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Comparison of the Embodied and Operating Energy in Agricultural Greenhouses and in Residential Buildings

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Abstract

The increase of the energy efficiency in buildings and greenhouses is important for reducing the use of fossil fuels and the emissions of greenhouse gases. Energy efficiency evaluation requires the consideration of both the embodied and the operational energy. Many estimations regarding the embodied and the operational energy in various types of buildings have been reported so far. However, studies regarding the embodied energy in agricultural greenhouses are rare while there are many estimations regarding their operational energy. The goal of our study is the comparison of the embodied and the operational energy in residential buildings and in agricultural greenhouses. The embodied and operational energies are compared in greenhouses as well as in low-energy and in conventional residential buildings. Our results indicate that the ratio of embodied energy to life-cycle energy in low-energy residential buildings and in nearly-zero energy buildings varies in the range at 36% to 83% that is significantly higher than the ratio in conventional residential buildings which is in the range of 6% to 20%. The ratio of embodied energy to life-cycle energy in agricultural greenhouses, at 0.86% - 70.41%, varies significantly depending on many parameters. The importance of carbon emissions related to embodied energy in low-energy buildings, in net-zero energy buildings and in agricultural greenhouses is highlighted. Our work could be useful to policy makers who are willing to accelerate the green transition to a low carbon economy in the coming decades.

Keywords: Embodied energy, Operational energy, Greenhouses, Life-cycle energy, Renewable energies, Residential buildings

1. Introduction

Climate change mitigation requires the increase in energy efficiency and the replacement of fossil fuels with renewable energies. Residential buildings and agricultural greenhouses consume energy during their construction, operation, refurbishment and maintenance as well as during their demolition. The energy used during their construction, refurbishment, maintenance and demolition is called embodied energy (EE) which together with their operational energy (OE) consists of their life-cycle energy (LCE). The importance of the EE in the LCE depends on the energy efficiency of residential buildings and greenhouses and the operational energy (OE) used in them. After 2010 the EU legislation made obligatory the construction of nearly-zero energy buildings (nZEBs) (*EU directive 2010/31/EU*). In low-energy buildings and in nZEBs the low consumption of operational energy OE increases the significance of EE in the LCE (*Chastas et al, 2017).* Estimations concerning the embodied energy EE in greenhouses are limited (*Canakci et al, 2006*) while the possibility of creating net-zero carbon emissions greenhouses due to energy use has been analyzed (*Vourdoubas, 2020*).

The aims of the current research are:

- *a) To estimate the embodied and the operational energy in conventional and low-energy residential buildings,*
- *b) To estimate the embodied and the operational energy in agricultural greenhouses, and*
- *c) To compare the embodied and the operational energy in residential buildings and in agricultural greenhouses.*

The current work could be useful to manufacturing and construction companies as well as to authorities who are interesting to reduce the energy consumption and the carbon emissions in residential buildings and in greenhouses. The structure of the work is as follows: After the literature survey the energy consumption in greenhouses is examined as well as the EE and the OE in residential buildings. In the next sections the EE in greenhouses is analyzed followed by the comparison of the EE and the OE in residential buildings and in agricultural greenhouses. The text ends with discussion of the findings, the conclusions drawn and the citation of the references used.

2. Literature Survey

The literature survey is separated in two sections. The first section is focused on the EE and the OE in residential buildings while the second on the EE and the OE in agriculture including greenhouses.

2.1 Embodied and Operational Energy in Residential Buildings

Ramesh et al, 2010 have analyzed the life-cycle energy in buildings. The authors stated that the life cycle energy consumption in residential buildings is at around 150-400 KWh/m^{2}year while in offices at 250-550 KWh/m^{2}year. They also mentioned that the ratio of EE to LCE is at around 10-20% while the ratio of OE to LCE at around 80-90%. *Chastas et al, 2017* have studied the embodied energy in nearly-zero energy residential buildings. The authors stated that the share of EE to LCE in low-energy buildings could reach up to 57%, or even up to 83%, when renewable energy sources are used for electricity generation while in nearly-zero energy buildings (nZEBs) up to 100%. They also mentioned that in conventional buildings the share of EE to LCE varies between 6% to 20%. *The European directive 2010/31/EU* is related with the energy performance of buildings introducing the concept of nZEBs. The directive sets minimum requirements in the energy performance of new buildings while it introduces the concept of “Energy Certificate in Buildings” and the obligation of implementing national plans related with the increase of nZEBs. *Koezjakov et al, 2018* have studied the relationship between embodied and operational energy demand in Dutch residential buildings. The authors stated that the embodied energy is in the range of 14.46 KWh/m^{2}year to 29.50 KWh/m^{2}year while their operational energy at 34.47 KWh/m^{2}year to 190 KWh/m^{2}year. They also mentioned that in conventional residential buildings the ratio of EE to LCE is at around 10-12% while in energy efficient residential buildings at 36-46%. They concluded that the relative importance of embodied energy in low-energy buildings is increasing. *Haynes, 2010* has analyzed the embodied energy in residential buildings. The author stated that the life-cycle energy is the sum of the embodied and the operational energy while the role of embodied energy is important in low-energy residential buildings. *Dixit et al, 2010* have studied the embodied energy in buildings. The authors stated that, according to the published research, the embodied energy in residential buildings varies between 1 000 KWh/m^2 to 2 435 KWh/m^2 while in commercial buildings between 945 KWh/m^2 to 5 282 KWh/m^2. *Chen et al, 2001* have analyzed the embodied energy in residential buildings in Hong Kong. The authors stated that the EE could reach up to 40% of the LCE in residential buildings. *Troy et al, 2003* have investigated the embodied and operational energy use in cities. The authors mentioned that the embodied energy and the carbon emissions related to it are more significant that it was in the past. They also stated that the embodied energy in several Australian cities is at around 20% of their total energy demand including both the embodied and the operational energy. *Jaysawal et al, 2022* have reviewed the concept of net-zero energy buildings in the existing literature. The authors stated that the concept of zero-energy buildings (ZEBs) is related with “buildings using no more energy that is provided by the building on-site renewable energy sources on annual basis”. They also stated that the benefits of ZEBs include: a) reduced energy consumption, b) reduced carbon emissions, and c) very low energy cost.

2.2 Embodied and Operational Energy in Agriculture

A report from Michigan State University, 2021 stated that energy is the second largest operational cost expense behind labor in agricultural greenhouses. It is also mentioned that 88% of the total energy is used in heating, 11% in water heating and the 1% in lighting. *A report related with the energy use in the EU food sector and the opportunities for improvements has been published, 2015.* The report stated that agriculture contributed at about 26% of the EU’s final energy consumption in 2013. It is also mentioned that fossil fuels account for almost 79% of the energy consumed by the food sector. The report concluded that key points in EU agriculture are: a) the increase in energy efficiency, and b) the increase of the share of renewable energies in the total energy mix. *Paris et al, 2022* have examined the energy use in greenhouses in EU. The authors stated that energy consumption in greenhouses is related with fossil fuels while in high energy greenhouses dominated in northern Europe heating and cooling has the highest share in the total energy mix. *Blom et al, 2022* have investigated the life-cycle embodied carbon emissions of lettuce production in vertical farming greenhouses and in open fields including four cultivation systems: a) open field, b) soil-based greenhouse, c) hydroponic greenhouse, and d) vertical farming. The authors estimated the carbon footprint at 8 177 $kgCO_2/kg$ in vertical farming systems, b) at 0.390 $kgCO_2/kg$ in open fields, c) at 1 211 $kgCO_2/kg$ in soil-based greenhouses, and d) at 1 451 $kgCO_2/kg$ in hydroponic greenhouses. They also mentioned that in vertical farming systems 85% of the carbon footprint was attributed to electricity consumption. *Vourdoubas, 2020* has examined the possibility of creating net-zero carbon emissions greenhouses due to energy use in Mediterranean region. The author stated that several sustainable energy technologies can be used for that including solar photovoltaics, solid biomass burning, co-generation of heat and power (CHP), high efficiency heat pumps, low-enthalpy geothermal energy and reuse of rejected heat. *Avetisyan et al, 2014* have studied the greenhouse gas (GHG) emission impacts of consuming imported versus domestically produced food. The authors stated that redirecting consumption to domestically produced ruminant products reduces global GHG emissions only when implemented in regions with relatively low emissions intensity. They also mentioned that in many cases the concept of "food miles" does not imply that local products have lower emissions than products imported from other regions. *A historical perspective of embodied energy in agricultural inputs has been published, 2015.* Estimations have included human labor, energy carriers such as fuels and electricity, materials, machinery, synthetic fertilizers and pesticides, organic inputs, propagation material, irrigation inputs, buildings, greenhouses, transport and nonmaterial services. The results of the study have shown the large changes that have occurred in the energy efficiency of agricultural processes. *Vourdoubas, 2015* has studied the use of solid biomass for heating greenhouses in Crete, Greece. The author stated that the total operational energy consumption in a modern greenhouse in Crete used for flowers cultivation is at 228 KWh/m^2year while the use of grid electricity and fuel oil covering all its electricity and heating demand results in carbon emissions at 96.36 $kgCO_2/m^2$year. He also mentioned that electricity consumption had a share at 4.69% in the overall energy use while heat had a higher share at 95.31%. The greenhouse was covering all its heating needs with olive kernel wood which was produced locally from the olives processing industry. *Bibbiani et al, 2016* have examined the use of wood biomass for heating greenhouses in Italy. The authors stated that the power demand in greenhouses in Italy varies from 30 W/m^2, in the south, to more than 175 W/m^2 in the north. They also mentioned that the total energy consumption in Italian greenhouses varies between 21 KWh/m^2year to 546 KWh/m^2year. *Koesling et al, 2015* have studied the embodied and operational energy consumption in buildings in 20 Norwegian dairy farms. The authors stated that embodied energy in barns contributes at around 10-30% of the total energy use on dairy farms while the ratio of the OE to LCE is at around 70%. They also estimated that the embodied energy in the buildings of 20 dairy farms in Norway was at around 595 KWh/cow-place year. *Hassanien et al, 2016* have studied the applications of solar energy in agricultural greenhouses. The authors stated that solar energy can cover the energy demand in greenhouses including heating, cooling, lighting and operation of several electric devices. The solar energy technologies which are appropriate for that include solar photovoltaics, solar thermal panels and solar thermal cooling systems. *Canakci et al, 2006* have studied the pattern of energy consumption in greenhouses used for production of vegetables in Antalya, Turkey. The authors stated that the operational energy requirements in typical greenhouses used for cultivation of tomato, cucumber, pepper and eggplant are in the range of 6.64 KWh/m^{2}year to 7.79 KWh/m^{2}year. They also mentioned that the embodied energy of the greenhouses was estimated at 4.76 KWh/m^{2}year. *Cao et al, 2010* have studied the total embodied energy requirements (TEER) in China's agricultural sector focusing on farming and on animal husbandry. The authors estimated the direct fossil fuels inputs (oil and electricity), the indirect inputs (fertilizers, pesticides and machinery) and the biological energy (seeds, agricultural and animal residues and labor power). They stated that the TEER in farming has been reduced between 1978 and 2004 indicating higher energy productivity. On the contrary the TEER in animal husbandry has been reduced indicating the decrease in energy productivity. *Liu et al, 2023* have examined the evolution of GHG emissions of China's agricultural plastic greenhouses. The authors stated that the area of agricultural plastic greenhouses in China grew by 42.4% during 2000-2020. They also mentioned that GHG emissions from nitrogenous fertilizers and greenhouse construction materials accounted for 45% and 36% of the total GHG emissions respectively. *Shamsabadi et al, 2017* have estimated the operational energy consumption and the carbon emissions in agricultural greenhouses and open fields with tomato crops in Iran. The authors mentioned that the total carbon emissions in greenhouses were in the range of 4.33 KgCO$_2$/m^2 to 13.66 KgCO$_2$/m^2. They also stated that energy consumption, including diesel oil and electricity, attributed at around 65% to 80% of the total carbon emissions while the rest in fertilizers, pesticides and machinery. *Pishgar-Komleh et al, 2013* have studied the operational energy and GHG emissions in a greenhouse used for cucumber production in Iran. The authors estimated the total GHG emissions at 8.27 kgCO$_2$/m^2. They also stated that the share of diesel oil in the overall GHG emissions was at 61%, of electricity at 19% and of manure at 14%. The carbon emissions in several agricultural greenhouses reported so far are presented in table 1.

Table 1. Operational and embodied energy consumption and carbon emissions in agricultural greenhouses

Author, year	Country	Cultivated crop	Operational energy consumption	Embodied energy	Carbon emissions due to operational energy
Vourdoubas, 2015	Greece	Flowers	228 KWh/m^{2}year	-	96.36 kgCO$_2$/m^{2}year
Shamsabadi et al, 2017	Iran	Tomato	3.25-3.66 KWh/m^2	-	4.33-13.66 kgCO$_2$/m^2
Pishgar-Komleh et al, 2013	Iran	Cucumber	35.7 KWh/m^2	-	8.27 kgCO$_2$/m^2
Canakci et al, 2006	Turkey	Various vegetables	6.64 to 7.79 KWh/m^{2}year	4.76 KWh/m^{2}year	-

Source: various authors

3. Energy Consumption in Greenhouses

Agricultural greenhouses utilize energy in their daily operations. They require energy for heating and cooling the crops, for lighting and for the operation of their electric devices and machinery. Their operational energy depends on the location of the greenhouse, the cultivated crop, the type and construction of the greenhouse and the local climate. The annual electricity consumption in agricultural greenhouses in different locations is presented in table 2. According to the data presented the annual electricity consumption varies significantly depending on the location and the electric loads of the greenhouse. Heating has a high share in the operational energy consumption in greenhouses. Table 3 indicates that heating and cooling has the highest share in their energy consumption that could reach up to 99%. Fossil fuels have a high share in the total energy consumption in greenhouses while the use of renewable energies is rather limited. The percentage of the energy sources used for heating greenhouses in Germany is presented in table 4 indicating that renewable energy sources have a share at 20% in the total energy sources used. Several authors have proposed that renewable energies could have an increasing role in the future for covering the energy requirements in greenhouses and decreasing their carbon footprint while their technologies are reliable, mature and cost-effective (*Vourdoubas, 2020, Hassanien et al, 2016, Bibbiani et al, 2016*). These benign energy sources include solar energy, solid biomass, geothermal energy et cetera (*Vourdoubas, 2020).*

Table 2. Annual electricity consumption in agricultural greenhouses in different locations

Location	Electrical loads	Annual electricity consumption (KWh/m^{2}year)
Mediterranean basin	Heat, cooling, lighting,	2-9
Spain	Lighting, electric devices	3
Spain	Lighting, electric devices	7
Greece	Ventilation, lighting, electric devices	20
Saudi Arabi	Ventilation, lighting, electric devices	56
Sweden	Ventilation, lighting, electric devices	140
Finland	Heat, cooling, lighting, electric devices	528
Netherlands	Heat, cooling, lighting, electric devices	417
Southern France	Heat, cooling, lighting, electric devices	139-444
Japan	Heat, cooling, lighting, electric devices	0.1-0.2
Italy	Heat, cooling, lighting, electric devices	134-209

Source: Hassanien et al, 2016

Table 3. 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

Source: Paris et al, 2022

Table 4. Percentage of the energy sources used for heating greenhouses in Germany

Energy source	%
Natural gas	21
Renewable energies	20
Black coal	28
Fuel oil	15
Other	16
Total	100

Source: Paris et al, 2022

4. Embodied and Operational Energy in Residential Buildings

Residential buildings use energy in their daily operations while their energy consumption depends on several parameters. They also require energy in their construction phase, in renovation phase and during their demolition which is called embodied energy. The sum of their embodied and operational energy is their life-cycle energy. The life-cycle energy in conventional buildings has been reported in the range at 150 KWh/m^{2}year to 400 KWh/m^{2}year (*Ramesh et al, 2010*) and at 48.93 KWh/m^{2}year to 219.50 KWh/m^{2}year (*Koezjakov et al, 2018*). In conventional buildings operational energy dominates in their life-cycle energy pattern while their embodied energy is less important. The ratio of EE to LCE in conventional residential buildings has been reported at 6%-20% (*Chastas et al, 2017*), 10%-12% (*Koezjakov et al, 2018*) and 10%-20% (*Ramesh et al, 2010*). However, in low energy and in nearly-zero energy buildings the importance of embodied energy in their life-cycle energy pattern is increased. The ratio of EE to LCE in low-energy buildings has been estimated in the range of 36% - 46% (*Koezjakov et al, 2018*) to 57% - 83% (*Chastas et al, 2017*). Buildings in EU consume approximately 40% of the total energy consumption in the continent and have a share at around 40% in the total European carbon emissions. According to the EU directive 2010/31/EU European buildings should reduce their operational energy consumption and adopt the concept of nZEBs and the “Energy Performance Certificate” which indicates their energy behavior. Nearly-zero energy buildings utilize less operational energy, compared to conventional buildings while their life-cycle energy is also lower. The ratio of EE to LCE in nZEBs is significantly higher than in conventional buildings while in net-zero energy buildings the ratio could reach at 100%. The embodied and operational energy in conventional as well as in low-energy buildings and in nZEBs are presented in table 5.

Table 5. Embodied and life-cycle energy in residential buildings

	Conventional energy buildings	Authors, year	Low-energy and nZEBs	Authors, year
Ratio of EE to LCE	6 - 20%	*Chastas et al, 2017*	57% - 83%	*Chastas et al, 2017*
Ratio of EE to LCE	10 - 12%	*Koezjakov et al, 2018*	36% - 46%	*Koezjakov et al, 2018*
Ratio of EE to LCE	10% - 20%	*Ramesh et al, 2010*		

Source: various authors

5. Embodied Energy in Greenhouses

Published research related with the life-cycle energy analysis in agricultural greenhouses is limited so far. The operational energy consumption in greenhouses in several countries has been estimated in the range at 2 KWh/m^{2}year to 528 KWh/m^{2}year (*Hassanien et al, 2016*). Other studies have estimated the operational energy consumption in greenhouses located in Italy in the range of 21 KWh/m^{2}year to 546 KWh/m^{2}year (*Bibbiani et al, 2016*). The embodied energy of typical greenhouses located in Antalya, Turkey has been estimated at 4.76 KWh/m^{2}year (*Canakci et al, 2006*). Assuming that the operational energy is in the range at 2 KWh/m^{2}year to 528 KWh/m^{2}year and their embodied energy at 4.76 KWh/m^{2}year their life-cycle energy consumption is in the range of 6.76 KWh/m^{2}year to 532.76 KWh/m^{2}year. The operational energy consumption of greenhouses varies significantly depending on many factors. Construction of nearly-zero energy greenhouses is more difficult and expensive than the construction of nZEBs. Consequently, the ratio of EE to LCE in greenhouses varies significantly. In low-energy greenhouses and in net-zero energy greenhouses their carbon emissions due to operational energy are very low while their embodied energy characterizes their life-cycle energy and carbon emissions pattern.

6. Comparison of Embodied and the Operational Energy in Residential Buildings and in Agricultural Greenhouses

The operational energy in conventional residential buildings varies according to several parameters. The embodied energy in conventional residential buildings has a share at around 6%-20% in their life-cycle energy use. The share of EE to their LCE in low-energy buildings and in nZEBs is higher at 36%-83% while it could reach at 100% in net-zero energy buildings. This fact indicates that the significance of the embodied energy in the low-energy buildings is much more important than in conventional buildings. On the contrary the operational energy in agricultural greenhouses varies significantly in the range at 2 KWh/m^{2}year to 546 KWh/m^{2}year (*Hassanien et al, 2016, Bibbiani et al, 2016)* depending on many factors. Although there are not many studies regarding the estimation of embodied energy in agricultural greenhouses the embodied energy of a typical greenhouse in Mediterranean basin has been calculated at 4.76 KWh/m^{2}year (*Canakci et al, 2006*). The embodied energy in agricultural greenhouses varies depending on many factors. Taking into account the abovementioned data it is concluded that the ratio of EE to LCE in agricultural greenhouses is in the range from 0.86% to 70.41%. This ratio in net-zero energy greenhouses could reach at 100%. The operational and embodied energy in residential buildings and in agricultural greenhouses are presented in table 6.

Table 6. Operational and embodied energy in residential buildings and in agricultural greenhouses

	Conventional energy buildings	Low energy buildings	Agricultural greenhouses
Ratio of EE to LCE	6% - 20%	36% - 83% (It could reach up to 100% in net-zero energy buildings)	0.86% -70.41% (It could reach up to 100% in net-zero energy greenhouses)
Ratio of OE to LCE	80% - 94%	17% - 64%	29.59% - 99.14%

Source: own estimations

7. Discussion

Our research indicates that the ratio of EE to LCE in low energy buildings is higher than in conventional buildings. Operational energy in greenhouses varies in a wide range depending on many parameters. The share of EE to LCE in agricultural greenhouses varies in a range greater than the corresponding range in residential buildings. Unfortunately, estimations regarding the embodied energy in greenhouses are very limited so far. Our findings indicate that the increase of energy efficiency in residential buildings increases the significance of their embodied energy. Taking into account that operational energy-related carbon emissions in nZEBs can be significantly reduced their life-cycle carbon emissions are mainly related with their embodied energy. Construction of low-energy greenhouses is not always easy, particularly in energy intensive crops while the share of embodied energy in their life-cycle energy is lower than in nZEBs. Replacement of fossil fuels with renewable energies in residential buildings and in greenhouses can zero their net-carbon emissions. In this case their carbon emissions are related only with their embodied energy. It should be taken into account though that there are limited published data regarding the embodied energy in greenhouses compared to embodied energy in residential buildings. Therefore, our estimations concerning the contribution of EE to LCE in greenhouses have limited accuracy. Further research should be focused in estimating the embodied energy in various types of greenhouses. It should be also focused in the investigation of using low carbon-emission materials in the construction of residential buildings and agricultural greenhouses.

8. Conclusions

The embodied and operational energy in agricultural greenhouses and in residential buildings have been estimated and compared. The ratio of EE to LCE in low-energy residential buildings and in nZEBs varies in the range of 36% to 83% that is significantly higher than in conventional residential buildings which is in the range of 6% to 20%. Published data regarding the embodied energy in agricultural greenhouses are limited. The ratio of EE to LCE in agricultural greenhouses, at 0.86% - 70.41%, varies significantly depending on many parameters while the ratio of OE to LCE has also large variations in the range of 29.59% - 99.14%. The use of reliable, mature and cost-efficient green energy technologies in residential buildings and in agricultural greenhouses can zero their net-carbon emissions related with their operational energy. In nearly-zero emissions residential buildings and in low-energy greenhouses the life-cycle carbon emissions depend mainly on their embodied energy. Therefore, achievement of net-zero emission buildings and agricultural greenhouses, due to life-cycle energy use, requires the elimination of the carbon emissions related with both the operational and the embodied energy. Our study indicates that in low-energy residential buildings, in nearly-zero energy buildings and in low-energy agricultural greenhouses the importance of EE to LCE is increased. It is also indicated that decrease of their life-cycle related carbon emissions requires the reduction of the carbon emissions related to their embodied energy. Therefore, low- or zero-carbon emissions raw materials should be used in the construction of residential buildings and agricultural greenhouses for decreasing or completely eliminate their life-cycle carbon footprint.

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