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Cumulative Energy Demand and Carbon Footprint of the Greenhouse Cultivation System

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Abstract: The paper describes the influence of horticultural production in greenhouses under Polish climate conditions on energy consumption, contributing to greenhouse gas emissions and global warming. Four scenarios were studied, two of which were non-renewable fuels: coal and natural gas, while the other two were renewable energy sources: wood pellets and wood chips, to identify opportunities for reducing energy costs and greenhouse gas emissions. Cumulative energy demand was defined to assess these four scenarios. The environmental impact was determined using the carbon footprint of the principal greenhouse gases emitted and using CO_2 as the reference gas (CO_2-equivalents). Renewable energy sources in greenhouse production can reduce the cumulative energy demand by 83.3% and greenhouse gas emissions by 95% compared to the coal-burning scenario. The presented research results relate to a greenhouse intended for growing flowers in pots, which has not been conducted so far. The article also updates the data on the environmental impact of crops grown in greenhouses located in Poland. The study provides important information for horticultural producers, mainly due to increasing competition and consumer awareness of the origin of products. Renewable energy sources in horticulture reveal a great potential in the reduction in greenhouse gases, and thus may become an inspiration to look for new solutions in this area.

Keywords: carbon dioxide emission; greenhouse; energy demand; fuel

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Citation: Grabarczyk, R.; Grabarczyk, S. Cumulative Energy Demand and Carbon Footprint of the Greenhouse Cultivation System. *Appl. Sci.* **2022**, *12*, 8786. https://doi.org/10.3390/app12178786

Academic Editor: Nikolaos Koukouzas

Received: 1 August 2022
Accepted: 30 August 2022
Published: 1 September 2022

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1. Introduction

Horticulture uses a significant amount of energy, contributing to greenhouse gas emissions and global warming [1]. Greenhouses (GH) are among the most energy-absorbing structures, mainly due to the thermal efficiency of the envelope. Energy savings can be achieved through the use of multi-layer roof panels or movable insulating screens. The heat transfer coefficient for greenhouse envelopes [2] without energy-saving measures is many times higher than for envelopes in typical buildings.

In addition to typical energy-saving solutions in GHs, it is essential to pay attention to the possibility of using new covering materials integrated with photovoltaic technology. They have been extensively studied to improve light transmission and capture the solar energy needed to produce electricity [3]. The choice of materials is made depending on the type of cultivation carried out and the geographical location of the facility. Physical properties are crucial but economic factors, and environmental sustainability must always be considered [4]. Very promising materials for shading GHs are semi-transparent organic photovoltaic cells with strong absorption of near-infrared radiation (NIR) and visible light transmittance favourable to crop cultivation [5]. Renewable sources are taken into account in newly designed greenhouses instead of fossil fuels. An interesting option is the use of heat pumps. The advantage of heat pumps is the possibility of heating or cooling the GH, depending on the current requirements of the facility. The application of heat pumps is conditioned by the availability of a lower heat source at appropriate parameters [6,7]. Another option is to power the GH with a cogeneration unit, which

produces heat and electricity simultaneously [8]. In any case, GH energy efficiency issues, due to their lightweight construction and inefficient operation, have to be aimed at reducing energy consumption and carbon footprint [9].

According to [10], there is great potential for reducing the environmental footprint of horticultural systems, especially in heated GHs [11]. Research on this issue, based on the life cycle assessment (LCA) method, focuses mainly on the production of tomatoes and less frequently on ornamental plants and cut flowers. Ntinas et al. have analysed tomato cultivation in Greece and Germany [1]. The considered GHs were fuelled with natural gas and pellet, respectively. Boulard et al. have assessed the environmental impact of tomato cultivation in France [12]. Year-round production in GH heated with natural gas was compared to seasonal cultivation under unheated plastic tunnels. In the paper [13], the LCA method was used to compare tomato production in an unheated GH located in Morocco with output in a natural gas-heated GH in France. Torrellas et al. developed the tool to perform LCA analysis, and subsequently, they studied the production of tomatoes (in Spain, Hungary and the Netherlands) and cut roses cultivation in the Netherlands [11–14]. In turn, Bosona and Gebresenbet evaluated the organic cultivation of tomatoes in Sweden. SimaPro 8.2 software was used for the calculations [15].

In Poland, however, the environmental footprint of GH cultivation has not previously been studied. The climate in Poland can be described as transitional, with hot summers and cold winters with the possibility of intense snowfall.

In line with Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe [16], and in order to protect human health and the environment as a whole, it is particularly important to combat pollutant emissions at their source. At the same time, it is essential to identify and implement the most effective emission reduction measures at local, national and community levels.

The IPCC report [17] identifies technologies and practices that can reduce greenhouse gas emissions in key sectors of the economy. For the energy supply sector, it is proposed to implement measures covering fuel switching from coal to gas as well as renewable electricity and heat production. In this sector, actions to be taken to achieve these goals include reducing fossil fuel subsidies while subsidising renewable energy technologies. In agriculture, the proposed measures include replacing fossil fuels with energy crops and improving energy efficiency through financial incentives and regulations. In forestry, it is proposed to use forest products as bioenergy to replace fossil fuels. In the waste treatment sector, it is proposed to incinerate waste for energy recovery by adopting financial incentives as well as commitments to use renewable energy.

By ratifying the Kyoto Protocol, Poland committed to reducing greenhouse gas emissions by 6% compared to the base year in 2008–2012 and by 20% in 2013–2020, in line with the Doha Amendment, i.e., Decision 1/CMP.8. Compliance with these commitments requires the production of greenhouse gas inventory reports divided into five categories: 1. Energy, 2. Industrial processes and product use, 3. Agriculture, 4. Land use, land change and forestry, and 5. Waste [18]. Four of these categories correspond to key economic sectors listed in the IPCC report [17] that can be analysed for reducing the environmental footprint of horticultural production. Another IPCC report describes different sketches for biomass deployment for energy on a global scale by 2050 [19]. The increase in energy demand results in high energy prices and drives biomass demand. National policy frameworks control biomass production and its potential use for specific regional conditions. Additionally, from an energy security perspective, high fossil fuel prices push demand for renewable energy such as biofuels and photovoltaics.

Under the EPBD—Energy Performance on Buildings Directive [20], Member States may choose not to implement certain requirements for certain categories of buildings. It will be crucial for the owners of horticultural facilities to identify what actions to take and where to look for potentially significant energy savings and reduction in negative environmental impact. The importance of heat costs and savings both from an economic

and environmental point of view was found to be significantly high when surveying several greenhouse locations in Europe [15]. Therefore, it is likely to be considered that locations of new GHs are close to industrial facilities offering significant amounts of waste processing heat [21]. Another solution that has already aroused interest is the use of combined heat and electricity generation [22,23]. Nevertheless, the greatest economic and environmental benefits from the use of renewable fuels, such as wood biomass, are to be expected [24–26].

The reason for the lack of significant changes in the emission of gases and solid particles to the atmosphere in Poland is the fact that the structure of energy consumption of energy carriers has not undergone any significant changes. Hard coal remains the main carrier of primary energy. Its share in the structure of energy consumption in Poland in 2016 amounted to 39.8% [27]. In Poland, the total area of cultivation in greenhouses in 2017, according to the Statistical Yearbook of Agriculture [28], amounted to 16,342,000 m^2, which is approx. 29% of the total cultivated area under available covers. It is expected that the increase in fuel prices and/or environmental fees may soon have significant negative consequences for GH owners.

For this reason, it seems justified to study the environmental footprint of GH cultivation in Polish conditions. To undertake this, it was decided to define the cumulative energy demand (CED) and carbon footprint (CF) for the use phase of GH, which was in operation for nearly a year. The study is based on measurements of heat and electricity consumption in a facility where ornamental plants are grown. As the available literature in this GH production sector relates primarily to the cultivation of tomatoes, an attempt was made to provide new research results related to the energy and heat needs of GH, i.e., factors that contribute most to the total value of CED and CF.

The aim of this work was to study energy flow and the environmental impact of the greenhouse production phase using different fuels as energy sources. Energy performance of GH was determined, which was then used as a source of information to calculate the real impact of heating on the energy demand, primary energy consumption and emissions of carbon dioxide.

Analytical research focused on obtaining information on the amount of energy consumed (usable, final and primary) as well as the auxiliary energy that is needed to drive electric motors in technical systems. As a result of this study, fuel demand, as well as CED and CF values, was determined for the operating phase of a continuously heated GH for growing potted flowers. The method of calculating the energy performance of buildings made it possible to compare the results of the calculations with the actual fuel consumption. This helped, in turn, to analyse both the existing state in which the measurements were carried out and other scenarios for the combustion of various fuels.

It was assumed that testing would be carried out for the existing coal-burning facility, as well as for selected scenarios for both non-renewable and renewable energy sources. In addition, calculations were made for a shorter operation per year to show the difference in fuel and energy consumption as well as the environmental footprint.

With this in mind, proposals for changes to greenhouse gas production are put forward, focusing mainly on energy supply, in line with the relevant economic sectors identified in the 2007 IPPC Report [17].

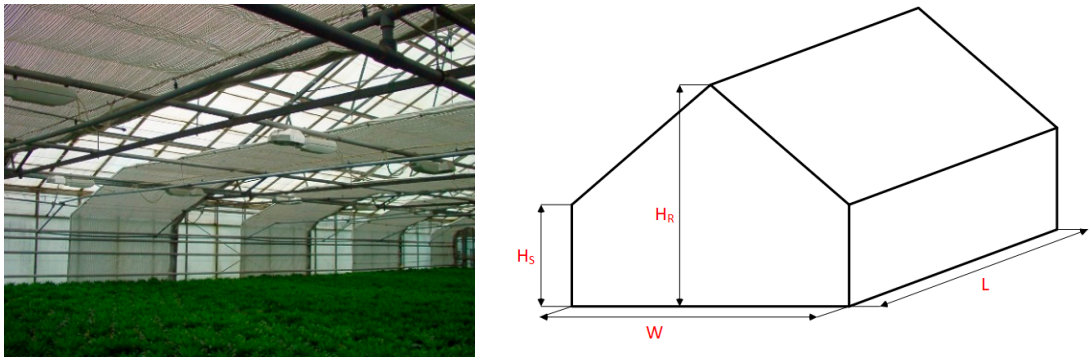
This study presents examples of scenarios with an analysis of the environmental impact of greenhouse gas exploitation and the choice of energy carrier. The analysis was based on relevant regulations and national guidelines, in particular concerning the energy performance of buildings or the emission rates of pollutants from the combustion of fuel.

What is new in the article is the description of CED and CF for a GH located in Central and Eastern Europe, which has not been analysed so far. Moreover, there are no reports in the literature corresponding to the environmental impact of potted flower greenhouse cultivation. Another novelty is that the research results cover the same greenhouse, while retaining its functions, to obtain information on the effects of switching from a non-renewable to a renewable energy fuel. This reflects the situation of many owners of horticultural plants in Poland, who use coal-fired heat sources and, in the face of the current changes,

are looking for options to reduce costs, increase the reliability of operating heating systems and reduce the environmental footprint. The Polish Ministry of Developments Funds and Regional Policy, as part of The National Recovery and Resilience Plan in the field of Green Energy and Reduction in Energy Intensity, offers financial support for the industry [29]. Beneficiaries may also be owners of horticultural facilities. Support will cover investments with the most significant potential for reducing greenhouse gas emissions and related to energy saving. Among others, CED and CF will be taken as evaluation criteria.

2. Materials and Methods

A typical GH with a movable thermal screen is a facility with a variable envelope efficiency and a variable operating time, which acts as an additional cover (Figure 1).



(**a**) (**b**)

Figure 1. GH under study: (**a**) A view of GH with thermal screen; (**b**) Main dimensions.

Based on measurement data, it was possible to determine the actual energy performance of a GH. Measurements were made in a self-contained GH, which is part of a larger GH facility. This GH facility is located in central Poland, in the town of Skierniewice. The territory of Poland is divided into five climatic zones. Skierniewice is in zone III, which covers more than 50% of the part of Poland. Zones I and II together cover 30% of the territory of Poland. The average annual outside temperatures in zones I, II and III are 7.6 °C, 7.9 °C and 7.7 °C, respectively. The average annual outside temperatures in zones IV and V are lower and amount to 6.9 °C and 5.5 °C, respectively. Therefore, production under cover in Poland is concentrated in zones I–III. Moreover, the analysed GH is fired with coal, which, in Poland, is still the most commonly used fuel in such facilities. The main limitation of the LCA method is the inability to directly compare the results, which are dependent on many factors, i.e., boundary conditions, production strategy and geographical location [30]. Since, in the present paper, different scenarios are analysed in the same facility, the disadvantage related to a geographical location is eliminated.

The GH floor is intended for growing flowers in pots. The natural soil is covered with a 0.2 m layer of sand. It has thermal insulation made of 20 mm thick extruded polystyrene foam and 2 mm thick plastic fabric. The basic technical parameters of the analysed greenhouse are summarized in Table 1.

Apart from the heat generated from coal combustion, auxiliary energy also needs to be taken into account. It sustains the operation of the heating systems, technical equipment of the GH and the source of heat. In the facility under study, electricity applies to:

- The heating system to drive circulation pumps in a double way: the lower system located in between the plants, and the upper system consisting of heating pipes next to the side walls, at 2.5 m above the cultivation surface;
- The technical equipment of GH—to drive positioning motors of the thermal insulation screen and vent servos;
- The heat source to drive main circulation pumps of the heating system;

- The heat source to power the boiler grate, induction draft fan, exhaust gas fan and the de-duster fan.

Table 1. Characteristics of the GH under study.

Description	Value	Units
floor area	1250	m^2
width (W)	20.0	m
roof height (H_R)	7.7	m
sidewall height (H_S)	2.2	m
length (L)	62.5	m
cubage undercover	6188	m^3
overall heat transfer coefficient without a thermal screen	6.68	$W \cdot m^{-2} \cdot K^{-1}$
overall heat transfer coefficient with a thermal screen	4.66	$W \cdot m^{-2} \cdot K^{-1}$

In the existing facility, the heat source is a set of grate boilers for the combustion of fine coal with a lower heating value (LHV) of 21,000–23,000 $kJ \cdot kg^{-1}$. The boilers are equipped with dust removal devices with an efficiency of 85%, which reduces the number of solid particles carried in the flue gas.

The basis for the analysis was the heat and electricity consumption tests carried out over the course of a full year with a 10-min interval between measurements. Such an interval between measurements gives a fairly accurate picture of the operation of the greenhouse's technical equipment, the variability of the outdoor weather conditions and indoor temperatures, as well as energy consumption. The total amount of data collected during the test period was 52,560 records. The relative error of the heat consumption measurement was 3.7%.

The heat measurements were supplemented by recording additional parameters that make it possible to determine the operating time of electric drives used to maintain the operation of heating systems, vents, and the thermal screen in the GH. Additionally, the measurements were taken in the heat source, which is necessary to determine the operating time of individual boilers and heating system pumps. The measurements were carried out using two systems. The first of them, DGT Volmatic, records the outside air and greenhouse air temperature, solar radiation, air humidity, the position of thermal screens and vents, as well as the operating time of circulation pumps. The second one, Aquatherm, measures the heat consumption in the greenhouse and in the supply manifold as well as the temperature and flow of the heating medium in the greenhouse and in the boiler.

Regardless of the heat from coal combustion, the study has taken into account the auxiliary energy necessary to keep the heating systems operational, the GH technical equipment and the heat source. Auxiliary electricity consumed in the heat source, which was included in the calculations, was calculated as the share identical to the share of the tested GH area in the total area of the facility.

Scenario 1 (reference) is a coal combustion scenario that reflects the real state of the measurement site. Scenarios 2 to 4 are variants that assume that the heat source will burn fuel other than coal while the GH operating system will remain unchanged. It is assumed that coal-fired boilers will be replaced in scenario 2 by gas-fired boilers, while in scenarios 3 and 4—biomass will be burnt; wood pellets and wood chips, respectively.

It was assumed that the annual average values of heat generation efficiency are consistent with the methodology for determining the energy performance of buildings [31]. The scenarios are intended to demonstrate the impact of fuel choice on final energy demand, fuel quantity and the environment.

Based on the measurement results, and in accordance with the national methodology for calculating the energy performance of buildings [31], efficiency values were established

for heat generation and distribution systems, in order to determine the annual final energy consumption, by following Equation (1):

$$Q_F = Q_U / \eta_{tot}, \quad (1)$$

where
Q_U—heat consumption in the heating system of the greenhouse, MWh·y^{-1};
η_{tot}—average seasonal total efficiency of the GH heating system—from generating heat to transferring it to the interior of the greenhouse, calculated according to Equation (2):

$$\eta_{tot} = \eta_g \cdot \eta_s \cdot \eta_d \cdot \eta_e, \quad (2)$$

where
η_g—average seasonal efficiency of energy carrier generation from the energy supplied to greenhouse's balance boundary (final energy),
η_s—average seasonal efficiency of heat accumulation in storage components of the greenhouse's heating system,
η_d—average seasonal efficiency of heat carrier transport (distribution) within the greenhouse (within balancing boundaries or outside),
η_e—average seasonal efficiency of heat control and utilisation in the greenhouse (within the balancing boundaries).

The values of the efficiencies listed above are adopted from [31].

The amount of non-renewable primary energy consumed by the greenhouse for heating purposes over an entire year was calculated using Equation (3):

$$Q_P = w_H \cdot Q_F + w_E \cdot Q_{E,aux}, \quad (3)$$

where
w_i—primary non-renewable energy consumption factor for generation and supply of final energy carrier (or energy) to the interior of the greenhouse; w_H—refers to the heat used for heating, w_E—refers to electricity;
$Q_{E,aux}$—annual demand for final electricity used to drive auxiliary equipment of the heating system.

Primary non-renewable energy consumption factors for fossil fuels, i.e., coal and natural gas, are 1.3 and 1.2, respectively, while for biomass, it is 0.2 (scenarios 3 and 4). It is assumed that the non-renewable primary energy consumption for electricity supplied through the national energy system amounts to 3.0 [31].

The amount of fuel needed to produce the final energy was determined by taking into account the LHV of coal, according to information obtained from the fuel supplier for the horticultural plant. Other parameters for coal and natural gas are in line with the national data [32], while the LHV and carbon dioxide emission factors were obtained from the National Centre for Emissions Management [33,34], which, in turn, correspond to the IPCC guidelines [35] (Table 2). The Centre's emission factors are used to determine the fees for using the environment. Therefore, the analyses were based on national data on pollutant emissions.

Table 2. The lower heating value (LHV) and carbon dioxide emission factor [32–35].

Description	Scenario				
	1	2	3	4	
	Coal	Natural Gas	Wood Pellets	Wood Chips	Electricity
lower heating value (LHV) [MJ·kg^{-1}] or * [MJ·m^{-3}]	21.71	36.62 *	15.6	11.6	-
carbon dioxide emission factor [kg CO_2·GJ^{-1}] or ** [kg·MWh^{-1}]	94.94	55.43	112.0	100.0	778 **

* in MJ·m^{-3} for natural gas; ** in kg·MWh^{-1} for electricity.

According to the rules set out in the emission allowance trading scheme, CO_2 emissions from biomass combustion are not included in the total emissions from fuel combustion. This is equivalent to using a zero-emission factor for biomass. In the analysis and discussion, the results obtained for scenarios 2 to 4 are compared with the reference scenario 1 (burning coal). The analysis is based on the LCA [36,37] methodology used as a business assessment instrument that provides comparable research results when considering many of the GH environmental footprint issues. Energy and environmental analysis address the impact of energy carriers and air pollution.

The CED and CF values are based on a continuously heated GH intended for growing plant flowers in pots. The use phase of GH is a fundamental process because it is only through its operation that the needs for which it was built are met. Previous publications indicate that the most visible factors are those influencing the CED and CF use phase, with the exception of design, fuel and electricity [1]. In line with the 2006 IPCC Guidelines, a national methodology for determining pollutant emissions was used whenever possible to obtain more accurate emission data. Two functional units (FU), defined as the number of potted plants during the annual cultivation cycle and the reference cultivation area of one square meter per year (land-based FU), were applied to determine the CED and CF values.

The research has focused on determining the impact described by CF and CED. CF as a measure of the potential to generate the greenhouse effect enables conversion from emissions of other gases to the reference gas, i.e., carbon dioxide equivalent (CO_2-eq). The conversions between emissions are in line with the 2006 IPCC report [35]. As the calculations refer to the period considered, absolute emissions are expressed as annual values, while specific emissions refer to the number of potted flowers and to the GH unit. The ProBas database was used to perform these conversions [38].

CED is understood as the sum of the primary energy supplied to the GH during the use phase. The system boundary is understood as from the raw material extraction phase to the farm gate, with an emphasis on the operational phase—cultivation in the GH system. The study was restricted to two main input categories in the use phase of GH. The inputs for the use phase of GH included fuel and electricity, while the production involved specific emissions of pollutants and FU, which influences its efficiency. Production efficiency is defined as the number of potted plants during the annual cultivation cycle (units·y^{-1}) and land-based FU—cultivation area per year ($m^2 \cdot y^{-1}$). For further analysis, it was assumed the actual yield of 294 units·$m^2 \cdot y^{-1}$.

As in [1], gas emissions at the production stages, maintenance and capital expenditure at the end of the life cycle are not accounted for within the system boundaries. The establishment and construction of the facility were not included due to the scope of the research and limited access to data. It is expected that the construction contribution of both CED and CF in the GH construction phase would be significant, as in the case of similar German solutions [1], mainly due to the significant amounts of aluminium, steel, concrete, glass and plastics. Other processes related to the operation of the facility have also been excluded from the analysis, for its purpose was only to identify the impact of energy carriers on the environment in the greenhouse operating phase.

3. Results and Discussion

The GH energy performance was established on the basis of measurements made in GH, which operated for about a year (Table 3).

Table 3. Average monthly air temperature inside and outside the GH, and monthly sums of solar radiation for the town of Skierniewice (to download raw sampling data, see Supplementary Materials).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
greenhouse air (°C)	18.8	17.9	16.4	17.5	22.3	21.0	25.4	24.5	24.1	21.8	19.3	18.3
outside air (°C)	−7.8	−2.3	0.2	9.6	16.4	17.2	21.2	18.4	16.6	9.9	3.4	−0.2
solar rad. [kWh·m^{-2}]	9.3	17.3	64.7	97.3	163	144	159	123	78.7	35.2	11.3	5.0

The results of measurements and calculations of primary energy consumption are presented graphically for a period of one year. The conducted tests, their scope and completeness allow for an initial assessment and analysis, including an option of a periodic shutdown of the facility during the year.

3.1. Greenhouse Energy Performance

The study revealed that the consumption of useful heat for heating purposes was 679.77 MWh·y^{-1}. The average seasonal total efficiency of the production, distribution and use of GH heat is 0.604 (expressed by Equation (2)). The final energy used to heat GH during the year, based on the total efficiency of the system, is 1125.04 MWh·y^{-1} (from Equation (1)). The specific annual final energy consumption for the GH is 900 kWh·m^{-2}·y^{-1}. The structure of final energy consumption in individual months of the period under examination is presented, taking into account both heat and auxiliary electricity (Figure 2).

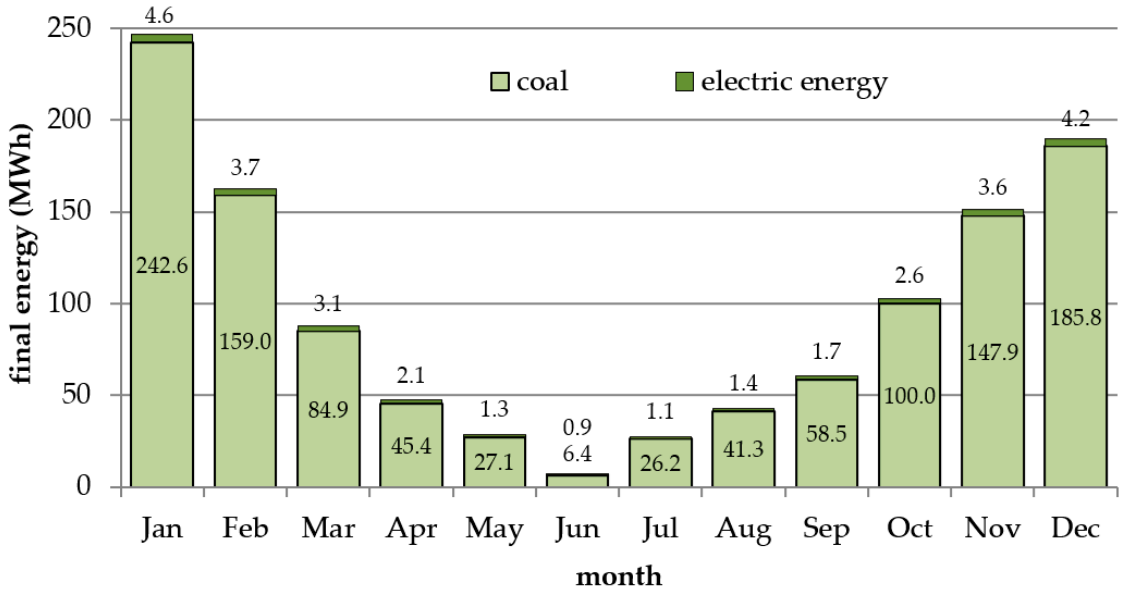


Figure 2. Monthly totals of final energy used for heating and auxiliary electricity used for the GH; fuel—coal (scenario 1).

The variability of final energy consumption depends on the external climate conditions, i.e., the outside temperature, the intensity of solar radiation and the length of the day. One can see that in the winter season, the final energy consumption is significantly higher than the consumption in the summer months. After determining the operation time of the GH heating system, its technical equipment, and the source of coal combustion heat, it was possible to calculate the consumption of auxiliary electricity at the level of 30.25 MWh·y^{-1} (Table 4).

Table 4. Structure of electricity consumption for driving motors in technical systems of the greenhouse (scenario 1).

	Electric Engine Drive	Energy	
		kWh·y^{-1}	%
in the greenhouse	drive of the thermal insulation screen	46.8	0.15
	drive of the vent servos	33.0	0.11
	circulation pumps—the lower system	1838.5	6.08
	circulation pumps—the upper system	4488.1	14.83
at the heat source	main circulation pumps at the heat source	6652.3	21.99
	boiler auxiliaries	17,194.8	56.84
sum of auxiliary electricity		30,253.4	100.00

The structure of electricity consumption shown in Table 4 indicates that 79% of electricity is consumed in the heat source, and 21% is consumed directly in the greenhouse for the operation of technical systems. In scenarios other than the reference scenario, the electricity demand varies depending on the auxiliary equipment of the boiler. The demand for electricity production was determined according to the catalogue data of boilers used for scenarios 2–4; in scenario 2 it was 16.60 MWh·y^{-1}, and in biomass-fired boilers, it was 22.12 MWh·y^{-1}. In the current state, the annual specific consumption of auxiliary electricity in the GH is 24.2 kWh·m^{-2}·y^{-1}, and in the natural gas scenario is 13.3 kWh·m^{-2}·y^{-1}, i.e., 45.1% less than in scenario 1. The corresponding value for the biomass scenario is 17.7 kWh·m^{-2}·y^{-1}, which is 73.1% compared to the reference scenario.

Scenario 2 for gas boilers assumes an average annual heat generation efficiency of 0.860, which means that the total efficiency of heat generation, distribution and use would change to 0.728. The final energy for heating the GH over a year is 933.99 MWh·y^{-1}, and the specific annual final energy consumption for the GH would be 747.23 kWh·m^{-2}·y^{-1}. The difference in final energy consumption for heating amounts to 17%. The structure of monthly final energy consumption for the scenario with gas boilers is presented in a similar way to that for the current state (Figure 3).

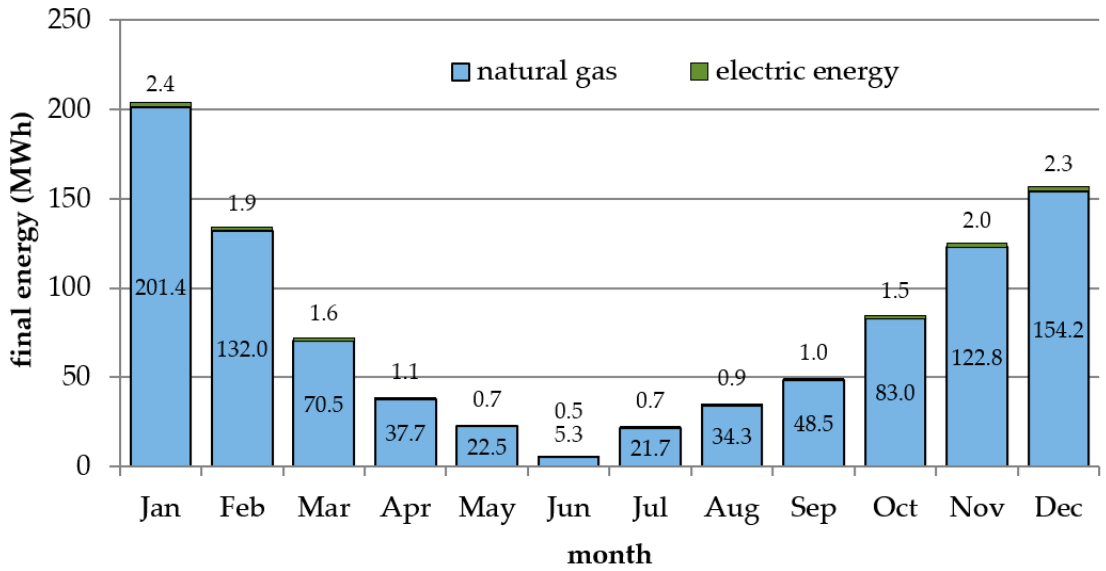


Figure 3. Monthly sums of final energy demand used for heating and auxiliary electricity; fuel—natural gas (scenario 2).

In scenarios 3 and 4 for biomass combustion, the average annual heat generation efficiency is 0.850, and the total system efficiency is 0.704. The final energy for heating is 966.21 MWh·y^{-1}, which means that the annual specific final energy consumption is 773.0 kWh·m^{-2}·y^{-1}. This means a decrease in final energy demand by 14.1% compared to scenario 1. The structure of monthly final energy consumption for the scenario with biomass boilers is presented below (Figure 4).

The final energy directly corresponds to the amount of fuel needed to generate heat. In its current state, the GH uses 186.6 Mg·y^{-1} of coal per year, corresponding to a value of 149.2 kg·m^{-2}·y^{-1}. In scenario 2, the demand for natural gas will amount to 91,817 m^3·y^{-1}, which corresponds to the characteristic value of 73.5 m^3·m^{-2}·y^{-1}. In the case of burning renewable fuels, the annual demand for wood pellets (scenario 3) is 223 Mg·y^{-1}, which translates into a value of 178.4 kg·m^{-2}·y^{-1}, and in scenario 4 with burning wood chips, the fuel demand is 299.9 Mg·y^{-1}, which converts to the characteristic value of 239.9 kg·m^{-2}·y^{-1}.

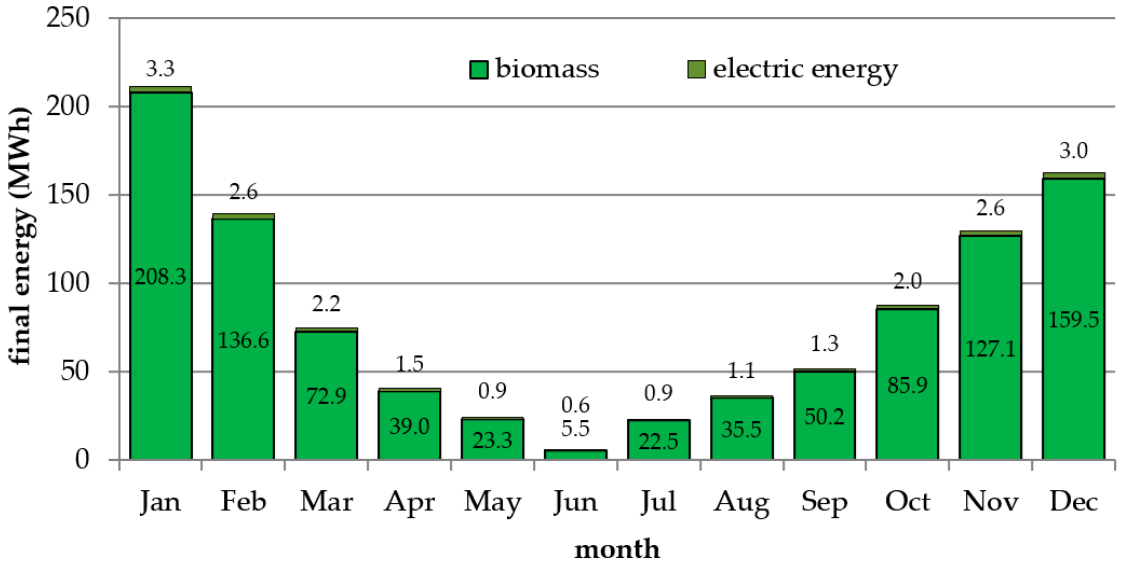


Figure 4. Monthly sums of final energy demand used for heating and auxiliary electricity; fuel—biomass (scenarios 3 and 4).

The results shown in Figures 1–3 provide an overall analysis as well as the determination of energy consumption and the environmental footprint, also for options such as a temporary shutdown of the facility.

The total amount of non-renewable primary energy (Equation (3)) consumed by the GH for heating in the reference scenario is 1553.31 MWh·y^{-1}, and the non-renewable primary energy index for the tested GH is 1242.6 kWh·m^{-2}·y^{-1}. In scenario 2 with natural gas combustion, the corresponding values are 1170.57 MWh·y^{-1} and 936.5 kWh·m^{-2}·y^{-1}, respectively (Figure 5).

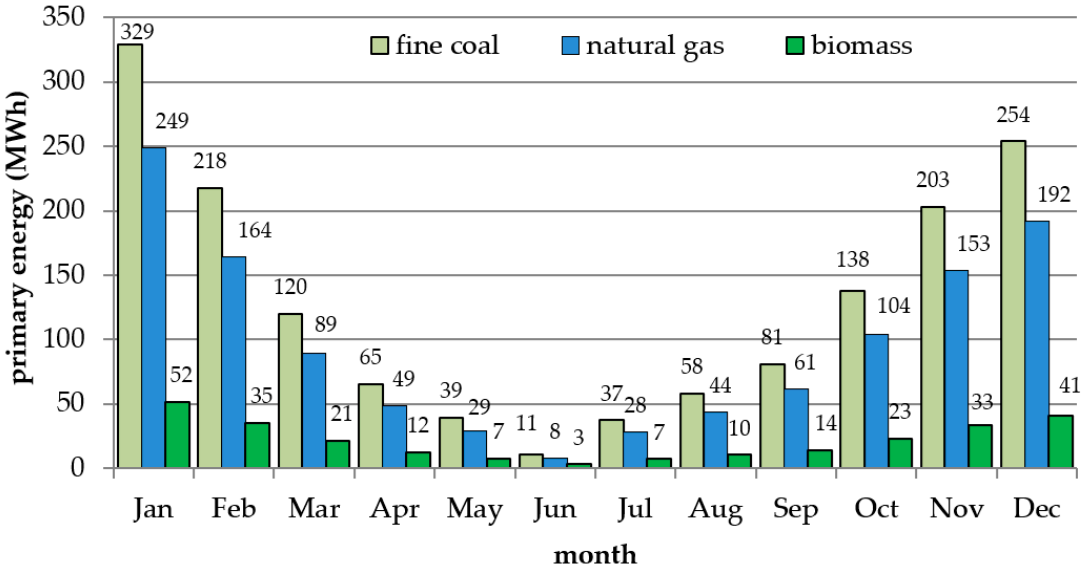


Figure 5. Monthly primary energy sums used for the purpose of GH heating.

In the biomass combustion scenarios, the total amount of non-renewable primary energy used for heating is 259.59 MWh·y^{-1} and the specific value is 207.67 kWh·m^{-2}·y^{-1}.

The key information on energy consumption presented (Table 5) shows the importance of gas or biomass intake compared to the coal-fired heat source (reference scenario). The non-renewable primary energy factor may be of particular importance, for its value suggests a reduction in the environmental footprint. In scenario 2 for natural gas combustion, the

environmental footprint was reduced by 24.6%, and in scenarios 3 and 4 for biomass combustion—by as much as 83.3%. In the case of natural gas combustion, the reduction in non-renewable primary energy demand is mainly due to the higher total efficiency of the heating system and less need for auxiliary energy compared to scenario 1. In turn, according to the methodology described in [31], biomass as a renewable fuel is not considered in calculating non-renewable primary energy demand.

Table 5. Energy performance of the GH.

Scenario/Fuel	Energy								
	Useful			Final			Primary		
	$MWh \cdot y^{-1}$	$kWh \cdot m^{-2} \cdot y^{-1}$	%	$MWh \cdot y^{-1}$	$kWh \cdot m^{-2} \cdot y^{-1}$	%	$MWh \cdot y^{-1}$	$kWh \cdot m^{-2} \cdot y^{-1}$	%
1/coal	679.77	543.82	100	1125.04	900.0	100	1553.31	1242.6	100
2/natural gas				933.89	747.2	83.0	1170.57	936.5	75.4
3/wood pellets 4/wood chips				966.21	773.0	85.9	259.59	207.7	16.7

3.2. Cumulative Energy Demand and Carbon Footprint during the Use Phase

The CED was determined on the basis of non-renewable primary energy needed for GH heating. As biomass has a zero-emission factor; hence, the CO_2 emissions in scenario 3 and scenario 4 are fully related to the generation of auxiliary electricity needed for electric propulsion. The analytical work produced the total values of the annual CED during the use phase in GH cultivation (Table 6).

Table 6. CED and CF for individual scenarios expressed as absolute values, as well as specific values per unit area and per unit of a potted flower.

Scenario/Fuel	CED				CF			
	$MJ \cdot y^{-1}$	$MJ \cdot m^{-2} \cdot y^{-1}$	$MJ \cdot unit^{-1} \cdot y^{-1}$	%	kg CO_2-eq$\cdot y^{-1}$	kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$	kg CO_2-eq$\cdot unit^{-1} \cdot y^{-1}$	%
1/coal	5,591,921	4473.5	15.2	100.0	458,305	366.6	1.245	100.0
2/natural gas	4,214,067	3371.3	11.5	75.4	212,604	170.1	0.578	46.4
3/wood pellets	934,523	747.6	2.5	16.7	25,600	20.5	0.070	5.6
4/wood chips	934,523	747.6	2.5	16.7	23,013	18.4	0.063	5.0

The annual exploitation of a GH, for growing flowers in pots, with coal combustion in the heat source (scenario 1), consumes 5592 $GJ \cdot y^{-1}$ of energy, so the specific value referred to in the unit of the cultivated area is 4473.5 $MJ \cdot m^{-2} \cdot y^{-1}$. In scenario 2 for natural gas combustion, the annual CED is 4214 $GJ \cdot y^{-1}$ and 3371.3 $MJ \cdot m^{-2} \cdot y^{-1}$ of the GH surface, which means that the CED is reduced by 24.6% compared to scenario 1. In the biomass scenarios (scenarios 3 and 4), the combustion of which, irrespective of the source, is described by a factor or non-renewable primary energy 0.2 [31], the annual CED is the lowest at 934.5 $GJ \cdot y^{-1}$, with a specific value referred to the GH are 747.6 $MJ \cdot m^{-2} \cdot y^{-1}$.

CED specified in a FU $MJ \cdot unit^{-1} \cdot y^{-1}$ of a potted flower is, in coal combustion scenario, 15.2 $MJ \cdot unit^{-1} \cdot y^{-1}$, and in gas combustion scenario 11.5 $MJ \cdot unit^{-1} \cdot y^{-1}$. In the scenarios with biomass combustion, the CED is 2.5 $MJ \cdot unit^{-1} \cdot y^{-1}$, which corresponds to a reduction of 83.3%.

The CF in scenario 1 is 458,305 kg CO_2-eq$\cdot y^{-1}$ per unit of cultivated area 366.6 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$. Scenario 2 has an absolute value of 212,604 kg CO_2-eq$\cdot y^{-1}$, target value per unit area is 170.1 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$. Combustion of natural gas brings a reduction of 46.4% compared to scenario 1. In scenario 3, the CF in absolute terms is 25,600 kg CO_2-eq$\cdot y^{-1}$, and the specific value per unit area is 20.5 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$, which is only 5.6% CF determined for the coal combustion scenario. In scenario 4 with wood chips burning, the CF is 23,013 kg CO_2-eq$\cdot y^{-1}$, which converts to the specific value of 18.4 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$, which is also 5.0% of the CF of scenario 1.

The CF per single potted flower in the reference scenario is 1245 kg CO_2-eq·unit^{-1}·y^{-1}, and in the case of natural gas combustion 0.578 kg CO_2-eq·unit^{-1}·y^{-1}, i.e., 46.4% less than in scenario 1. In scenarios with renewable fuels, the CF is 0.070 kg of CO_2-eq·unit^{-1}·y^{-1} of the potted flower when burning wood pellets, which is 5.6% CF when burning carbon and 0.063 kg CO_2-eq·unit^{-1}·y^{-1} when burning wood chips, which is 5.0% CF in scenario 1.

In order to demonstrate the impact of energy carriers on the environment, the obtained results are broken down into individual stages of the analysis (Table 7), which provided information on carbon dioxide emissions expressed in kg CO_2·y^{-1}. In the first stage, emissions relating to fuel combustion are highlighted; the second one included emissions related to the generation of electricity used by drives in technical systems. The last item is cumulative CF, which is the final information on the environmental footprint of energy carriers in the use phase of GH.

Table 7. Annual emissions of carbon dioxide and CF—comparison of the analysis stages.

Analysis Stage	**Scenario/Fuel**							
	1 Coal		**2 Natural Gas**		**3 Wood Pellets**		**4 Wood Chips**	
	kg CO_2·y^{-1}	**%**	**kg CO_2·y^{-1}**	**%**	**kg CO_2·y^{-1}**	**%**	**kg CO_2·y^{-1}**	**%**
fuel	384,521	100.0	186,375	100.0	389,576	100.0	347,836	100.0
fuel + electricity	408,058	106.1	199,287	106.9	406,782	104.4	365,042	104.9
CF (CO_2-eq)	458,305	119.2	212,604	114.1	25,600	6.6	23,013	6.6

The analysis shows that the increase in emissions caused by the inclusion of electric drives in the technical systems of the analysed GH and its heat source ranges from 4.4 to 6.9% of the emission level that can be attributed to fuel combustion.

The main impact regarding the use phase of GH is due to the fuel selection. In the fossil fuel scenarios, a reduction in the environmental footprint can be observed when natural gas is burned (scenario 2). When it comes to local emissions related to fuel combustion, an increase in carbon dioxide emissions, expressed in equivalent units, can be observed. In scenario 1, it is increased by 19.2% compared to the emission of coal combustion. In scenario 2 for natural gas combustion, there is an increase of 14.1% compared to local emissions. The adoption of renewable fuels in the form of biomass offers a significant reduction in environmental impact by reducing CF. In absolute terms, this is a reduction of 363,976 kg of CO_2·y^{-1} when burning wood pellets (scenario 3), which means 93.4% of the negative impact on the environment. In scenario 4 involving the combustion of wood chips, the annual emission reduction in absolute terms is 324,823 kg CO_2·y^{-1}, which means 93.4% lower emissions as well.

The results allow further analysis to determine the CED and CF values in the use phase for different operating periods. It was assumed to determine the CED and CF values in the event that the facility closes between November and February.

Analytical work produced totals for annual CED for operation with 273 GH cultivation days. The operation of GH for growing flowers in pots with carbon combustion in the heat source (scenario 1′) consumes 2.762 GJ·y^{-1} of energy, so the specific value referred to in the unit of the cultivated area is 2209.9 MJ·m^{-2}·y^{-1}. In scenario 2′ for natural gas combustion, the annual CED is 2075 GJ·y^{-1} and 1659.8 MJ·m^{-2}·y^{-1} of the GH area, meaning CED is reduced by 24.9% compared to scenario 1′. The biomass combustion scenarios (scenarios 3′ and 4′) have the lowest CED at 481.3 GJ·y^{-1} expressed as target value per unit GH of area 385.1 MJ·m^{-2}·y^{-1}. This means a reduction in CED by 82.6% compared to the coal combustion scenario (Table 8).

Table 8. CED and CF for individual scenarios expressed as absolute values, as well as specific values per unit area and per unit of a potted flower; GH operation of 273 days, from February till October.

Scenario/Fuel	CED				CF			
	$MJ \cdot y^{-1}$	$MJ \cdot m^{-2} \cdot y^{-1}$	$MJ \cdot unit^{-1} \cdot y^{-1}$	%	kg CO_2-eq$\cdot y^{-1}$	kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$	kg CO_2-eq$\cdot unit^{-1} \cdot y^{-1}$	%
1′/coal	2,762,322	2209.9	9.2	100.0	226,054	180.8	0.754	100.0
2′/natural gas	2,074,723	1659.8	6.9	75.1	105,089	84.1	0.350	46.5
3′/ wood pellets	481,327	385.1	1.6	17.4	14,326	11.5	0.048	6.4
4′/wood chips	481,327	385.1	1.6	17.4	13,063	10.5	0.044	5.8

CF in the coal burning scenario (scenario 1′) is 226,054 kg CO_2-eq$\cdot y^{-1}$, and per unit cultivation area is 180.8 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$. Scenario 2′ has an absolute value of 105,089 kg CO_2-eq$\cdot y^{-1}$, target value per unit area is 84.1 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$. Combustion of natural gas results in a 53.5% reduction compared to scenario 1′. In scenario 3′, the CF in absolute terms is 14,326 kg CO_2-eq$\cdot y^{-1}$ and the specific value per unit area is 11.5 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$, i.e., only 6.4% CF was determined for the coal burning scenario. In scenario 4′ involving the combustion of wood chips, the CF is 13,063 kg CO_2-eq$\cdot y^{-1}$, which converts to the specific value of 10.5 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$, which is also 5.8% CF of scenario 1′. The impact of energy carriers on the environment for a shorter period of GH operation (Table 9) is presented as the amount of carbon dioxide emissions expressed in kg CO_2-eq$\cdot y^{-1}$.

Table 9. Annual emissions of carbon dioxide and CF—comparison of the analysis stages; GH operation of 273 days, from February till October.

Analysis Stage	Scenario/Fuel							
	1′ Coal		2′ Natural Gas		3′ Wood Pellets		4′ Wood Chips	
	kg $CO_2 \cdot y^{-1}$	%	kg $CO_2 \cdot y^{-1}$	%	kg $CO_2 \cdot y^{-1}$	%	kg $CO_2 \cdot y^{-1}$	%
fuel	187,558	100.0	90,909	100.0	190,024	100.0	169,664	100.0
fuel + electricity	201,541	107.5	98,592	108.5	200,253	105.4	179,893	106.0
CF (CO_2-eq)	226,054	120.5	105,089	115.6	14,326	7.5	13,063	7.7

The analysis shows that the increase in emissions due to the inclusion of electric drives in the GH technical systems and its heat source ranges from 5.4 to 8.5% of the emissions that can be attributed to fuel combustion. When comparing the results of scenarios 1–4 with the results of scenarios 1′–4′, an increase in emissions related to electricity should be noted. This increase is due to a change in the GH operating regime: presumably, there are more favourable environmental conditions when the heating medium requirements are lower, which translates into lower fuel consumption, while maintaining the circulation of the heating medium in the system remains relatively constant.

In the fossil fuel scenarios, the negative environmental impact is halved. In scenarios involving renewable fuels, we can see a reduction in environmental impact by reducing the CF. In absolute terms, this is a reduction of 175,698 kg of $CO_2 \cdot y^{-1}$ when burning wood pellets (scenario 3′), which means a 92.5% negative environmental impact. In scenario 4′ involving wood chip combustion, the annual emission reduction in absolute terms is 156,601 kg $CO_2 \cdot y^{-1}$, which means 92.3% lower emissions.

A comparison of the CED values for year-round operation and for the period shortened by the three coldest months reveals a 50.6% reduction in demand for coal combustion and 50.8% for natural gas combustion. The use of renewable fuels means a CED reduction of 48.5% when burning wood pellets and wood chips. In the case of a GH operated in Germany [1] assessed in terms of fuel consumption and electricity consumption over a similar lifetime, the CED values are lower. The difference may result from the locations of the analysed facilities and their slight distinctions in shape. The German multi-span greenhouse is more compact than the free-standing, even-span greenhouse studied in the present paper. Due to the abovementioned reasons, the results are not directly comparable.

The CF values for scenarios 1′–4′ were reduced by 50.7% for coal combustion and 50.6% for natural gas. Combustion of biomass in shorter periods of GH operation should reduce the emission of pollutants by 44.0% when using wood pellets, and by 43.2% when burning wood chips.

4. Conclusions

The paper discusses the issues of reducing the CF in a greenhouse's use phase, resulting from the change of the fuel supplying the boiler. The analyses aimed to reduce the negative impact on the environment and move away from fossil fuels, assuming that the changes concern only the heat source. For this purpose, the LCA method and the methodology for calculating the energy performance of the building were used.

The CED and CF values indicate that there is significant potential to reduce the operating costs of GH production and reduce its environmental footprint. In the coal-burning scenario, the CED value is 4473.5 $MJ \cdot m^{-2} \cdot y^{-1}$, and the CF is 366.6 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$. In the most favourable scenario with wood chips combustion, the CED value is 747.6 $MJ \cdot m^{-2} \cdot y^{-1}$, while the CF is 18.4 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$. The use of a renewable energy source (wood chips) means a reduction in the cumulative energy demand (CED) compared to the coal-burning scenario. As a result, the carbon footprint in the wood chips scenario is only 5% of the carbon footprint of scenario 1 with a non-renewable energy source such as coal. Importantly, carbon dioxide emissions from the combustion of biomass are not included in the total emissions.

The scenarios to determine the CED and CF values for reduced GH uptime lead to the conclusion that the shutdown of production in the three coldest months of the year could reduce heat demand by 48.5% and carbon footprint by 43.2% when burning wood chips. This would mean, however, that GH would not fulfil the role it is intended for. The scenarios for biomass combustion show a significant potential to reduce the heat demand and reduce the negative environmental impact in the operational phase of GH production in Poland.

The results of the analysis of potted flower cultivation in the year-round exploitation of GH in Polish weather conditions make it possible to make a high-level comparison of the key CED and CF indicators per unit of cultivated area. The CED for the use phase when burning wood pellets is 385.1 $MJ \cdot m^{-2} \cdot y^{-1}$, which means that it is comparable to facilities in Germany with a similar lifetime. In turn, the CF value for the GH use phase is set to 11.5 kg CO_2-eq$\cdot m^{-2} \cdot y^{-1}$, which indicates that the production of GH in Polish conditions, when biomass is used as fuel and devices with similar operating times are compared, has a greater negative impact on the environment than in Germany. Assuming a temporary shutdown of the facility, it is possible to determine the reduction in the environmental footprint of the planned cultivation in heated GH, directly by comparing the CED and CF values for the use phase.

Further research on greenhouse cultivation systems could explore the concept of GH integrated with hybrid heat and electricity supply equipment based on cogeneration units or different types of heat pumps supported by solar collectors and photovoltaic panels.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app12178786/s1, Raw Sampling Data.

Author Contributions: Conceptualization, S.G.; methodology, R.G. and S.G.; validation, S.G. and R.G.; investigation, S.G.; data curation, R.G.; writing—original draft preparation, S.G.; writing—review and editing, S.G. and R.G.; visualization, S.G.; supervision, R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

GH	Greenhouse;
CED	Cumulative Energy Demand;
CF	Carbon Footprint;
CO_2-eq	Carbon Dioxide Equivalent;
LCA	Life Cycle Assessment;
LHV	Lower Heating Value;
FU	Functional Units.

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