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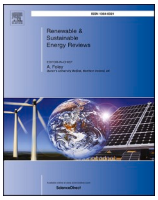

Energy use in open-field agriculture in the EU: A critical review recommending energy efficiency measures and renewable energy sources adoption

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ABSTRACT

This review combines results from a large number of studies investigating energy use in EU open-field agriculture, providing an overview of energy use and its concentrations. Such a review and its findings are important as it informs stakeholders and policymakers with evidence for supporting a green energy transition in open-field agriculture. Our review indicates that annual energy use in EU open-field agriculture is at least 1431 PJ, equivalent to around 3.7% of total EU annual energy consumption, with the majority of energy sourced from non-renewable energy sources. Our meta-analysis finds that the production 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 31% of total energy inputs, while the production pesticides and seeds accounts for 5% of total energy inputs. Other energy uses, mainly irrigation, storage and drying, account for 8% of total energy inputs. This suggests that energy use in EU agriculture is significantly underreported and that around 55% of total energy inputs, associated with the production of fertilizers and pesticides, come from indirect sources which can be assigned to the agricultural sector but is used prior to reaching farms. The importance and potential of various fossil-energy-free technologies and strategies are discussed. In addition, this review highlights that in the medium and long term there is need for the development and application of detailed and standardized methodologies for energy use analysis of agricultural systems, as well as for meta-analyses investigating energy use in agriculture.

1. Introduction

Open-field agriculture, which includes the cultivation of cereals, potatoes and sugar beet, oilseeds, vegetables, orchards, vineyards and olives, is the largest agricultural sector in the EU by land area and production [1]. Multiple studies have developed data on the energy use in open-field agriculture in the EU, but these are generally limited to specific crops in specific geographic areas and a clear overview and agreement of all energy use in the EU open-field sector does not exist. In addition, existing data on energy use in EU agriculture is often fragmented containing data gaps with EUROSTAT providing the most comprehensive dataset available.

It is well recorded that energy use in the global and European agriculture sector is dominated by energy produced from fossil fuels [2–7] and that a clear positive correlation between energy use and greenhouse gas emissions (GHGs) in agriculture currently exists, one of the main reasons for which is the dependence on fossil fuels [2]. 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 loss of biodiversity, soil depletion and the pollution of natural ecosystems [8,9]. With the launch of the Green Deal,

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; AFF, AgroFossilFree; CAP, Common agricultural policy; FADN, The farm accountancy network; FEAT, Farm energy analysis tool; FEFTS, Fossil-energy-free strategies and technologies; GHG, Greenhouse gas emissions; IPCC, Intergovernmental panel on climat change; LCA, Life-cycle assessement; PV, Photovoltaic; RES, Renewable energy sources; UAA, Utilized agricultural area.

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Units and Conversion table

MJ	- Megajoules
GJ	- Gigajoules
PJ	- Petajoules
Ha	- Hectare
kg	- Kilogram
Toe	- Tonne of oil equivalent
kWh	- Kilowatt-hour

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. In order to successfully achieve these targets and develop relevant policies, it is crucial to have an accurate overview of the energy use within EU agriculture.

A number of databases provide energy use data and related indicators on energy use in EU agriculture including Eurostat, Faostat, and the farm accountancy data network (FADN). Faostat publishes data on energy use in agriculture on a country and regional basis as well as according to energy carriers [10]. Eurostat publishes data annually on direct energy consumption within the EU based on the 'agri-environmental indicator on energy use', and it estimates that 3.2% of the total energy consumed in the EU is used in the agriculture and forestry sectors. This data is mainly sourced from the joint Eurostat/IEA/UNECE questionnaire and aggregate data figures are slightly lower than Faostat data. These datasets 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 [2]. FADN provides an overview of EU farmers' income and business activities and provides detailed information on a range of income related indicators [11].

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 aggregated energy use in the entire agricultural sector and a detailed breakdown on energy use in specific crops or agricultural sectors is not publicly available. In addition, this data is generally focused on direct on-farm energy uses and inputs and does not include data on indirect energy inputs. Simultaneously, Eurostat and national agencies recognize that the energy use data that does exist is generally of lower quality and underreported as compared to other energy sector statistics due to errors and incomplete data. For instance, data on energy use in the German agriculture sector is not included in Eurostat statistics due to incomplete data [2]. 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% [12]. 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 and highlights that energy use in EU agriculture is underreported [4]. 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 [7]. Martinho (2016) investigates energy consumption across farms in 12 European countries [13]. Rega et al. (2020) investigate the spatial energy intensity of EU agriculture [14] while Rokicki et al. (2021) investigate changes in the energy consumption in agriculture in EU countries [3].

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 [15]. 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 (2016) compile data from a range of studies on energy consumption in the EU wheat sector [16]. Similarly, the Farm Energy Analysis Tool (FEAT) provides a framework for users to calculate energy use and GHG emissions within various agricultural systems [17].

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 [18]. While a number of studies investigate the energy use required in different fertilizer production processes [19–21], 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 [22].

By contrast, only a few studies have compiled data on energy use attributed to pesticides, while most existing studies rely heavily on Green's (1987) analysis on energy in pesticide manufacture, distribution and use [23]. 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 [19,24]. 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 of production in the Handbook of Energy Utilization [15]. 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 [8,25,26], increasing renewable energy use, adoption of energy efficient and alternative strategies and technologies [7,27–29], optimal energy management strategies [5]. In particular, various 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 [30,31].

Due to the inherent complexity of EU's 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.

In this context, this study provides a review of the current energy use status within open-field agriculture in the European Union, 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 presents and combines data from multiple sources supporting stakeholders and policymakers in their understanding of energy use and their ability to design and implement fossil-energy-free strategies and technologies (FEFTS) supporting the energy transition and the EU energy targets for 2030 and beyond.

The paper includes section 2 describing the approach utilized for the deployment of this study including the conceptual framework; section 3 provides an overview of the analysis and corresponding findings; section 4 discusses and presents major insights derived from the findings presented in section 3 along with possible transition pathways to fossil free open-field agriculture, and; section 5 provides concluding remarks.

2. 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, as explained below [15,32]. Our approach for defining indirect energy use is in line with approaches adopted by other studies [4]. Indirect energy use refers to the energy used for the production of agricultural inputs. These inputs account for energy use that can be assigned to the agricultural sector but is used prior to reaching farms, including energy used in the:

- Production of fertilizers (raw materials, manufacturing, transport)
- Production of pesticides (raw materials, manufacturing, transport)
- Production, storage and transportation of seeding materials

In this study we include all the energy associated with these three categories. This is important as in most other cases, energy use attributed to the above activities is included in sectors other than agriculture (e.g., industry, transportation) [33].

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 [4]. This generally includes energy consumed for: on-farm operations, transportation, heating and cooling, lighting, electrical equipment, machinery, automation processes, farm management and irrigation. The main energy uses that the study focuses on are:

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

Energy use that is related to the development of agricultural infrastructure, such as energy used in the production of agricultural machinery and agricultural buildings, is not included in our definition and not included in this review. This is because there are significant issues with measuring energy use related to agricultural infrastructure accurately. Further to this, 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 are not 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 [13].

2.2. 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 [3,34]. To provide a reliable and detailed overview of energy use in agriculture, this study conceptually divides open-field agriculture into several categories: arable, orchards and vineyards. This distinction is chosen in order to separate energy use from the greenhouse and livestock sectors. Our approach has been informed by FADN's allocation of farms according to 'type of farming' and includes farms specialized in horticulture, orchards, wine, cereals oilseeds protein (COP) and other field crop farms [11]. 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 this review, other references to specific crops, geographic locations and farm types are also included where appropriate.

2.3. Data sources

Data was drawn from LCAs presented in a variety of sources including databases, journals and scientific articles, legal agreements and national data (see acknowledgements). LCAs were chosen as the main source of data in order to provide an overview of direct and indirect energy use as existing databases, such as Eurostat and FAOSTAT are mainly dependent on questionnaires, include data from the forestry and aquaculture sectors and do not include data from indirect sources. 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 hundreds of different sources allowing for an analysis of energy use in EU open-field agriculture as a whole.

2.3.1. Selection process

The study selection process followed a couple of detailed steps. First, potentially relevant studies were identified through keyword searches of SCOPUS and google scholar as well as through individual meetings with relevant stakeholders at the following organizations: the Agricultural & Environmental Solutions (AGENSO), Aarhus Universitet (AU), the Comite Europeen Des Groupements De Constructeurs Du Machinisme Agricole (CEMA), the Confederazione Generale Dell Agricoltura Italiana (CONFAGRICOLTURA), Delphy, the European Conservation Agriculture Federation (ECAF), Iniciativas Innovadoras Sal (INI), the Instytut Uprawy Nawozenia I Gleboznawstwa, Panstwowy Instytut Badawczy (IUNG-PIB), Landbrug & Fodevarer F.M.B.A. (L&F), Lubelski Osrodek Doradztwa Rolniczego W Konskowoli (LODR), RESCOOP EU ASBL, the Agriculture and Food Development Authority (TEAGASC), Trama Tecnoambiental S.L. (TTA) and Wirtschaft Und Infrastruktur Gmbh & Co Planungs Kg (WIP).

2.3.2. Eligibility criteria

The study selection criteria for the meta-analysis were as follows, studies were included that were peer-reviewed and published primary studies. All the data presented in these studies needed to be based on detailed LCA methodologies that use a well-respected software (SimaPro, GaBi, openLCA) and relevant database reference values. In this regard, studies had to provide primary quantitative research data on the energy use associated with the cultivation of individual crops in standard production systems. Studies investigating marginal and non-conventional production systems were excluded. Regarding time period, we focused mainly on studies conducted in the past 10 years, however, in a few cases, in order to fill in data gaps, studies that were older but adhered to the selection criteria were included.

In addition to the above data from two reports were included, de Visser et al.'s (2012) study on the State of the Art on Energy Efficiency in Agriculture and Klepper's (2011) report on energy use for different agricultural crops in Germany. These reports were included as there are widely cited in the literature and by Eurostat and provide a wealth of data, through LCAs, on energy use in EU agriculture for different crops.

2.4. Estimating energy use

Due to the scale of this study and in order to combine data as accurately as possible, multiple methodologies are adopted to calculate and illustrate energy use in EU agriculture. It is important to note that multiple methodologies for conducting a meta-analysis exist, including random and fixed effects models [35]. However, energy use data for open-field agriculture is an emerging field with some significant limitations, as discussed in section 2.5, and therefore a relatively simple methodology was developed for estimating energy use. Adopting a more accurate and well-developed methodology is an important area for future research and is dependent on improvements in the quality of primary energy use data for open-field agriculture.

A meta-analysis, which combines the results from multiple scientific studies, across European countries is used to present and estimate energy use in open-field systems.[1] Data is presented according to the crop cultivated and, where applicable, to the following main energy input categories, namely: seed, fertilizers, pesticides, diesel use and other. Data is drawn mostly from LCAs. Depending on the specific crop and adequate availability of data, results are combined for each crop which allows us to calculate EU averages per hectare in terms of energy per category. It is important to note that this method of estimating total energy per hectare is preferred over energy use per output (for instance per kilogram) as the majority of available studies investigate energy use per hectare and not per output and as such, despite variations in yields per country, we consider such an estimation more reliable. Except for the cases of wheat where we consider that there is enough data to present data in terms of energy inputs per hectare and per kilogram of output and the case of apples which are depicted according to GJ per tonne as the EU averages provided by Canals et al. (2007) are according to GJ per tonne of production [36]. Our results section presents the results from this meta-analysis, for a more detailed data breakdown per crop and category and specific data sources please refer to the Appendix.

Data is presented without uncertainties as the vast majority of LCA studies on energy use in agriculture do not provide confidence intervals for their data. It is important to highlight that this is a drawback of this study and leads to considerable uncertainty for our energy use estimates. This lack of confidence intervals is a common problem with LCAs and uncertainty with agricultural energy use data in general [13,16,25,37,38]. Considering this, the estimates provided by our study should be considered solely as providing a rough indication of energy use in EU agriculture, integrating confidence intervals is an important component for future research.

These averages were then used to estimate total energy use per crop and input as well as total energy use per category. These estimates are based on the methodology presented by de Visser et al.'s (2012) widely referenced study in 'the State of the Art on Energy Efficiency in Agriculture,' where averages energy use per crop are used to estimate total energy use per crop. This method provides us with estimates of the total amount of energy use per crop as well as of the total amount of direct energy use for each category and sub-category as well as energy use per activity. This is represented by Eq. (1) where Y refers to the total energy inputs per crop or per category (seeds, diesel, fertilizers, pesticides or other), C refers to the total area (in hectares) of the crop in question under cultivation in the EU and I refers to the average energy input per hectare per crop or category.

$$Y = C \times I \tag{1}$$

We also attempt to provide direct energy use breakdowns per crop, based on proportions and percentages found in other studies and taken directly from relevant LCAs, which are mainly associated with diesel and tractor use.

In addition, we provide aggregate figures on indirect energy use embodied in the production of fertilizers and pesticides in the EU as a whole. These are calculated by multiplying EU consumption levels of each input drawn from Eurostat and national surveys to the average energy embodied in each agricultural input for the EU presented in the literature and databases. This is represented by Eq. (2) where X refers to the total energy embedded in either fertilizer or pesticide use in the EU, T refers to the total amount of pesticides or fertilizers consumed in the EU, and E refers to the total amount of energy associated with the production and transportation of pesticides or fertilizers prior to reaching the farm. The advantage of this methodology is that it provides us with estimates on indirect energy from two sources, namely: total fertilizer and pesticide consumption and the energy use associated with fertilizers and pesticides for each crop covered in the meta-analysis.

$$X = T \times E \tag{2}$$

Data was not weighted per country in the energy use for individual crops but data was weighted in the estimates on energy use totals. Data was not weighted per country in the energy use for individual crops due to the fact that one the one hand, not enough data was available on a country level to accurately account for the different agro-climatic production systems present within each country. On the other hand, due to the fact that the majority of EU countries have a variety of agro-climatic production systems and these span across national borders and regions It was determined that weighing the data on a country level would not improve the reliability of the data represented. Instead, where multiple studies are conducted in the same country but the study area is focused on a different agro-climatic area both studies are included and provided with an equal weighting. Accurate weighting of this data an area for future research and will require significantly more data points per country. Data was weighted in the estimates on energy use totals, according to the area of production of each crop in the EU in order to account for the differences in area under cultivation per crop.

2.5. Data limitations and bias risk

There are some inherent risks of bias within and across studies. As LCAs rely on reference database researchers are at risk of choosing reference values that may not accurately represent reality. Across studies, by focusing on LCAs other accepted methods of categorizing energy use, for instance through detailed questionnaires, may be excluded thereby limiting the overall quality of the data used. In addition, a variety of factors between studies, including agro-climatic conditions, market access, input prices, social factors, government policy, farmer knowledge, all affect energy use in agriculture. Variation in these factors is likely to contribute to variations in observed energy use across studies. By not weighing the data, countries that have a number of data points in the literature are likely to over influence the data. These factors all increase the risk of bias in this study, the goal of this review is to provide an overview of reliable studies that exist in energy use in EU agriculture and to infer certain trends and estimations of energy use.

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 agriculture, permaculture, etc.) are not analyzed in detail, as they currently constitute a relatively small percentage of agriculture in the EU and there is limited data available which would allow for accurate estimations [39]. By doing so, the energy use of some and alternative parts of the EU agricultural system is not accounted for. Similarly,

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[1] Data from studies investigating energy use in the United Kingdom were excluded from this study. However, agricultural production data of the UK was included until Brexit.

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 [40]. As this study focuses on energy use per hectare, certain studies that provide data solely on energy use per output are not included in our review. Integrating the results from these two types of outputs is identified as an area for future research. 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 is 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, including indirect energy uses but excluding data from post-harvest processing and retail. 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. Results

3.1. *Energy use in open-field agriculture*

Our results are presented as total energy inputs per crop in the EU, in GJ per hectare, % breakdowns of direct on-farm energy inputs, as well as per the following categories: cereals, oilseeds, orchards and vineyards. In all results presented in this section the categories seeds, fertilizers and pesticides refer to indirect energy use while diesel use and other refer to direct energy use. For more detailed breakdowns of the data please refer to the Appendix.

3.1.1. *Energy use per hectare*

Fig. 1 provide an overview of the energy inputs per hectare for open-field crops covered in this study in the EU-27 (for more detailed data see Table A1). These results indicate that energy use in EU open-field agriculture varies significantly per hectare depending on the crop cultivated, while the energy inputs for most crops range between 15 GJ/ha to 25 GJ/ha. The notable exception is citrus fruits which have particularly high overall energy inputs per hectare.

3.1.2. *Total energy inputs in EU agriculture (EU-27)*

Fig. 2 depict our estimates according to the total energy inputs for the open-field crops covered in this study (for more detailed data see Table A2). Our results show that open-field agriculture accounts for 1431 PJ of energy inputs. The three main cereals cultivated in the EU account for the clear majority of energy consumed in open-field agriculture while the two main oilseeds, rapeseed and sunflower seed, and the production of olives also require significant energy inputs. By contrast, the overall energy inputs for potatoes, sugar beet, apples and citrus are considerably lower. In addition, Figs. 2 and 3 also clearly illustrate that for all crops, except for sunflower and soybean, fertilizer production and use is the largest energy consuming activity in EU agriculture accounting for around 50% of all energy inputs. 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 is generally powered by electricity. Pesticides and seeds account for a relatively minor 5% and 6%, respectively, of total energy inputs.

3.1.3. *On-farm operations*

It is clear that 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 1 illustrates that for cereals and oilseeds, tillage operations generally 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 2 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. For olive systems, energy consumption is mainly associated with irrigation in intensive production systems and to

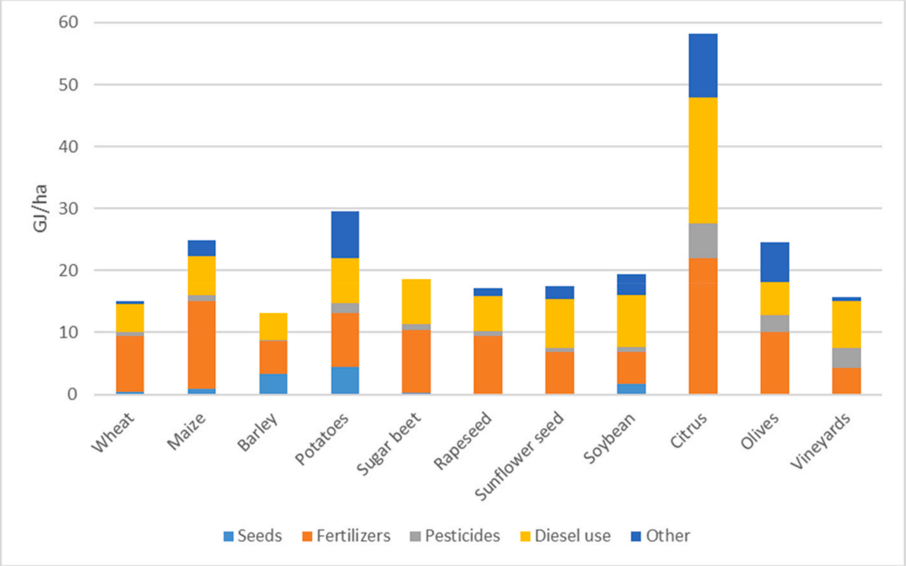

Fig. 1. Energy inputs for selected crops EU-27 GJ/ha.

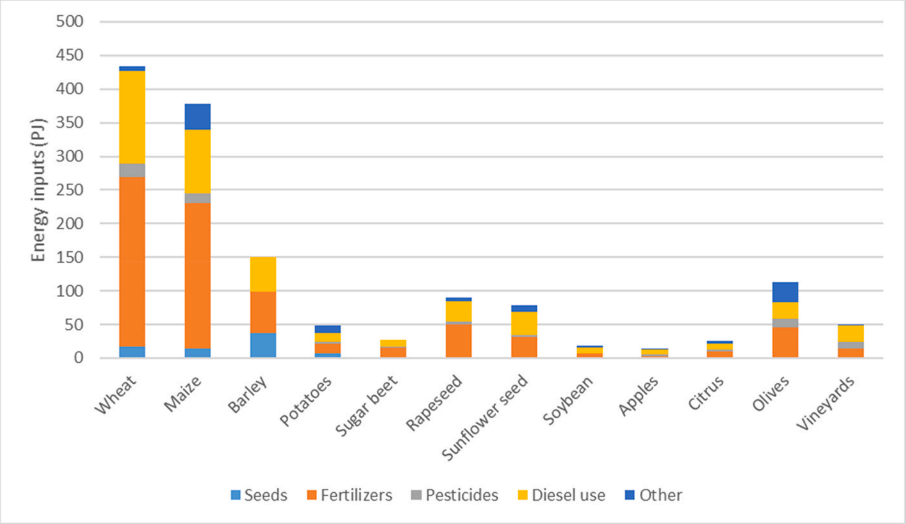

Fig. 2. Total energy inputs for selected open-field crops EU-27 (PJ).

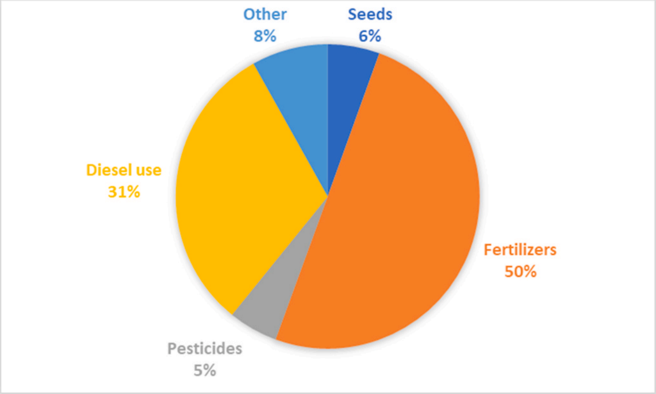

Fig. 3. Energy inputs open-field agriculture EU-27 (%).

a lesser extent with soil cultivation and harvesting, while in traditional systems diesel use is mainly associated with harvesting followed by pruning. Irrigation in the majority of olive systems is electric powered, while the rest of the activities are powered by diesel [41].

3.2. Cereals

Our review presents results on energy use inputs for the three largest cereals cultivated in the EU, namely wheat, maize and barley which account for 43.7%, 23.4% and 19.2% of total cereal production respectively. Fig. 4 depicts the total energy inputs in the cereal sector in the EU as whole. It is clear that the majority of these energy inputs are concentrated in a few Member States as the largest cereal producer is 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. Fig. 5 shows that, on average, indirect energy inputs dominate with fertilizers accounting for 56% of total energy inputs, followed by diesel use at 29%, seeds at 7%, other at 5% and pesticides at 3%.

Compared to all the open-field crops covered, the available data on wheat is the most comprehensive and is available both in terms of MJ per kg and GJ per hectare. Our meta-analysis (see Tables A1 and A2) illustrates 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 1 ha [4,16,45–47]. 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 and 3 MJ per kg. According to Achten and Acker's study (2016), around 90% of all energy consumed in wheat production in the EU comes from non-renewable fossil sources [16].

Table 3 provides an overview of the breakdown of energy inputs regarding on-farm activities for wheat production. This table illustrates that on average around 47% of all on-farm energy (predominantly

Table 2
% of energy inputs in selected orchards according to on-farm operations [41,44].

Source	Crop	Soil cultivation	Harvesting	Pruning	Irrigation
[44]	Oranges	9%	74%	2%	15%
[44]	Lemons	17%	63%	2%	18%
[41]	Olives -Traditional	73%	0%	27%	0%
[41]	Olives - Intensive	15%	17%	3%	65%
[41]	Olives - Super intensive	12%	34%	2%	51%

Table 1
% of energy inputs in selected arable crops according to on-farm operations [16,42,43].

Source	Crop	Tillage	Harvest	Sowing	Fertilizer application	Pesticide application	Other
[16]	Wheat	43%	31%	12%	NA	NA	8%
[42]	Maize	57%	32%	9%	1%	1%	NA
[42]	Rapeseed	35%	23%	32%	2%	7%	NA
[43]	Sunflower	61%	14%	25%	NA	NA	NA
[43]	Soybean	61%	16%	23%	NA	NA	NA

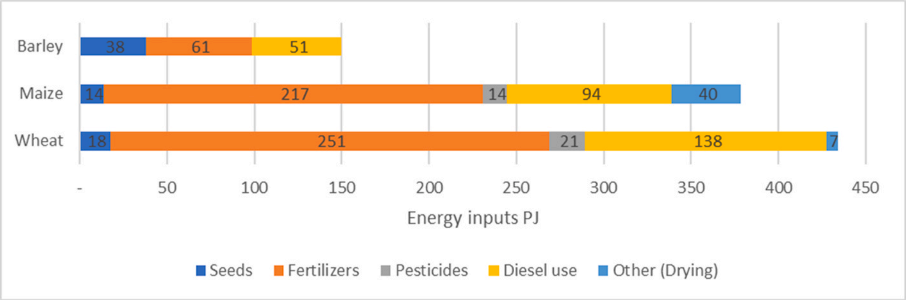

Fig. 4. Energy inputs for cereals EU-27 (PJ).

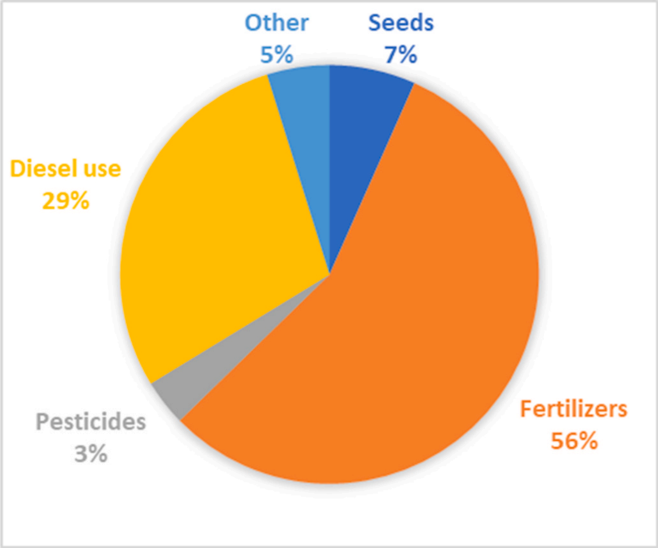

Fig. 5. Energy inputs for cereals EU-27 (%).

Table 3

Direct energy % according to agricultural activity for wheat production [16].

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%**

diesel) is related to tillage operations, followed by harvesting at 34%, seed and sowing at 12% and transport at 7%.

The meta-analysis for maize finds that on average around 24.84 GJ are consumed per hectare of maize cultivated in the EU (see Table A5) [37,42,45,48–51]. 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. For barley, our meta-analysis (see Table A6) suggests that on average around 13.21 GJ are consumed per hectare of barley cultivated in the EU [45,49,52,53]. 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%.

3.3. 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. 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 with fertilizers accounting for 38% of all energy inputs and diesel use for 30% (see Figs. 6 and 7).

Our meta-analysis indicates that on average around 29.61 GJ are consumed per hectare of potatoes (see Table A7) cultivated in the EU [4,45,46]. 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%. While for sugar beet our meta-analysis (see Table A8) indicates that on average around 18.61 GJ are consumed per hectare of sugar beet cultivated in the EU without irrigation [4,43,45,48,54]. 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, but suggest that further research is needed on the total energy use of irrigation in sugar beet cultivation especially in Southern Europe.

3.4. Oilseeds

Fig. 8 illustrates the total energy inputs associated with the three

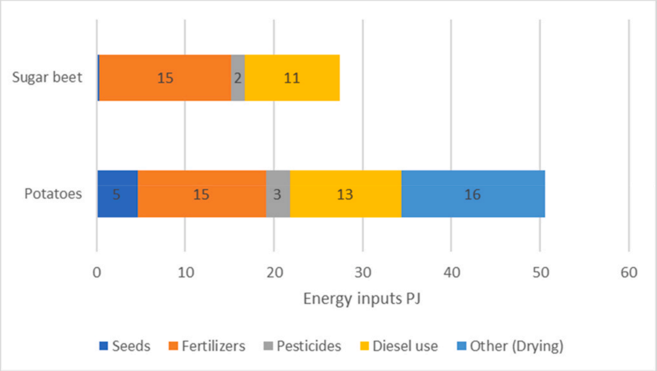

Fig. 6. Energy inputs for sugar beet and potatoes EU-27 (PJ).

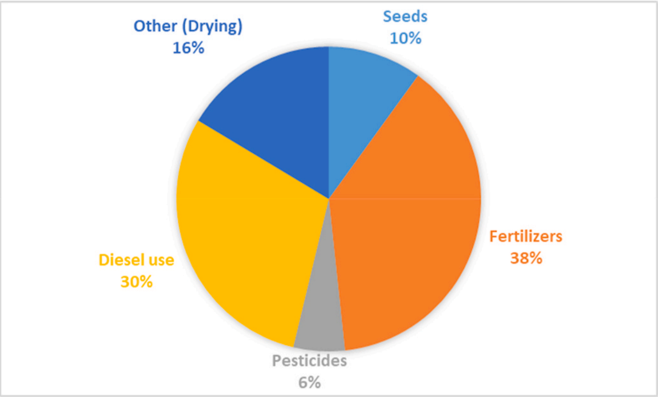

Fig. 7. Energy inputs for sugar beet and potatoes EU-27 (%).

main oilseeds cultivated in the EU and shows that overall, the rapeseed and sunflower production require significant energy inputs. Fig. 9 depicts the average distribution of energy inputs in the EU oilseed sector showing that fertilizers (46%) and diesel use (39%) are the main energy consuming inputs while seeds and pesticides constitute relatively small proportions of energy inputs.

Our meta-analysis finds that on average around 17.10 GJ are consumed per hectare of rapeseed (see Table A9) cultivation [42,43,45,55], 17.54 GJ are consumed per hectare of sunflower seed (see Table A10) cultivation [43,45,56,57] and 19.34 GJ are consumed per hectare of soybean cultivation (see Table A11) [43,45,48,49] in the EU. For rapeseed production the largest energy input is associated with fertilizers (55%) followed by diesel use (33%), while for sunflower and soy production systems the largest energy inputs are associated with diesel use (45% and 43% respectively) followed by fertilizers (39% and 26% respectively).

3.5. *Fruit orchards, vineyards and olive groves*

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 (see Fig. 10). This can be explained due to the larger area covered by olive groves (4.6 million hectares) in the EU as compared to vineyards (3.2 million hectares) and fruit trees (1.3 million hectares). Fig. 11 shows that, overall, fertilizers account for around 35% of energy inputs, followed by diesel use, irrigation and pesticides.

Apple trees are the dominant type of orchard in the EU, covering around 473,500 ha. Canals et al. (2007) finds that the range of MJ per kg of apple produced in the EU ranges from 0.4 to 2 MJ with a mean of 1.2 MJ [36]. This is in line with other studies from around the world which find 0.9–1.1 MJ/kg for the US [36] and 1.2 MJ/kg for Switzerland. We 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 (see Table A12).

The total area under citrus fruit plantations across the EU amounts to around 455,000 ha, of this orange production accounts for around 56% of the total area, followed by small citrus fruits at 31% and lemons at 13% [58]. Geographically, around 60% of total citrus plantations are located in Spain, followed by Italy with 27% and Greece with 9%. Our meta-analysis, including data on orange, lemon, clementine and tangerines [44,52,59], suggests that around 58.26 GJ/ha of energy inputs are used in citrus cultivation (see Tables A11, 12 and 13). The most energy consuming inputs are fertilizers at 37%, followed by diesel use at 35%, irrigation at 17% and pesticides at 10%. Within citrus, 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.

Based on the studies identified [4,60,61], it is clear that the energy intensity of olive cultivation varies considerably and that a clear indicator of this variation is whether they are irrigated. 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 and 399 trees per hectare) and super-intensive (high inputs and over 400 trees per hectare) [62]. In the EU, it is estimated that 48% of all olive farming systems are categorized as traditional, 47% as

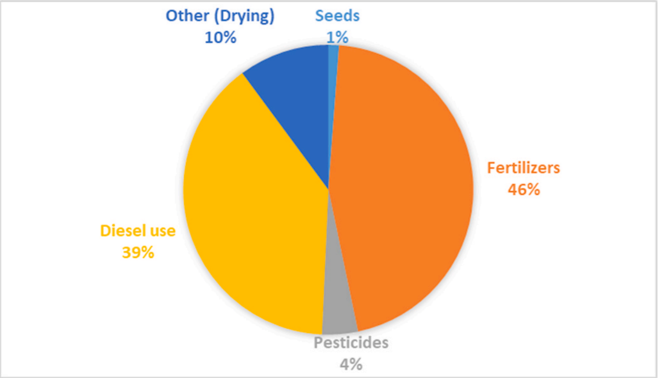

Fig. 9. Energy inputs for oilseeds EU-27 (%).

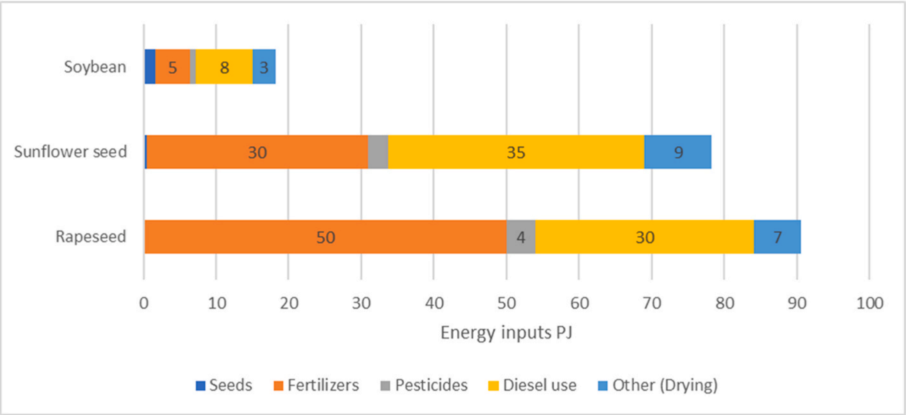

Fig. 8. Energy inputs for oilseeds EU-27 (PJ).

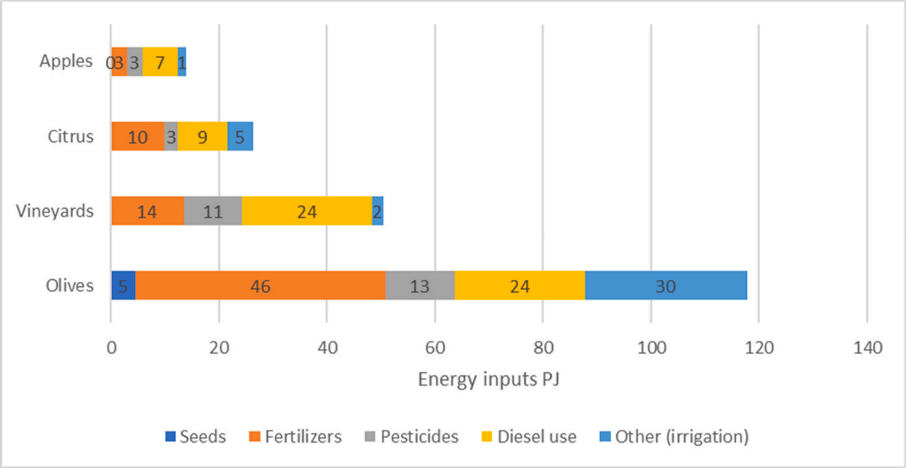

Fig. 10. Energy inputs for orchards EU-27 (PJ).

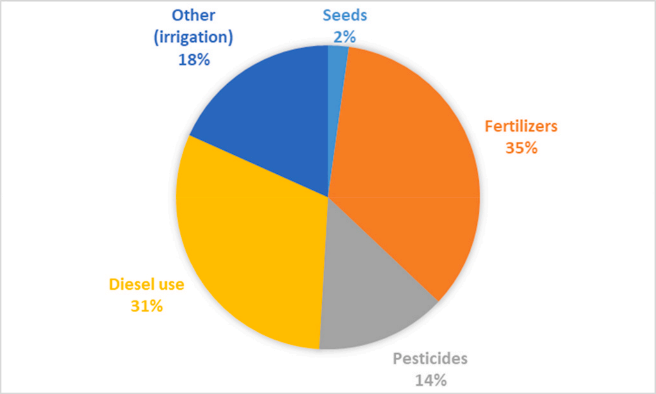

Fig. 11. Energy inputs for oilseeds EU-27 (%).

semi-intensive and 5% as super-intensive [62]. 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.

For those studies that do not include irrigation (see Table A16) [4,60, 61], we find that on average 12.58 GJ are required to cultivate 1 ha of olives, with fertilizers accounting for 45% of the final energy consumption, followed by diesel use at 40% and pesticides at 15%. For those studies that do include irrigation and are more energy intensive [4,60], our results find that on average 35.71 GJ are required to cultivate 1 ha of olives (see Table A17), with fertilizers accounting for 39% of the final energy consumption, followed by irrigation at 35%, diesel use at 15% and pesticides at 10%. Based on these results, we estimate that overall, 113.19 PJ are required for all olive cultivation in the EU.

Our meta-analysis from studies providing data on energy in vineyards (see Table A18) [4,52] shows 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%.

3.6. Indirect energy use

3.6.1. Energy use in fertilizers

The EU open-field sector is fertilizer intensive, using large amounts of manufactured (synthetic/chemical) fertilizers annually. 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 [63]. 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 [64].

Table 4
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%**

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 Tables 4) and 1.93% of total energy consumedTables in the EU (which is in line with estimates above). 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 [65] and according to Ramirez & Worrell (2006), over 1% of global energy use is for fertilizer production [66]. Data on the annual sales of fertilizer[2] is taken from Eurostat and is referenced against the average energy consumption value per fertilizer presented in the FEATs model [17,63].

Table 5 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.

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[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.

Table 5

Energy proportions in the production, transport and use of fertilizers [20,22].

Source	Type of fertilizer	Production	Packaging	Transportation	Application
Fertilizers Europe	Nitrogen	91.0%		2.2%	6.8%
[20]	Nitrogen	88.9%	3.3%	5.8%	2.0%
[20]	Phosphate	44.0%	14.9%	32.6%	8.6%
[20]	Potash	46.4%	13.0%	33.3%	7.2%

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 [29].

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 [22]. In the EU, natural gas is the main feedstock and energy source for the production of manufactured nitrogen fertilizers [29]. The proportions generally presented in the literature estimate that 60–80% of natural gas is used as feedstock and 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 [22]. 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 [20].

3.6.2. Energy use in pesticides

Over the past decade, the sale of manufactured pesticides in the EU has remained stable at around 0.35 million tonnes per year [67]. Pesticides[3] 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 6 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.

The production of pesticides is extremely fossil intensive, mainly because petroleum products (oil and natural gas) are the main inputs in their production [18,19,24]. 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 [24].

Table 6

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%**

4. Discussion

It is clear from our results, and other studies investigating energy use in EU agriculture [2–7], that the majority of the energy inputs for open-field agriculture come from non-renewable sources, in particular on-farm diesel use and the energy embedded in fertilizer production. According to Eurostat, which measures only direct energy use, energy use in agriculture coming directly from renewable sources and biofuels reached 9% in 2018, up from 4% in 1998 [2]. In addition, it is clear that the production of synthetic fertilizers and pesticides, which accounts for the vast majority of indirect energy inputs, is also extremely fossil dependent [66]. This suggests that 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 fossil energy free technologies, 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.

A few previous studies have investigated energy use in EU agriculture and food systems. Monforti-Ferrario et al.'s (2015) study investigating energy use in the entire EU food sector [7] relies mainly on data taken from Eurostat and Faostat and highlights that a study detailing direct and indirect energy flows in EU agriculture does not exist. This suggest that the data presented in our study on both direct and indirect energy uses for open field crops would be valuable for other studies looking at energy use in EU agriculture. This is particularly relevant as existing primary data has, to our knowledge, not previously been compiled in such a comprehensive manner. Similarly, Rokicki et al. (2021) study investigating the changes in energy consumption in EU agriculture [3] relies on Eurostat data, and including data from our study would allow for a more detailed analysis into changes in energy consumption in EU agriculture, this would be particularly important for addressing indirect energy inputs in the transition to a more sustainable agricultural sector.

The methodology used to estimate energy use in open-field agriculture has considerable limitations, as such, the results should be seen to provide a rough indication of energy use in open-field agriculture that allows us to provide indications of energy use concentrations. In fact, our review indicates that for a clearer understanding of energy use in open field agriculture considerably more data points are required for each crop and studies need to adopt more extensive methodologies that also include variance and uncertainty within and between studies. The establishment of a standardized methodology for calculating energy use in open-field agriculture would, in our view, aid this process considerably and allow for a more comprehensive meta-analysis into energy use in open-field agriculture in the future. Our results clearly indicate that fertilizer production and use in particular 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 is line with Pelletier et al.'s (2011) finding that in the United Kingdom 50% of

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[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.

energy inputs for the production of wheat, potatoes, barley and rapeseeds production is attributed to the production of fertilizers and pesticides [68] but higher than Beckman et al.'s (2013) US study on agriculture's supply and demand for energy and energy products which estimates that 37% of all energy inputs are indirect energy inputs [12]. The high use of synthetic fertilizers and pesticides can to a large extent be explained by previous policies as EU farm subsidies used to be directly connected to agricultural productivity which in practice supported the use of synthetic fertilizers. This is changing and discussions for the new Common Agricultural Policy (CAP) which is expected to be implemented in 2023 are increasingly centered around providing incentives for supporting a green transition in agriculture [69]. Some of the interventions proposed are for farmers to use a nutrient management tool, payments for 'agri-environment-climate commitments,' and specific funding for 'eco-schemes' [70].

Various FEFTS, such as increasing the use of organic fertilizers (from agricultural and other organic wastes/feedstocks), using renewable hydrogen as feedstocks and using renewable energy to power the Haber-Bosch process [6], 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 minimizing the consumption of manufactured pesticides, increasing their use efficiencies, transitioning to more sustainable production systems and increasing the share of locally produced organic pesticides.

The large proportion of energy from indirect sources also suggests that energy use data on EU agriculture significantly underreports energy use. On the one hand, underreporting inhibits our understanding of energy use in agriculture and the potential of designing effective and targeted FEFTS but it also impacts the decisions of policy makers. This could suggest that integrating these indirect energy uses in official statistics and policy would help support a green transition in EU agriculture.

Regarding direct energy inputs, the largest input in open-field agriculture is on-farm diesel use (31%). This is in line with Pelletier et al.'s (2011) study for 26% for direct field energy inputs [68]. Most of this energy is associated with tractor use; according to a rough estimate provided by CEMA [71], 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 minimize tillage and improve farm management efficiencies, could have a large impact on overall diesel use [6,72].

Our findings suggest that almost 8% of open-field agriculture is powered by electricity, which is used mainly for irrigation, storage and drying activities. This is in line with Eurostat findings which suggests that around 12% of direct energy inputs are currently powered by electricity [2]. EU electricity systems are rapidly transitioning to renewable sources (reaching 34% in 2019) [73], 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 often more efficient than fossil fuel powered systems [6].

Different crops in different geographical areas will require different, context-specific interventions at different scales. For instance, scaling the adoption of FEFTS in the cereal sector in Northern Europe will require different interventions as compared to orchards in Southern Europe. Initiatives such as the "AgEnergy Platform" [74] that provide a repository of and easy access to FEFTS can help drive context-specific transformations. In recent years, interest and discussions around combining renewable energy production and use with agricultural systems have also increased significantly. Studies are increasingly showing that certain designs, through for instance incorporating agrivoltaics or innovative bioenergy solutions in agricultural systems, can increase renewable energy use both in agriculture and the wider economy [75–77].

5. Conclusion

In conclusion, our review indicates that energy use in open-field EU agriculture is at least 1435 PJ, equivalent to around 3.7% of the total EU annual energy consumption, with the majority of energy sourced from non-renewable energy sources. Around 55% of total energy inputs come from indirect sources, which are often not reported in official energy use in agriculture statistics, suggesting that energy use is significantly underreported. Our study finds that the use of fertilizer is the largest energy consuming activity in EU open-field 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, pesticides and seeds, each accounting for 5% of total energy inputs.

The above illustrate that for the EU to achieve the goals outlined in the Green Deal and Farm to Fork strategy, the adoption of new technologies, improvements in energy efficiency and the further development and adoption of non-fossil energy sources for agriculture are required. The adoption and scaling of a wide range of context-specific FEFTS by stakeholders is likely to support the achievement of these goals.

Building on this review there are a number of important areas for future research. Considering that EU agricultural energy statistics have various limitations, such as simplistic and conflicting methodologies and considerable data gaps, our understanding and accuracy of estimates of energy use in EU agriculture would benefit from the adoption of consistent definitions and methodologies on what is included in the measurement of energy use in agriculture. In addition, the accuracy of the data presented in this review would be further complemented if further studies are conducted on energy use for all crops in EU open-field agriculture. Further research is also required in the energy use of non-conventional systems (e.g., organic, conservation) and crops that are currently cultivated on a minor scale, as well as into the correlations between farm indicators (size, location, specialization) and energy use.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Energy inputs for selected crops EU-27 GJ/ha

Crop	Seeds	Fertilizers	Pesticides	Diesel use	Other	Total
Wheat	0.49	8.94	0.61	4.47	0.58	15.08
Maize	0.89	14.25	0.91	6.19	2.60	24.84
Barley	3.33	5.36	0.02	4.50		13.21
Potatoes	4.39	8.73	1.60	7.33	7.55	29.61
Sugar beet	0.23	10.10	1.03	7.25	0.00	18.61
Rapeseed	0.01	9.44	0.73	5.69	1.23	17.10
Sunflower seed	0.12	6.81	0.62	7.91	2.08	17.54
Soybean	1.75	5.10	0.85	8.31	3.33	19.34
Apples (1)		0.26	0.25	0.57	0.13	1.20
Citrus		21.99	5.64	20.37	10.27	58.26
Olives		10.04	2.80	5.26	6.52	24.61
Vineyards		4.23	3.33	7.57	0.64	15.78

(1) for apples data is in GJ per tonne of production

Table A2
Total energy inputs for selected open-field crops EU-27 PJ (%)

Crop	Seeds (1)	Fertilizers	Pesticides	Diesel use	Other	Total
Wheat	18 (4)	251 (58)	21 (5)	138 (32)	7 (2)	434
Maize	14 (4)	217 (57)	14 (4)	94 (25)	40 (10)	379
Barley	38 (25)	61 (41)	0 (0)	51 (34)	0 (0)	150
Potatoes	7 (15)	15 (29)	3 (5)	12 (25)	13 (26)	49
Sugar beet	0 (1)	15 (54)	2 (6)	11 (39)	0 (0)	27
Rapeseed	0 (0)	50 (55)	4 (4)	30 (33)	7 (7)	91
Sunflower seed	1 (1)	30 (39)	3 (4)	35 (45)	9 (12)	78
Soybean	2 (9)	5 (26)	1 (4)	8 (43)	3 (17)	18
Apples		3 (22)	3 (21)	7 (47)	1 (11)	14
Citrus		10 (38)	3 (10)	9 (35)	5 (18)	26
Olives		46 (41)	13 (11)	24 (21)	30 (26)	113
Vineyards		14 (27)	11 (21)	24 (48)	2 (4)	50
EU Total	**79 (6)**	**716 (50)**	**75 (5)**	**444 (31)**	**116 (8)**	**1431**

[1] Data in parentheses are percentages.

Table A3
Energy inputs in wheat production EU MJ/kg [4,16].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Drying)	Total
[4]	Portugal	0.15	2.12	0.13	1.89	0.00	4.29
[4]	Poland	0.10	1.70	0.08	0.72	0.00	2.60
[4]	Netherlands	0.05	1.16	0.12	0.70	0.03	2.06
[4]	Greece	0.09	1.76	0.14	2.01	0.00	3.99
[4]	Germany	0.06	1.46	0.08	0.52	0.30	2.42
[4]	Finland	0.14	1.52	0.12	0.38	0.50	2.66
[16]	Belgium	0.05	1.68	0.16	0.73	0.00	2.62
[16]	Greece	0.27	2.92	0.32	1.89	0.00	5.41
[16]	Italy	0.15	1.84	0.12	0.91	0.00	3.02
[16]	Netherlands	0.11	1.53	0.36	0.78	0.00	2.79
[16]	France	0.14	2.47	0.29	0.68	0.00	3.58
[16]	Spain	0.32	3.99	0.13	1.99	0.00	6.43
[16]	Denmark	0.09	1.79	0.06	0.95	0.03	2.91
[16]	Germany	0.17	2.03	0.17	1.00	0.00	3.35
[16]	Sweden	0.14	1.50	0.14	0.96	0.00	2.73
[16]	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 A4
Energy inputs in wheat production (GJ/ha) [4,45–47].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Drying)	Total
[4]	Portugal	0.40	6.30	0.40	5.70	0.00	12.80
[4]	Poland	0.60	9.90	0.45	4.10	0.00	15.05
[4]	Netherlands	0.40	10.10	1.10	6.10	0.00	17.70
[4]	Greece	0.40	8.80	0.70	10.00	0.00	19.90
[4]	Germany	0.40	11.20	0.60	4.00	2.30	18.50
[4]	Finland	0.70	6.80	0.50	1.70	2.30	12.00
[46]	Germany	1.00	6.85	0.55	1.85	0.00	10.25
[45]	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%**

Table A5
Energy inputs in maize production (GJ/ha) [37,42,45,48–51].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
[48]	Italy	0.21	21.54	0.88	8.09	5.40	36.11
[37]	Italy	0.09	13.92	2.07	10.54	9.53	36.15
[49]	Italy	1.78	21.62	1.41	7.67	8.50	40.97
[50]	Lithuania	0.46	12.62	0.63	2.66	0.00	16.38
[42]	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
[45]	Germany						39.90
[51]	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 A6
Energy inputs in barley production (GJ/ha) [45,49,52,53].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Total
[49]	Italy	4.42	1.18		4.70	10.30
[45]	Germany					21.21
[53]	Poland	1.36	11.60	0.01	3.42	16.39
[52]	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 A7
Energy inputs in potato production (GJ/ha) [4,45,46].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Storage)	Total
[46]	Germany	3.8	4.6	1	4.2		13.6
[45]	Germany						73.15
Stawinski, 2011	Poland	10.9			6.5	3.2	20.50
[4]	Germany	1.5	10.5	1.6	7.2	6.1	26.9
[4]	Poland	3.1	6.7	0.2	6.8		16.8
[4]	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 A8
Energy inputs in sugar beet production (GJ/ha) [4,43,45,48,54].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
[4]	Poland	0.20	10.90	1.40	7.10		19.60
[4]	Poland	0.20	9.90	1.00	6.00		17.10
[4]	Poland	0.20	9.00	0.90	5.10		15.20
[4]	Netherlands	0.10	7.20	1.20	5.20		13.70
[4]	Germany	0.20	9.00	0.00	4.90		14.10
[4]	Germany	0.20	9.00	0.00	4.80		14.00
[4]	Germany	0.20	9.00	0.30	4.70		14.20
[54]	Germany						8–16
[45]	Germany						24.19
Venturi & Venturi, 2011	Italy average	0.30	14.30	1.10	14.10	0.00	29.80
[48]	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 A9
Energy inputs in rapeseed production (GJ/ha) [42,43,45,55].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
[45]	Germany						19.94
[42]	Germany	0.02	5.58	0.36	2.68	0.00	8.64
[43]	Italy Low		5.60	0.20	5.00	2.20	13.00
[43]	Italy High		11.90	0.90	19.00	5.20	37.00
Dobek & Dobek, 2010	Poland	21.47			3.68	0.00	25.15
[55]	Poland	0.00	13.24	1.33	2.08	0.00	16.65
[55]	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 A10
Energy inputs in sunflower production (GJ/ha) [43,45,56,57].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
[56]	Greece	0.18	4.88	0.43	3.56	0.00	9.05
[57]	Italy	0.05	6.01	0.14	6.18		12.38
[43]	Italy		9.55	1.30	14.00	4.15	29.00
[45]	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 A11
Energy inputs in soybean production (GJ/ha) [43,45,48,49].

Source	Country	Seeds	Fertilizers	Pesticides	Diesel Use	Other (Irrigation)	Total
[48]	Italy	0.71	3.951	0.411	6.227	5.4	16.699
[43]	Italy Average		5.35	1.5	13.05	4.6	24.5
[49]	Italy	2.791	5.995	0.626	5.66	0	15.072
[45]	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 A12
Energy inputs in apple production MJ/kg [36,78].

Source	Country	Fertilizers	Pesticides	Diesel use	Other (Storage)	Total
[36]; [78]	EU Average	0.26	0.25	0.57	0.13	1.2
	EU Average (%)	**22%**	**21%**	**47%**	**11%**	**100%**

Table A13
Energy inputs in orange production (GJ/ha) [44,52].

Source	Country	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
[44]	Italy	32.21	7.98	31.32	5.58	77.09
[52]	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 A14
Energy inputs in clementine and tangerine production (GJ/ha) [52,59].

Source	Country	Fertilizers	Pesticides	Diesel use	Other (Irrigation)	Total
[59]	Italy	19.44	5.97	14.04	19.65	59.09
[52]	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 A15
Energy inputs in Lemon production (GJ/ha) [44].

Source	Country	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
[44]	Italy	30.66	4.35	40.56	6.60	82.17
	Average (%)	**37%**	**5%**	**49%**	**8%**	**100%**

Table A16
Energy inputs in olive groves (GJ/ha) - without irrigation [4,60,61].

Source	Country	Fertilizers	Pesticides	Diesel use	Total
[60]	Spain dryland	15.53	3.45	3.58	22.56
[79]	Spain dryland	8.36	1.71	7.10	17.17
[4]	Greece	4.30	0.50	1.10	5.90
[61]	Greece	0.29	2.08	4.73	7.10
[61]	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 A17
Energy inputs in olive groves (GJ/ha) - with irrigation [4,60].

Source	Country	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
[79]	Spain Irrigated	29.14	3.62	4.21	19.18	56.15
[79]	Spain Irrigated	10.68	4.77	8.39	17.53	41.37
[4]	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%**

Table A18
Energy inputs in vineyards (GJ/ha [4,52].

Source	Country	Fertilizers	Pesticides	Diesel use	Other (irrigation)	Total
[4]	Portugal average	1.20	4.40	5.10	0.13	10.83
[4]	Greece average	9.10	3.20	2.20	1.80	16.30
[4]	Germany Average	2.40	2.40	15.40	0.00	20.20
[52]	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%**

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