

Economic Evaluation of Renewable Fuels through Pollutants Derived from Internal Combustion Engine

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Abstract

Renewable fuels cannot be evaluated clearly as a part of sustainability from their air pollution point of view. A comparison test series have been conducted and from their results external cost has been calculated. Three different fuels and their controlled blends have been investigated, which are the fossil diesel, conventional, standardized biodiesel, and a new type, so called TBK-biodiesel. Fuels have been investigated in a bus Diesel-engine, which operated in steady state points. Air pollution components like CO₂, CO, HC, NO_x and particulate have been taken into consideration for the calculation. The calculation method is a self-made one. On the basis of the results it can be stated that the overall external costs are higher in all cases of engine operating if renewable fuel is blended in the tested fuel.

Keywords

external cost, air pollution, renewable fuel, Diesel-engine

1 Introduction

Diesel engines are the basic engine in a wide range of applications. The number of vehicles, applications propelled with diesel engines is growing continuously [1]. A wide range of alternative fuels is offered in the transport sector, among them, biofuels [2, 3]. Biofuels were introduced for a number of reasons: first of all for diversification of the energy sources, secondly reducing the consumption of fossil fuels, and finally increasing energy security. So bio derived fuels can be an important part of sustainability from energy source, energy security point of view. Additionally, biofuels have a more favorable exhaust gas emission and greenhouse gas emission [2, 4]. But they cannot be classified clearly as elements of sustainability if particulate emissions of an internal combustion engine are involved [5, 6].

Energy production, transportation is a part of our daily life. Making these activities result not only positive but negative effects as well. Externality is one kind of external or overflow effect, which occurs, when the production or the consumption cause additional cost, while these costs are being not compensated by the causer. It can also mean that the external economy effect is caused by one economic operator to the operator, which doesn't appear in the market transaction [7].

Negative externality can be the air pollution, the noise pollution, the increased travel time caused by traffic jam as well as the increased fuel consumption. The infrastructure splits the region, which situation has a negative effect on the communities live there. Furthermore changes in our built environment, culture values, heritage as well as the deterioration in the clarity of the air can be listed to the externality [8]. Chronic diseases, increase in mortality can also be mentioned among the long term effects.

The natural environment, namely the clean air's monetary valuation can be justified as follows [9]:

1. It contributes the consideration of environmental damages for economy decisions.
2. It promotes that natural capital components would not be represented in the calculations with zero value.
3. It enables comparative analyzes and evaluations of natural capital.

Cost based methods (replacement cost method, shadow project, cost recovery method, defense cost, production factor method, cost-benefit analysis) → Revealed preference methods (travel cost method, hedonic pricing method) → Stated preference methods (contingent valuation method, contingent selection method, contingent ranking method) [10].

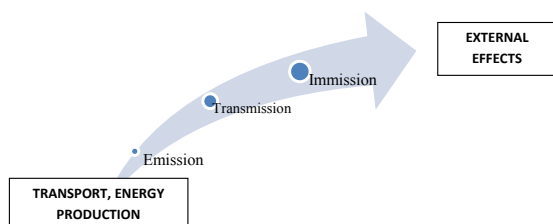


Fig. 1 The pollution chain (own editing)

Benefit transfer method cannot be categorized into either above mentioned category. It can be considered as a comprehensive method, which combines all the methods. The benefit transfer method uses the results of earlier conducted researches instead of performing the introduced original surveys, assessments [11].

Since this work's aim is not to evaluate monetarily the external effects of emission derived from road transport, thus the benefit transfer method will be used with the help of literature's data to determine the external cost effect of the different tested fuels.

A basic aim of this work is to make a comparing assessment on a natural capital basis regarding external cost effect of the emission of a bus Diesel-engine running on different kind of biofuels and their controlled blends. The benefit transfer method has been used for the calculations.

2 Experimental investigation, emission data for calculation

2.1 Tested fuels and their controlled blends

For the comparison tests series fossil-derived diesel fuel (D2) - corresponding to the standard [12] - purchased from a gas station in Hungary has been used as a reference fuel. The second tested fuel was a rapeseed biodiesel meeting the standard [13]. The TBK-biodiesel - the third tested fuel -, or also called Triglycerides of Modified Structure is a new type biofuel [14, 15]. Table 1 shows the most important physicochemical properties of the unblended fuels. Beside the pure fuels four different blends have been made in a controlled way. So the seven different fuel compositions were according to the following: pure fossil diesel, blend of both bio fuels with blending ratio of 25V/V% and 75V/V%, pure FAME and pure TBK. It is important to mention that reference fuel, which is diesel, may consist of 7 % of FAME. So blends have been created that this conjecture has been taken into consideration. This means that there is a small amount of conventional biodiesel in the TBK-Biodiesel and diesel blends.

Table 1 The most important basic properties of the tested fuels

Fuel	Density [kg/dm ³] at 15 °C	Kin. viscosity [mm ² /s.] at 40 °C	Lower heating value [MJ/kg]
Diesel	0.837	2.98	42.12
Biodiesel	0.877	5.05	36.29
TBK	0.905	6.43	34.81

2.2 Tested engine

The tests series have been carried out in engine type RÁBA D10 UTSL 160, which is the most commonly used engine in the Hungarian bus fleet. Because of this it is very important to know, how the emission properties are changing with the different fuels, because it has a high influence on the immission situation in larger towns in Hungary. This engine is able to run on higher level of bio blending rate. Modifications on the engine haven't been performed during the test series. The engine operated with the basic settings of the engine for fossil diesel.

2.3 Test method

The three test points have been chosen in relation to combustion process in the engine and the emission of the engine. In these three test points the combustion process and the pollutants emitted by the engine may be very different. (Measuring more than three points did not seem justified and it was avoided in order to prevent damages caused to the engine or the measurement system during the 30 to 50 minutes' test, which requires a high quantity of fuel). Three points were chosen for the tests from the speed-load range of the engine as follows: 1. 1300 rpm - 50 % load, 2. 1900 rpm - 25 % load 3. 1900 rpm - 75 % load, where 50 % means 450 Nm, 25 % load equal with 200 Nm and 75 % load equivalent to 600 Nm torque.

These control points are a part of the formal emission type approval requirement and they have been taken from [16]. The settings of the engine remained unchanged during the measurement series with any kind of tested fuel, which means the required torque had to be reached with any kind of fuel.

3 Cost data, calculation method

Specific emission factors are needed to be used for calculating the external cost of the emission components derived the bus Diesel-engine. These factors have been taken from different research studies [17-21] composed on this field.

Table 2 shows the selected and used cost factors connected to the different emission components. Emission components are carbon-dioxide, carbon-monoxide, hydrogen-carbon, nitrogen-oxides and particulate. This is the first data set which will be used for calculations.

The factors are given with different reference year, therefore a recalculation is needed. After the recalculation with the help of the inflation and exchange rate factor values are given to the year 2016 and in Ft.

The second main data set contains the emission values of the engine in the three tested operation points and regarding all the tested fuel derivative. Data set can be seen in Table 3.

Emission values have been determined in the measurement unit of g/kWh. In order to be able to calculate cost, emission values must be in measurement unit g/km. For the transfer between the two measurement units a method has been developed. The essence of this method is performing a simulation, namely at all engine operating points, with all of the tested fuels the engine runs until 800.000 km [18], with a tested engine related characteristic average fuel consumption. Calculation steps are as follows:

- (i) a fuel consumption value of 25 l/100 km have been selected which value is fit for a bus relevant from the engine point of view.
- (ii) The energy content or heating value of diesel is known in [MJ/liter] from [22], thus 100 km specific energy consumption can be calculated [kWh/km].

- The km related fuel consumption values of bio blends and pure biofuels is calculated with the help of the fuel consumption in case of diesel and the proportion of heating values between diesel and actually tested fuel. The fuel consumption values will always be higher in case of bio blends and pure biofuels compared to diesel.
- (iii) if the values from (ii) are multiplied with values in Table 3 and 4 the results will be the values of pollutants' emission related 1 km.
- (iv) if values from (iii) are multiplied with mileage value, which is 800.000 km, the results will be related to pollutants' emission of the engine of the mileage in the measurement unit of ton.
- (v) if values in (iv) are multiplied with factors from Table 2 then we can get the cost values regarding whole mileage per emission components [Ft/ton*component].
- (vi) costs for each component can be summarized and the results will be regarding mileage and per ton of pollutants' component [Ft/ton*pollutant].
- (vii) steps (i)-(vi) have been carried out for all of the tested fuels.

4 Results and discussion

4.1 Pollutant components

In the first part of this section the cost effect of emitted pollutants will be shown. Components are nitrogen-oxides,

Table 2 Cost specific emission factors

Literatur	Ref. year	CO	NMHC (VOC)	CH ₄	NO _x	PM _{2,5}	PM ₁₀	CO ₂
Specific damage value in €/ton								
Bickel et al. [20]	2002		800		5 000	102 000		
DG MOVE [17]	2010		1 569		19 580	114 576		90
IPCC [21]	2010			2 520				
2009/33/EK [18]	2007		1 000		4 400	87 000		30-40
Gerbec et al. [19]	2010	4.9						
Specific damage value in 2016 in Ft/ton								
Bickel et al. [20]	2002		317 600		1 985 000	40 494 000		
DG MOVE [17]	2010		486 390		6 069 800	35 518 560		27900
IPCC [21]	2010			781 200				
2009/33/EK [18]	2007		329 000		1 447 600	28 623 000		11515
Gerbec et al. [19]	2010	1 519						
Average		1 519	377 663	781 200	3 167 467	34 878 520		19708
Average of specific damage value in 2016 in Ft/ton								
Used external cost factors [Ft/ton]		1 519	579 432		3 167 467	34 878 520		19708
		CO	HC		NO_x	particulate		CO₂

Table 3 Specific emission values of pollutants

Engine operating point	1300 rpm - 50 % load				1900 rpm - 25 % load				1900 rpm - 75 % load			
Emission [g/kWh]	NO _x	CO	HC	PM	NO _x	CO	HC	PM	NO _x	CO	HC	PM
Diesel	8.49	1.22	0.55	1.66	6.33	3.98	1.00	3.39	5.21	1.17	0.50	0.98
25 % FAME	8.43	1.18	0.42	1.70	6.44	4.09	0.87	3.78	5.20	1.00	0.36	1.14
75 % FAME	8.73	1.12	0.41	1.74	6.64	3.97	0.82	4.53	5.64	1.04	0.43	1.37
100 % FAME	8.64	1.24	0.42	1.84	6.67	3.98	0.86	5.72	5.42	1.01	0.43	1.45
25 % TBK	7.94	1.20	0.49	1.75	6.25	3.96	0.93	4.22	5.24	1.15	0.49	1.33
75 % TBK	8.09	1.17	0.48	1.83	6.23	4.16	0.96	5.25	5.33	1.12	0.50	1.78
100 % TBK	8.74	1.15	0.42	2.06	6.40	4.29	0.98	6.48	5.52	1.10	0.47	1.87

Table 4 Specific emission values of CO₂

CO ₂ emission [g/kWh]	1300 rpm - 50 % load	1900 rpm - 25 % load	1900 rpm - 75 % load
Diesel	804.5	924.7	645.3
25 % FAME	797.7	900.0	638.9
75 % FAME	789.5	909.8	637.9
100 % FAME	819.4	932.7	659.7
25 % TBK	793.3	903.1	641.0
75 % TBK	789.9	939.3	656.7
100 % TBK	804.1	927.5	656.7

carbon-monoxide, hydrogen-carbon and particulate. Fig. 2 show the calculated specific emission of these air-phase components in the function of the tested fuel. Notable can be that the emission of nitrogen-oxides has the highest level while particulate the second highest. It can be clearly observed that the emission of these two components increases with the growing bio blending rate. Results are presented just for the 1. operating point which is 1300 rpm and 50 % load. The tendencies of the other two operating points are similar to this. The external cost results of these emission values are shown in the Fig. 3. Results are shown in million Ft.

On the basis of the Fig. 3 particulate has the highest cost effect for all kind of tested fuel. Beside particulate, NO_x also has a remarkable external cost. Cost are in the order of magnitude of hundred of millions Ft in case of particulate and in tens of millions Ft in case of nitrogen-oxides. Compared to these two components the cost of the other two components are negligible. Sum of cost for all engine operating points are presented in Fig. 4. Sum have been calculated from the above mentioned four components. It is important first to mention that cost increases with growing blending ratio of bio-derived fuel to the tested fuel. It is proved to be true at all operating points. Sum of cost values reach the hundreds of millions in Ft.

1. operating point

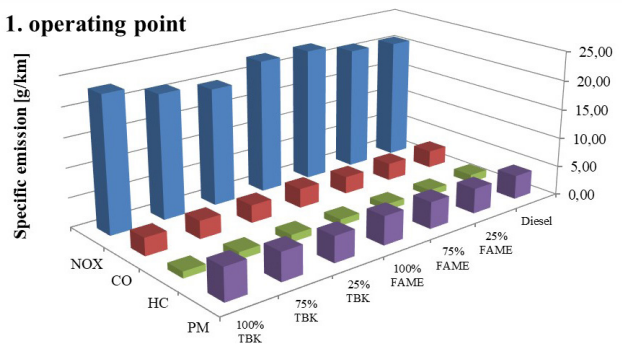


Fig. 2 Pollutant component's emission values with different measurement unit

1. operating point

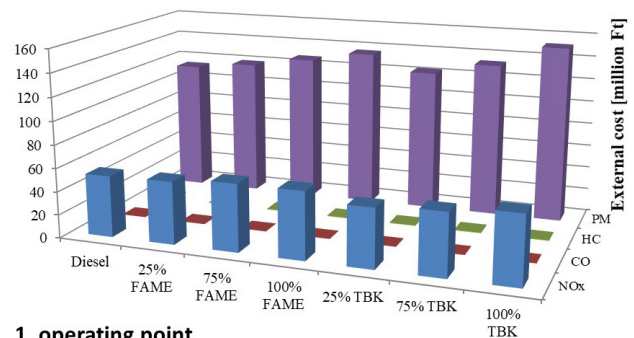


Fig. 3 The cost of the four different pollutants

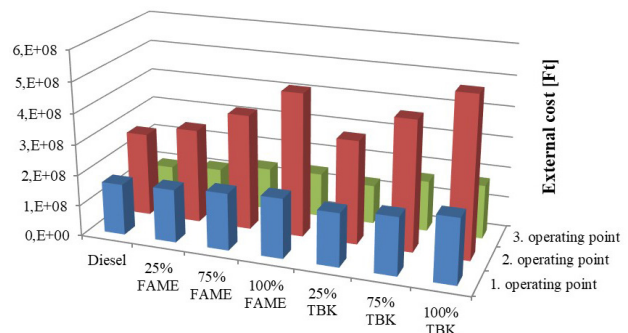


Fig. 4 The cost of the sum of the four different pollutants

In this subsection above the cost of four most important components have been presented. The calculation with carbon-dioxide will be introduced with the in the next subsection.

4.2 Calculation with carbon-dioxide

The greenhouse gas emission saving in case of rape-seed-biodiesel is 45 per cent [4]. This value has also been used in case of TBK-biodiesel, because a fit value for TBK could not be found in the document. With help of this information calculation of CO₂ have been made for the different blends and engine operating points as follows:

$$CO_2(25\% \text{ bio}) = 0.75 * CO_2 + 0.25 * 0.55 * CO_2 \quad (1)$$

$$CO_2(75\% \text{ bio}) = 0.25 * CO_2 + 0.75 * 0.55 * CO_2 \quad (2)$$

$$CO_2(100\% \text{ bio}) = 0.55 * CO_2 \quad (3)$$

Using the data set of Table 4 and by the help of Eqs. (1)-(3) the calculated CO₂ values are shown in Fig. 5. As expected the CO₂ emission decreases continuously with increasing bio blending rate. It is independent from the engine operating point. The rate of decline is the same for both of the two biodiesel. The following subsection shows how much effect has the cost reduction of CO₂ on the total external cost. Whether can the declining tendency of CO₂ compensate the cost of increasing NO_x and particulate.

4.3 External costs of all the emission components

In this section the results of the calculations will be shown where costs of all the relevant emission components have been taken into consideration. Fig. 6 shows the results for the 1. operating point of the engine and in case of all the components. It is remarkable that particulate emission has the highest cost effect among the components. It can be seen the declining tendency in the CO₂ emission with growing renewable blending rate. The answer to the question raised in the last subsection can be read from the diagram, namely the decreasing cost of CO₂ cannot compensate the growing cost of particulate and NO_x.

On the basis of the results of Fig. 7 the final conclusions can be established. At all engine operating points the blending of renewable blending component to the tested fuel has a cost-increasing effect. The cost values are in the order of magnitude of hundreds of millions Ft. It belongs for one bus for its mileage. This information is very important to know and to use it as part of the complex evaluation of renewable fuels.

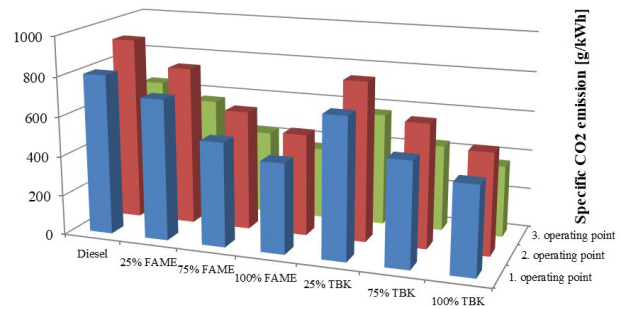


Fig. 5 Calculation results of CO₂ taken into consideration the CO₂ saving of renewable fuels

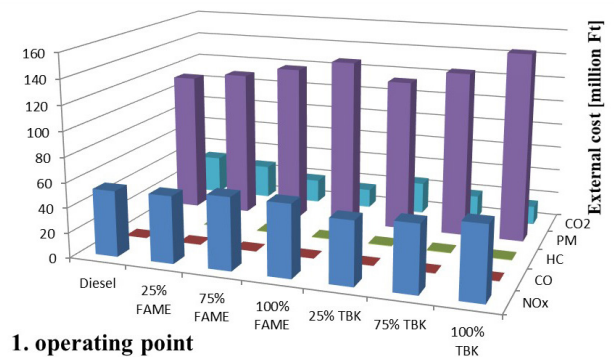


Fig. 6 External cost values per the emission components

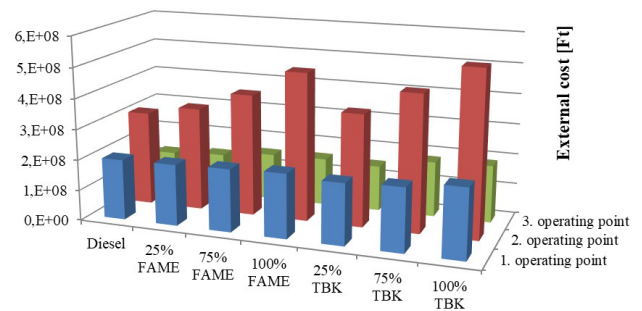


Fig. 7 Sum of external cost values per tested fuels and per engine operating point

5 Conclusions

An emission related economic evaluation of renewable fuels have been carried out and introduced in the paper above. Two different kinds of renewable fuels have been investigated in a bus compression ignition engine while the exhaust gas emission has been measured. Components of the exhaust gas were the basic information for the calculation of external cost. An own calculation method has been composed for the calculation. On the basis of the results the most important findings can be stated as follows:

- Blending bio-derived fuel to the tested fuel has a negative effect on the air pollution related external cost.
- The negative effect proved to be true at all the engine operation points.
- The negative effect proved to be true for both kinds of the investigated biofuel and also for their blends.
- On the basis of first three findings renewable fuels cannot be part of sustainability neither from air pollution nor from economic point of view.

- Emission related economic evaluation of renewable fuels must be a part of a complex technical-economic evaluation.

It can be a next task to carry out measurements on other engines and to do calculations where the composition of the Hungarian bus fleet is taken into account.

References

- [1] European Automobile Manufacturers Association "Diesel Penetration", 2014. [online] Available at: <http://www.acea.be/statistics/tag/category/dieselpenetration> [Accessed: 25 April 2018]
- [2] Lonza, L., Hass, H., Maas, H., Reid, A., Rose, K. D. "EU renewable energy targets in 2020: Analysis of scenarios for transport", JRC, EUCAR and CONCAWE, 2011. <https://doi.org/10.2788/74948>
- [3] International Energy Agency "World Energy Outlook 2013 Renewable Energy Outlook", IEA, Paris, France, 2013.
- [4] European Union "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC", Official Journal of the European Union, 5(6), pp. I. 140/16–I. 140/62, 2009.
- [5] Wang, Y., Liu, H., Lee, C.-F. F. "Particulate matter emission characteristics of diesel engines with biodiesel or biodiesel blending: A review", *Renewable and Sustainable Energy Reviews*, 64, pp. 569–581, 2016. <https://doi.org/10.1016/j.rser.2016.06.062>
- [6] Shahir, V. K., Jawahar, C. P., Suresh, P. R. "Comparative study of diesel and biodiesel on CI engine with emphasis to emissions—A review", *Renewable and Sustainable Energy Reviews*, 45, pp. 686–697, 2015. <https://doi.org/10.1016/j.rser.2015.02.042>
- [7] Samuelson, P. A., Nordhaus, W. D. "Közgazdaságtan" (Economics), 3rd ed., KJK, 1987. (in Hungarian)
- [8] Nash, C. (ed.) "Handbook of research methods and applications in transport economics and policy", 1st ed., Edward Elgar Publishing, Cheltenham, UK, 2015.
- [9] Csete, M. "Regionális és környezetgazdaságtan" (Regional and Environmental Economics), EDUTUS Főiskola, Digitális Tankönyvtár, 2012. (in Hungarian)
- [10] Szlávik, J. "Környezetgazdaságtan", (Environmental Economics) 1st ed., Typotex, Budapest, Hungary, 2007. (in Hungarian)
- [11] Marjainé Szerényi, Zs., Csutora, M., Harangozó, G., Krajnyik, Zs., Kontár, R., Nagypál, N. "A természetvédelemben alkalmazható közgazdasági értékelési módszerek" (Economical evaluation methods applicable in environmental protection), Környezetvédelmi és Vízügyi Minisztérium Természetvédelmi Hivatala, 2005.
- [12] European Committee for Standardization "EN 590 European Standard Automotive fuels - Diesel - Requirements and test methods", CEN, Brussels, 2014.
- [13] European Committee for Standardization "EN 14214 Liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods", CEN, Brussels, 2014.
- [14] Thesz, J., Kondor, L. "EU's EN 590 welcomes new fuel blends - Out with the old", *Biofuels International*, 8(6), pp. 4–5, 2014.
- [15] Thesz, J., Kondor, L. "Triglycerides of modified structure", *Oils & Fats International - Biofuels Issue*, p. 16, 2014.
- [16] United Nations Economic and Social Council Economic Commission for Europe Inland Transport Committee Working Party on the Construction of Vehicles "E/ECE/TRANS/505. Revision 2. Uniform Provisions Concerning the Approval of Compression-ignition (C.I.) Engines and Vehicles Equipped with C.I. Engines with Regard to the Emissions of Pollutants by the Engine.-United Nations Economic and Social Council Economic Commission for Europe Inland Transport Committee Working Party on the Construction of Vehicles", 1993.
- [17] RICARDO-AEA "Update of the Handbook on External Costs of Transport", Report for the European Commission: DG MOVE, Brussels, Belgium, Rep. Ricardo-AEA/R/ ED57769, 2014.
- [18] European Union "Directive 2009/33/EC of the European parliament and of the council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles", Official Journal of the European Union, 15(5), pp. L. 120/5 – L. 120/12, 2009.
- [19] Gerbec, M., Samuel, R. O., Kontić, D. "Cost benefit analysis of three different urban bus drive systems using real driving data", *Transportation Research part D: Transport and Environment*, 41, pp. 433–444, 2015. <https://doi.org/10.1016/j.trd.2015.10.015>
- [20] Bickel, P., Friedrich, R., Burgess, A., Fagiani, P., Hunt, A., Jong, G. D., Lieb, C., Laird, J., Lindberg, G., Mackie, P., Navrud, S., Odgaard, T., Ricci, A., Shires, J., Tavasszy, L. "HEATCO—Developing harmonised European approaches for transport costing and project assessment", IER, Germany, 2006. [online] Available at: <http://heatco.ier.uni-stuttgart.de/> [Accessed: 25 April 2018]
- [21] Core Writing Team, Pachauri, R. K., Meyer, L. (eds.) "IPCC, 2014: Climate Change 2014: Synthesis Report", Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 2015.
- [22] Szabados, Gy., Bereczky, Á. "Experimental investigation of physicochemical properties of diesel, biodiesel and TBK-biodiesel fuels and combustion and emission analysis in CI internal combustion engine", *Renewable Energy*, 121, pp. 568–578, 2018. <https://doi.org/10.1016/j.renene.2018.01.048>