67	24.21	2.05	50.48
EU Average (%)	27%	21%	48%	4%	100%

5. Energy use in the Livestock Sector

The following section provides an overview of energy use in the EU livestock sector. Based on data from 2018, the main livestock populations in the EU consisted of 148 million pigs, 87 million bovine animals and 98 million sheep and goats. Most livestock populations are concentrated in just a few Member States, with almost 60% of the EU's bovine population in France (21.2%), Germany (13.7%), Ireland (7.5%), Spain (7.4%), Italy (7.2%) and Poland (7.1%). Regarding the pig population, approximately three quarters of the total population were found among Spain (20.8%), Germany (17.8%), France (9.3%), Denmark (8.5%), the Netherlands (8.1%) and Poland (7.4%). Of the total sheep population, large populations exist in Spain (18.5%), Romania (11.9%) and Greece (9.9%), while, two thirds of the goats were found in Greece, Spain and Romania alone (see Figure 26) (Eurostat 2020d).

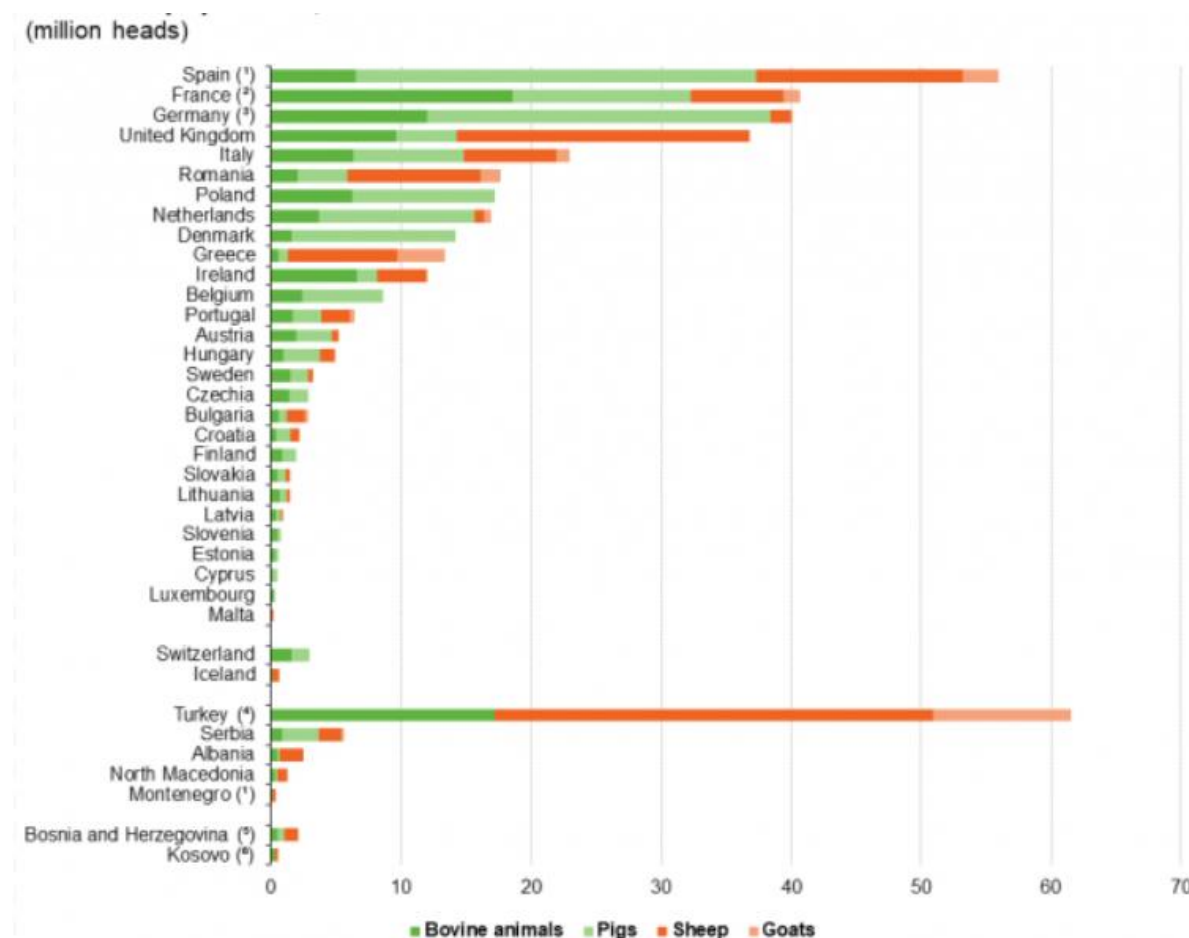


Figure 26. Total livestock population in the EU-28 (Eurostat 2020d)

The rearing of livestock for animal products is widespread with more than half, 5.7 million, of the agricultural holdings in the EU keeping livestock. In Ireland, nine out of ten holdings kept livestock in 2016 (92%) and Slovenia, Luxemburg and Romania also had high figures. On the other hand, less than 30% of the farms kept livestock in Italy, Spain, Cyprus and Malta, with the lowest figure reported in Italy (13.5%). Between 2005 and 2016, the number of farms with livestock decreased by more than a third, with the biggest decreases being observed in Slovakia (72.2%), Bulgaria (71.9%) Estonia, Lithuania and Poland.

Livestock densities vary significantly throughout the EU, overall, in 2016 the livestock density reached 0.8 livestock units (LSU) per hectare of utilized agricultural area (UAA), with the highest density reported in the Netherlands at 3.8 LSU/ha in 2016, followed by Malta and Belgium with densities of 2.9 and 2.8 LSU/ha respectively. The Member States with the lowest LSU were Bulgaria with 0.2 LSU/ha, Slovakia and the three Baltic Member States (Estonia, Latvia and Lithuania) who all had 0.3 LSU/ha (Eurostat 2019a). The highest livestock densities were reported in a cluster of regions in south and central Netherlands, north Belgium and western Germany. Whereas the lowest livestock densities were registered in regions with capital cities such as Vienna, Paris, Helsinki, Brussels, tourist destinations like Jadranska Hrvatska and Algarve, as well as areas that have an extensive share of grasslands such as the Scottish Highlands.

Despite significant variations between geographical areas and production systems, our findings indicate that in all main production systems in the EU-27, except for beef production systems, animal feed is the main energy input in livestock systems, accounting for around three quarters of all energy requirements (see Figure 27). In meat production systems, the main direct energy requirements are for housing and feeding (mainly in the form of electricity), and manure management (mainly through diesel use). In milking systems, the main direct energy consuming activities are related to milking, milk cooling and water heating. For this, in certain countries, the main energy source is related to electricity and in others to direct fossil fuels. Other electricity consuming activities, such as water pumping and lighting, are found to be relatively minor. Our findings also show that beef is the most energy intensive production system per kg of meat, followed by pork and poultry.

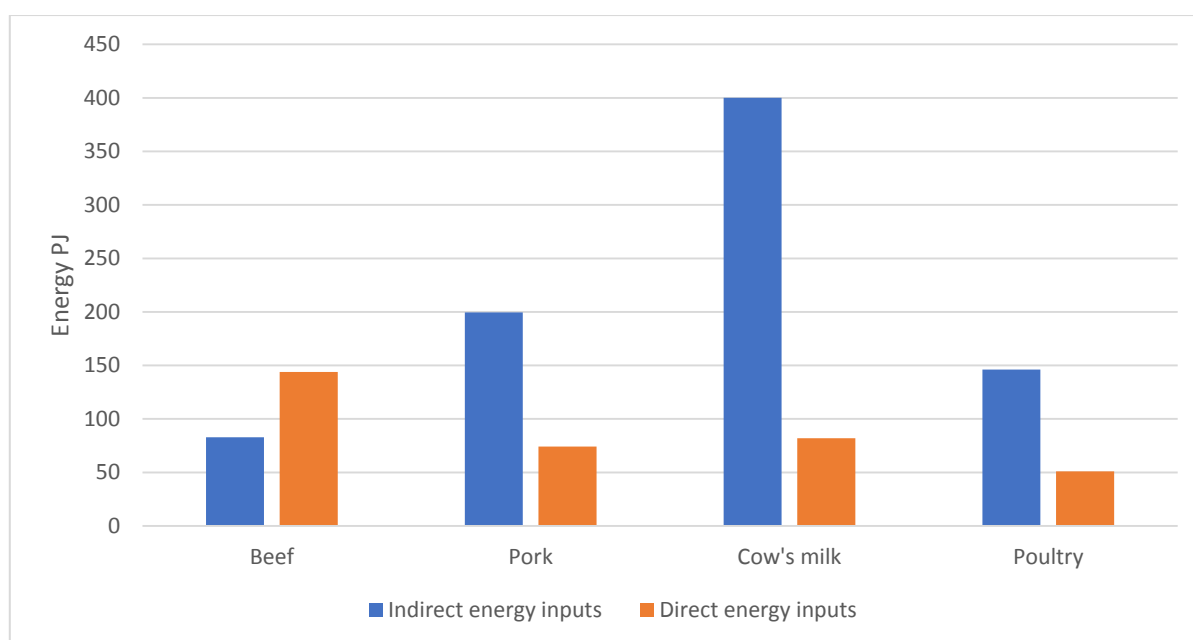


Figure 27. Total direct and indirect energy inputs for selected livestock systems EU-27 (PJ)

5.1 Bovine Animals

Bovine meat consists of beef derived from certain cattle breeds as well as veal. According to Eurostat, in 2018 the EU production of bovine meat stood at 7.9 million tonnes. The main beef producing countries were France and Germany, for beef and The Netherlands and Spain for veal (Eurostat 2019a) (Figure 28).

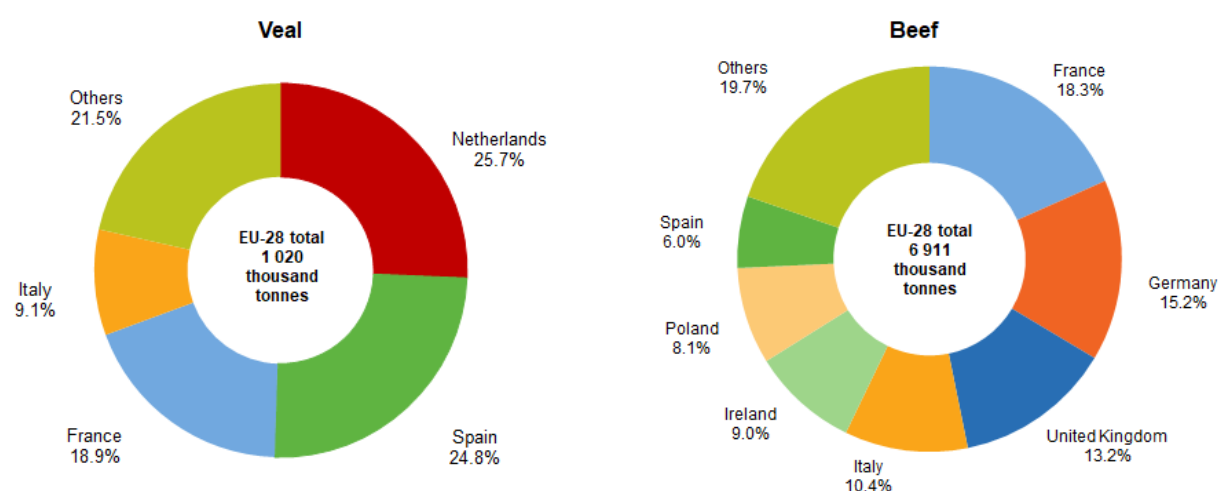


Figure 28. Bovine meat production in EU-28, 2018 (Eurostat 2020d)

5.1.1 Beef

Multiple studies highlight that, compared to the main livestock systems, the production of beef carries the highest environmental production load per kg of meat produced (McAuliffe et al. 2018; Nguyen, Hermansen, and Mogensen 2010a). For this study, we extract data from Nguyen et al. (2010) that conducts an LCA on four types of beef production systems in the EU (Nguyen, Hermansen, and Mogensen 2010a), which is further complemented by a beef production study by Veysset et al. (2014) (Veysset, Lherm, and Bébin 2010). Our results show that on average 59.2 MJ/kg of beef is required for a suckler cow-calf and 43.73 MJ/kg for a dairy bull.

Considering that around 60% of beef production in the EU comes from dairy bulls and 40% from suckler cows-calves, we estimate the total energy inputs for beef production systems at 226.76 PJ for the EU as a whole, 36% of which is associated with feed and fertilizers (Table 43). European cows are generally grown on a combination of home-grown grass and cereals as well as imported soy meal and minerals (Nguyen, Hermansen, and Mogensen 2010a). However, it is important to note that the energy input in feed can vary significantly depending on whether a cow is fed on grass-pasture or concentrate-confinement, as pasture requires much less energy inputs for cultivation and fertilization operations (Frorip et al. 2012).

Table 42. Energy inputs beef production MJ/kg (slaughter weight) (Nguyen, Hermansen, and Mogensen 2010a; Veysset, Lherm, and Bébin 2010)

Source	Country	Feed	Fertilizers	Fuel	Other	Total
Nguyen et al., 2010, Veysset et al., 2014	EU Suckler cow-calf	11.46	10.18	22.49	15.07	59.20
Nguyen et al., 2010, Veysset et al., 2017	EU Dairy bull average	8.46	7.52	16.62	11.13	43.73

Table 43. Total energy inputs for beef production EU-27 (PJ)

Production System	Total beef production EU-27	Feed	Fertilizers	Fuel	Other	Total
EU Suckler cow-calf	3.16	20.82	18.51	40.87	27.37	107.57
EU Dairy bulls	4.74	23.07	20.51	45.29	30.33	119.20
EU Total	7.90	43.89	39.01	86.15	57.71	226.76
EU Average %		19%	17%	38%	25%	100%

Our findings suggest that 63% of energy consumption in beef production systems is associated with on-farm activities. Nguyen et al. (2010) also provides a breakdown of direct energy use (Table 44). His study highlights that on-farm diesel use accounts for 71% of direct energy use, which can mainly be attributed to manure management and field operations, while on-farm electricity used in stables and housing accounts for 17% and in crop processing for 11% of total energy requirements (Table 44). The study also highlights that direct energy use in fattening is the largest consumer, accounting for 50-58% of the total energy consumption in beef production systems (Nguyen, Hermansen, and Mogensen 2010a).

Table 44. Direct energy inputs according to activity (Nguyen, Hermansen, and Mogensen 2010a)

Activity	% of direct energy inputs
Housing - Electricity used in stables	17%
Electricity used in crop processing	11%
Diesel use	71%

5.1.2 Cow milk

The EU produces around 158 million tons of cow milk annually (Eurostat 2020g). The main milk producing countries were Germany (20.8%), France (15.8%), Netherlands (8.9%) and Poland 7.7%. Our results show that on average each kilogram of milk produced requires 3.42 MJ of energy inputs (Table 45). The energy embedded in feed is by far the main energy input, accounting for around 74% of the total energy. In total, we estimate that 540 PJ are required for the entire production of cow milk in the EU. Diesel use (mainly manure handling) accounts for around 9% and other (mainly electrical energy in milking systems, feeding, lighting and ventilation) accounts for around 17%.

Table 45. Energy inputs cow milk MJ ECM (de Visser et al. 2012; Upton 2014; Cederberg and Stadig 2003; Guerri et al. 2013)

Source	Country	Feed	Diesel Use	Other (mainly electricity)	Total
de Visser et al. 2012	Portugal	2.12	0.30	0.80	3.22
de Visser et al. 2012	Poland	3.90	0.60	0.42	5.05
de Visser et al. 2012	Netherlands	3.30	0.60	0.70	4.60
de Visser et al. 2012	Germany	1.70	0.15	0.60	2.71
de Visser et al. 2012	Finland	2.90	0.00	0.70	3.86
Upton, 2014	Ireland	1.86	0.19	0.35	2.40
Cederberg and Flysjö, 2003	Sweden	1.76		0.95	2.70
Thomassen et al., 2009	NL	4.40		0.87	5.3 FPCM
Guerri et al., 2013	Denmark average	2.02		1.76	3.78
Guerri et al., 2013	Germany average	1.34		0.97	2.32
Guerri et al., 2013	Italy average	2.47		1.08	3.54
	EU Average	2.52	0.31	0.59	3.42
	EU Average (%)	74%	9%	17%	100%

Table 46. Total energy inputs for cow milk production EU-27

Total cow milk production EU-27 (m tonnes)	Feed	Diesel Use	Other (mainly electricity)	Total
158.52	400.04	48.61	94.27	542.92

A number of studies provide data on direct energy use (Table 47), from which we estimate that on-farm electrical consumption is attributed to milk cooling (36%), milk harvesting (32%), water heating (23%) and water pumping (9%) (Shine et al. 2020). From the studies that include liquid fuel energy use, there is relatively little information available on its specific uses but it is generally assumed that this is allocated to tractor use associated with pasture management (Shine et al. 2020). It is important to note that individual studies provide different sets of data depending on a range of factors including the production system and type of milking system (Shine et al. 2020).

Table 47. Electrical energy breakdown dairy farms EU (Shine et al. 2020)

Source	Country	Milk cooling	Milk harvesting	Water heating	Water pumping
Murgia et al. 2013	Italy	38%	31%	13%	18%
Todde et al. 2018	Italy	29%	35%	23%	14%
Rajaniemi et al. 2017	Finland	42%	23%	32%	3%
Shine et al. 2018	Ireland	41%	25%	28%	6%
Shortall et al. 2018	Ireland	29%	53%	11%	7%
Upton et al. 2013	Ireland	39%	25%	29%	6%
	EU average %	36%	32%	23%	9%

5.2 Swine / Pigs

Around half, an estimated 23.8 million tonnes, of the EU's meat production in 2018 came from pigs. Compared to 2017, there was an increase of 2.7% in pork meat production which represented a new overall high peak. More than three quarters of pork production occurs in just 6 Member States: Germany (22.4%), Spain (19%), France (9.1%), Poland (8.7%), Denmark (6.6%), Netherlands (6.4%) and Italy (6.2%) (Figure 29).

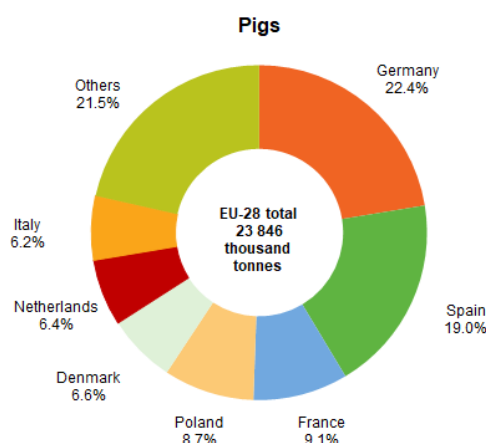


Figure 29. Pork production EU-28 (Eurostat 2020d)

Our results suggest that for each kg of slaughter weight of pork produced 17.91 MJ of energy inputs are required, of which 73% is related to feed production and use and 27% to direct on-farm energy use. Our findings indicate some variation between different studies, but in all studies feed is the largest energy consumer by a significant margin.

Table 48. Energy inputs for pig production slaughter weight MJ/kg (de Visser et al. 2012; Basset-Mens and Van Der Werf 2005; Nguyen, Hermansen, and Mogensen 2010b)

Source	Country	Feed	Maintenance	Diesel Use	Other	Total
de Visser et al. 2012	Portugal	13.4			5.9	19.3
de Visser et al. 2012	Poland	13.9		1.5	2.4	17.8
de Visser et al. 2012	Netherlands	11.90			2.60	14.50
de Visser et al. 2012	Germany	11.80		0.20	2.90	14.90
de Visser et al. 2012	Finland	11.60	1.60		9.50	22.70
Basset-Mens & van der Werf, 2005	France	11.77		4.13		15.90
Nguyen et al., 2010	Nguyen EU	16.41		3.84		20.25
	EU Average	12.97		4.94		17.91
	EU Average (%)	72%		28%		100%

Table 49. Total energy inputs for pork production EU-27 (PJ)

Total pork production EU-27 (m tonnes)	Feed	Direct energy use	Total
23.8	199.58	74.17	273.74

There is also some geographical variation in the breakdown of the direct energy inputs in pig farming systems, but in all cases most direct energy use is associated with manure management, housing and feeding systems in the form of electricity and fuels. Nguyen et al. (2010) provides an overview of on-farm energy use for Northern Europe, this production system covers 70% of pig farming in the EU. On average, this study finds that 3.84 MJ of direct energy is required per kg of slaughter weight pig meat (Nguyen, Hermansen, and Mogensen 2012), 22% of this is associated with diesel use for manure handling, while 50% is associated with electricity of housing, 10% with electricity for manure pumping and stirring and 17% with oil in the form of heating (Table 50). The study also finds that the use of manure for energy production, fertilization and reducing feed use are the most significant factors in reducing the use of fossil energy use in pig systems (Nguyen, Hermansen, and Mogensen 2012).

Table 50. Direct energy inputs in pig production systems according to activity (Nguyen, Hermansen, and Mogensen 2012)

Activity	Energy input MJ	% of direct energy inputs
Diesel use	0.87	22%
Housing – Electricity	1.95	50%
Housing heat –oil	0.65	17%
Manure pumping and stirring – Electricity	0.4	10%

Markou et al. (2017) conduct energy audits on two pig farms in Cyprus. Regarding direct energy inputs, their study finds that 44% of energy consumption is associated with transportation, 31% with feeding, 12% with ventilation, 3% with watering, 3% with waste removal, 2% with lighting and 5% with other uses. Regarding specific energy carriers in direct energy consumption, the study finds that 29% is electricity associated with lighting, ventilation, feeding, watering and other uses, 23% is LPG mainly associated with heating and 48% is diesel associated with vehicle use and heating (Figure 30) (Markou et al. 2017).

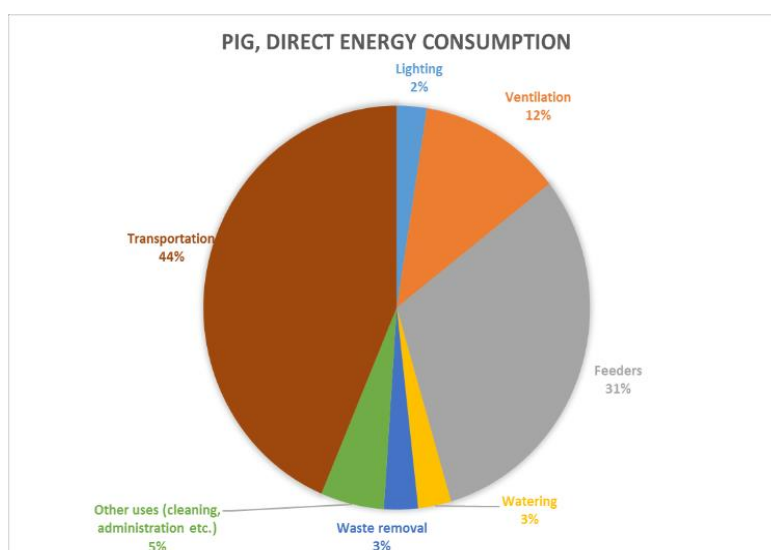


Figure 30. Direct energy consumption in pig farms in Cyprus (Markou et al. 2017)

Similarly, Winkler et al. (2016) state that in Austria and Germany 1.26 MJ of electrical energy and 0.684 MJ of thermal energy is needed for heating, ventilation, light and manure management and 4.356 MJ of mechanical energy is used for field manipulation and on-farm transportation per kg of pork produced (Winkler et al. 2016) .

5.3 Poultry

Poultry is the second largest category of meat production in the EU. It was estimated that in 2018 poultry production reached an all-time high, with approximately 15.2 million tonnes being produced that year (an increase of 4.8% compared to 2017) (Figure 31). Among the main poultry meat producers in the EU, the biggest is Poland with 2.5 million tonnes followed by the United Kingdom

with 2 million tonnes, France with 1.7 million tonnes, Spain with 1.6 million tonnes, Germany with 1.6 million tonnes and Italy with 1.3 million tonnes. During 2018, production levels rose sharply in Poland (8.6%) and in the United Kingdom (8.1%) whereas in Italy they experienced a decrease of 3.2% (Eurostat 2019a). In addition, there were around 350 million egg laying hens in the EU producing an estimated 6.7 million tonnes of eggs (European Commission 2017).

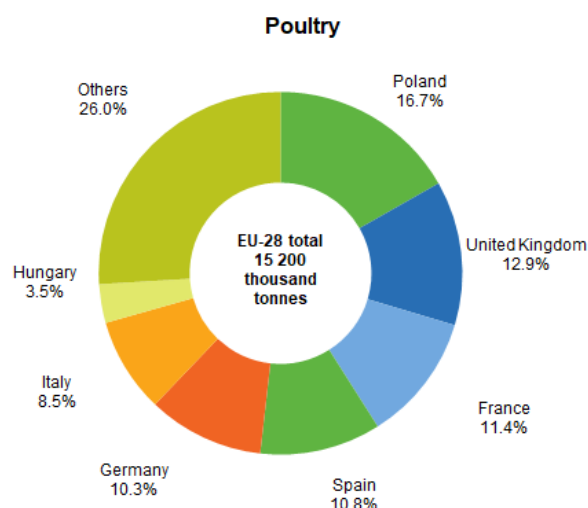


Figure 31. Poultry production in EU-28, 2018 (Eurostat 2020d)

5.3.1 Chicken Broilers

Our results suggest that for each kg of meat produced in broilers 12.96 MJ of energy is required, of which 74% is related to feed production and use and 26% to on-farm energy use.

Table 51. Energy inputs chicken broilers carcass weight MJ/kg (de Visser et al. 2012; Prudêncio da Silva et al. 2014)

Source	Country	Feed	Maintenance	Diesel Use	Other	Total
de Visser et al. 2012	Portugal	8.3		0.2		8.5
de Visser et al. 2012	Portugal	12.1			0.5	12.6
de Visser et al. 2012	Poland	8.20		2.90	3.70	14.80
de Visser et al. 2012	Netherlands	10.10	1.00		2.80	13.90
de Visser et al. 2012	Germany	6.50	0.30	2.90		9.70
de Visser et al. 2012	Finland	7.30	0.30		4.60	12.20
Silva et al., 2014	France	14.82		4.28		19.10
	EU Average	9.62		3.35		12.97
	EU Average (%)	74%		26%		100%

Table 52. Energy inputs for poultry production EU-27 (PJ)

Total poultry production EU-27	Feed	Other	Total
15.20	146.18	50.99	197.17

Regarding direct energy consumption, by combining and presenting data from a range of sources, Costantino et al. (2016) concluded that heating is by far the largest on-farm energy consuming activity, accounting for around 92% of the total energy consumption, followed by ventilation at 5% and lighting at 3% (Table 53). Of the total, 92% is associated with thermal energy and 8% with electrical energy (Table 54) (Costantino et al. 2016).

Table 53. Heating, ventilation and lighting energy consumption broiler farms (Costantino et al. 2016)

Source	Country	Heating	Ventilation	Lighting
Amand et al. 2009	France	1.37	0.11	0.07
ADEME 2010	France	1.51	0.15	0.10
Arellano 2011	Spain	5.45	0.17	0.03
Arellano 2011	Spain	2.73	0.17	0.01
Arellano 2011	Spain	1.64	0.17	0.01
Rossi et al. 2013	Italy	2.23	0.12	0.03
Hörndahl 2008	Sweden	1.73	0.07	0.22
	EU Average	2.38	0.14	0.07
	EU Average %	92%	5%	3%

Table 54. Thermal and electrical energy consumption broiler farms (Costantino et al. 2016)

Source	Country	Thermal	Electrical
Amand et al. 2009	France	1.37	0.18
ADEME 2010	France	1.51	0.25
Arellano 2011	Spain	5.45	0.19
Arellano 2011	Spain	2.73	0.18
Arellano 2011	Spain	1.64	0.17
Blázquez & Del Olmo, 2008	Italy	1.40	0.01
Rossi et al. 2013	Italy	2.15	0.23
Hörndahl 2008	Sweden	1.73	0.30
	EU Average	2.25	0.19
	EU Average %	92%	8%

The above Tables 53 and 54, however, do not include energy inputs related to feeding and manure management, while it is also important to note that there may be significant geographical variation, especially in warmer climates. For instance in Cyprus, Markou et al. (2017) find that 40% of energy is associated with heating, 28% with ventilation, 24% with transportation, 5% with lights, 2% with feeding and 1% with watering. This study also finds that closed chicken houses have 30-40% less energy consumption as compared to open houses. Closed broiler houses get 35% of their energy from electricity, and 65% from fuels, while for open broiler houses 20% is from electricity and 80% from fuels. The specific energy carriers found are 35% electricity, 17% LPG, 29% biomass and 19% diesel for open broilers, while for the closed type it is 20% electricity, 44% LPG, 11% biomass and 25% diesel (Figure 32) (Markou et al. 2017).

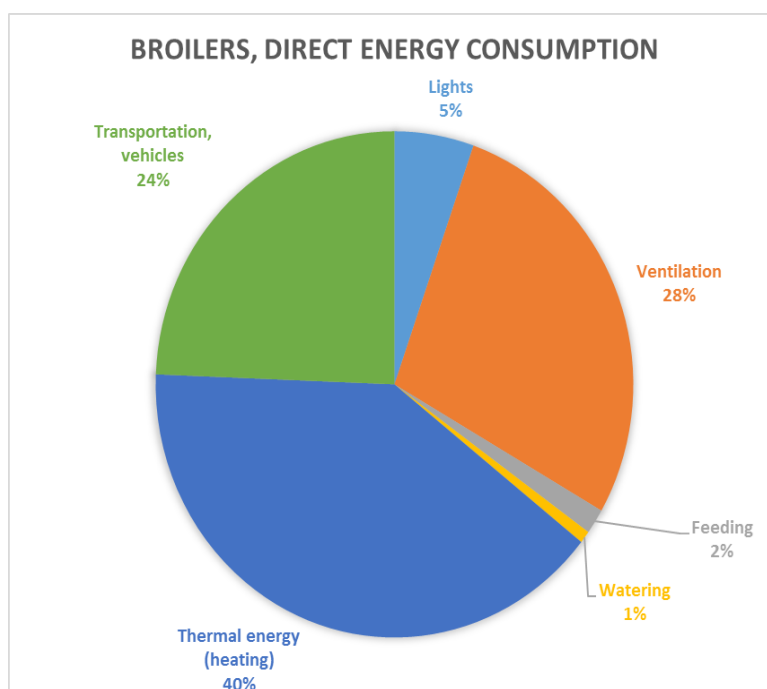


Figure 32. Direct energy consumption in broiler farms in Cyprus (Markou et al. 2017)

5.3.2 Chicken egg production

There is relatively little information available on chicken egg production in the EU which makes it difficult to draw conclusions. Dekker et al.'s (2011) study looks at four egg production systems in the Netherlands, which though geographically limited covers the main production systems in the EU. This study finds that to produce 1 kg of eggs 20.5-23.5 MJ of energy inputs are needed, and that in all cases at least 50% of all energy inputs are associated with feed.

Table 55. Energy inputs for egg producing systems MJ/kg (Dekker et al. 2011)

Source	Country	Feed	Hatching and Rearing	Laying hen husbandry	Transport	Total
Dekker et al., 2011	NL Battery Cage	11.2	0.9	1.9	6.6	20.6
Dekker et al., 2011	NL Barn	12.90	1.00	0.80	8.25	22.95
Dekker et al., 2011	NL Freerange	13.20	1.05	0.80	8.45	23.5
Dekker et al., 2011	NL Organic	10.30	1.50	1.10	7.65	20.55
Average %		50%	7%	5%	37%	100%

Leinonen et al.'s (2012) study conducts an LCA on the environmental impacts of chicken egg systems in the UK. This study finds that feed represents between 54-75% of the total energy use. This is followed by on-farm electricity use (mainly for ventilation, automatic feeding and lighting), consuming between 16-38% of the total energy use. Gas and oil (used mainly for heating and incineration of dead layer birds) used 7-14% of the total primary energy (Leinonen et al. 2012). Similarly, Markou et al. (2017) finds that feed represents around 83% of the total energy consumption. Regarding direct energy consumption, the study finds that ventilation accounts for 33% of energy use, lighting for 15%, transportation for 17%, thermal energy for 3%, waste removal for 2%, packaging for 14%, watering for 1% and feeding for 15%. The specific energy carriers are found to be 55% electricity, 12% LPG and 33% diesel (Figure 33) (Markou et al. 2017).

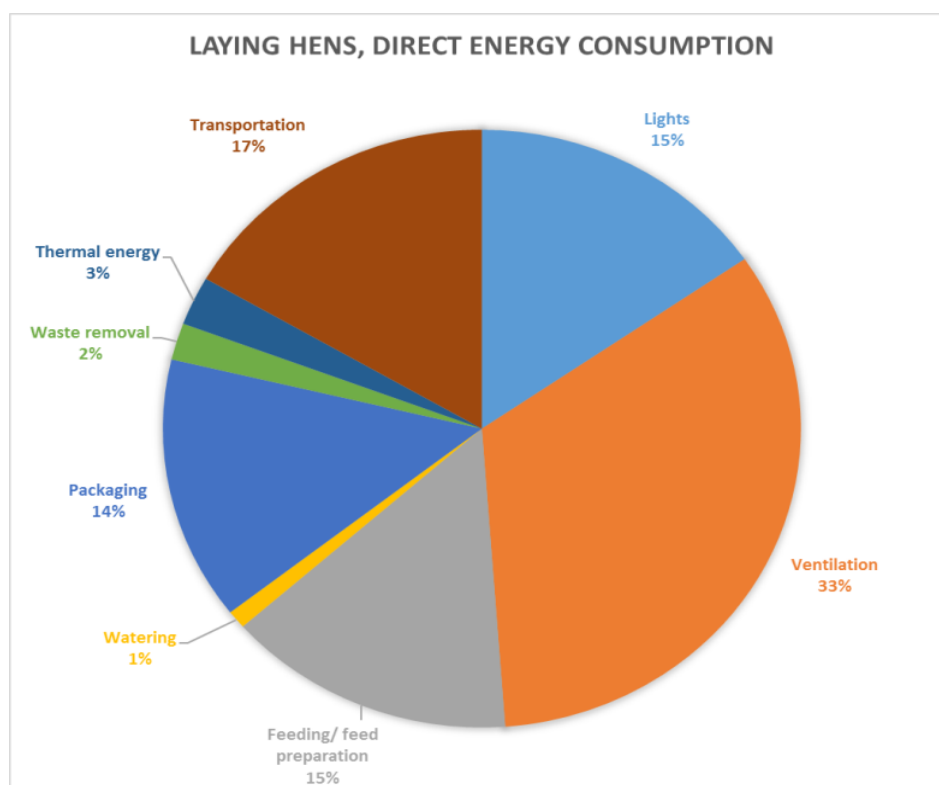


Figure 33. Direct energy consumption in egg production systems in Cyprus (Markou et al. 2017)

5.4 Sheep and Goat

A small number of studies have been conducted on sheep and goat production in the EU but not enough to give us reliable figures for the EU as a whole. This is mainly due to their relatively small size as compared to the other livestock systems, as goat and sheep milk account for around 1.5% and 1.8% of the total milk produced in the EU respectively and 0.8 million tonnes of meat each. However, a few studies have been done which can give us an indication of the energy use status of these systems. The main sheep meat producing country is Spain and the main goat meat producing countries Greece and Spain (Eurostat 2019a).

5.4.1 Sheep and Goat meat

Benoit and Laignel (2010) investigate the non-renewable energy consumption in 4 sheep farming systems in South West France and find that 59.8-88.7 MJ of energy inputs are required per kg of carcass weight. This study finds that in almost all cases, fertilizers and feed are the main energy inputs accounting for around three quarters of the total energy consumption, followed by direct on-farm diesel use. The study also finds that sheep reared in a grazing system consumed on average 42% less energy overall as compared to other systems (Benoit and Laignel 2010).

Wallman et al. (2011) conducted a study on lamb farming in Sweden. This study finds that around 33 MJ of total energy inputs were required per lamb carcass, of which 17 MJ was attributed to feed and 16MJ to on-farm diesel (67%) and electricity use (33%). The study also finds that within organic systems, average energy inputs are around half due to decreased use of manufactured feed and fertilizers (Wallman, Cederberg, and Sonesson 2011).

5.4.2 Sheep and Goat milk

Several member states produced significant amounts of milk from animals other than cows with Spain, Greece and France producing 1, 0.8 and 0.8 million tonnes of sheep and goat milk respectively. Italy also produced 0.7 million tonnes of non-cow milk producing almost the entire EU production of milk from buffaloes. The data that we managed to locate suggests that both sheep and goat milk has a higher energy requirement than cow milk. Kanyarushok et al. (2008) conducted a study on goat milk in France, finding that per FPCM a total of 5.06 MJ is required, of which 3.87 is allocated to feed and 1.19 to on-farm production (Kanyarushoki, Fuchs, and van der Werf 2008), while Idele (2011) finds that 4.9 MJ is required per FPCM of sheep milk (no breakdown provided). This is supported by Cossu et al.'s (2020) study on milk cooling which finds that the energy input for sheep milk cooling is significantly higher than cow's milk (Cossu et al. 2020).

6. Energy use in greenhouses

The following section provides an overview of energy use for selected countries in the EU greenhouse sector. Data on the energy use in greenhouse cultivation in the EU is fragmented, therefore, this section provides data on greenhouse energy use both on a country level (for the Netherlands, Italy, Spain, Germany, Denmark, Ireland) and energy use for the three main greenhouse vegetables (tomatoes, cucumber and peppers) grown in the EU.

Greenhouses are complex structures, which aim to create ideal conditions for plant growth and production throughout the year, by controlling temperature, humidity, water, light and carbon dioxide (Von Elsner et al. 2000). There are different types of greenhouses in operation in the EU, ranging from intensive structures that heavily regulate the internal environment to those that are solely plastic sheet covered structures in which production inputs are similar to open-field crops. Due to this difference, data throughout this section is divided into high-energy intensive and low-energy intensive greenhouses. Over the last 2 decades the technology associated with the construction of and agricultural production within advanced greenhouses has advanced considerably with significant changes in design, materials, agricultural techniques etc. Consequently, the potential yield in 'technology intensive' greenhouses have seen dramatic increases, for instance 'good' tomato yields have increased from 100 tonnes per hectare to 600 tonnes per hectare in recent years (Aznar-Sánchez et al. 2020).

According to the FAO an estimated 405 thousand hectares of greenhouses are spread throughout the EU (Baudoin et al. 2017), this figure includes both glass and plastic covered structures. By contrast, Table 56, taken from Eurostat, provides an overview of the area of vegetables, flowers and permanent crops under glass in the EU-27 from 2005-2013. It is important to note that these figures do not include plastic covered structures, but are useful as they provide us with an indication of the extent of greenhouse cultivation under glass (which generally has a large degree of climate control and energy intensity) in the EU-27. Therefore, these two sources taken together roughly suggest that the area under more advanced and energy-intensive greenhouse production in the EU is around 33% whereas around 66% is covered by basic less energy-intensive greenhouse production systems.

Table 56. Area of vegetables, flowers and permanent crops under glass EU-27 (ha)

Country	2005	2007	2010	2013
Belgium	2,140	2,120	2,060	1,800
Bulgaria	900	1,140	1,090	1,080
Czechia	180	190	0	0
Denmark	450	470	460	400
Germany (until 1990 former territory of the FRG)	3,370	3,430	3,170	3,110
Estonia	60	60	40	40
Ireland	60	30	60	180
Greece	4,670	5,340	4,290	4,730
Spain	52,170	52,720	45,700	45,200
France	9,620	9,790	:	11,190
Croatia	:	250	410	500
Italy	28,640	26,500	39,100	38,910
Cyprus	420	430	450	420
Latvia	110	80	50	40
Lithuania	1,010	450	310	330

Luxembourg	0	10	0	0
Hungary	1,910	1,760	1,960	2,260
Malta	70	70	80	100
Netherlands	10,540	10,370	9,820	9,330
Austria	290	580	620	720
Poland	7,170	7,560	6,630	8,080
Portugal	2,310	2,220	2,360	2,490
Romania	2,790	3,250	3,020	3,300
Slovenia	170	180	170	160
Slovakia	250	190	150	100
Finland	450	440	420	400
Sweden	420	180	200	260
Total	130,170	129,810	122,620	135,130

Our research also indicates that there is significant geographical variation in energy intensity between greenhouses in the EU, in general, the more advanced greenhouses are located in northern Europe and basic greenhouse structures in southern Europe. This difference can to a large extent be explained due to climatic conditions as crops grown in Northern European greenhouses have larger heating requirements. An FAO study which focuses on greenhouse production in South-Eastern Europe (including non-EU countries) highlights that in this region around 18% of greenhouses are glasshouses and 82% plastic greenhouses (a higher proportion than the EU average), of all area under greenhouses in the region 97 % are not heated (Table 57) while it is clear that most commercial greenhouses in the Netherlands are heated.

Table 57. Greenhouse surface in South-Eastern Europe (ha)

Glasshouses		Plastic greenhouses		Total		
With heating	Without heating	With heating	Without heating	With heating	Without heating	Total
363	8305	1151	46280	1514	54585	56099
Total (%)				3%	97%	100%

Overall, our findings from this section indicate that energy use varies considerably depending on the type of greenhouse, geographical area and crop grown (see Table 58). From the studies focused on energy use for specific vegetable crops (tomatoes, cucumbers, sweet peppers) in high energy intensity systems heating account for up to 99% of the total energy consumption. Indeed, it has been estimated that the heating/cooling of greenhouses represents 1.5% of Europe's total energy consumption (Santamouris et al. 1996). Methods of heating greenhouses vary throughout the EU, but previous studies have suggested that gas boilers are generally popular as are air-unit heaters for small scale installations (Tataraki et al. 2020) as well as cogeneration (Combined Heat and Power) in certain countries (mainly the Netherlands) (van der Velden and Smit 2019). In recent years sustainable sources of heat, mainly geothermal, have been growing rapidly. Indirect energy sources, mainly fertilizers, constitute a considerable amount of energy inputs in low-energy intensity greenhouses (6-27%), however this proportion falls to around 1% in energy intensive greenhouses.

Table 58. Range of energy consumption per category in EU greenhouses (%)

Energy consumption per category	Range of total energy consumption
Heating and cooling	0-99%
Irrigation	1-19%
Fertilizers	1-27%
Pesticides	0-6%
Lighting	1%

Similarly, considerable variations are found between countries. In the Netherlands, where most greenhouses are heavily managed, 11,000 GJ are consumed on average per hectare of greenhouse cultivation (van der Velden and Smit 2019), our research also suggests that high energy intensity greenhouses in other countries consume similar amounts of energy. By contrast low energy intensity greenhouses, mainly located in Southern Europe, consume 50-70 times less energy per hectare.

6.1 Southern Europe

6.1.1 Spain

Spain has the largest greenhouse sector by area in the EU with an estimated 43,964 hectares under greenhouse production and is the largest supplier of greenhouse vegetables in Europe, 60% of which (approximately 30,000 ha) are located in Almeria (Bibbiani et al. 2016) (Valera et al. 2017) which constitutes the largest concentration of greenhouses in the world. The main types of crops cultivated in these greenhouses are tomato with 26% of total area, pepper (22%), zucchini (16%), cucumber (11%), aubergine (4.5%) and green bean (3%) (Aguilar et al. 2015). There is variation in the type of greenhouses, with a mixture of intensive and non-intensive greenhouses, and the average holding sizes are relatively small.

The available data on energy consumption for the Spanish greenhouses that have heating and cooling focus on energy use associated with tomato production. Our findings illustrate that in greenhouses where heating and cooling takes place they are on par with the energy consumption in greenhouses in the Netherlands with heating accounting for around 72.5% and cooling 27.5% of total energy consumption. By contrast, in greenhouse agriculture, that are not artificially heated or cooled overall energy consumption per hectare is 79 times less.

Table 59. Energy consumption in high energy intensity tomato greenhouses Spain (GJ/ha)

Source	Zone	Product	Heating	Cooling	Total
Baptista et al., 2012	Almeria	Tomato	5760	5400	11160
Baptista et al., 2012	Castellon	Tomato	8640	5400	14040
Baptista et al., 2012	Coruna	Tomato	10080	738	10818
Baptista et al., 2012	Huelva	Tomato	5400	6120	11520
Baptista et al., 2012	Madrid	Tomato	14040	3978	18018
Baptista et al., 2012	Navarra	Tomato	16560	1260	17820
Spain Average			10080	3816	13896
Spain Average (%)			72.50%	27.50%	100%

Table 60. Energy consumption in low energy intensity greenhouse production Spain (GJ/ha) [99]

Source	Crop	Fertilizers	Pesticides	Irrigation	Others	Total
Alonso & Guzman 2010	Tomato (average)	24.97	21.54	13.91	140.60	201.03
Alonso & Guzman, 2010	Lettuce	2.66	0.89	3.00	138.49	145.03
Alonso & Guzman, 2010	Pepper	12.09	1.03	21.00	166.11	200.23
Alonso & Guzman, 2010	Beans	5.29	0.24	4.70	145.12	155.35
	Spain Average	11.25	5.93	10.65	147.58	175.41
	Spain Average (%)	6%	3%	6%	84%	100%

6.1.2 Greece

In Greece, the area under greenhouse cultivation in Greece is approximately 5,600 ha, which represents around 0.12% of the country's total cultivated land area. The majority of this area, around 92%, is allocated to vegetable production, whereas the remaining 8% is allocated to the production of ornamental crops. The most common vegetable crops grown in Greek greenhouses are tomato, cucumber and pepper. Besides vegetable crops, a small part of greenhouses are dedicated to floriculture. Geographically, Crete has the largest area of greenhouse production with 2,166.5 ha (38.7%), followed by the Peloponnese with 1,185.9 ha (21.2%) and Macedonia with 698 ha (12.5%) (Savvas et al. 2016).

Regarding the types of greenhouses found in Greece, nearly 93% of the total area is plastic covered whereas glasshouses are mainly used in floriculture. The limited use of glass coverage is due to two main factors; the very low mean area per greenhouse enterprise, which is 0.48 ha for vegetables, and the fact that the majority of the greenhouse area used for vegetables is occupied by high tunnels. However, greenhouses in Greece are characterised by a relatively low level of automation. Automation systems are specifically used only in vegetable production and are generally neither heated nor cooled. Generally, the productivity of Greek greenhouses has been shown to benefit from both heating and cooling systems. However, the cost of greenhouse heating fuel and cooling in Greece is relatively high and as a result most vegetable greenhouses are not heated. (Savvas et al. 2016).

Table 61. Energy consumption in low energy intensity greenhouse production Greece (GJ/ha)

Source	Product	Fertilisers	Pesticides	Materials	Diesel Use	Irrigation	Heating/Cooling/Lighting	Total
de Visser et al. 2012	Tomato	101	4.5	85	0.5	53	13	257
de Visser et al. 2012	Cucumber	67	7.5	80.5	1		92.5	248.5
	Total Average	84	6	82.75	0.75	26.5	52.75	252.75
	Average (%)	33%	2%	33%	0%	10%	21%	100%

Table 62. Energy consumption in high energy intensity greenhouse production Greece (GJ/ha)

Source	Zone	Crop	Fertilisers, Pesticides, Materials, Fuel, Irrigation	Heating	Cooling	Lighting	Total
Kittas et al. 2013	Thessaly	Tomato	76.86	8137.8	328.32	7.2	8550.18
Trypanagnostopoulos et al. 2017	Pyrgos	Lettuce		5400		1800	7200
Vourdoubas 2015	Crete	Flowers	3024	7920		504	11448
		Total Average	1033.62	7152.6	109.44	770.4	9066.06
		Average (%)	11%	79%	1%	8%	100%

Table 61 illustrates that for low energy intensive greenhouses fertilizers and materials each account for 33% of energy inputs, followed by irrigation (10%) and pesticides (2%). Whereas heating, cooling and lighting account for around 21% of energy inputs. By contrast in high energy greenhouses heating cooling and lighting account for up to 99% of all energy inputs. This mainly occurs because Southern European countries like Greece have higher temperatures all year long when compared to Central European countries like Germany or the Netherlands. Furthermore, it should also be noted that even though greenhouses in Greece need heating and cooling due to the climate conditions, (Savvas et al. 2016).

The total consumption presented in the tables above are based on the studies conducted by Bibbiani et al. (2016) (Bibbiani et al. 2016) and Savvas et al. (2016) (Savvas et al. 2016). These studies suggest that almost 83.5% of the total greenhouse cultivation systems are non-heated and 16.5% are heated. Our research shows that the greenhouses that are not heated have much larger indirect energy inputs than those that are heated. This suggests that even though the majority of the available studies on Greek greenhouses consist of data on heated greenhouses, this information does not depict reality accurately as these only constitute a small percentage of the total greenhouse facilities.

6.1.3 Italy

The area under greenhouse cultivation in Italy is approximately 30,000 ha, with 6,000 ha serving as permanent greenhouse structures (Bibbiani et al. 2016). The greenhouses in Italy are distributed all over the Italian peninsula with the majority, about 60%, located in southern regions. There are different types of greenhouses used ranging from simple structures covered by plastic films to fully automated glass structures (Pardossi and Tognoni 1999). The former greenhouse type is predominant in southern regions due to the favourable climatic conditions, which allow for the use of simple and inexpensive structures for winter cropping of warm season species and are usually equipped with simple heating systems. On the other hand, greenhouses situated in the northern areas of Italy consist mostly of structures covered with glass. It is calculated that approximately 20-30% of the Italian greenhouses are equipped with heating and cooling systems (Carlini, Honorati, and Castellucci 2012). Due to favourable growing conditions and reduced costs greenhouse cultivation has been moving southward. The cultivation of pot plants occurs in glasshouses and is situated in the north (Pardossi and Tognoni 1999). The Italian greenhouse sector is of considerable

economic importance for the national agricultural systems. Even though Italian greenhouse systems only represents around 0.032% of the EU UAA, Italian greenhouse crops account for a turnover of more than 3 billion € (Campiotti et al. 2014).

Figure 34, produced by the Italian Ministry of Economy and Finance, illustrates that heating powered by fuel accounts for 0.72 Mtoe, which is equivalent to nearly 24% of the direct energy consumption in Italian agriculture, while electricity use in greenhouses accounts for only 0.02Mtoe.

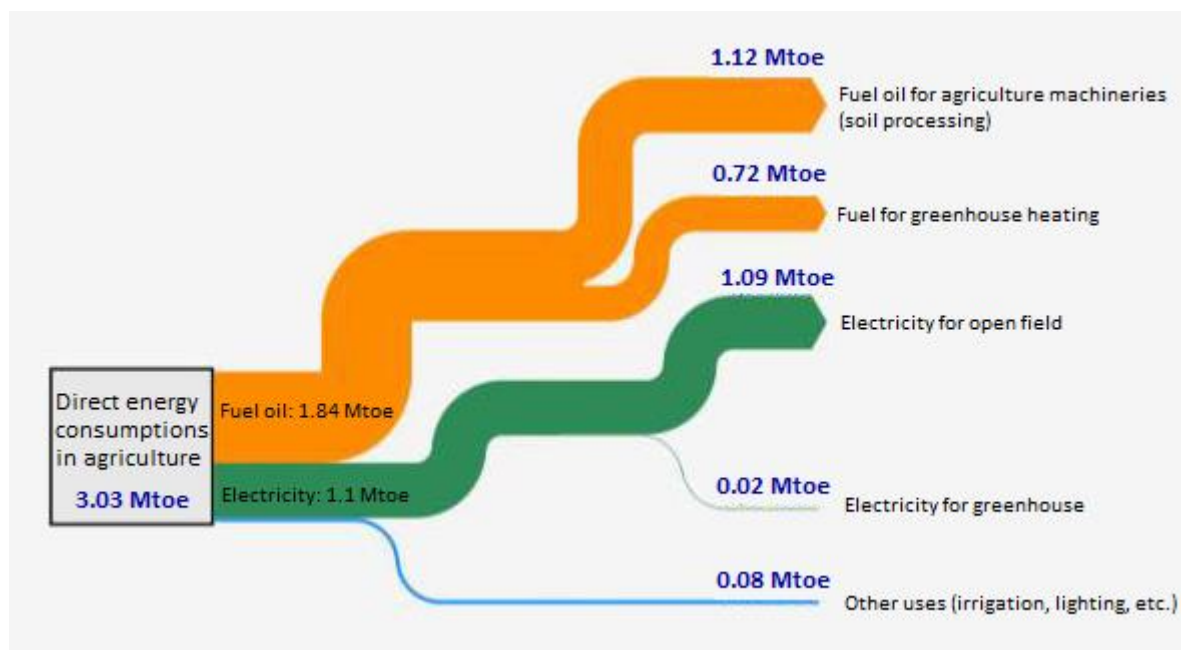


Figure 34. Sankey diagram of the direct energy consumption (Mtoe) in the Italian agriculture (2011) (Bibbiani et al. 2016)

Table 63 illustrates the energy consumption in low-energy intensity greenhouse production in Italy, that are not heated. Overall these results suggest that electricity accounted for 56% of total energy consumption, followed by diesel 24%, and followed by fertilizers 12%, seeds 6%, pesticides 2% and irrigation 1%.

Table 63. Energy consumption low-energy intensity greenhouse production Italy (Campiglia et al. 2007)

Source	Crop	Seeds	Fertilizers	Pesticides	Diesel	Electricity	Irrigation	Total
Campiglia et al. 2007	Tomato	5.52	21.95	1.76	28.83	65.62	1.97	125.63
Campiglia et al. 2007	Lettuce	20.70	8.23	1.52	11.09	20.46	0.87	62.87
Campiglia et al. 2007	Melon	1.44	13.56	2.12	36.26	85.09	1.39	139.86
Campiglia et al. 2007	Zucchini	2.30	12.41	2.71	26.35	59.07	1.28	104.13
Campiglia et al. 2007	Parsley	0.01	7.18	1.42	21.79	62.10	0.91	93.41
	Total	5.99	12.67	1.91	24.87	58.46	1.28	105.18
	Average %	6%	12%	2%	24%	56%	1%	100%

6.2 Northern and central Europe

6.2.1 The Netherlands

In the Netherlands, 9,688 ha are covered by greenhouses; around 45% of this is devoted to vegetable production, 25% to flower production and 15% to fruit production. Production is generally intensive, and yields are high, especially compared to greenhouse production in other countries, average production per m² in 2019 was 50 kg for tomatoes 68kg for cucumbers (FAOSTAT 2021). Due to this on a relatively small area, 21% of the peppers, 20% of the cucumbers, and 17% of the tomatoes are produced of the total vegetables grown in Europe (Lambregts, Bakker, and Van Hoof 2019). Dutch greenhouses are generally characterized by large permanent structures that are heavily climate controlled, with large scale heating, cooling, lighting and ventilation facilities. In recent years, large transitions have occurred that have started to improve the efficiency and dramatically cut the amounts of inputs used such as water and pesticides.

According to the annual publication of the energy monitor of the Dutch greenhouse sector, the total current energy consumption in the Dutch greenhouse sector stands at 106.8 PJ. Most energy consumption is associated with heating, accounting for around 74% of the total energy inputs, and electricity at 26% (Figure 35). Overall, energy use is dominated by energy from natural gas (accounting for 99.9% of the total fossil sources). Around 58% of electricity was produced at the greenhouses by cogeneration while 42% was purchased. In 2019 10 PJ (9.4%) of the energy consumed in the Dutch greenhouse sector came from renewable sources, the energy from renewable sources has been growing rapidly in recent years and increased by 35% between 2017 and 2018. In particular sustainable (mainly geothermal) heat has been growing rapidly, this rapid transition is likely to continue (van der Velden and Smit 2019).

Table 64. Energy consumption in greenhouses in Netherlands (van der Velden & Smit 2019)

	unit	2010	2015	2019
Natural gas use	million m ³	4.5	3.212	3.295
Other fossil	million m ³	2	1	1
Renewable energy consumption	PJ	2.4	4.9	10
Total energy consumption	PJ	127.1	99.4	106.8

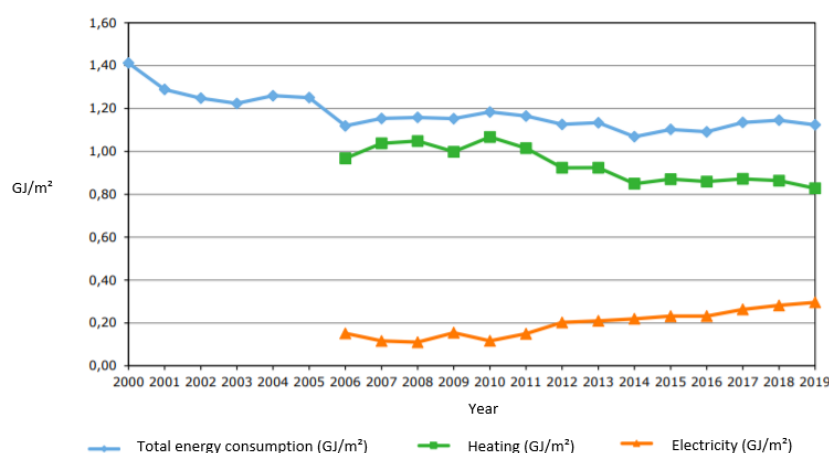


Figure 35. Energy consumption in greenhouses in Netherlands (van der Velden & Smit 2019)

Table 65. Greenhouse energy consumption for selected crops in the Netherlands (GJ/ha)

Source	Country	Crop	Fertilizers	Pesticides	Heating	Total
de Visser et al. 2012	The Netherlands	Sweet pepper	112.6	2.5	11424	11539
Stanghellini et al. 2016	The Netherlands	Sweet Pepper				15540
de Visser et al. 2012	The Netherlands	Tomato	119	1	14990	15110
Stanghellini et al. 2016	The Netherlands	Tomato				11480
de Visser et al. 2012	The Netherlands	Cucumber	0	0	14245	14360
Stanghellini et al. 2016	The Netherlands	Cucumber				11320
Stanghellini et al. 2016	The Netherlands	Strawberry				6310
Stanghellini et al. 2016	The Netherlands	Eggplant				11320
Stanghellini et al. 2016	The Netherlands	Zucchini				9510
Stanghellini et al. 2016	The Netherlands	Radish				1550
Stanghellini et al. 2016	The Netherlands	Lettuce				2820

On a per crop basis, for the three studies that have detailed data, the vast majority of the total energy inputs are connected with heating, accounting for over 99% energy use while other inputs, such as fertilizers, are minor. It is important to note that these energy requirements are amongst the highest recorded for all greenhouses in the EU-27. The most important activities for greenhouses in the Netherlands are heating, ventilation and air circulation, cooling, humidification, irrigation, pesticides, CO₂ enrichment and others. The basic indirect energy inputs needed to produce tomatoes, cucumbers and sweet peppers are mostly nitrogen and potassium fertilizers.

6.2.2 Denmark

The Danish greenhouse sector is relatively small covering an estimated 500 hectares which are mostly owned and operated by small farming households (Gadtke 2010). The majority of the greenhouses are heated and the main crops grown are ornamental plants and vegetables (tomato, cucumber, lettuce, mushrooms). The main areas of production occurs on the island of Funen, Jutland and eastern Zealand (Andersen 1989). According to the Danish National Statistic Agency, the total amount of vegetables produced in greenhouses has decreased in recent years for salad and tomatoes and increased for cucumbers.

According to Dansk Gartneri and Gartnerirådgivningen it is estimated that the Danish greenhouse sector accounts for over 99% of the total energy consumption in the horticulture industry. The data provided include only the energy consumed by greenhouse nurseries and for Christmas tree cultivation. Table 66 presents the available data on the energy consumption from greenhouse nurseries and Christmas tree cultivation for 2011 (Hedelund Sørensen et al. 2015).

Table 66. Distribution in energy consumption in TJ by main energy source in the horticulture sector

Source	Country	Type	Oil Products	Coal	Gas	VE	District Heating	Electricity	Total
KORTLÆGNING AF ENERGIFORBRUG I VIRKSOMHEDER	Denmark	Nurseries	420	644	1539	19	1585	798	5005
	Denmark	Christmas Trees	29						29
Total			449	644	1539	19	1585	798	5034
Total (%)			9	13	31	0	31	16	100

The energy needed for heating the nurseries holds the biggest share among the total energy consumption, followed by gas and electricity. On the other hand, for Christmas tree production only diesel oil is being used. This sector compared to the nurseries accounts for only 1% of the total energy consumption.

6.2.3 Ireland

The Irish greenhouse industry is an important economic sector in Ireland. The greenhouses are mainly family run businesses and the majority of production occurs in glass houses. The main crops cultivated are strawberries as well as other berries, tomatoes, lettuce, cucumbers and sweet peppers. Also, there are some facilities, glass house nurseries, dedicated to the cultivation of flowers. These small nurseries are usually less than 2.5 ha in area (Bourke 2020). Data on energy consumption within the Irish horticulture are scarce due to the fact that energy inputs are extremely variable depending on the temperature requirement and the season of the crop. Another factor is the relatively small extent of the Irish horticulture industry which makes it difficult to study the sector in detail. Table 67 presents an average case of energy consumption in the Irish greenhouses shared with use by our partners at TEAGASC.

Table 67. Typical energy consumption in kWh/m² in an Irish greenhouse

Source	Country	Type	Heating	Cooling	Lighting	Other	Total Energy Consumption
TEAGASC	Ireland	Glasshouse	310	3	2	2	317

6.2.4 Germany

In Germany 3,689 hectares are covered by greenhouses, of which an estimated 80% are glass greenhouses 15% foil and 5% stiff plastics while 2500 hectares are heated (Voss 2011). The main crops cultivated in the German greenhouses are tomato, cucumber, certain plants and other crops. It is important to note that, most of the facilities are relatively old; 43.1% of the total number of greenhouses which accounts for almost 1600 ha were built before 1982. Even though some of these facilities were upgraded to comply with the modern-day standards, most of the facilities are still outdated and only 10.6% of the total facilities were built after 2000. Furthermore, most of the production area under glass which is specialized for vegetable crops is owned by “small” farmers. Regarding holding size, 3800 facilities are 1000 m², almost 5600 facilities cover between 1000 m² and 5000 m² and the remainder of facilities are larger than 5000 m².

For Germany, the studied crops regarding energy consumption in greenhouses were tomato and cucumber. The biggest share of the energy inputs is attributed to heating purposes, whereas a small portion of the energy inputs account for fertilizers (Table 68).

Table 68. Energy consumption in the German greenhouse sector GJ/ha

Source	Country	Product	Fertilizers	Heating	Total
de Visser et al. 2012	Germany	Tomato	42	12612	12654
de Visser et al. 2012	Germany	Cucumber	53	13000	13053
Average			47.5	12806	12853.5

The available data suggests that on average 12853.5 GJ of energy inputs are consumed per hectare of greenhouse cultivation, of which 99.6% accounts for heating purposes. Table 69 illustrates that fossil fuels dominate the share of energy sources for greenhouse heating (Kuntosch et al. 2020).

Table 69. Percentages of the energy sources used for greenhouse heating in Germany

Greenhouse heating breakdown	
Black Coal	28%
Natural Gas	21%
Renewable sources	20%
Fuel Oil	15%
Other	16%
Total	100%

6.3 Greenhouse crops

6.3.1 Tomatoes

Tables 70 and 71 provide an overview of studies that have performed an energy analysis of tomato production in the EU. In the high energy intensity systems up to 99% of energy use is associated with heating and cooling activities while in the low energy intensity systems fertilizers (25%) and other (35%) are the largest energy inputs. Importantly, this illustrates that energy inputs in high energy intensive tomato production systems are on average 58 times greater per hectare than in low energy intensive systems. This energy intensity translates to large differences in final yield, for instance, in the Netherlands the average tomato yield is around 50 kg/m² while in southern Italy is 7.6 kg/m² (Palmitessa, Paciello, and Santamaria 2020).

Table 70. Energy inputs in high energy intensity tomato production systems (GJ/ha)

Source	Country	Fertilizers	Pesticides	Heating	Cooling	Other	Total
de Visser et al. 2012	Germany	42.00		12612.00			12654.00
de Visser et al. 2012	The Netherlands	119.00	1.00	14990.00			15110.00
Kittas et al., 2014	Greece	58.86		8137.80	328.32	25.20	8550.18
Baptista et al., 2012	Spain			10080.00	3816.00		13896.00
EU Average		80.50	0.33	11454.95	1036.08	6.30	12578.16
EU Average (%)		1%	0%	91%	8%	0%	100%

Table 71. Energy inputs in low energy intensity tomato production systems (GJ/ha)

Source	Country	Seeds	Fertilizers	Pesticides	Diesel	Electricity	Irrigation	Other	Total
Campiglia et al. 2007	Italy	5.52	21.95	1.76	28.83	65.62	1.97		125.63
de Visser et al. 2012	Greece		101	4.5	0.5		53	98	257
de Visser et al. 2012	Portugal average		70	19.5	26.5		92.5	64.5	273
Alonso & Guzman, 2010	Spain average		24.97	21.54			13.91	140.60	201.03
	EU Average	1.84	54.48	11.83	13.96	16.40	40.34	75.78	214.63
	EU Average (%)	1%	25%	6%	7%	8%	19%	35%	100%

6.3.2 Cucumber

Our findings suggest that energy inputs in high energy intensive cucumber systems are on average 55 times greater per hectare than in low energy intensive systems. In high energy intensive systems up to 99% of energy use is associated with heating while in low energy intensive systems around 37% is associated with heating and cooling, 32% with other and 27% with fertilizers. Similarly, to tomatoes this energy intensity translates to large differences in final yield, for instance, in the Netherlands the average cucumber yield is around 70 kg/m² while in Spain, the largest producer in the EU, it is just under 10 kg/m².

Table 72. Energy inputs in high energy intensity Cucumber production systems (GJ/ha)

Source	Country	Fertilizers	Pesticides	Heating	Total
de Visser et al. 2012	Germany	53	0	13000	13053
de Visser et al. 2012	The Netherlands	115	0	14245	14360
	Average	84	0	13622.5	13706.5
	Average (%)	1%	0%	99%	100%

Table 73: Energy inputs in low energy intensity cucumber production systems (GJ/ha)

Source	Country	Product	Fertilisers	Pesticides	Diesel Use	Heating	Other	Total
de Visser et al. 2012	Greece	Cucumber	67	7.5	1	92.5	80.5	248.5
		Average (%)	27%	3%	0%	37%	32%	100%

6.3.3 Peppers

Similarly, our findings suggest that energy inputs in high energy intensive sweet pepper systems are on average 57 times greater per hectare than in low energy intensive systems. In high energy intensive systems up to 99% of energy use is associated with heating while in low energy intensive systems around 83% is associated with other, 10% with irrigation and 6% with fertilizers.

Table 74. Energy inputs in high energy intensity sweet pepper production systems (GJ/ha)

Source	Country	Fertilizers	Pesticides	Heating	Total
de Visser et al. 2012	The Netherlands	112.6	2.5	11424	11539
Average (%)		1%	0%	99%	100%

Table 75. Energy inputs in low energy intensity sweet pepper production systems (GJ/ha)

Source	Fertilizers	Pesticides	Irrigation	Others	Total
Alonso & Guzman, 2010	12.09	1.03	21.00	166.11	200.23
Average (%)	6%	1%	10%	83%	100%

7. Discussion

Table 76 provides an overview of our findings according to agricultural systems. Indirect energy uses make up the majority of energy inputs in open-field agriculture (mainly nitrogen fertilizers) and livestock systems (mainly animal feed), while direct energy uses (mainly diesel use associated with machinery use) are also significant. For greenhouses, however, the types and dominance of different energy inputs are dependent on the climate and type of greenhouse production system; the proportion of direct and indirect energy inputs are similar in low-energy intensive greenhouses (which constitute the majority of greenhouses in Southern European countries), whereas in North and Central Europe it is direct energy inputs (predominantly energy for heating) that make up the vast majority of energy inputs. Furthermore, it is clear that energy from non-renewable sources are dominant throughout the EU agricultural systems and that although energy from renewable sources is growing, it currently constitutes a minor proportion of the total energy use. This demonstrates that in order for the EU to reach the goals outlined in the Green Deal and its Farm to Fork strategy, a radical change in energy use in the agricultural sector is required. Such an approach would need to be multi-pronged, to entail multiple methods and directions, and would likely need to drastically improve the energy efficiency across the sector while at the same time focus on transitioning rapidly to energy from renewable sources.

Table 76. Energy inputs in EU agricultural systems %

¹ Agricultural System		Indirect (%) ²		Direct		Other/unclassified		Total	
Open field	Arable	63%	(769)	31%	(380)	6%	(78)	100%	(1227)
	Orchards and vineyards	51%	(106)	31%	(64)	18%	(38)	100%	(208)
Livestock	Meat	56%	(282)	44%	(218)			100%	(501)
	Dairy	74%	(400)	15%	(82)			100%	(543)
³ Greenhouse	High intensity	1%		99%				100%	
	Low Intensity	23%		27%		50%		100%	
¹ Only crops and systems covered in this study are included									
² Data in brackets are total energy consumption figures in PJ									
³ The data for greenhouses are simple averages based on studies that provided data on tomatoes, cucumbers and greenhouses and therefore should solely be seen as indicative									

In addition, energy use across EU agriculture varies significantly depending on production systems, cropping intensity, geographical area and farm size. Our study indicates that there may be a general positive correlation between larger farms and energy input per hectare. Further research on this is needed. As larger farms tend to benefit from economies of scale, these are also more likely to be earlier adopters of newer, more energy efficient technologies. Moreover, it is also suggested that non-conventional systems (organic, conservation) do not necessarily use less energy inputs, but do use more sustainable energy sources. However, in-depth research into the relationship between farming system, farm size, geographical location and energy use is outside of the scope of this study and further research on this is required.

7.1 Open-field agriculture

Our results clearly indicate that fertilizer production and use is the largest energy consuming activity in open-field agriculture, accounting for around 50% of all energy inputs and varying from 26% in apple and vineyard production systems to 58-59% in wheat production systems. This suggests that minimising the consumption of manufactured fertilizers and increasing their efficiency both in terms of production and use would have the largest impact in reducing energy use in open-field agriculture

in the EU. Various FEFTS, such as increasing the use of organic fertilizers (from agricultural and other organic wastes/feedstocks) and transitioning to lower input and more sustainable production systems (such as agroforestry, no-tillage or conservation agriculture), can reduce the fossil energy use associated with fertilizer use. Similarly, energy use associated with pesticide production, which accounts for 5% of the total energy inputs, could be reduced by minimising the consumption of manufactured pesticides, increasing their use efficiencies, transitioning to more sustainable production systems and increasing the share of locally produced organic pesticides.

As far as direct energy inputs are concerned, the largest input in open-field agriculture is on-farm diesel use. Most of this energy is associated with tractor use; according to a rough estimate provided to us by CEMA, there are an estimated 10 million tractors in the EU-28. However, 80% of all the heavy work is carried out by only 20% of these tractors, mainly the newest and most powerful ones. In open-field agriculture, the main direct energy consuming activities are related to soil tillage, harvesting and sowing. Various FEFTS, such as using more efficient tractor/implement combinations, switching to renewable sources for transport (such as tractors powered by on-farm produced renewable energy sources, for example electricity from photovoltaic panels or biofuels like biomethane from manure and waste residues), adopting agricultural practices that minimise tillage and improve farm management efficiencies, could have a large impact on overall diesel use. For instance, a report by VDMA (2019) (Götz and Köber-Fleck 2019) finds that by combining soil tillage and sowing operations, fuel use can be reduced by up to 42%.

Our findings suggest that almost 8% of open-field agriculture is powered by electricity, which is used mainly for irrigation, storage and drying activities. EU electricity systems are rapidly transitioning to renewable sources (reaching 34% in 2019), which suggests that, in the medium and long term, switching to electricity powered systems for on-farm operations could significantly reduce the share of fossil fuels in direct energy consumption. In addition, in many cases, electric powered systems are more efficient than fossil fuel powered systems.

7.2 Livestock

Our results clearly indicate that animal feed is the largest energy consuming activity in livestock systems, ranging from 19% in beef production systems to 74% in poultry and dairy cow production systems. This would suggest that reducing the reliance on animal feed, especially imported animal feed, and reducing the energy intensity of animal feed would reduce overall energy use. On the one hand, the EU market for feed is moving towards more locally produced, although a significant deficit in high-protein feed remains despite a large increase in EU-grown soy and other protein sources. In addition, multiple studies have shown that grass fed cattle consume less energy than those fed on other types of feed. However, switching to grass fed would require significant amounts of arable land and agricultural inputs (Capper 2012).

On the other hand, since a significant amount of the energy associated with feed is for the production of cereals and oilseeds, finding other feedstocks could reduce the energy intensity of feed. For instance, EIP-AGRI (2020) identified 5 new feed options for pig and poultry farming that would reduce the environmental footprint of animal feed; bakery products, green biomass (glass/clover), insects, micro-algae and single cell protein (EIP-AGRI Focus Group 2020).

On-farm energy use is concentrated in housing and manure management. Electricity is generally used for lighting, feeding and milking systems, though their intensity varies depending on the production system, while fossil fuels associated with direct energy inputs are often used for manure

management and heating. Switching to more renewable electricity sources could invariably help reduce the amount of fossil energy used for on-farm activities. However, further research is needed in the energy use associated with smaller farms in order to have a more comprehensive overview of the total energy consumption and concentration.

It is important to highlight the importance and the potential of livestock manure as a source of organic fertilizer as well as for renewable energy production in the EU. Overall, it is estimated that just under 10 million tonnes of nitrogen and around 1.5 million tonnes of phosphorus are applied to fields in the EU through manure application (European Commission 2019). Similarly, over the past two decades, there has been a significant rise in biogas production using manure as a feedstock, led by Germany. Scarlat et al. (2018) estimates that the amount of biogas produced from manure can be realistically increased by 18 billion m³ of biomethane across the EU in areas with high livestock densities (Scarlat et al. 2018). This also applies to the potential of developing other renewable energy plants that run on other agricultural wastes/feedstocks.

7.3 Greenhouses

Greenhouse energy use varies significantly depending on the type of greenhouse, geographical area and crop grown. In advanced greenhouse systems heating is dominant accounting for up to 99% of all energy inputs. Energy requirements for heating and cooling are so large in these systems that other energy inputs such as fertilizers are very minor. Methods of heating greenhouses vary throughout the EU but are currently still dominated by energy from fossil fuels. However, in recent years sustainable sources of heat, mainly geothermal, have been growing rapidly. Recent research indicates that the installation of these can also be economically advantageous as compared to alternatives (Kinney et al. 2019). This suggests that the transition to sustainable sources, which is already occurring at a rapid pace in certain countries, could open the door to major reductions in the dependency on fossil sources in the greenhouse sector.

In less energy intensive systems, overall energy requirements per hectare are significantly less but generally still multiple times the energy requirements of open-field agriculture and the mixture of energy inputs are split between direct (lighting, heating/cooling, irrigation, machinery use) and indirect (fertilizers and pesticides). This suggests that interventions, like those proposed for open-field agriculture, could both reduce overall energy use as well as move away from fossil-based energy sources. These could include reducing fertilizer and pesticide use and increasing their use efficiency, increasing the share of renewable energy sources and adopting efficient practices that minimize their use.

Despite our findings, there is relatively little data and few studies that have looked at energy use in greenhouses in the EU. As such our findings are limited to several countries and crops and highlights the importance of further research into the extent of energy use across the EU, the types of greenhouses that exist, the extent of greenhouse cultivation and their energy use, there seems to be a number of data inconsistencies, for example, the annual published greenhouse energy monitor for the Netherlands states that heating accounts for around three quarters of all energy inputs and other energy inputs around a quarter. However, most LCAs covered in this study suggest that heating/cooling accounts for up to 99% of all energy inputs. This discrepancy needs further research.

8. Conservation Agriculture

8.1 Conservation agriculture - A sustainable approach

It is well recognized that European croplands suffer from severe degradation from losses on soil organic carbon which, in turn, facilitate soil erosion, loss of soil fertility and soil compaction. According to Vleeshouwers and Verhagen (2002), the average loss of soil organic carbon (SOC) in the European Union is 78 Tg of carbon per year (Vleeshouwers and Verhagen 2002). A study in Spain by Janssens et al. (2005) encountered losses of 47 kg ha (I. A. Janssens et al. 2005) and in some susceptible regions, like the Ural Mountains, Janssens et al. (2003) estimated a loss of up to 300 Tg of carbon per year (Ivan A. Janssens et al. 2003).

In this context, this section investigates the potential that Conservation Agriculture (CA) presents – as an indicative example of a sustainable technique – in developing less energy intensive, more sustainable and resilient agricultural systems in the EU. This is especially significant as the adoption and scaling of these types of techniques (such as no-tillage, mulching) offer considerable potential in supporting the attainment of the 2030 and 2050 climate targets. Multiple studies highlight that CA can protect soils, improve long-term productivity, reduce the energy needs of agricultural systems and sequester carbon into the soil.

According to the European Conservation Agriculture Federation (ECAAF), CA is defined as a sustainable agricultural production system that includes a set of agronomic practices adapted to the demands of the crop and the local conditions of each region, whose techniques of cultivation and soil management protect it from erosion and degradation, improve its quality and biodiversity, contribute to the preservation of natural resources such as water and air, without impairing the production levels of the farms (ECAAF 2021). According to the FAO (FAO 2021), CA is based on the practical application of three context-specific and locally-adapted, interlinked principles, namely:

- **No or minimum mechanical soil disturbance.** This principle is implemented by the practice of no-till seeding or broadcasting of crop seeds, the direct placement of planting material into untilled soil and no-till weeding, causing the minimum soil disturbance possible from any agricultural operation. By implementing this principle, farmers protect the soil, promote overall soil health and functions, including improved retention of soil moisture, improve soil nutrition for plants and soil carbon, and also reduce any labor and energy requirements, thereby reducing GHG emissions associated with agriculture.
- **Permanent maintenance of a vegetative mulch cover on the soil surface.** The use of crop residues (including stubbles) and cover crops reduces soil erosion (at least 30% of the soil must be covered by organic material in order to gain efficient protection against erosion); protects the soil surface; increases water infiltration rates, reducing run-off; conserves water and nutrients, and; supplies organic matter and carbon to the soil system.
- **Diversification of species in cropping system** through rotations involving annual and perennial species so that soil fertility and soil biodiversity are improved, while pests and diseases are better controlled by breaking their cycles.

Besides the apparent benefits on soil conservation and productivity, CA is a system that can enormously help to mitigate climate change. Firstly, by supporting soil carbon fixation by returning greater amounts of CO₂ into the soil in the form of crop residues and cover crops that provide extra biomass for soil carbon enrichment. Secondly, by reducing GHG emissions through preventing the

oxidation of soil organic carbon. Thirdly, by reducing energy inputs either from energy savings through less fuel consumption, or reduced needs for agrochemicals such as fertilizers, plant protection products and improved water use efficiency that reduce the needs for irrigation (Figure 36).

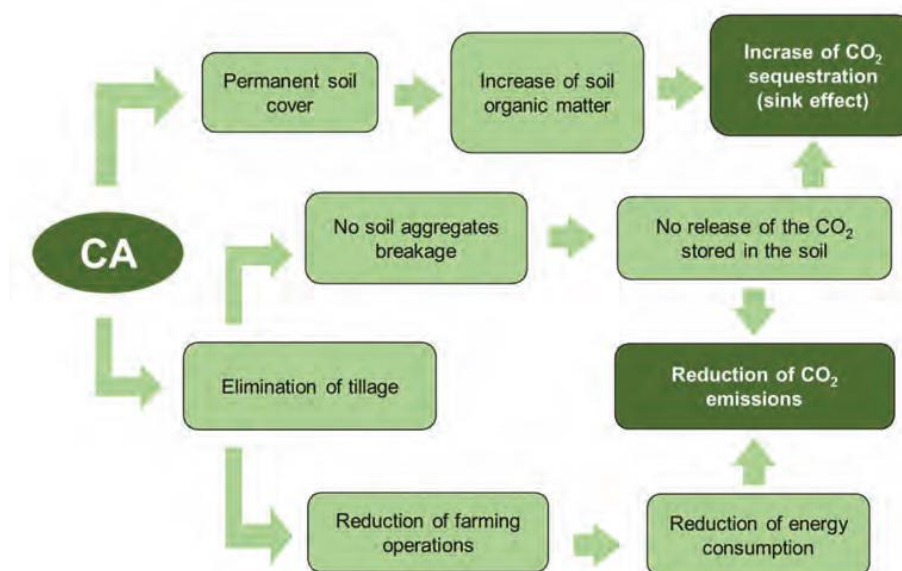


Figure 36. Mitigate Climate Change mechanisms through Conservation Agriculture. (Gil Ribes et al, 2017)

8.1.1 Enhanced soil carbon fixation

Carbon sequestration is a key element for achieving sustainable agricultural and ecological development and for meeting the global challenges for mitigation and adaptation to climate change. There are many ways for facilitating the incorporation of soil organic carbon (SOC) into agricultural soils; reduced tillage intensity and residue retention, which are central tenets of CA, are among the most effective, least expensive and most readily implementable near-term options (Smith et al. 2019).

Overall, according to González-Sánchez et al. (2012), conservation practices have the potential to promote in the EU the fixation of about 2 Gg year more carbon into the soil than traditional tillage systems. Another study by the same author maintains that CA can help achieve around 22% of the necessary reductions in GHGs emissions for the non-ETS sectors in the EU-28 by 2030, and at the same time, allow an additional 10% reduction over the non-ETS sectors (see Table. 77) (González-Sánchez et al. 2017). Lal (2004) (Lal 2004b) estimates the potential soil carbon fixing potential in the adoption of CA on 1500 million hectares globally to be between 0.6 and 1.2 Pg of carbon per year.

Table 77. Organic carbon CO₂ potential fixation through CA in annual crops in Europe
(adapted by Gonzalez-Sanchez et al., 2018)

	Biogeographical region	Increase of soil organic carbon (t ha ⁻¹ yr ⁻¹)	NT current area (ha)	Current SOC fixed (t yr ⁻¹)	Current CO ₂ fixed (t yr ⁻¹)	NT potential area (ha)	Potential SOC fixed (t yr ⁻¹)	Potential CO ₂ fixed (t yr ⁻¹)
Austria	Continental	0.42	28,330	11,927	43,731	1,232,040	518,670	1,901,791
Belgium	Atlantic	0.32	270	87	320	613,580	198,084	726,308
Bulgaria	Continental	0.42	16,500	6,946	25,470	3,197,800	1,346,225	4,936,160
Croatia	Continental	0.42	18,540	7,805	28,619	832,870	350,626	1,285,627
Cyprus	Mediterranean	0.81	270	219	803	61,770	50,085	183,646
Czech Republic	Continental	0.42	40,820	17,185	63,010	2,373,890	999,372	3,664,363
Denmark	Atlantic	0.32	2,500	807	2,959	2,184,120	705,107	2,585,391
Estonia	Boreal	0.02	42,140	843	3,090	578,660	11,573	42,435
Finland	Boreal	0.02	200,000	4,000	14,667	1,912,710	38,254	140,265
France	Atlantic	0.20	300,000	60,000	220,000	17,166,990	3,433,398	12,589,126
Germany	Continental	0.43	146,300	63,441	232,617	10,904,310	4,728,505	17,337,853
Greece	Mediterranean	0.81	7	6	21	1,600,950	1,298,104	4,759,713
Hungary	Continental	0.42	5,000	2,105	7,718	3,560,130	1,498,761	5,495,456
Ireland	Atlantic	0.32	2,000	646	2,367	999,550	322,688	1,183,190
Italy	Mediterranean	0.77	283,923	219,094	803,344	5,992,540	4,624,243	16,955,559
Latvia	Boreal	0.02	11,340	227	832	1,101,650	22,033	80,788
Lithuania	Boreal	0.02	19,280	386	1,414	2,129,630	42,593	156,173
Luxembourg	Continental	0.42	440	185	679	60,950	25,659	94,083
Malta	Mediterranean	0.81	ND	ND	ND	5,290	4,289	15,727
Netherlands	Atlantic	0.32	7,350	2,373	8,700	670,360	216,415	793,520
Poland	Continental	0.41	403,180	164,632	603,650	9,518,930	3,886,896	14,251,954
Portugal	Mediterranean	0.81	16,050	13,014	47,718	707,490	573,656	2,103,407
Romania	Continental	0.42	583,820	245,779	901,191	7,295,660	3,071,362	11,261,662
Slovakia	Continental	0.42	35,000	14,734	54,026	1,304,820	549,309	2,014,135
Slovenia	Continental	0.42	2,480	1,044	3,828	165,410	69,635	255,329
Spain	Mediterranean	0.85	619,373	526,467	1,930,379	7,998,655	6,798,857	24,929,141
Sweden	Boreal	0.02	15,820	316	1,160	2,324,650	46,493	170,474
United Kingdom	Atlantic	0.45	362,000	161,331	591,548	4,376,000	1,950,237	7,150,870
Total Europe			3,162,733	1,525,598	5,593,861	90,871,405	37,381,131	137,064,146

The process of soil carbon fixation into the soil requires a long period before significant SOC changes can be quantified and benefits on soil quality are revealed, changes in SOC may also be irregular. For instance, Gonzalez et al (2012) mention that carbon fixation rates were high in newly implemented systems during the first 10 years, reaching values of 0.85 Mg ha year for no-tillage and 1.54 Mg ha year for cover crops implemented in-between perennial tree rows. However, these first 10 years were followed by a period of lower but steady growth until equilibrium was reached. The same authors examined the potential for carbon fixation into the soil for different regions and crop rotations in Spain and found that the average annual potential was 0.72 Mg ha over a period of 2 to 20 years (González-Sánchez et al. 2012).

The positive impacts of CA to SOM are more certain and of higher confidence in more productive areas where crop residues are of minor commercial importance. Farina et al (2017) (Farina et al. 2017) performed a simulation study to estimate the carbon stocks and CO₂ emissions in the Foggia province of Southern Italy concluding that retention of crop residues into the field is a main land management recommendation to prevent soil organic carbon decline along with no-tillage

improvement of crop rotations by introducing also legumes, rational use of irrigation, use of cover crops to replace fallow periods, and utilization of compost or manure for crop fertilization.

Although CA has been extensively focused on with regards to its application to arable crops, orchards also present a region for CA applications; the retention of crop residues and the installation of cover crops within rows of woody crops are major practices for conserving soil quality and enhancing CO₂ fixation in orchards. In a Mediterranean peach orchard, Montanaro et al. (2012) (Montanaro et al. 2012) found that the application of alternative orchard management practices, including mulching of cover crops, retention of crop residues, composts etc., were able to increase SOC stocks by approximately 30% at a 0.1 m soil depth. On a relevant review study, Montanaro et al. (2017) (Montanaro et al. 2017) highlighted the significance of increasing SOC for fruit tree crops through conservative management practices and supportive environmentally friendly policies (Montanaro et al. 2017).

8.1.2 Reduced soil organic carbon losses

Changes in the forms of SOM is a natural process; SOM is decomposed by soil microorganisms producing CO₂ that is released in soil pores and emitted to the atmosphere mainly by diffusion and convection processes (Oertel et al. 2016; Camarda et al. 2019). These processes can be augmented enormously during tillage operations which increase soil porosity and soil aeration (Ellert and Janzen 1999; Alvarez, Alvarez, and Lorenzo 2001; Reicosky et al. 2005). On the other hand, minimum soil disturbance is obtained with no-tillage resulting in limited diffusion of CO₂. Moreover, the increase of soil enzymes with no-tillage facilitate aggregate stability and, consequently, the protection of SOM (K Paustian et al. 2000; Six et al. 2002). No-tillage was found to produce 3.8 times less CO₂ emissions compared to superficial tillage at 10 cm depth, and 10.3 times less as compared to deep mouldboard based tillage at 28 cm (Reicosky and Archer 2007). The majority of the CO₂ flux occurs in the short and mid-term after tillage. Álvaro-Fuentes et al. (2007) evaluated the potential of CA to reduce tillage-induced CO₂ emissions and found that the majority of the CO₂ flux immediately after tillage was from 3 to 15 times greater than the flux before tillage operations but in no-tillage, the CO₂ fluxes were low and steady during the whole study period (Álvaro-Fuentes et al. 2007). Carbonell-Bojollo et al. (2011) found that during the sowing operations, no-tilled plots emitted 34% to 75% less CO₂ compared to sowing in traditional tillage (Carbonell-Bojollo et al. 2011).

Table 78. Selected references of studies illustrating CO₂ emission from different tillage practices (adapted from Mehra et al., 2018)

Location	Soil Texture	Duration (Days)	Carbon content (g C /kg of Soil)	Soil Sample Depth (cm)	Bulk density (g/cm ³)	CO ₂ loss during different tillage		% of carbon reduction through different tillage		References
						CT	NT	CT	NT	
United States	Clay loam	19	31.7	0-7.5	1.50	131.0	26.3	0.36	0.07	Reicosky and Lindrom (1993)
United States	Clay loam	1	22.6	0-30	1.47	115.0	18.2			Reickosky (1997)
United States	Silt loam	60	0.0	0-30	1.47	4.8	2.5	0.01	0.00	Dao (1998)
Canada	Sandy loam	97	19.9	0-30	1.65	40.1	27.6	0.04	0.03	Rochette and Angers (1999)
Canada	Loam	2	18.0	0-7.5	1.52	13.0	10.3	0.06	0.05	Ellert and Janzen (1999)
Argentina	Sandy loam	40	15.5	0-30	1.65	28.3	43.8	0.08	0.06	Alvarez et al. (2001)
United States	Loam	20	29.0	0-15	1.52	7.0	4.1	0.01	0.01	Al Kaysi and Yin (2005)
United States	Loamy sand	51	13.1	0-7.5	1.75	4.1	41.2	1.64	0.24	Bauer et al. (2006)
Spain	Silt loam	16			1.47	105.1	52			Alvaro et al. (2007)
Denmark	Loamy sand	91	20.3	0-20	1.75	39.4	30.0	0.06	0.04	Chatskikh and Olesen (2007)
Turkey	Silt loam	46	10.0	0-30	1.47	11.8	2.0	0.03	0.00	Akbolat et al. (2008)
Spain	Loam	8	7.5	0-30	1.52	9.5	6.3			Morell et al. (2010)
New Zealand	Silt loam	365	35.3	0-10	1.47	59.9	62.5	0.04	0.04	Aslam et al. (2000)
United States	Silt clay loam	730	6.0	0-20	1.42	19.8	20.7	0.23	0.24	Franzluebbers et al. (1995)
United States	Sandy clay loam	490	32.3	0-20	1.65	27.6	32.1	0.03	0.03	Hendrix et al. (1988)
Australia	Sandy loam	4				552.5	67.5			Walting (1998)
Australia	Vertisol	4				85.5	50.0			Thomton (1998)
Australia	Silt loam	80h				732.0	287.0			Reicosky (1998)

Soil tillage has multiple effects over the soil profile and quite often its effects are in conjunction with weather conditions (rainfalls, temperature) and other farm practices such as fertilization and irrigation. Franco-Luesma et al. (2020) highlighted the importance of irrigation and soil tillage systems as key agricultural practices to minimize soil CO₂ and CH₄ emissions under Mediterranean conditions in a maize monocrop (Franco-Luesma et al. 2020). On their report, they mention up to 42% lower cumulative soil CO₂ emissions for no-tillage compared to conventional tillage and sprinkler irrigation. According to Abdalla et al. (2016), the reduction of soil CO₂ emissions depends on the tillage system applied, the soil type and the total soil organic carbon (Abdalla et al. 2016). They estimated, across different climates, that tilled soils have 21% higher CO₂ emissions than no-tillage. In semiarid farming systems, when intensive soil tillage practices are combined with recurring droughts, they may accelerate soil degradation by extensive losses on soil organic matter because drought reduces the amount of residue inputs and SOM restorative processes. Depending on the year of the study, Rutkowska et al. (2018) found that CO₂ emissions in the reduced tillage system were 7 to 35% lower than those in the conventional system (Rutkowska et al. 2018).

CA is a suitable strategy not only for mitigating climate change, but also for adapting and increasing the resilience of agrarian ecosystems to extreme weather events caused by the changes on climate, such as heavy rainfalls and droughts. Soils under CA retain an improved soil structure and are less susceptible to water or wind erosion (Van Pelt et al. 2017). They have greater SOM that enhances soil aggregation so they respond better to erosion risk events (González-Sánchez et al. 2017). Even on soils with a low organic matter content, reduction in tillage is a factor capable of significantly reducing CO₂ emissions (Rutkowska et al. 2018). Doetterl et al. (2012) estimate that for Europe, annual mobilization of SOC on agricultural fields is of the same magnitude as additional carbon sequestration induced through the use of fertilizers (Doetterl, Van Oost, and Six 2012).

8.1.3 Energy savings and reduced GHG emissions

CA also contributes to energy savings (and reductions in associated emissions) in agricultural systems that adopt CA as compared to conventional agricultural practices. Energy savings concern direct energy inputs in agricultural processes, such as fossil fuels for field operations, as well as indirect energy inputs in the reduction of fertilizer and pesticide use. Among the direct energy inputs, soil tillage, depending on the agricultural system, is one of the most intensive energy demanding operations in arable production (Zegada-Lizarazu, Matteucci, and Monti 2010).

Table 79. Carbon Emissions by Type of Tillage (adapted from Lal., 2004b)

Tillage operation	Tillage tools	Emission (kg Ceq ha)		Relative emission
		Range	Average	
Primary tillage	Moldboard plough	13.4-20.1	12.0	3.0
	Chisel plough	4.5-11.1		
	Subsoiler	8.5-14.1		
Secondary tillage	Heavy disking	4.6-11.2	6.7	1.7
	Standard disking	4.0-7.0		
Tertiary	Tine cultivation	3.0-8.6	3.9	1.0
	Hoeing	1.2-2.9		

As the implementation of CA involves minimum or no-tillage, it consumes less energy during seedbed preparation. By comparing different crop rotations in semi-arid central Spain, Hernanz et al. (1995) found that energy consumption under conventional tillage was about 10% greater than that associated with no-tillage (Hernández, Girón, and Cerisola 1995). Lal (2004) (Lal 2004a) found that the reduction in fuel consumption with no tillage was 73% compared to a conventional, plough-based system. In a study carried in Spain, Gonzalez-Sanchez et al., (2017) found that in no-tillage, annual CO₂ emissions linked to energy consumption were reduced by an average of 12% in wheat, 26.3% in sunflower and 18.4% in leguminous plants compared with conventional tillage systems. Filipovic et al., (2006) estimated the fuel consumption for three alternative tillage systems in Croatia by examining four major arable crops (maize, wheat, soybean and barley). They found that reduced tillage and no-tillage systems provided 35.3–42.9% and 87.8–88.1% respectively energy savings compared to conventional tillage, reducing accordingly the CO₂ emission. Lal (2004) estimates CO₂ emissions to be 35.3 kg ha in conventional tillage, 7.9 kg ha in minimum tillage based on the use of chisel plough, and 5.8 kg ha in a management system based on no-tillage, implying a potential reduction of 77.6 to 83.5% over conventional systems.

When performing energy analyses of the agricultural systems, energy budgets reveal controversial results. For a sugar beet crop in Greece, Cavalaris and Gemtos (2002) (Cavalaris and Gemtos 2002) estimated the direct energy use for seedbed preparation in a no-tillage based method to be 0.045 MJ ha while in a plough based conventional system was 2.998 MJ ha. No-tillage, however, required an extra operation with a total herbicide to control the weeds, when this extra energy was included this increased the total energy inputs for the no-tillage method by 2.656 MJ ha. Thus, compared to conventional tillage, no tillage required 98% less direct energy inputs but only 11.4% less direct and indirect inputs. When crop yield is translated into an energy outcome by using specific energy coefficients, the results were reversed. No-tillage led to a 27.9% lower yield compared to conventional tillage, resulting on an energy efficiency index (defined as the ratio of energy outputs

to energy inputs) of 2.54 compared to 3.40 for conventional tillage. In another study, Borin et al. (1997) (Borin, Menini, and Sartori 1997) assessed the energy efficiency for three tillage methods tested over a three crops system (maize, soybean and barley) in Northeastern Italy; despite the reduced yields in no-till, the energy savings led to an energy efficiency of 4.6 for no-till compared to 4.1 for conventional till and 4.2 for ridge till. This is corroborated by other studies that also report reduced yields for no-tillage systems resulting on declined energy use efficiency throughout the production process (Moreno et al. 2011).

However, no-tillage agriculture by itself is not considered as CA practice and cannot provide the full benefits that are expected by the full implementation of CA. For instance, the combination of no-tillage with diversified crop rotation and mulching, all three pillars of CA, can help sustain high yields even with no tillage (Kodzwa, Gotosa, and Nyamangara 2020; Mupangwa et al. 2021). Moreno et al. (2011) found that the inclusion of a leguminous forage crop, like vetch, increased the total energy output under different farming systems and crop rotations, including barley, sunflower vetch and fallow sequences (Moreno et al. 2011). Moreover, legumes provide symbiotic nitrogen that reduces the needs for chemical nitrogen fertilizers, which are a major input of indirect energy into the system and therefore further improve the energy efficiency. Pittelkow et al. (2015) agree that no-tillage may reduce crop yields in some regions but this effect can be counteracted when no-till farming is complemented by the other two principles of CA, namely residue retention and crop rotation (Pittelkow et al. 2015).

Energy analysis of agricultural systems may lead directly to estimations of CO₂ flows and, therefore, the identification of efficient pathways for reducing GHG emissions. Borin et al. (1997) measured the energy use and equivalent carbon emissions for three tillage systems and observed that the saving in fuel was equivalent to 44 kg/C/ha per year upon conversion from plow till to ridge till and 62 kg/C/ha per year upon conversion to no-till. When carbon sequestration was taking into account carbon savings increased significantly. In a similar study, Dachraoui et al. (2020) (Dachraoui and Sombrero 2020) assessed that the emissions in maize production, resulting from the energy inputs of electricity, fuel combustion and agricultural machinery, contributed to the carbon footprint with means ranging from 0.25 to 0.27 Mg CO_{2eq} ha and from 0.23 to 2.25 Mg CO_{2eq} ha for conventional tillage and no-tillage respectively. Their results also showed that the maize carbon footprint was mainly due to direct and indirect N₂O emissions produced by the application of synthetic fertilizers and ranged from 3.3 to 4.2 Mg CO_{2eq} ha and from 3.4 to 4.4 Mg CO_{2eq} ha under conventional tillage and no-tillage respectively. This illustrates that the agronomic practices selected to increase crop productivity should be carefully examined in terms of their effects in GHG emissions, taking into account all relevant factors, both direct and indirect. For example, if soil organic carbon stocks were increased by higher fertilizer inputs to increase crop productivity, emissions of nitrous oxide from fertilizer use could offset any climate benefits arising from carbon sinks (IPCC 2019).

All of the studies presented above indicate in a well-defined manner that converting conventional, moldboard based tillage to reduced or no-tillage can lead to significant reductions in energy use and consequently in carbon emissions.

8.2 Dynamics of Conservation Agriculture to combat Climate Change

Upscaling terrestrial fixation of atmospheric CO₂ into the soil in the form of SOC has significant potential to support climate change mitigation efforts. Agricultural soils occupy about 35% of the

global land surface (Betts et al. 2007). The global mitigation potential for increasing soil organic matter stocks in mineral soils is estimated to be in the range of 0.4–8.64 Gt CO₂ per year (IPCC 2019). At a European (EU-15) level, the increase in SOC in no-tillage combined with cover crops, as opposed to conventional tillage with a small fallow period, is 0.4 t ha per year (Freibauer et al. 2004; Smith et al. 2005).

Lal (1997) estimated the annual production of crop residue to be about 3.4 billion Mg globally. He suggested that, if 15% of carbon contained in the organic residues could be converted to passive soil organic carbon (SOC) fraction, it could lead to carbon sequestration at a rate of 0.2×10^{15} g per year. At an EU-28 scale, Gonzalez et al. (2018) estimated that the agricultural area suitable for the implementation of CA is about 38 million ha, approximately 1/3 of the crop land. If CA were implemented to this area, it has the potential of reducing overall carbon emissions by 22% by 2030 (Figure 37) (González-Sánchez et al. 2017).

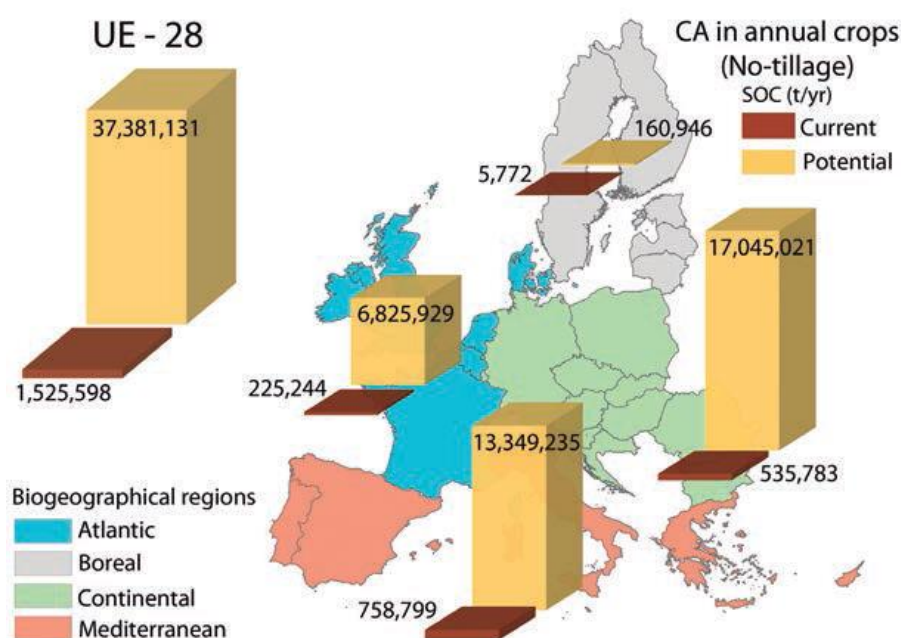


Figure 37. Current and potential SOC fixed by CA in annual crops compared to systems based on soil tillage in EU-28 and in the different biogeographical regions (adapted by Gonzalez-Sanchez et al., 2017 (González-Sánchez et al. 2017))

Table 80. Existing relationship between CO₂ sequestration that would occur in the soil when conventional farming system is substituted by Conservation Agriculture on the entire surface, and the emission reduction to be achieved in the non-ETS sectors by 2030. And with respect to non-ETS emissions allowed by 2030 (adapted by Gonzalez-Sanchez et al., 2017)

	(A) Non-ETS emissions allowed by 2030 (t yr ⁻¹)	(B) Reduction of emissions by 2030 from non-ETS compared to 2005 (t yr ⁻¹)	(C) Potential of CO ₂ fixed through CA (t yr ⁻¹)	Percentage of (C) over (B) (%)	Percentage of (C) over (A) (%)
Austria	36,268,800	20,401,200	2,019,403	9.90	5.57
Belgium	50,830,000	27,370,000	782,291	2.86	1.54
Bulgaria	24,570,000	0	5,145,996	-	20.94
Croatia	15,642,600	1,177,400	1,432,719	121.69	9.16
Cyprus	3,176,800	1,003,200	341,213	34.01	10.74
Czech Republic	53,793,000	8,757,000	3,752,510	42.85	6.98
Denmark	24,448,800	15,631,200	2,632,794	16.84	10.77
Estonia	4,724,100	705,900	42,435	6.01	0.90
Finland	20,496,000	13,104,000	140,265	1.07	0.68
France	249,221,700	146,368,300	14,358,615	9.81	5.76
Germany	290,432,800	178,007,200	17,723,982	9.96	6.10
Greece	51,895,200	9,884,800	9,729,155	98.43	18.75
Hungary	43,133,400	3,246,600	5,809,954	178.96	13.47
Ireland	33,264,000	14,256,000	1,186,900	8.33	3.57
Italy	220,523,800	108,616,200	26,374,586	24.28	11.96
Latvia	8,008,800	511,200	80,788	15.80	1.01
Lithuania	9,809,800	970,200	156,173	16.10	1.59
Luxembourg	6,078,000	4,052,000	96,532	2.38	1.59
Malta	834,300	195,700	23,611	12.06	2.83
Netherlands	78,643,200	44,236,800	874,935	1.98	1.11
Poland	163,689,300	12,320,700	15,391,891	124.93	9.40
Portugal	41,109,900	8,420,100	6,382,238	75.80	15.52
Romania	71,569,400	1,460,600	11,916,910	815.89	16.65
Slovakia	19,624,000	2,676,000	2,052,459	76.70	10.46
Slovenia	10,072,500	1,777,500	309,713	17.42	3.07
Spain	173,041,600	60,798,400	52,947,794	87.09	30.60
Sweden	25,740,000	17,160,000	170,474	0.99	0.66
United Kingdom	261,267,300	153,442,700	7,203,670	4.69	2.76
Total Europe	1,991,909,100	856,550,900	189,080,005	22.07	9.49

8.3 Future perspectives for Conservation Agriculture

In Europe, the adoption and expansion of CA has not been as rapid as in other parts of the world (Kertész and Madarász 2014). According to ECAF, the application of no-till practices in Europe covers around 3.5% of the arable land area (González-Sánchez et al. 2017) with significant variations between countries; 10.5% of arable land in Finland and close to 0% in Greece (although it is applied in some orchards in Greece). High adoption rates are also found in the UK and Romania (8.27% and 8% respectively). Some of the early reasons identified by ECAF for the delay in the adoption of CA in Europe were; the reluctance of farmers to undertake economic risks because EU agriculture was highly subsidized until the 1990s, the lack of specific technology developed for European conditions

and the lack of appropriate technology transfer, and finally the lack of institutional support. As most of these limitations were overcome early in the 21st century, the rate of adoption during the last decade has accelerated. Nonetheless, the fact that many farmers are still not aware of the socio-economic benefits of CA indicates the need for more explicit incentives for adopting these practices.

The EU SoCo project identified several drawbacks for CA adoption in the EU that need to be addressed by policies; first, there is a typical transition period of five to seven years before CA reaches equilibrium; second, yields may be lower in the first years after adoption; third, if crop rotations, soil cover and/or crop varieties are not adjusted to optimal levels, more chemicals may be necessary to control weeds and pests; fourth, farmers need to make an initial investment in specialized machinery and, as such, need to have access to affordable cover crop seeds that are adapted to local conditions; fifth, farmers need extensive training and access to skilled advisory services, and; sixth, a fundamental change in the agricultural approach is required as compared to conventional farming.

Table 81. Application of no-till farming in the EU countries and its comparison with the land planted with annual crops (adapted by Gonzalez-Sanchez et al., 2017)

	No-till area (ha)	Source	Annual crops area (ha)	Source	Percentage (%)
Austria	28,330	Eurostat, 2010	1,232,040	Eurostat, 2013	2.30
Belgium	270	ECAF, 2017	613,580	Eurostat, 2013	0.04
Bulgaria	16,500	Eurostat, 2010	3,197,800	Eurostat, 2013	0.52
Croatia	18,540	Eurostat, 2010	832,870	Eurostat, 2013	2.23
Cyprus	270	Eurostat, 2010	61,770	Eurostat, 2013	0.44
Czech Republic	40,820	Eurostat, 2010	2,373,890	Eurostat, 2013	1.72
Denmark	2,500	ECAF, 2017	2,184,120	Eurostat, 2013	0.11
Estonia	42,140	Eurostat, 2010	578,660	Eurostat, 2013	7.28
Finland	200,000	ECAF, 2017	1,912,710	Eurostat, 2013	10.46
France	300,000	ECAF, 2017	17,166,990	Eurostat, 2013	1.75
Germany	146,300	ECAF, 2017	10,904,310	Eurostat, 2013	1.34
Greece	7	ECAF, 2017	1,600,950	Eurostat, 2013	0.00
Hungary	5,000	ECAF, 2017	3,560,130	Eurostat, 2013	0.14
Ireland	2,000	ECAF, 2017	999,550	Eurostat, 2013	0.20
Italy	283,923	ECAF, 2017	5,992,540	Eurostat, 2013	4.74
Latvia	11,340	Eurostat, 2010	1,101,650	Eurostat, 2013	1.03
Lithuania	19,280	Eurostat, 2010	2,129,630	Eurostat, 2013	0.91
Luxembourg	440	Eurostat, 2010	60,950	Eurostat, 2013	0.72
Malta	0	Eurostat, 2010	5,290	Eurostat, 2013	0.00
Netherlands	7,350	Eurostat, 2010	670,360	Eurostat, 2013	1.10
Poland	403,180	Eurostat, 2010	9,518,930	Eurostat, 2013	4.24
Portugal	16,050	ECAF, 2017	707,490	Eurostat, 2013	2.27
Romania	583,820	Eurostat, 2010	7,295,660	Eurostat, 2013	8.00
Slovakia	35,000	ECAF, 2017	1,304,820	Eurostat, 2013	2.68
Slovenia	2,480	Eurostat, 2010	165,410	Eurostat, 2013	1.50
Spain	619,373	ECAF, 2017	7,998,655	MAPAMA, 2015	7.74
Sweden	15,820	Eurostat, 2010	2,324,650	Eurostat, 2013	0.68
United Kingdom	362,000	ECAF, 2017	4,376,000	DEFRA, 2016	8.27
Total Europe	3,162,733		90,871,405		3.48

According to Paustian et al. (2019) (Keith Paustian et al. 2019), there are currently three main ways in which the value of soil carbon sequestration can potentially be included in direct financial returns to land managers: first, government subsidies as direct payments or as cost sharing can incentivize farmers; second, agricultural land managers could be directly compensated for CO₂ removal and storage as SOC as a carbon 'offset', in which the sequestered carbon could be sold as a commodity to companies engaged in GHG emission reductions, in either a voluntary marketplace or a compliance cap-and-trade system; third, companies that produce and market products that are based on agricultural commodities, including food, beverages and fibers, are increasingly interested in developing more sustainable supply chains, including reducing their products' carbon footprint.

Yield performance and stability, operating costs, environmental policies and programs, and climate change will likely be the major driving forces defining the direction and the expansion of CA in Europe (Kertész and Madarász 2014). The Common Agricultural Policy (CAP) can provide incentives for protecting soil health and function, including maintenance of SOM (Hansen et al. 2016). With the launch of the EU's Green Deal, that provides an EU Climate Law framework for action in pursuit of the global adaptation goal established in Article 7 of the Paris Agreement, CO₂ sequestration became a main component to support the achievement of the objectives of the EU Climate Law.

This section has presented the case of Conservation Agriculture as a sustainable agricultural system with the confirmed potential to support the mitigation of Climate Change by sequestering carbon in the soil. The adoption of Conservation Agriculture practices at EU level would store around 190M tons of CO₂ that could account for over 22% of the EU commitments in non-ETS GHG reduction by 2030. Owing to the high capacity of carbon sequestration on the soil, the sustainable mechanization through CA systems reduces the need for fossil-derived energy and balances the carbon emissions to the atmosphere.

9. Conclusions

In conclusion, our results indicate that energy use throughout EU agriculture is significant and fossil fuel dependent. According to Eurostat, agriculture accounts for 3.2% of total energy consumption, 56% which is derived directly from crude oil and petroleum products, 17% from electricity, 14% from gas and 9% from renewables and biofuels. However, our results suggest that if indirect energy use associated with the production and transport of fertilizers and pesticides is included the proportion of energy use in the EU-27 would be 62% higher overall.

Our results also show that energy use, its concentrations and breakdown, vary significantly per production system (open-field, livestock, greenhouses). According to our estimates, of the crops and production systems included in our study, the annual energy inputs for arable agriculture are 1227 PJ, for orchards and vineyards are 208 PJ, for meat production systems are 501 PJ, for dairy production systems are 543 PJ.

For open-field agriculture, our study finds that the use of fertilizer is the largest energy consuming activity in EU agriculture, accounting for around 50% of all energy inputs. On farm diesel use accounts for 30%, while other uses are mainly dedicated to irrigation, storage and drying which accounts for 8%. Pesticides and seeds each account for 5% of total energy inputs. In all livestock systems, except for beef production systems, animal feed is the main energy input accounting for around three quarters of all energy requirements. The production of animal feed consumes around 60% of the cereal production in the EU and requires significant high-protein imports. On farm electricity use, which currently mainly comes from fossil sources, is also significant but varies considerably depending on the production system. In high yielding and high-energy intensive greenhouses energy use is dominated by energy use for heating and cooling. By contrast, lower yielding and less energy-intensive systems use little to no heating/cooling and instead energy use is mainly associated with fertilizers, diesel use for machinery, irrigation and other activities.

The above illustrate that for the EU to achieve the goals outlined in the Green deal and Farm to Fork strategy, it is likely that the adoption of new technologies, and improvements in energy efficiency and the further development and adoption of non-fossil energy sources for agriculture is required. In addition to this, a transition to more sustainable agricultural practices and farming systems is required. For instance, our chapter on conservation agriculture, as an indicative example of a FEFTS, highlights that scaling of conservation agriculture can significantly reduce on farm energy use and carbon emissions as well as sequester considerable amounts of carbon (up to 190M tonnes per year) and improve the overall climate resilience of the agricultural sector.

Providing an overview of energy use in EU agriculture is a challenging topic due to the plethora of the available, and in most cases inconsistent, data. However, there are multiple areas that would benefit from further research. Our understanding and estimates of energy use in EU agriculture would benefit from additional studies on energy use in all three main production systems, especially for greenhouse agriculture. In addition, further research into the energy use of non-conventional systems and crops that are cultivated on a minor scale is required as well as further research into the correlations between farm indicators (size, location, specialization) and energy use.

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