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Review

Energy Use in Greenhouses in the EU: A Review Recommending Energy Efficiency Measures and Renewable Energy Sources Adoption

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Abstract: This study conducts a review of energy use in the EU greenhouse agriculture sector. The studies presented illustrate that energy use in greenhouses is varied and generally dependent on fossil sources. High energy systems, which are more dominant in northern Europe, are generally heavily climate controlled and energy use is dominated by heating and cooling processes, while low energy systems, which are dominant in southern Europe, show a mixture of energy uses including heating, cooling, irrigation, lighting, fertilisers, and pesticides. Our review also provides a discussion of energy efficiency measures and renewable energy sources adoption for greenhouse production. Finally, our review indicates that accurate and reliable studies on energy use in greenhouse production are scarce and fragmented and that a range of differing methodologies are currently used to estimate on-farm energy use. The development of a comprehensive methodology and categorisation for measuring energy use in greenhouse agricultural production would, in our view, catalyse further studies in this sector, considerably improve our understanding of energy use in greenhouses and support the green transition. Based on this, this paper proposes a basic framework for measuring energy use in greenhouse agriculture.

Keywords: energy-use in agriculture; fossil-energy-free technologies and strategies; FEFTS; greenhouses; renewable energy; energy inputs

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1. Introduction

In the EU, greenhouse structure and cultivation show considerable variation, ranging from complex energy intensive structures that heavily regulate the indoor climate to simple structures that resemble open-field practices. This variation is dependent on a variety of factors, including, but not limited to, local climatic and socio-economic conditions [1]. According to the FAO, an estimated 405,000 hectares of greenhouses are spread throughout the EU [2], a figure that includes both glass and plastic covered structures. By contrast, data from Eurostat provide an overview of the area of vegetables, flowers and permanent crops under glass in the EU-27 from 2005–2013, highlighting that there are around 135,000 hectares of glass covered (excluding plastic covered) greenhouse cultivation in the EU [3].

Greenhouse agricultural production is generally seen as one of the most intensive parts of agricultural production [4,5] as compared to energy use in open-field agriculture [6], however the role of greenhouse agriculture in the European food systems is not well-documented [1], while a small number of studies have been conducted that document energy use in greenhouse production. In 2013, the European Commission published a report on greenhouse production, however this only includes only some minor energy use statistics [5]. Campioti et al. (2012) investigate some of the energy parameters in the greenhouse sector in four European countries [7]. Mohamed et al. (2017) investigate the energy profile of greenhouses in Cyprus [8], while Wageningen University releases an annual report monitoring energy use within the Dutch greenhouse sector [9]. Regarding geography, the Netherlands in particular has the largest and most relevant energy use data available [9]. Nikolaou et al. (2021) investigates energy parameters in greenhouse tomato and cucumber production in semiarid Mediterranean areas [10]. Other studies that look at agricultural production or energy use in the agricultural sector generally provide no data on energy use in greenhouses specifically [11].

In this context, where it is clear that greenhouse cultivation is a significant energy consumer but there is relatively little data available, and taking into account the implementation of EU climate targets and its farm to fork strategy in agriculture, it is apparent that there is a need to move towards sustainable production practices. In order to understand the future of greenhouse production in the EU and how they can contribute to a sustainable transformation of our agricultural systems, it is necessary to understand the energy use in greenhouses. As such, the goal of this paper is to provide an overview of the available data on energy use in the EU and to discuss significant transitions occurring in the sector. The rest of this section provides a brief overview of greenhouses in the EU and their energy use parameters, Section 2 discusses the methodology, Section 3 provides the results presenting available energy use data for greenhouse cultivation in the EU, and Section 4 provides an overall discussion, potential future scenarios, and a proposed framework for measuring energy use in greenhouse agriculture.

Greenhouses in the EU and Their Energy Use Parameters

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 [12]. There are different types of greenhouses currently 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 [5]. Over the last two decades, the technology associated with the construction of and agricultural production within advanced greenhouses has progressed considerably with significant changes in design, materials, agricultural techniques, etc. Consequently, the potential yield in 'technology intensive' greenhouses has seen dramatic increases, for instance, what is considered a 'good' tomato yield has increased from 100 tonnes per hectare to 600 tonnes per hectare in recent years [13].

There are a variety of options for heating a greenhouse, including air heaters, central heating through pipes, boilers, cogeneration, natural gas, electricity, heat pumps [14]. Energy sources vary, with small systems often running on direct fossil fuels, such as gas or oil, while larger systems may run on cogeneration/combined heat and power from power plants, or geothermal heat pumps. It is important to note that a large proportion of greenhouses, especially in Southern Europe, are not heated, while in temperate and northern European countries greenhouses often have large heating requirements. Conversely, there are a number of options for cooling a greenhouse, including shading, whitening, natural, mechanical or evaporative cooling/ventilation. One or a combination of these are utilised in areas that have high average temperatures for parts of the year [5].

All production in greenhouses requires irrigation for which there are a variety of systems, generally powered through fossil fuels directly or via the electricity network [5]. Other areas that consume direct energy include lighting and machinery use. Greenhouses generally are also dependent on a number of indirect sources of energy; energy that is not directly used in agricultural production but can clearly be assigned to the agricultural sector. Indirect energy use includes energy use associated with the building of greenhouses and greenhouse machinery, as well as energy embedded in the production of fertilizers and pesticides [15].

There are a number of trends and parameters that affect the energy inputs of greenhouses. Multiple studies highlight that older systems are generally less energy efficient and require higher energy inputs per output [16,17]. Geography and climate conditions also clearly play an important role [18], while the type and philosophy of agricultural practices and techniques-conventional, organic, conservation, soilless cultivation, hydroponic, etc., employed in greenhouses are also likely to impact energy inputs. In practice, greenhouse systems in the EU vary significantly ranging from commercial large-scale systems to small-scale subsistence systems and their design and structure varies considerably, having large implications on energy use and energy sources [5].

The extent of greenhouse production per country is not well documented. For most EU countries, other than the Netherlands, there are rough estimates on the extent of greenhouse cultivation, in particular regarding greenhouses with a low technological profile. Eurostat used to provide an indicator on the area of vegetables, flowers, and permanent crops under glass EU-27 (ha), this has now been discontinued. Based on the data presented in Table 1, from Eurostat, the countries covered in this study cover around 72% of the total area under glass in the EU. In addition, in order to overcome the general lack of detailed available information on greenhouse production this study focused on the 'hubs' that are part of the Horizon AgroFossilFree project as this allowed local agricultural experts in each country to provide us with relevant data.

Table 1. Area of vegetables, flowers, and permanent crops under glass EU-27 (ha) [19].

Country	2005	2007	2010	2013
Belgium	2140	2120	2060	1800
Bulgaria	900	1140	1090	1080
Czechia	180	190	0	0
Denmark	450	470	460	400
Germany (until 1990 former territory of the FRG)	3370	3430	3170	3110
Estonia	60	60	40	40
Ireland	60	30	60	180
Greece	4670	5340	4290	4730
Spain	52,170	52,720	45,700	45,200
France	9620	9790	:	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	1010	450	310	330
Luxembourg	0	10	0	0
Hungary	1910	1760	1960	2260
Malta	70	70	80	100
Netherlands	10,540	10,370	9820	9330
Austria	290	580	620	720
Poland	7170	7560	6630	8080
Portugal	2310	2220	2360	2490
Romania	2790	3250	3020	3300
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

2. Materials and Methods

2.1. Search Strategy and Selection Process

This study conducts a review of the available literature on energy use data in greenhouse cultivation within the EU. Our search strategy used a key word search of Google Scholar and SCOPUS and the selection criteria for a paper's inclusion in this study were:

the presentation of energy use data based on either LCA methodologies or surveys, whether they were peer-reviewed, and whether they were published by well-respected journals or institutions. In some cases, data from reports were used if they were extensively cited in existing literature. The methodology, relevancy and accuracy of each study was evaluated for relevancy and accuracy and the wider project partners of the AgroFossilFree consortium [20]. Overall, 24 relevant published articles and reports were located in the first part of the search process. Of these, after the evaluation process, 13 were discarded due to methodological issues. From the remaining 11 studies, data were extracted and used for this review.

For this study, energy use was defined according to operations and included direct energy uses—on-farm operations, heating and cooling, lighting, irrigation—and indirect energy uses—energy embedded in the production of fertilizers and pesticides. Energy assigned to the production and establishment of agricultural infrastructure, such as agricultural machinery and greenhouse constructions, was not included due to difficulties associated with accurately measuring and reporting on this and most studies do not provide data on this. This is mainly because agricultural infrastructure is often in use for multiple decades and undergoes a variety of production processes which makes it difficult to accurately assign a yearly energy use values to these components. These energy input data for greenhouse production were extracted from each study and compiled and compared to existing studies for verification.

The research questions that guided our research included: what are the specific energy sources in greenhouse production processes? What are the energy needs for different types (high intensive to low intensive) greenhouses? How do the energy needs of greenhouses vary depending on geography and climate across the EU?

2.2. Types of Greenhouses

It is widely accepted that significant variations in the energy intensity and overall energy use between greenhouses exist and are dependent on a variety of factors. In practice, this variation makes it difficult to collate results without further assigning greenhouses to conceptual categories. Due to this, this study divides results according to high and low energy intensity greenhouses. The benchmark employed for this is that all studies with energy inputs below a 1000 GJ/ha were assigned as low energy intensity greenhouses and everything above 1000 GJ/ha as high energy intensity greenhouses. In practice, such an approach works well for this study as all studies were either much lower or higher than 1000 GJ/ha allowing for more meaningful comparisons and is justified as it splits energy use into intensive systems that use extensive climatic control, generally energy inputs in these systems are around 8–12 times more in these systems, and non-intensive systems that implement minimal climatic control, generally energy inputs are around 8–12 times less in these systems.

In addition, it is important to note that data on the energy use in greenhouse cultivation in the EU are fragmented and that available data are extremely limited. Therefore, our results provide data on greenhouse energy use both on a country level, for which there is some data available (for The Netherlands, Italy, Spain, Germany, Ireland), and specifically for tomato production, a crop which has by far the most available data. For a more detailed breakdown of our results, please see the Appendix A.

2.3. Limitations and Bias Risk

A main risk of this study is the lack of data on energy use in greenhouse cultivation in the EU. As such, this study is dependent on a relatively small number of studies. In effect, our understanding of energy use in EU agriculture may be disproportionately influenced by these studies and in instances may not be representative of the EU as a whole. This is a crucial limitation and highlights the importance of future studies investigating energy use in greenhouses across crops and climatic conditions in the EU.

The studies that provide energy use data on greenhouses generally present data without any uncertainty attached, while there are no established standardised methodologies for accounting for energy use in greenhouses [15,21]. LCAs in greenhouse systems often employ simple yet heterogenous methodologies which render comparisons difficult [22–24]. In our view, in order to obtain a clearer understanding of the energy use in greenhouses in the EU, the development of standardized methodologies and terminologies for approaching the specific investigation is a prerequisite for future studies. Based on this review we discuss some of the prerequisites and framework needed for the development of such a methodology.

Furthermore, greenhouse agriculture as a term is used to refer to a wide array of production systems. In practice, this means that production systems that have little in common, except that they occur in covered structures, are labelled together. Further conceptual distinctions and categorisations, as used in this paper, would, allow for improved analysis of greenhouse production.

3. Results

3.1. Overview

The following section provides a review of energy use data for Spain, Greece, Italy, The Netherlands, and Germany, as well as according to tomato production in the EU. Overall, the data presented illustrates significant variation between varying production systems with significant ranges depending on the type of greenhouse, geographical area, and crop grown (Table 2).

Table 2. 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%

3.2. 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. In total, 60% of Spain's greenhouses (approximately 30,000 ha) are located in Almeria [25,26], 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%) [27]. There is variation in the type of greenhouses, with a mixture of intensive and non-intensive greenhouses, while the average holding sizes are relatively small.

Two studies that document energy use in Spanish greenhouses were located; Baptista et al. (2012), which provides data on the heating and cooling greenhouses with tomato production [28], and Alonso and Guzman (2010), who investigate energy use in a range of Spanish production systems [22]. In Baptista et al.'s (2012) study, the greenhouses studied are heavily climatically controlled and exhibit large energy inputs (Figure 1 and Table A1), while the greenhouses covered by Alonso and Guzman (2010) are less climate-controlled and exhibit considerably—up to 150 times—less energy inputs per hectare (Figure 2 and Table A2). The largest energy use category for these greenhouses is the category 'others,' unfortunately the study does not provide a breakdown of what inputs/activities this refers to. In our view this category likely refers to ventilation and lighting.

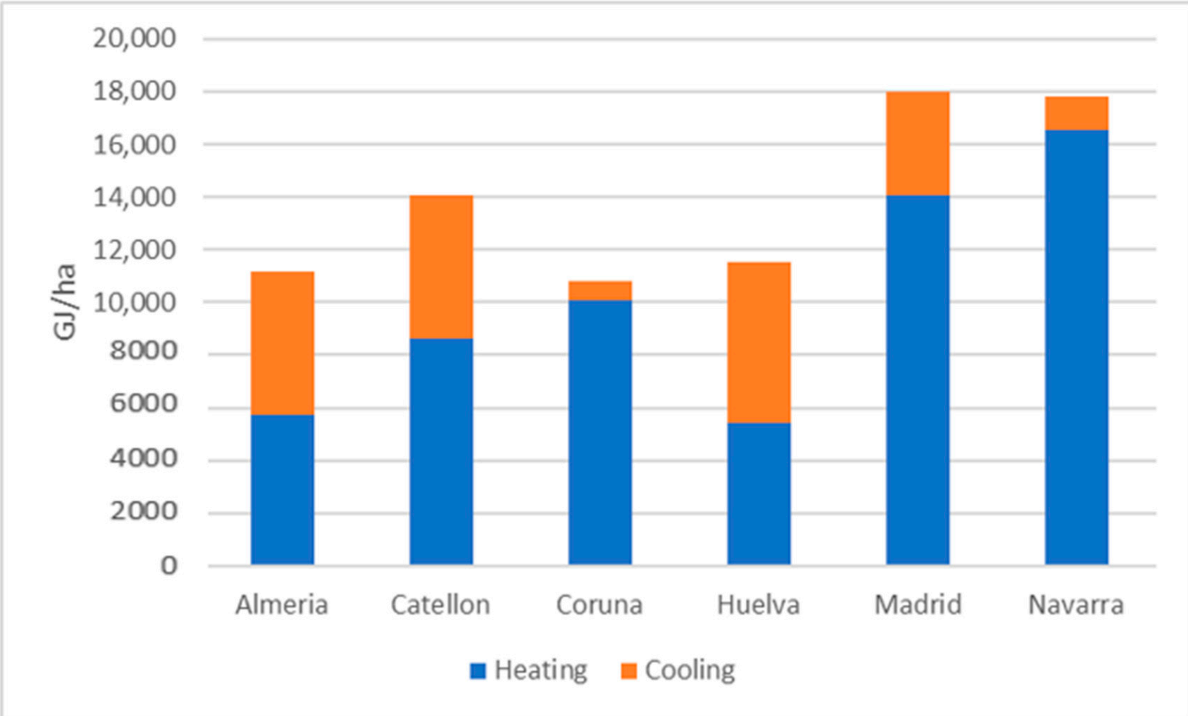

Figure 1. Energy consumption in high energy intensity tomato greenhouse production in Spain (GJ/ha) (based on [28]).

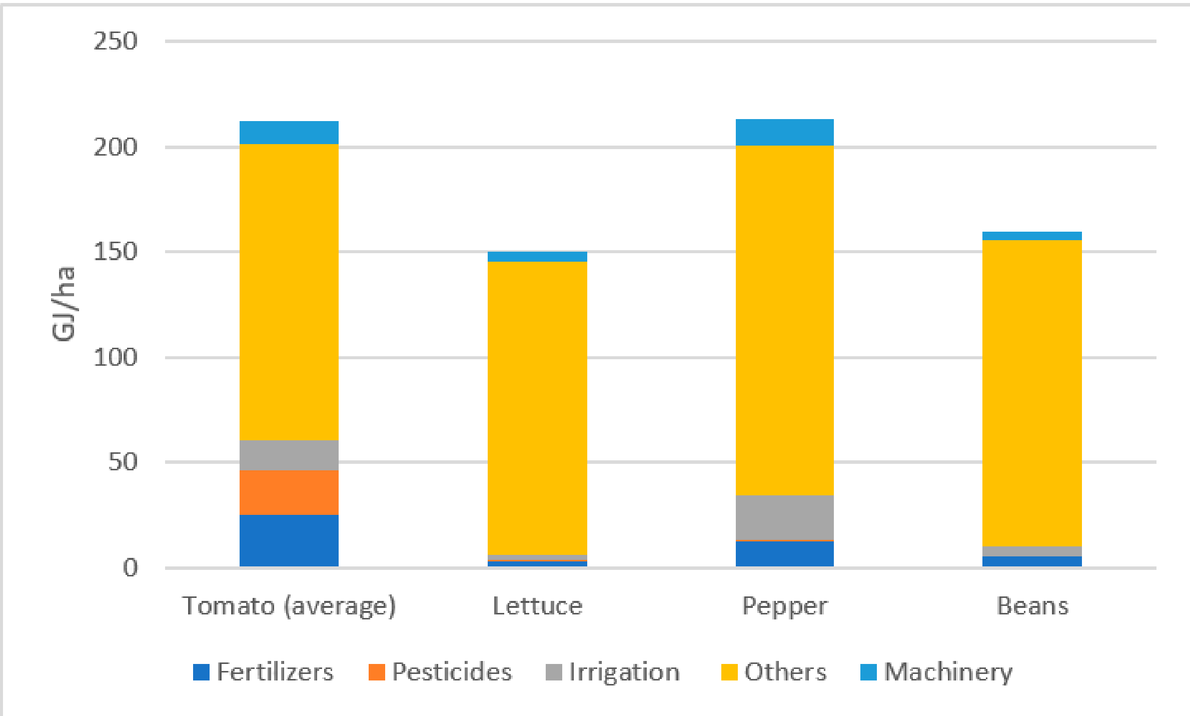

Figure 2. Energy consumption in low energy intensity greenhouse production in Spain (GJ/ha) (based on [22]).

3.3. Greece

In Greece, the area under greenhouse cultivation is approximately 5600 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. Geographically, Crete has the largest area of greenhouse production with 2166.5 ha (38.7%), followed by the Peloponnese with 1185.9 ha (21.2%) and Macedonia with 698 ha (12.5%) [29]. Around 93% of the total area are plastic covered greenhouses, 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 at 0.48 ha for vegetables, and the fact that the majority of the greenhouse area used for vegetables is occupied by high tunnels. Greenhouses in Greece are characterized by a relatively low level of automation. 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 is a major barrier to the implementation of these systems [29].

Four studies were located that provide data on energy use in greenhouse production in Greece; De Visser et al. (2012) conduct two LCAs for low energy intensity greenhouse production [15] (Figure 3), while Kittas et al. (2014) [23], Trypanagnostopoulos et al. (2017) [30] and Vourdoubas (2015) [24] each provide data on energy use for a specific crop—tomato, lettuce, flowers—in a high energy intensity production (Figure 3 and Table A3). Figure 4 illustrates that for low energy intensive greenhouses, demand for energy inputs is spread across fertilizers, materials, irrigation, pesticide, lighting, heating, and cooling (Table A4). By contrast, in high energy intensity greenhouses, energy used for heating dominates the consumption. For both crops covered in the low energy intensity greenhouses, the energy inputs are around 250 GJ/ha, whereas in high energy intensity greenhouses they are many times higher, ranging from around 7000 GJ/ha to 11,500 GJ/ha.

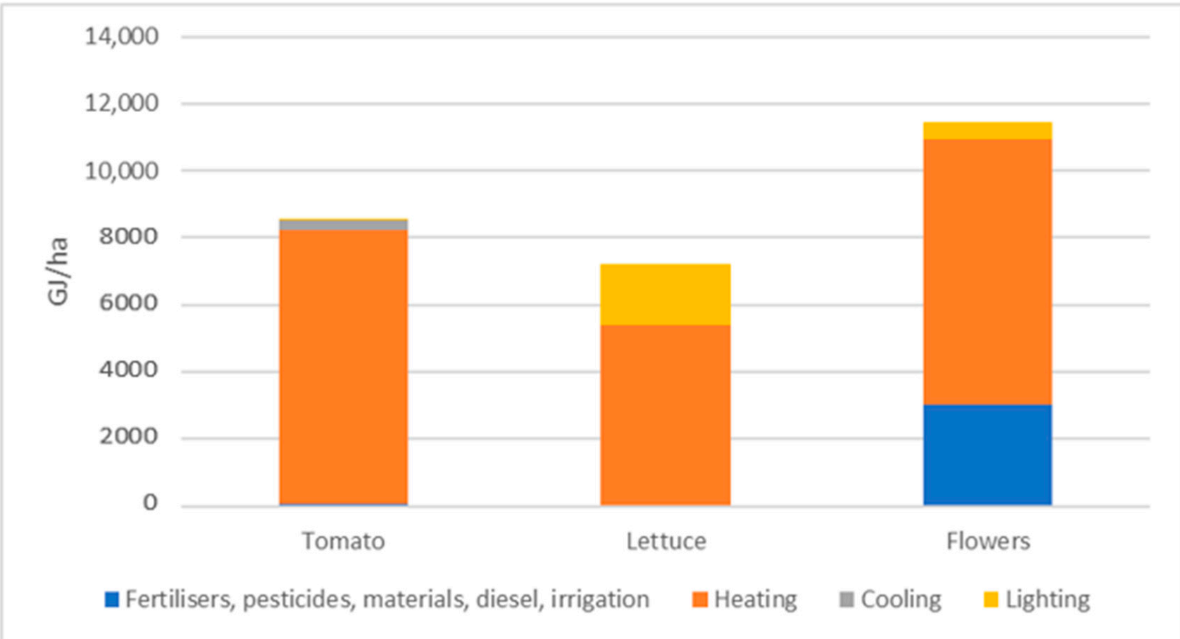

Figure 3. Energy consumption in high energy intensity greenhouse production in Greece (GJ/ha) (based on [23,24,30]).

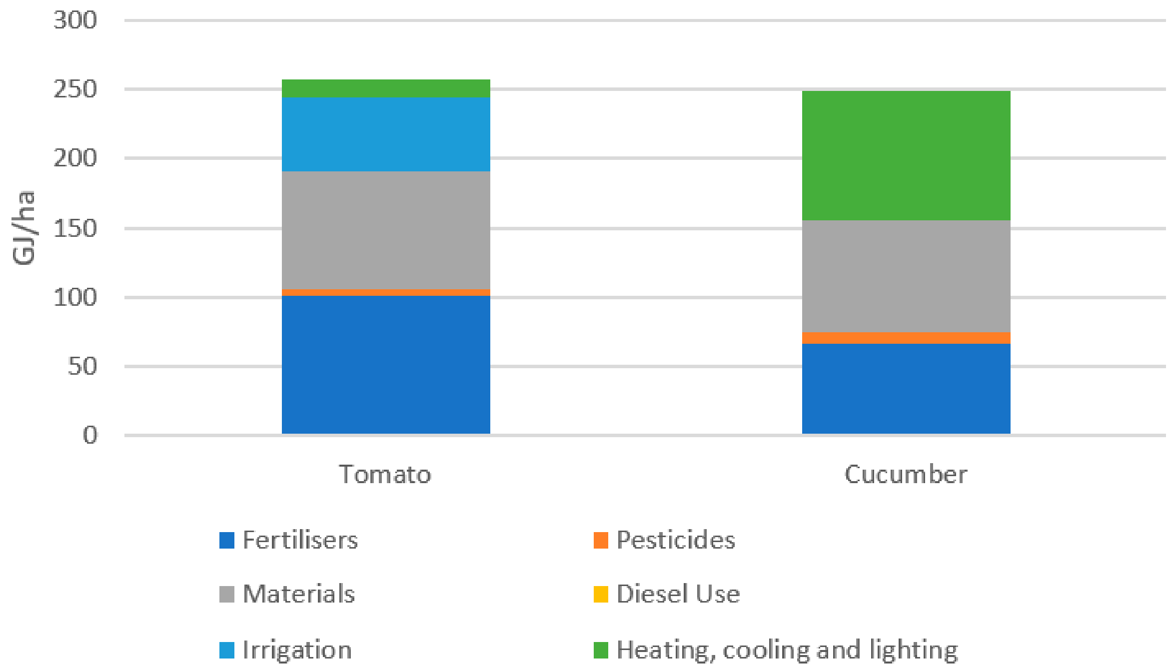

Figure 4. Energy consumption in low energy intensity greenhouse production in Greece (GJ/ha) (based on [15]).

3.4. Italy

The area under greenhouse cultivation in Italy is approximately 30,000 ha, with 6000 ha serving as permanent greenhouse structures [25]. 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 [31]. The former greenhouse type is predominant in southern regions due to 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 [32]. Due to favourable growing conditions and reduced costs, greenhouse cultivation has been moving southward. The cultivation of pot plants occurs in glasshouses and is generally found in northern regions [31]. The Italian greenhouse sector is of considerable economic importance for the national agricultural systems and a significant energy consumer. Even though Italian greenhouse systems only represent around 0.032% of the EU UAA, Italian greenhouse crops account for a turnover of more than EUR 3 billion [33], and according to the Italian Ministry of Economy and Finance, heating for greenhouses powered by fuel accounts for 0.72 millions of tonnes of oil equivalent (Mtoe), which is equivalent to nearly 24% of the direct energy consumption in Italian agriculture, while electricity use in greenhouses accounts for only 0.02 Mtoe [25].

Data for Italy were only located for crops cultivated in low energy intensity greenhouses in central Italy (Figure 5 and Table A5). Within these data, energy use ranges between 60 GJ/ha to 140 GJ/ha and suggest that electricity accounts for around half of all energy inputs, followed by diesel at around a quarter of all energy inputs [34].

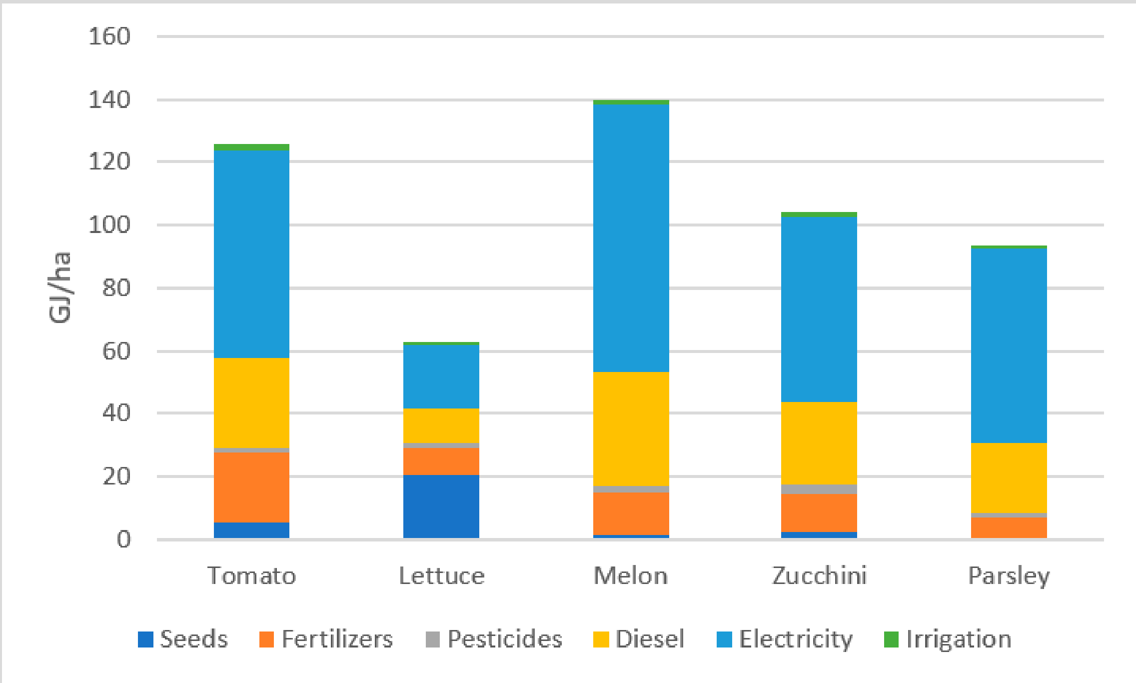

Figure 5. Energy consumption low-energy intensity greenhouse production in Italy (GJ/ha) (based on [34]).

3.5. The Netherlands

In the Netherlands, 9688 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 as compared to greenhouse production in other countries, with average production per m^2 in 2019 at 50 kg for tomatoes and 68 kg for cucumbers [35]. Due to this production intensity, The Netherlands produces 21% of the peppers, 20% of the cucumbers and 17% of the tomatoes grown in Europe [36]. 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 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 petajoules (PJ) [9]. Most energy consumption is associated with heating, accounting for around 74% of the total energy inputs, and electricity at 26%. 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. 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, a trend that is likely to continue [9].

On a per crop basis, for the studies that have detailed data, the vast majority of the total energy inputs are connected with heating, accounting for over 99% of energy use, while other inputs, such as fertilizers, are minor (Figure 6 and Table A6). 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, CO_2 enrichment, and others [9,37].

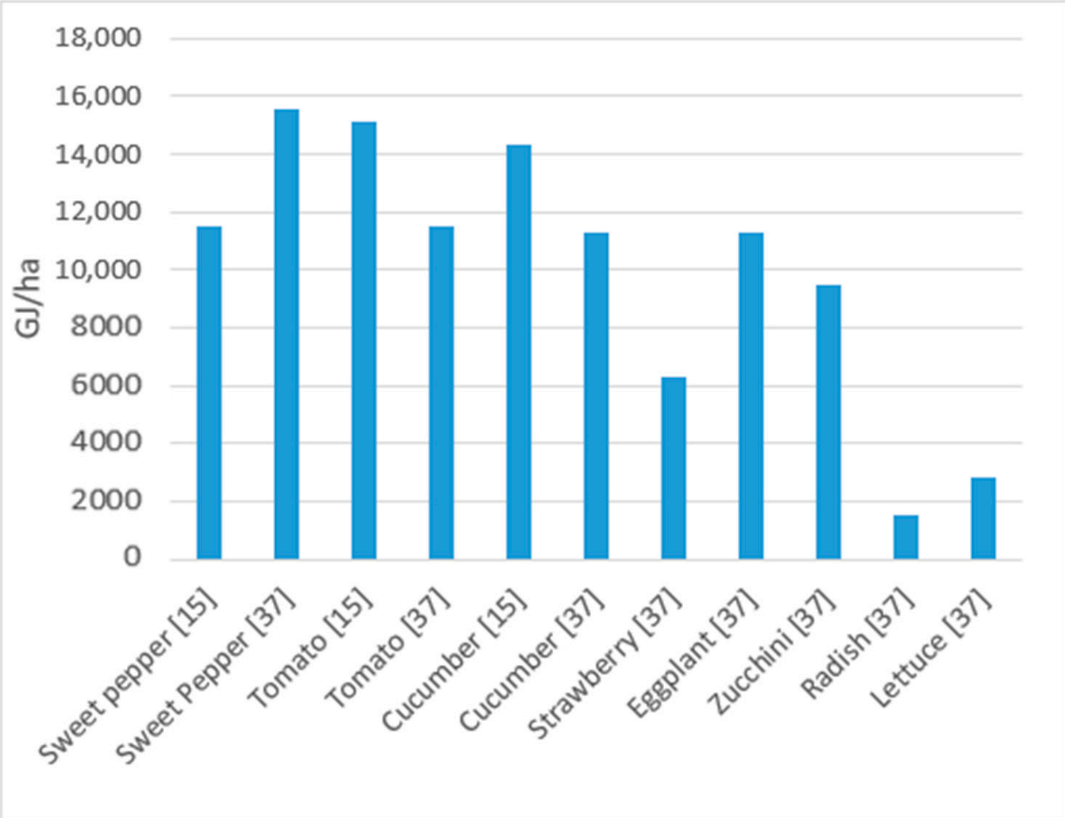

Figure 6. Greenhouse energy consumption for selected crops in the Netherlands (GJ/ha) (based on [15,37]).

3.6. Germany

Data on greenhouse production in Germany is relatively scarce. Voss (2011) suggest that only 3689 hectares are covered by greenhouses, of which an estimated 80% are glass greenhouses, 15% foil, and 5% stiff plastics, while 2500 hectares are heated [38]. 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 corresponds to almost 1600 ha, were built before 1982. Even though some of these facilities were upgraded to comply with the modern-day standards, most of them 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 m^2, almost 5600 facilities cover between 1000 m^2 and 5000 m^2 and the remainder of facilities are larger than 5000 m^2 [38].

For Germany, Visser et al. (2012) investigates the energy consumption in greenhouses for tomato and cucumber production. The biggest share of the energy inputs is attributed to heating purposes, whereas a small portion of the energy inputs account for fertilizers (Figure 7). The available data suggest that close to 13,000 GJ/ha are consumed in the greenhouse cultivation of both crops, of which 99.6% accounts for heating purposes. According to Kuntosch et al. (2020), black coal is the largest source of energy for heating purposes followed by natural gas and renewables (Figure 8 and Table A7) [39].

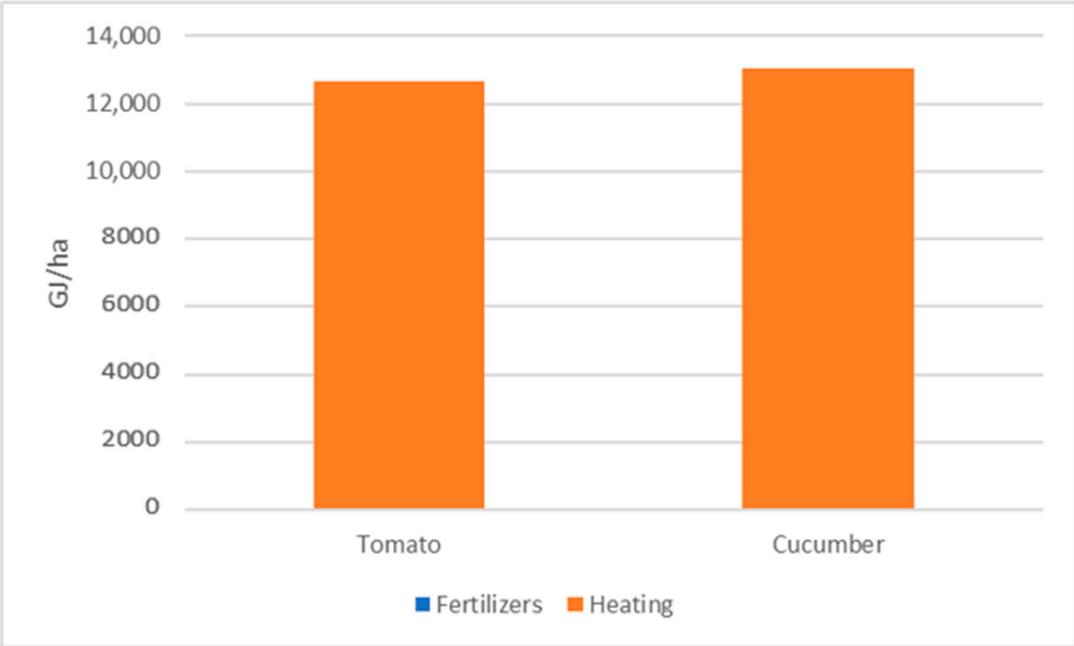

Figure 7. Energy consumption in the German greenhouse sector (GJ/ha) (based on [15]).

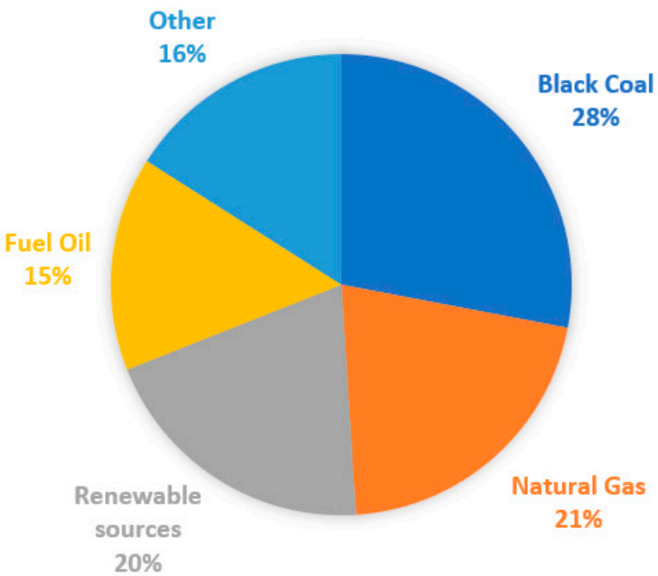

Figure 8. Percentages of the energy sources used for greenhouse heating in Germany (based on [39]).

3.7. Tomatoes

Figures 9 and 10 provide an overview of the energy data of high and low energy intensity greenhouse tomato production. They are presented according to country and in cases where multiple data points are available for one country simple averages were calculated (Tables A8 and A9). These data show some variations within categories, with energy inputs for high energy systems ranging from around 8000 GJ/ha in Greece to around 15,000 GJ/ha in the Netherlands. In the high energy intensity systems, the vast majority of energy inputs are associated with heating and cooling activities, while in the low energy intensity systems fertilizers are the largest energy inputs. Importantly, this illustrates that energy inputs in high energy intensive tomato production systems are around 50 times greater per hectare than in low energy intensive systems. This energy intensity translates into large differences in final yield, for instance, in the Netherlands the average tomato yield is around 50 kg/m^2 while in southern Italy it is 7.6 kg/m^2 [18].

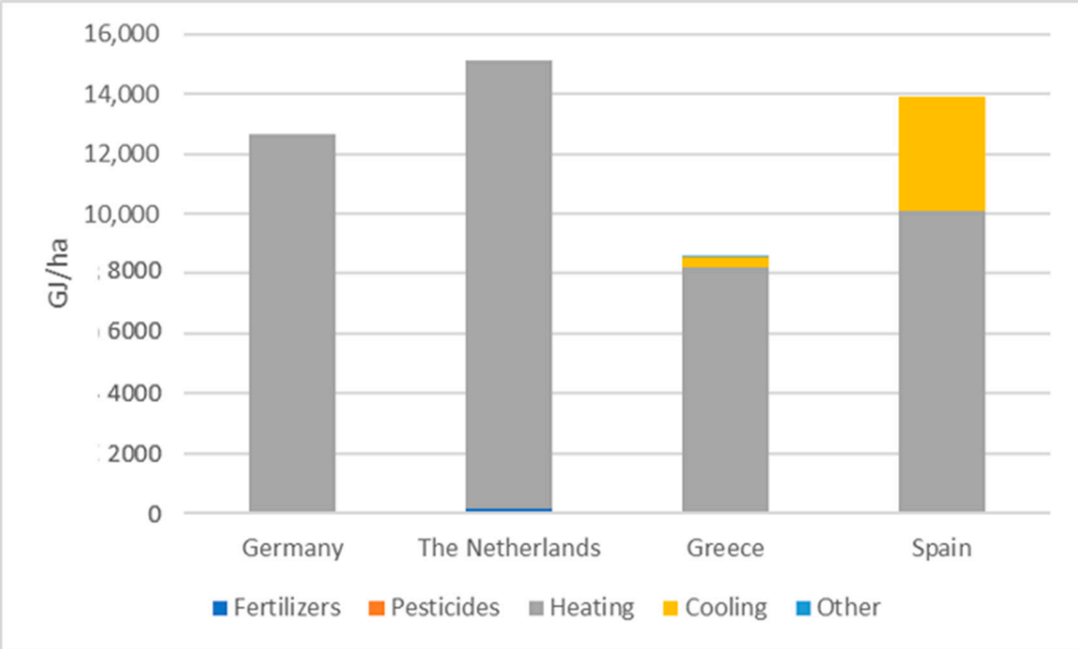

Figure 9. Energy inputs in high energy intensity tomato production systems (GJ/ha) (based on [15,28,40]).

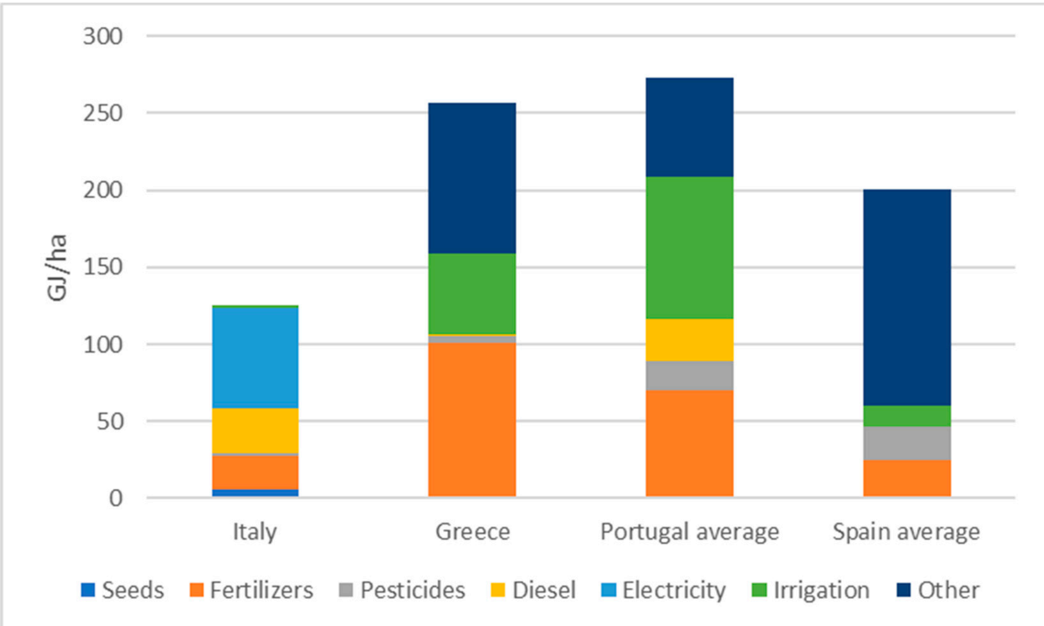

Figure 10. Energy inputs in low energy intensity tomato production systems (GJ/ha) (based on [15,22,34]).

4. Discussion

The data presented in this study illustrate that energy use in greenhouses in the EU varies considerably depending on the type of greenhouse, geographical area, and crop grown. In advanced greenhouse systems, heating is the dominant energy requirement and in some studies accounts for up to 99% of all energy inputs. In our view this needs more detailed research with more data points from accepted methodologies as 99% appears high. In any case, our review indicates that energy requirements for heating and cooling in energy intensive systems are so considerable that other energy inputs, such as fertilizers, are extremely minor. Indeed, it has been estimated that the heating and cooling of greenhouses represents 1.5% of Europe's total energy consumption [41]. Methods of heating greenhouses vary throughout the EU; gas boilers are generally popular, as are air-unit heaters for small scale installations [42], as well as cogeneration (Combined Heat and Power) in certain countries (mainly The Netherlands) [9]. In most cases, heating and cooling systems are powered by energy from fossil fuels but in recent years sustainable sources of heat, mainly geothermal, have been growing rapidly.

In less energy intensive systems, overall energy requirements per hectare are significantly less (50–70 times less energy per hectare) as compared to high energy systems, but generally still multiple times higher than the energy requirements of open-field agriculture. The mixture of energy inputs in these systems are split more evenly, depending on the crop and production system, between direct (lighting, heating/cooling, irrigation, machinery use) and indirect (fertilizers and pesticides). It is important to note that indirect energy sources, mainly fertilizers, constitute a considerable amount of energy inputs in low energy intensity greenhouses (6–27%).

Studies also indicate that there is significant geographical variation in energy intensity between greenhouses in the EU as, in general, more advanced greenhouses are located in northern Europe and basic greenhouse structures in southern Europe. An FAO study which focuses on greenhouse production in South-Eastern Europe (including non-EU countries) highlights that around 18% of greenhouses are glasshouses and 82% plastic greenhouses (a higher proportion than the EU average), and that of all area under greenhouses in the region 97% are not heated. By contrast, in Northern Europe, especially in the Netherlands, where most greenhouses are heavily managed, it is normal for greenhouse cultivation to be heated, consuming around 11,000 GJ/ha [9]. This difference can to a large extent be attributed to climatic conditions as crops grown in Northern European greenhouses for large parts of the year are dependent on external heating sources. However, it is likely that other factors, including market conditions, accessibility, knowledge, also play a role.

Identifying these areas where energy use is concentrated can help support the development and implementation of energy efficiency measures (EEM) and renewable energy sources (RES) interventions that support a transition of the entire greenhouse sector. In recent years, various studies have investigated and proposed EEM in different forms: Nikolaou et al. (2021) discuss a range of practical EEM for greenhouses located in Mediterranean countries [10], while Fabrizio (2012) finds that energy demand in greenhouses in northern Italy can be reduced by 30% by the usage of better insulated transparent materials. [17]. Zhang et al. (2020) conduct a review of different control strategies for improving the energy efficiency of greenhouses finding that traditional control strategies combined with intelligent algorithms have become a popular way to reduce the energy demand of greenhouses and can lead to substantial energy savings [43]. Chen et al. (2012) show that such a system can improve energy efficiencies by up to 15.1% [44]. Various studies highlight that traditional light sources in greenhouses are relatively energy inefficient and generally generate radiant heat and highlight that switching to LED sources can lead to considerable energy savings [45–47]. Studies generally show that improving the design, operation, and technology used in greenhouses can also significantly improve overall energy efficiency [43]. However, implementing these systems can be expensive and, due to variation in greenhouses, EEM interventions are often context specific, highlighting that further research in these areas would be useful [43]. Various studies investigate the transition to RES for greenhouse production, including the potential for: integrating solar technologies within greenhouse production [17,32,48]; biogas and bioenergy [49]; and geothermal [14,16,50]. Regarding geothermal, Arpa et al. (2016) find that geothermal are economically comparable with conventional systems [14] and Russo et al. (2014) find that geothermal heat pumps are environmentally beneficial over conventional systems. Other recent research indicates that the installation of these can also be economically advantageous as compared to alternatives [51]. This suggests that the transition to RES, which is already occurring at a rapid pace in certain European countries, could open the door to major reductions in the dependency on fossil sources in the greenhouse sector. Similar to EEM measures, RES interventions are likely dependent on context specificity and economics, while various factors need to be taken into account to support a sustainable transition. For instance, one of the reasons fossil fuels are used to provide energy in greenhouses is that they are source of CO_2 that can be used to enhance productivity [4].

Taking local and international contexts into account there are various policy interventions that will likely support the transition to the use of RES and EEM in greenhouse production. In our view, these include increased taxes for fossil fuels, subsidies for RES adoption EEM interventions and higher carbon prices. For instance, direct subsidies as implemented in the Netherlands can accelerate this transition for greenhouse heating [52]. The new CAP is generally supportive of this by including a range of policies that support the targets of the Green deal including considerable funding for eco-schemes and climate supportive policies [53].

Despite our findings, there are relatively little data available and few studies were identified that investigated energy use in greenhouses in the EU, the studies that do exist employ varying methodologies and boundaries for measuring energy use ranging from LCAs to surveys to advanced models. Although this is similar to data and methodological issues experienced in other agricultural sectors [6,54], in the greenhouse sector the lack of data is more considerable. In our view, the development of a widely accepted methodology for measuring energy use in agriculture is of utmost importance and its establishment will catalyse future studies on energy use. In addition, one of the limitations highlighted by this review is that greenhouse agriculture shows extreme variation but is often labelled under one term or category. In our view, an approach that further categorises greenhouse production into, for instance, low and high energy intensity greenhouses is useful for our understanding and for comparing greenhouse production across agro-climatic conditions. Our review also highlights a few other general areas for further research, including the potential of EEM and RES technologies, especially in the context of the European Green Deal, as well as on energy demands per crop and within different geographical and agro-climatic areas.

Proposed Framework for Measuring Energy Use in Greenhouse Agriculture

Based on these limitations we propose a framework that would, in our view, allow for considerably more accurate measurement and understanding of energy use in greenhouse production systems and indeed in all agricultural systems. We propose that this framework is centred around conducting several LCAs at regular intervals for all crops in different production systems in all countries. In practice this would first require the categorization of production systems and the identification of 'standard' systems in each country. At a later stage non-standard and non-conventional production systems can also be considered. We also recommend that a wide, accurate and measurable definition of direct and indirect energy is included in these studies. Though indirect energy is consumed prior to the farm it can clearly be attributed to the agricultural sector and is important to be included.

In such a system, an effective approach to conducting individual LCA for crops in each production system needs to be developed. For energy use we propose that the LCA methodology uses a wide, standardized, and detailed categorisation of energy inputs. The categories that we propose include energy use for: seeds; soil; growing media; pesticides; fertilizers; diesel use for machinery, heating and ventilation; electricity use for machinery, heating, ventilation, irrigation, storage, machinery. Such a process that also differentiates between the likely main energy sources, diesel and electricity, would support a detailed understanding of energy inputs in greenhouses. We consider this overall categorisation particularly important as, currently, a small number of non-standardized energy use categories are generally used between LCAs. For instance, one LCA might have the categories fertilizers, pesticides, diesel use, and lighting, while another one might have fertilizers pesticides, machinery use, and electricity. In practice, this makes effective comparisons extremely difficult and prone to errors as these categories often overlap, are not exclusive and often there is little transparency on what was included in each of these inputs.

In addition, it would be useful if results are presented as energy use per hectare, as well as energy use per kilogram/tonne and also include uncertainty and confidence intervals.

A major drawback of existing LCAs in agriculture is that they generally do not include any degrees of uncertainty. This entire methodology would need to rely on detailed data that rely on accurate real-world parameters and/or accurate database reference values. For this to occur considerable effort is required for the finding of accurate and updatable parameters and reference values. Once a large number of LCAs have been conducted, using appropriate statistic tools, an effective meta-analysis can be conducted that provides accurate greenhouse energy use profiles in different countries and production systems.

In our view such a framework can also be applied to the open-field agriculture and livestock sectors. This is a large piece of work that requires significant funding to be carried out but would support a more detailed understanding of energy use in agriculture and support effective policy and interventions for the transition away from fossil-based agriculture.

5. Conclusions

In conclusion, the review presented in this paper illustrates that energy use in greenhouses is variable and generally dependent on fossil sources. High energy systems, which are more dominant in northern Europe, are generally heavily climate controlled and energy use is dominated by heating and cooling processes, while low energy systems, dominant in southern Europe, show a mixture of energy uses. Our review also provides a discussion of trends in EEM and RES adoption for greenhouse production. Finally, our review indicates that accurate and reliable studies on energy use in greenhouse production is scarce and fragmented and that a range of differing methodologies are currently used to estimate on-farm energy use. The development of a comprehensive methodology and further categorisation for measuring energy use in greenhouse production, based on the framework presented in this paper, would, in our view, catalyse further studies in this sector and significantly improve our understanding of energy use in greenhouses, further supporting the green transition.

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Appendix A

Table A1. Energy consumption in high energy intensity tomato greenhouse production in Spain (GJ/ha) (based on [28]).

Source	Zone	Crop	Heating	Cooling	Total
Baptista et al., 2012 [28]	Almeria	Tomato	5760	5400	11,160
Baptista et al., 2012 [28]	Catellon	Tomato	8640	5400	14,040
Baptista et al., 2012 [28]	Coruna	Tomato	10,080	738	10,818
Baptista et al., 2012 [28]	Huelva	Tomato	5400	6120	11,520
Baptista et al., 2012 [28]	Madrid	Tomato	14,040	3978	18,018
Baptista et al., 2012 [28]	Navarra	Tomato	16,560	1260	17,820

Table A2. Energy consumption in low energy intensity greenhouse production in Spain (GJ/ha) (based on [22]).

Source	Crop	Fertilizers	Pesticides	Irrigation	Others	Total
Alonso & Guzman 2010 [22]	Tomato (average)	24.97	21.54	13.91	140.60	201.03
Alonso & Guzman 2010 [22]	Lettuce	2.66	0.89	3.00	138.49	145.03
Alonso & Guzman 2010 [22]	Pepper	12.09	1.03	21.00	166.11	200.23
Alonso & Guzman 2010 [22]	Beans	5.29	0.24	4.70	145.12	155.35

Table A3. Energy consumption in high energy intensity greenhouse production in Greece (GJ/ha) (based on [23,24,30]).

Source	Zone	Crop	Fertilisers, Pesticides, Materials, Diesel, Irrigation	Heating	Cooling	Lighting	Total
Kittas et al., 2014 [23]	Thessaly	Tomato	76.86	8137.8	328.32	7.2	8550.18
Trypanagnostopoulos et al., 2017 [30]	Pyrgos	Lettuce		5400		1800	7200
Vourdoubas 2015 [24]	Crete	Flowers	3024	7920		504	11,448

Table A4. Energy consumption in low energy intensity greenhouse production in Greece (GJ/ha)(based on [15]).

Source	Crop	Fertilisers	Pesticides	Materials	Diesel Use	Irrigation	Heating, Cooling and Lighting	Total
de Visser et al., 2012 [15]	Tomato	101	4.5	85	0.5	53	13	257
de Visser et al., 2012 [15]	Cucumber	67	7.5	80.5	1		92.5	248.5

Table A5. Energy consumption low-energy intensity greenhouse production in Italy (GJ/ha) (based on [34]).

Source	Crop	Seeds	Fertilizers	Pesticides	Diesel	Electricity	Irrigation	Total
Campiglia et al., 2007 [34]	Tomato	5.52	21.95	1.76	28.83	65.62	1.97	125.63
Campiglia et al., 2007 [34]	Lettuce	20.70	8.23	1.52	11.09	20.46	0.87	62.87
Campiglia et al., 2007 [34]	Melon	1.44	13.56	2.12	36.26	85.09	1.39	139.86
Campiglia et al., 2007 [34]	Zucchini	2.30	12.41	2.71	26.35	59.07	1.28	104.13
Campiglia et al., 2007 [34]	Parsley	0.01	7.18	1.42	21.79	62.10	0.91	93.41

Table A6. Greenhouse energy consumption for selected crops in the Netherlands (GJ/ha) (based on [15,37]).

Source	Crop	Fertilizers	Pesticides	Heating	Total
de Visser et al., 2012 [15]	Sweet pepper	112.6	2.5	11,424	11,539
Stanghellini et al., 2016	Sweet Pepper				15,540
de Visser et al., 2012 [15]	Tomato	119	1	14,990	15,110
Stanghellini et al., 2016	Tomato				11,480
de Visser et al., 2012 [15]	Cucumber	0	0	14,245	14,360
Stanghellini et al., 2016 [37]	Cucumber				11,320
Stanghellini et al., 2016 [37]	Strawberry				6310
Stanghellini et al., 2016 [37]	Eggplant				11,320
Stanghellini et al., 2016 [37]	Zucchini				9510
Stanghellini et al., 2016 [37]	Radish				1550
Stanghellini et al., 2016 [37]	Lettuce				2820

Table A7. Energy consumption in the German greenhouse sector (GJ/ha) (based on [15]).

Source	Country	Crop	Fertilizers	Heating	Total
de Visser et al., 2012 [15]	Germany	Tomato	42	12,612	12,654
de Visser et al., 2012 [15]	Germany	Cucumber	53	13,000	13,053

Table A8. Energy inputs in high energy intensity tomato production systems (GJ/ha) (based on [15,28,40]).

Source	Country	Fertilizers	Pesticides	Heating	Cooling	Other	Total
de Visser et al., 2012 [15]	Germany	42.00		12,612.00			12,654.00
de Visser et al., 2012 [15]	The Netherlands	119.00	1.00	14,990.00			15,110.00
Kittas et al., 2014 [40]	Greece	58.86		8137.80	328.32	25.20	8550.18
Baptista et al., 2012 [28]	Spain			10,080.00	3816.00	0.00	13,896.00

Table A9. Energy inputs in low energy intensity tomato production systems (GJ/ha) (based on [15,22,34]).

Source	Country	Seeds	Fertilizers	Pesticides	Diesel	Electricity	Irrigation	Other	Total
Campiglia et al., 2007 [34]	Italy	5.52	21.95	1.76	28.83	65.62	1.97	0.00	125.63
de Visser et al., 2012 [15]	Greece		101	4.5	0.5		53	98	257
de Visser et al., 2012 [15]	Portugal average		70	19.5	26.5		92.5	64.5	273
Alonso & Guzman 2010 [22]	Spain average		24.97	21.54			13.91	140.60	201.03

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