The paper deals with the issue of greenhouse gas emissions that are produced by the road freight transport sector. These emissions affect the structure of the ozone layer and contribute to the greenhouse effect that causes global warming—issues that are closely associated with changing weather patterns and extreme weather events. Attention is drawn to the contradictions linked to FAME (Fatty Acid Methyl Esters) biofuels, namely the fact that although their use generates almost zero greenhouse gas emissions, their production requires high levels of energy consumption. The first part of the paper deals with the theoretical basis of the negative impacts of transport on the environment and the subsequent measurement of the extent of the harmful emissions generated by the road freight transport sector. In the methodical part of the paper, the calculation procedures and declared energy consumption and greenhouse gas emissions generated by transport services are analyzed according to the EN 16258 standard. The experimental part of the paper focuses on the application of the methodology to a specific shipment on a specified transport route, where the total energy consumption and production of greenhouse gas emissions is determined. These calculations are based on comprehensive studies carried out for a particular transport company that assigned the authors the task of determining to what extent the declared energy consumption and greenhouse gas emissions change when the type of fuel used is changed.

Keywords: energy consumption; greenhouse gas emissions; road freight transport; calculation; transport service

1. Introduction

Transport, as one of the fundamental parts of a logistics chain, has significant economic influence on the standards of living in the developed countries of the European Union. With the development of transport in the 1990s, came early warning signs of the negative impact of different means of transport on the environment. Initially, it concerned the impact on the environment in urban agglomerations, where emissions from (fossil fuel) engines and noise pollution started to reach permitted limits. The issue of reducing the negative impacts of transport subsequently started to be addressed by a wide range of governmental and non-governmental research organizations [1].

Over time, plans for reducing the negative environmental impact of transport were developed not only at the municipal and regional levels but also at the national and international levels. Scientists started to deal with the issue and developed studies that addressed a much wider range of negative aspects and their impact on the global environment. These works contain, inter alia, many proposals to address the situation, proposals which are considered more or less acceptable in terms of sustaining the growth of national economies and the standards of living of their inhabitants. This poses a fundamental dichotomy, i.e., how do we reduce the negative impacts of transport, as well as all other
human activities on the environment, whilst trying to maintain current levels of economic growth and living standards [2,3]?

This article focuses on the specific issue of the declaration of energy intensity and greenhouse gas emissions of biofuels. Biofuels have much more positive results in terms of greenhouse gas emissions, but the efficiency of biofuel production is questionable. FAME (Fatty Acid Methyl Esters) are acids that are created during the transesterification of vegetable oils and animal fats that create biodiesel. FAME is the generic chemical term for biodiesel derived from renewable sources [4]. Therefore, the authors have identified a research question: “How does an increase of the bio-components in diesel fuel affect the energy intensity of biofuel production?” For this research work, the authors used the verified methodology EN 16258, which is characterized in Section 3.2. Using this methodology, the energy intensity of production was calculated for the individual shares of the bio-component [5,6]. In addition to the energy intensity of production, the authors also calculated the production of greenhouse gas emissions, but the calculation is illustrative only and aims to point to the environmental benefits of biofuels [7,8].

2. Literature Review

The issue of greenhouse gas emissions in association with freight transport and its sustainability have been extensively discussed in literature. For example, Quiros et al. [5] suggest that 70% of freight transport is conducted with the use of road vehicles that are responsible for producing 20% of greenhouse gas emissions in the area of transport. A study by Pan et al. [6] focuses on the possibilities for reducing energy consumption and greenhouse gas emissions through the consolidation of freight transport. In particular, they state: “It is well established that the consolidation of freight transport represents an effective way of improving the use of logistics resources.” The authors explore the impact the pooling of supply chains at the strategic level might have on the environment. The suggested that pooling of supply networks represents a practical approach to CO$_2$ emissions reduction. The study presented by Woodcock et al. [7] produced similar results.

The majority of authors [8–13] suggest that the sustainability of freight transport lies in a more effective synchronization of individual kinds of transport; so-called synchromodality. As stated by Agho and Zhang [8], synchromodality has the potential to increase the use of transport services. The advantages in terms of environmental sustainability lie in the reduced use of lorries and the subsequent reduction in greenhouse gas emissions, congestion, noise, etc.

As stated by several authors [14–17], the use of alternative fuels in road freight transport is another means by which to reduce energy consumption and greenhouse gas emissions. For example, according to Floden and Williamsson [17], the use of biofuels presents a practical way for developing a sustainable system of freight transport. In a study by de Jong et al. [16], measures are examined that could make future biofuel production more efficient.

In contrast to previously published results [8–11,16], the submitted article focuses on a different way of assessing the efficiency of biofuel use, namely from the point of view of the energy consumption required for its production. The methodology of the European Committee for Standardisation [18] was used as a basis for the assessment and was quoted from a study by Konecny and Petro [19].

The methodology is explained in Section 3.2. Having employed this method, the authors tried to point out the changes of the energy consumption of FAME biofuel production in regard to the increasing share of biofuels. The authors did not find this methodology and procedure in any professional literature.

3. Materials and Methods

3.1. Emissions Theory

According to Pohl [20], the negative impacts of transport on the environment can be divided into five basic categories, namely:
- emissions—air pollution associated with the imperfect combustion of fossil fuels;
- noise pollution—from combustion engines and the movement of vehicles along transport routes;
- vibrations—due to the movement of vehicles along transport routes;
- water pollution—from the leakage of working fluids, as well as the leakage of transported substances and fluids due to traffic accidents;
- traffic accidents—in terms of the people and animals killed.

Airborne pollutants are partially transported by air and therefore do not only influence the place where the emissions are generated. In order to fully analyze the negative impacts of transport, it is essential to fully understand the relationship “emission—transmission—deposition—immission”.

1. **Emission**—this term describes the generation and release of harmful substances. Emissions are expressed in absolute terms, such as the weight of a specific airborne pollutant, or the pollutants generated by one vehicle in relation to (per) distance travelled.

2. **Transmission**—this term describes the spread of pollutants by air. Transmission depends on a variety of factors (type and amount of emissions, meteorological conditions, etc.).

3. **Deposition**—this term describes the deposition of pollutants at different sites on the Earth’s surface due to transmission. Wet deposition includes precipitation in liquid form (e.g., rain, fog, etc.). Dry deposition includes pollutants that fall from the atmosphere due to transmission, mostly in the form of dust.

4. **Immission**—this term describes the concentration of pollutants in the air and their impact on humans and the environment, as well as on, for example, buildings. The scope of the impact directly depends on the concentration of the pollutant at the point and period of its activity. Immissions are expressed in absolute units of mass per volume (e.g., g/m³).

When describing the impact of specific pollutants, it is necessary to analyze the complex path from emission to immission, since it is the only way to determine with precision the harmful effects, i.e., the relationship between cause and effect [21].

Gases that trap heat in the atmosphere are called greenhouse gases. The Kyoto Protocol highlights six fundamental gases that influence climate change the most: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulfur hexafluoride (SF₆), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) [2,22].

The Kyoto Protocol [16–19] also states that these greenhouse gases must be converted into aggregate average emissions as expressed in CO₂e units (carbon dioxide equivalent). This conversion takes into account the different ability of the identified gases to cause the greenhouse effect, as well as their atmospheric lifetime. Although CO₂ is not the gas with the greatest ability to cause the greenhouse effect, it is the most significant anthropogenic greenhouse gas. It is for this reason that the other gases are converted into CO₂e (see Table 1).

<table>
<thead>
<tr>
<th>GHG</th>
<th>Chemical Formula</th>
<th>Atmospheric Lifetime (Years)</th>
<th>Global Warming Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>50–200</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>12 (±3)</td>
<td>21</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N₂O</td>
<td>120</td>
<td>310</td>
</tr>
<tr>
<td>Sulfur hexafluoride</td>
<td>SF₆</td>
<td>3200</td>
<td>23,900</td>
</tr>
</tbody>
</table>

Source: Authors based on Telang [3].

An example of the CO₂e calculation process follows. The calculation is based on the production of electricity by a diesel aggregate that consumes 100 L of diesel oil.

1. CO₂ emissions = Fuel consumption in unit of volume × CO₂ emission factor
2. CH$_4$ emissions = Fuel consumption in unit of volume × CH$_4$ emission factor
3. N$_2$O emissions = Fuel consumption in unit of volume × N$_2$O emission factor

Overall greenhouse gas (GHG) emissions in tCO$_2$e = (CO$_2$ emissions) + (CH$_4$ × 21) + (N$_2$O × 310)

1. CO$_2$ emissions = 100 × 0.00265 [3,23]
2. CH$_4$ emissions = 100 × 0.00000036 [3,23]
3. N$_2$O emissions = 100 × 0.00000021 [3,23]

Overall GHG emissions = 0.265299393 + (0.000035819 × 21) + (0.00000215 × 310) = 0.2667 tCO$_2$e

3.2. Methodology for the Calculation and Declaration of Energy Consumption and Greenhouse Gas Emissions for Transport Services According to the EN 16258 Standard

The EN 16258 standard sets out the methodology and requirements for the calculation and declaration of energy consumption and greenhouse gas emissions for transport services. The standard was developed for the purpose of unifying existing carbon footprint calculations and their comparison. In calculations of energy consumption and emissions in relation to vehicles, energy consumption and emissions relating to the production and distribution of fuels or electric energy are taken into account. This ensures that the standard assumes a “Well-to-Wheel” (WtW) approach in terms of calculations and declarations (see Figure 1).

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Vehicle life cycle assessment. Source: Authors based on the European Committee for Standardisation [18].

WtW therefore includes the aforementioned energy and emissions for the production of fuels or electric energy, Well-to-Tank (WtT), as well as the energy consumption and greenhouse gas emissions relating to the operation of vehicle Tank-to-Wheel (TtW) [18,19,24–28].

The Well-to-Wheel analysis therefore determines the consumption of fossil fuel energy and the production of CO$_2$e for driving conditions that correspond to the European homologation cycle. The standard further specifies individual processes and principles that are essential for the correct calculation of energy consumption and greenhouse gas emissions [29–32].

The operational processes of a vehicle must include the operation of all vehicle systems, including propulsion units (main engines), ancillary services, auxiliary equipment used for maintaining the temperature of the load area, and vehicle handling and transshipment systems.

The energy processes for the consumed fuel must include the extraction or primary energy production, refining, transformation, transport, and distribution of energy during all production stages. The principles for calculating the energy consumption and greenhouse gas emissions of transport services must take into consideration all vehicles used for providing transport services, including those that are subcontracted. Furthermore, it must include the overall fuel consumption of each energy carrier and all laden and unladen journeys [18].
3.2.1. Individual Steps of the Calculations for a Specified Transport Service

The calculation(s) for a specified transport service must include the following steps:

1. Identification of the various journeys (legs) that make up the specified transport service.
2. Calculation of energy consumption and greenhouse gas emissions for each leg of the specified transport service.
3. Sum of the results for each leg of the specified transport service [33,34].

The calculation of overall energy consumption and greenhouse gas emissions is performed as follows:

\[
E_w(VOS) = F(VOS) \times e_w
\]

\[
G_w(VOS) = F(VOS) \times g_w
\]

\[
E_t(VOS) = F(VOS) \times e_t
\]

\[
G_t(VOS) = F(VOS) \times g_t
\]

where is:

- \(E_w(VOS)\) — Well-to-Wheel energy consumption vehicle operating system (VOS);
- \(G_w(VOS)\) — Well-to-Wheel greenhouse gas emissions VOS;
- \(E_t(VOS)\) — Tank-to-Wheel energy consumption VOS;
- \(G_t(VOS)\) — Tank-to-Wheel greenhouse gas emissions VOS;
- \(F(VOS)\) — overall fuel consumption VOS;
- \(e_w\) — Well-to-Wheel energy factor for fuel used;
- \(g_w\) — Well-to-Wheel greenhouse gases factor for fuel used;
- \(e_t\) — Tank-to-Wheel energy factor for fuel used;
- \(g_t\) — Tank-to-Wheel greenhouse gases factor for fuel used.

The values for the energy and greenhouse gas factors are taken from the EN 16258 standard (2013).

3.2.2. Principles for Allocating the Share of Energy Consumption and Emissions per Unit of Cargo

The overall energy consumption and greenhouse gas emissions of the vehicle operation system (VOS) must be allocated to a unit of cargo. The EN 16258 standard applies tkm as the unit for determining transport performance, which is the product of the mass (weight) of the cargo carried and the kilometers travelled [35–37]. The mass is the weight of the cargo transported, including packaging, container(s), pallet, etc. The basic formulas for allocating the cargo are as follows:

\[
S(\text{leg}) = (T(\text{leg}))/\left( T(VOS) \right)
\]

\[
E_w(\text{leg}) = E_w(VOS) \times S(\text{leg})
\]

\[
G_w(\text{leg}) = G_w(VOS) \times S(\text{leg})
\]

\[
E_t(\text{leg}) = E_t(VOS) \times S(\text{leg})
\]

\[
G_t(\text{leg}) = G_t(VOS) \times S(\text{leg})
\]

where is:

- \(S(\text{leg})\) — factor for calculating the share of energy consumption and emissions of the vehicle operation system (VOS) to be allocated to a specified transport service;
- \(T(\text{leg})\) — transport performance for leg of the specified transport service;
- \(T(VOS)\) — transport performance VOS.
4. Results

The results presented in this article are taken from a study conducted for a private transport company [38] that entrusted the authors with the task of finding out how a change in the kind of fuel used by its lorries for international road freight transport might influence their energy consumption and greenhouse gas emissions. The calculations were made for a specified transport route, namely Aschaffenburg to Domoradice, as determined by the transport company. The results of the calculations with regard to energy consumption and greenhouse gas emissions according to EN 16258 for the route are summarized in Table 2.

Table 2. Calculated results for diesel.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Consumed Fuel (L)</th>
<th>Cargo Weight (t)</th>
<th>Gw (kgCO2e/L)</th>
<th>Gt (kgCO2e/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>582</td>
<td>169</td>
<td>17,251</td>
<td>534.04</td>
<td>424.19</td>
</tr>
</tbody>
</table>

Source: Authors.

Table 3 shows the energy consumption and greenhouse gas emissions figures on the basis of the use of 100% FAME biodiesel. The route is the same but with slight nuances in the distance travelled due to the lorry landing at a different hall.

Table 3. Calculated results for FAME (Fatty Acid Methyl Esters) biofuel.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Consumed Fuel (L)</th>
<th>Cargo Weight (t)</th>
<th>Gw (kgCO2e/L)</th>
<th>Gt (kgCO2e/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>596</td>
<td>184</td>
<td>16,830</td>
<td>353.28</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Source: Authors.

Figure 2 shows a clearer comparison of the results. The results clearly show that the share of energy consumed for FAME production is much higher than that for diesel. This fact is logical when it is taken into consideration that this type of fuel is made from industrial crops. In this case, it does not concern extraction but the cultivation of crops and the process of their transformation into a substance that can be used, for example, as a fuel for compression-ignition engines.

![Figure 2. Comparison of diesel with 6% biocomponent and FAME biodiesel. Source: Authors.](image)

Figure 2. Comparison of diesel with 6% biocomponent and FAME biodiesel. Source: Authors.

What is even more important is the fact that there are no greenhouse gas emissions during combustion in compression-ignition engines. Greenhouse gas emissions are generated only in the production and distribution of FAME, which is also partly influenced by the natural production of CO2 during the cultivation of the plants. However, it should be stressed that this article only deals
with greenhouse gas emissions, i.e., carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulfur hexafluoride (SF₆), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) [39–42].

5. Discussion

Having conducted their study of energy consumption and greenhouse gas emissions for various kinds of fuels, the authors were motivated by previous existing literature [13–16,43–50] to apply the methodology to the calculation of the energy consumption related to FAME biofuel production and the EN 16258 standard.

The results (see Figure 2) reveal a relatively large increase in energy consumption for FAME biodiesel. The applied method enables a quick and easy analysis of the energy consumption and greenhouse gas emissions related to the production of mixed fuels.

The calculations that follow are based on the following assumption: that the same model of vehicle goes from point A to point B and always consumes 100 L of diesel, but that the volume of the biocomponent in the diesel differs—from pure diesel (0% biocomponent) up to 100% FAME biodiesel.

The calculations were made for all available volume shares of diesel/biodiesel [51,52]. In order to calculate the energy consumption on the basis of fuel production and distribution, so-called WtT (Well-to-Tank), the difference in the numbers for total energy consumption (WtT) and the energy consumed for the transport service (TtW) needed to be explored. The results for WtT are presented in MJ units in Table 4.

Table 4. Energy consumption analysis for FAME biofuels.

<table>
<thead>
<tr>
<th>Biocomponent (in %)</th>
<th>0%</th>
<th>1%</th>
<th>2%</th>
<th>5%</th>
<th>8%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
<th>50%</th>
<th>85%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>TtW e [MJ]</td>
<td>3590</td>
<td>3590</td>
<td>3580</td>
<td>3570</td>
<td>3570</td>
<td>3560</td>
<td>3540</td>
<td>3530</td>
<td>3440</td>
<td>3330</td>
<td>3280</td>
</tr>
<tr>
<td>WtW e [MJ]</td>
<td>4270</td>
<td>4300</td>
<td>4320</td>
<td>4400</td>
<td>4480</td>
<td>4530</td>
<td>4660</td>
<td>4790</td>
<td>5560</td>
<td>6460</td>
<td>6850</td>
</tr>
<tr>
<td>TiW gₑ [kgCO₂ₑ]</td>
<td>267</td>
<td>264</td>
<td>262</td>
<td>254</td>
<td>246</td>
<td>240</td>
<td>227</td>
<td>214</td>
<td>134</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>WtW gₑ [kgCO₂ₑ]</td>
<td>324</td>
<td>323</td>
<td>321</td>
<td>317</td>
<td>313</td>
<td>311</td>
<td>304</td>
<td>298</td>
<td>258</td>
<td>212</td>
<td>192</td>
</tr>
<tr>
<td>WtT [MJ]</td>
<td>680</td>
<td>710</td>
<td>740</td>
<td>830</td>
<td>910</td>
<td>970</td>
<td>1120</td>
<td>1260</td>
<td>2120</td>
<td>3130</td>
<td>3570</td>
</tr>
</tbody>
</table>

Source: Authors based on [17,22,38].

The following Figure 3 compares an increase in energy consumption for WtT production of mixed fuel diesel/biodiesel in relation to a percentage volume share of biocomponents with a decreasing production of greenhouse gas emissions from the entire life cycle of WtW fuels.

Figure 3. Comparing results of analysis on FAME biofuels energy consumption. Source: Authors.

It is clear from Figure 3 that under current technologies the production of biofuels, namely FAME biofuels, is unacceptably energy-intensive. This results in very poor competitiveness in the fuel market. Fossil fuels are currently considered environmentally unsuitable and, as a result, are presently listed...
as non-renewable energy sources. Biofuels have the character of a renewable source of fuel, but their huge drawback is their overly “expensive production” (which is shown in Figure 3). It will therefore be necessary to look for a more energy-efficient biofuel production process in order to be competitive with other types of fuels.

6. Conclusions

If we compare the lowest greenhouse gas emissions of 100% FAME biodiesel and the lowest energy consumption necessary for the production of 100% diesel (fuel with 0% biocomponent), it is possible to draw an interesting conclusion. To reduce greenhouse gas emissions by 69% compared to common diesel, we must produce biofuel, the production and distribution of which would consume more than four times more energy than diesel.

Biofuels, therefore, have considerably more favorable parameters than conventional fossil fuels in terms of greenhouse gas emissions, but their production is inefficient in terms of energy intensity. The high energy intensity of the FAME biofuel production is negatively reflected in its fuel price. The price is still higher than the price of conventional fuels, which results in a lack of interest in using more environmentally acceptable types of fuel. There is still a large group of customers who do not take into account the production of greenhouse gas emissions but only fuel costs.

This opens up a new area of research, namely into the search for possibilities to lower this level of energy consumption to an acceptable level so that 100% FAME biodiesel becomes competitive on the fuel market, thereby contributing to the reduction of the negative impacts of transport on the environment and ensuring sustainable transport development.

In conclusion, the authors want to highlight the need for a new approach in the assessment of energy consumption and greenhouse gas emissions in transport due to the high energy consumption linked to the production of FAME biofuels. Within this context, the presented results should open up a broader discussion into the sustainability of biofuels as a whole.

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Conflicts of Interest: The authors declare that there are no conflicts of interest.

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