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Effects of Oxymethylene Ether in a Commercial Diesel Engine

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Abstract

Oxymethylen Ether (OME) is a promising alternative fuel for diesel engines. It can be produced sustainably, and its combustion is clean and efficient. This study investigates the effects of different $OME_{3\text{-}5}$ mixtures on emissions and combustion. The measurements were done on a four-cylinder common rail commercial diesel engine equipped with an exhaust gas recirculation system (EGR). Five different blends of $OME_{3\text{-}5}$ and B7 diesel were applied with 0, 7, 15, 25 and 45 vol% $OME_{3\text{-}5}$ content at four loads. The NO_x–PM trade-off was investigated at 11 EGR rates for each mixture at each load. Increasing $OME_{3\text{-}5}$ mixing ratio reduced the PM emission, improved the NO_x–PM trade-off, and increased the brake thermal efficiency. The maximum achieved PM emission reduction was 86.8% for high loads. However, NO_x emission increased, and also low heat capacity and viscosity can be a problem for real applications.

Keywords

Advanced fuels, Oxymethylen Ether, NO_x–PM trade-off, Sustainable mobility

1. Introduction

Global mobility has faced serious challenges in the last decades. The transportation sector has one of the largest shares in the worldwide greenhouse gas emissions, thus strict regulations are introduced all over the world (Török et al., 2005). The requirements of new legislation usually cannot be met with the use of conventional drives. Advanced internal combustion engine technologies and electrified drivetrains are expensive; therefore, the price of the new cars increase. This also drives the value of the used cars up. In most countries, the provoked high prices lead to the strong aging of the vehicle fleet, and thus newly developed technologies cannot spread widely. Advanced fuels offer a promising solution for these issues (Alahmer et al., 2022). If fuels can be produced that may result in carbon-neutral mobility and ensure low pollutant emission in existing engines, then the use of the old technologies become more eco-friendly (Zöldy et al., 2022). Thereby alternative fuels provide a great medium-term solution for this problem until the new sustainable transportation structure forms in the following few decades. There is already some progress in the market. For example in Sweden, hydrogenated vegetable oil (HVO) can be purchased and used in modified trucks (Soam et al., 2019).

Diesel engines have higher efficiency compared to gasoline engines; therefore, if higher soot and NO_x emission can be diminished, it can still be a favorable fuel for commercial vehicles. There are many advanced fuels and additives described in the literature on diesel engines, such as the previously mentioned HVO. Recently, polyoxymethylene dimethyl ether, which is also called oxymethylene ether (OME) is one of the most recognized substances for compression ignition engines. It is an oligomeric compound containing oxygen, which has the molecule structure of $CH_3\text{-O-}(CH_2\text{-O})_n\text{-}CH_3$, where n is the chain length, which highly affects the physico-chemical properties of the material. The compound is usually called dimethoxy methane (DMM) when the degree of polymerization is one (n = 1), but according to the common nomenclature, it is mostly labeled as OME_1 (Härtl et al., 2015). As the properties of this substance in Table 1 prove, it has a lower cetane number (CN) than 51, so it does not meet the requirements of EN590. The viscosity and the density of OME is also out of the bounds of this standard, thus this substance can only be used with additives, or as a blending component for fuels suitable for existing engines. The CN increases greatly with chain length, so excellent ignitability is provided at higher degrees of

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polymerization. Still, viscosity remains under the lower limit, and the already high density increases further. The lower heating value (LHV) is nearly half of the B7 diesel fuel's LHV because of the high oxygen content. The oxygen content rises with chain length, which results in the diminution of the LHV (Pélerin et al., 2020).

Table 1. Fuel properties at different degree of polymerization (Pélerin et al., 2020; Liu et al., 2022; Omari et al., 2019; Norhafana et al., 2020)

Property	EN 590	B7 diesel	OME_1	OME_2	OME_3	OME_4	OME_5	OME_6
Lower heating value (LHV) [MJ/kg]	-	42.8	23.3	21	19.6	19	18.5	17.7
Cetane number (CN) [-]	>51	57.5	28	68	72	84	93	104
Density at 15 °C [kg/m^3]	820-845	832.6	860	980	1030	1070	1110	1140
Kinematic viscosity at 40 °C [mm^2/s]	2-4.5	3.1	0.37	0.559	0.866	1.33	1.96	n.i
Boiling point [°C]	-	180-390	42	105	156	202	242	273
Flashpoint [°C]	>55	77	-32	12	54	88	115	169
Oxygen content [wt%]	-	0.8	42.1	45.2	47	48.1	48.9	49.5

To explore the possible practical uses of OME in existing engines, some important aspects need to be considered. The size of the fuel tanks should be increased due to the small LHV mentioned above. The different density requires the recalibration of the engine. The low viscosity results in poor lubrication properties, thus unmodified common rail systems may be damaged. The lubricity of OME_{3-6} is acceptable, but OME_1 is really weak, so additives must be used to improve it. Cavitation might be another problem, because this substance has high saturation pressure. The OME is strongly polar due to its oxygen content; therefore, non-polar elastomers should be used in the fuel system. This means that the conventional fluorocarbon rubber sealings are not suitable for the application of OME, especially in the case of $OME_{1,}$ as it highly dissolves the sealing material. An alternative sealing material could be ethylene propylene diene rubber (Pélerin et al., 2020).

In addition to the appropriate properties for engine operation, safety is another important aspect. OME is non-toxic, and OME_{3-5} has higher flashpoint than diesel fuel, so the usage is safe for the costumers. However, OME_1 has a flashpoint under -20 °C, which can lead to flaming hazards. The high vapor pressure of OME further increases this danger, but vapor escape can be impeded by sealed fuel tanks. This compound is non-biodegradable, and it is harmful for the ecosystem, thus the accidental release of the fuel into the environment must be avoided (Liu et al., 2022).

OME is usually produced from dimethyl ether (DME) or methanol. There are a lot of studies that investigate the application of these compounds as fuels, but they are toxic, so it is better to produce OME from them. Both DME and methanol can be produced from fossil resources, biomass or from CO_2 and H_2. The well-to-wheel (WTW) greenhouse gas emission of OME mainly depends on the used resources. The WTW CO_2 equivalent emission of diesel fuel is 127 g/MJ. If OME is produced from coal-based methanol, this value is 228 g/MJ. If it is produced from natural gas-based methanol, then it is 136 g/MJ. This means that fossil OME production is worse than the use of conventional diesel. However, the WTW emission becomes significantly lower if the liquid is produced from renewable resources, because in this case WTW emission is equal to the well-to-tank emission, as the CO_2 released during combustion is part of a closed CO_2 cycle. If OME is made from residual forest-based methanol, then the WTW CO_2 equivalent emission is only 18 g/MJ (Wu et al., 2019).

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OME has mostly positive effects on combustion and emission, depending on the degree of polymerization as well. The low CN of OME_1 is unfavorable, and it can lead to high pressure gradients during the premixed phase. The high volatility can also enhance the premixed flame and can reduce soot emission. However, the high CN of OME compounds with longer chain length results in good ignitability, thus the ignition delay (ID) is reduced. Therefore, the proportion of the premixed phase decreases, which reduces the combustion noise (Omari et al., 2019). The CN is so high, that even pre-injections can be eliminated. Another effect on the combustion is the decrease of the duration of combustion (DoC). This is the result of the oxygen content, because during the diffusion flame phase, less oxygen should diffuse from the air to the reaction zone. This shorter DoC can improve the indicated efficiency as well.

This oxygenate reduces soot formation so much, that it can be nearly zero when neat OME is applied. There are several reasons for that, but the main cause is the high oxygen content of the fuel. OH roots can easily be formed from the oxygen atoms of the molecule, and these help the oxidation of the soot. In addition to the O/C ratio, the H/C ratio also affects PM emission, since the higher H_2 content of the longer chains reduces the degree of soot formation. OME is a C1 fuel, thus the absence of C-C bonds also contributes to low PM emission. The molecule structure has another important positive effect on PM emission reduction: CO can be easily formed from the C-O bonds of the molecule, and this suppresses the formation of acetylene, which is a key compound for soot generation. Finally, good volatility can further reduce the PM emission, since it enhances air-fuel mixing. These effects abolish the NO_x–PM trade-off for pure OME, but great improvements can be achieved even with small blends (Härtl et al., 2015).

Other emissions can be problematic. The oxygen content of the fuel rises the NO_x emission because of the Zeldovich mechanism, but it also has a contrary effect. The shorter DoC arising from the oxygen content results in a shorter residence time at high temperature, thus this may reduce the NO_x formation. Since the NO_x–PM trade-off is minimized, extreme high EGR rates can be used to further reduce the NO_x emission without the risk of high PM emission (Parravicini et al., 2021).

As mentioned above, the C-O bonds enhance the generation of CO, thus this emission may be high, but the oxygen content can help its oxidation. Methane emission can also be high, since there are methyl groups in the molecule. This compound has 25 times higher global warming potential than CO_2, which must be reduced. The OME chain contains formaldehyde structures, thus carcinogenic formaldehyde emission can also emerge. These emissions are only high when a high EGR rate is applied. In addition to these, the HC emission can also increase: the small LHV leads to a longer duration of injection (DoI), which means that the start of injection (SoI) must be placed earlier for the same center of heat release (CoHR). The early SoI leads to enlarged wall wetting. To avoid the increased HC emission and oil dilution from this effect, the energy flow can be increased with higher rail pressure and with higher injector nozzle holes (Barro et al., 2018).

The exhaust aftertreatment system can be simplified if pure OME is used. PM emission is so low in this case that the application of diesel particulate filter (DPF) is not necessary. The eliminated NO_x–PM trade-off allows EGR rates to be so high that even stochiometric conditions can be achieved. Therefore, only a three way catalyst is enough in this extreme case. However, the increased methane and formaldehyde emission makes this solution problematic. Some improvement can also be achieved if OME is used only as a blending component. In this case, the DPF requires less frequent regeneration, thus the fuel consumption can be reduced (Wu et al., 2019).

In this research the effects of OME are investigated in a four cylinder commercial diesel engine. OME_{3-5} is used, because it has better effects on the combustion than OME_1, and its properties are more suitable for an unmodified common rail system. No additives were used, thus only lower mixing ratios (7, 15, 25 and 45 vol%) were applied to avoid possible engine damage. Combustion characteristics, NO_x emission and PM emission were examined without EGR. Several EGR rates were applied with a HP-EGR system to study the NO_x–PM trade-off of the blends. The investigation was carried out at 1400 rpm with 0, 100, 250 and 400 Nm loads. It was found that the OME mostly has positive effects on the engine operation.

2. Data and methods

2.1. The measurement system

The experiment was carried out in a Cummins ISBe 170 30 turbocharged, medium-duty commercial diesel engine. This Euro 3 level engine is equipped with a common-rail injection system, an intercooler, and a high-pressure EGR system. The engine was installed on an engine dynamometer in which all the necessary operating parameters were measurable. Temperature and pressure can be measured at several points of the gas exchange system. The main parameters of the engine are given in Table 2.

Table 2. Cummins ISBe 170 30 engine properties

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Engine displacement	Bore	Stroke	Compression ratio	Rated effective power
3922 cm^3	102 mm	120 mm	17.3	125 kW

The EGR rate is varied with a HP-EGR valve that can be controlled via CAN communication by a dSpace MicroAutoBox DS1401/1505/1506. The cylinder pressure was measured with an AVL GH13P piezoelectric sensor, which is connected to the seat of the glow-plug. To measure the crank angle position, an AVL 365C crank angle encoder was used with a resolution of 0.5 °CA. The combustion analysis was carried out with an AVL 612 Indi-Smart. The O_2 and NO_x concentration was measured with a Continental UniNOx-Sensor, while opacity was measured with an AVL 439 Opacimeter. The emissions are not treated with catalysts, nor with DPF.

2.2. The applied mixtures

The used $OME_{3\text{-}5}$ fuel was provided by the Karlsruhe Institute of Technology (Haltenort et al., 2018). Table 3 gives the chemical components of the substance.

Table 3 $OME_{3\text{-}5}$ properties

OME_1	OME_2	OME_3	OME_4	OME_5	OME_6	Other compounds
0.16 wt%	0.34 wt%	45.55 wt%	27.26 wt%	12.73 wt%	5.61 wt%	8.35 wt%

The LHV of the substance can be estimated from the LHV of its OME_n compounds the he other compounds are neglected:

$$(1) \qquad LHV_{OME_{3-5}} = \frac{\sum_{n=1}^{6} \gamma_{wt,\,OME_n} \cdot LHV_{OME_n}}{\sum_{n=1}^{6} \gamma_{wt,\,OME_n}},$$

where

$LHV_{OME_{3-5}}$ is the lower heating value of the applied $OME_{3\text{-}5}$ [J/kg],

LHV_{OME_n} is the lower heating value of each component [J/kg],

$\gamma_{wt,\,OME_n}$ is the mass fraction of each OME_n component in the liquid [-].

Thereby, the LHV of the $OME_{3\text{-}5}$ is 19,164 MJ/kg. Density can be estimated similarly: the LHV must be replaced with the density in Equation (1). The calculated density of the $OME_{3\text{-}5}$ is 1059.26 kg/m3.

In the course of the measurements, 5 different blends were investigated: 0, 7, 15, 25, and 45 vol%. These can be converted into mass percentages by using the density of B7 diesel and $OME_{3\text{-}5}$. Then, the LHV of the blends can be calculated with Equation (2).

$$(2) \qquad LHV_i = \gamma_{wt,i} \cdot LHV_{OME_{3-5}} + (1 - \gamma_{wt,i}) \cdot LHV_{B7\ diesel},$$

where

LHV_i is the lower heating value of the i^{th} blend [J/kg],

$LHV_{B7\ diesel}$ is the lower heating value of B7 diesel [J/kg],

$\gamma_{wt,i}$ is the mass fraction of $OME_{3\text{-}5}$ in the i^{th} blend [-].

The density of the blends can be calculated similarly as Equation (2). The kinematic viscosity of the B7-$OME_{3\text{-}5}$ blends was measured with a Cannon-Fenske viscometer (Csemány et al., 2022). The pure $OME_{3\text{-}5}$ viscosity was also measured: 1.187 mm^2/sec. The properties of the blends can be seen in Table 4. The kinematic viscosity of the 7 vol% blend meets the requirements of EN590, but the 15 vol% blend is also near the required values. Further investigations should use additives to improve this property.

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Table 4. Properties of the used blends

OME_{3-5} [vol%]	OME_{3-5} [wt%]	Density at 15 °C [kg/m^3]	Lower heating value [MJ/kg]	Kinematic viscosity at 40 °C [mm^2/s]
0	0	832.6	42.8	3.1
7	8.74	852.41	40.73	2.321
15	18.33	874.16	38.47	1.788
25	29.78	900.09	35.76	1.557
45	51	948.20	30.75	1.401

2.3. The measurement methods

The previously described 5 different B7-OME_{3-5} mixtures were studied on the test engine at 4 different loads with 11 different EGR rates, which resulted in 220 measurement points. The engine was warmed up with B7 diesel to 80 °C oil temperature before the experiment. The first measurement was done with pure B7, and then blends were applied with increasing OME_{3-5} content. The fuel system was emptied after the measurement of each mixture and 300 g new mixture was used to flush it before the new measurements. The engine was conditioned to the new loads for one minute before the measurements of each load, and after that the 11 EGR rates were set. Each measurement with the new EGR rate lasted for 20 seconds. The first 10 seconds, and the last second were considered as a transient, thus the results of the measurement points are the average of the remaining 9 seconds of data. The EGR rate was set with the HP-EGR valve, and its position was varied between 0 and 100% with a 10% resolution. The investigation was carried out at no load (0 Nm), low load (100 Nm), medium load (250 Nm) and high load (400 Nm) at the engine speed of 1400 rpm.

The temperature of the combustion chamber can be estimated from the ideal gas law assuming that the medium in the chamber is air (Eriksson et al., 2017). The latent heat release rate is calculated from Equation (3) by neglecting heat loss. The released heat is the integral of the result of this equation.

$$\frac{dQ_b}{d_\phi} = \frac{\kappa p}{\kappa - 1} \cdot \frac{dV}{d_\phi} + \frac{V}{\kappa - 1} \cdot \frac{dp}{d\phi} - \frac{dQ_w}{d_\phi}, \quad (3)$$

where

Q_b is released heat [J],

κ is the adiabatic gas constant of air [-],

p is the pressure in the combustion chamber [Pa],

V is the volume of the combustion chamber [m^3],

Q_w is heat loss [J],

ϕ is crank angle [°CA].

NO_x concentration is converted into NO_x emission in g/kWh with the exhaust mass flow rate and the engine power. The exhaust mass flow rate can be calculated form engine geometry, dose and volumetric efficiency. PM emission is calculated from opacity (Lakshminarayanan et al., 2016). Firstly, filtered smoke number (FSN) has to be calculated from Equation (4).

$$N = 0.12 \cdot FSN^3 + 0.62 \cdot FSN^2 + 3.96 \cdot FSN, \quad (4)$$

where

N is opacity [%],

FSN is filtered smoke number [-].

After this, smoke concentration can be derived from Equation (5).

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$$C_{smoke} = \frac{4.95}{0.405} \cdot FSN \cdot e^{0.38 \cdot FSN}, \quad (5)$$

where

C_{smoke} is smoke concentration [mg/m^3].

The volumetric exhaust flow rate can be calculated form the exhaust mass flow rate and the pressure and temperature at the sampling point. As a simplification, the gas constant of air is used for the calculation. Then PM emission can be calculated form Equation (6).

$$PM = \frac{C_{smoke} \cdot \dot{V}_{exh}}{P_{mot}}, \quad (6)$$

where

PM is particulate matter emission [g/kWh],

$\dot{V}_{exh}$ is volumetric exhaust flow rate [m^3/h],

P_{mot} is engine power [W].

3. Results and Discussion

3.1. Emissions

In this investigation, the emissions are specified to brake power, so the no load curves will not be presented, since they would be infinite. Figure 1 demonstrates the effects of the rising OME_{3-5} content on PM emission. The baseline measurement shows that the 400 Nm load generates drastically higher PM emission than other loads. Soot generation is reduced drastically by increasing the oxygenate portion. The extent of reduction is lower for the 100 Nm case, because its emission is already low, but for the 250 Nm and 400 Nm loads, the effect is significant. These latter two cases have a similar extent of PM emission diminution and only 15 vol% OME_{3-5} is enough for about 70% decrease. The higher mixing ratios only create a little more reduction. The 45 vol% blend reduced PM emission by 86.8%. This result was expected due to the considerable soot generation minimizing effect of the substance described in the introduction. There are similar results in the literature, Omari et al. (2017) could achieve 90% PM emission reduction with 35 vol% OME_1 content.

Figure 2 presents NO_x emission as a function of the blending ratio. As expected, the NO_x emission increases with the rising oxygenate content due to the Zeldovich mechanism. However, the effect is moderate, the growth is only about 30% in the worst case. The increasing NO_x emission can also be be reduced with EGR.

To study the possibilities of emission optimization, 11 EGR rates were applied to investigate the NO_x–PM trade-off. The results revealed that the trade-off change is similar for all loads, thus only the medium load is presented in *Figure 3*. The trade-off decreases with the increasing amount of OME_{3-5}. The test engine is Euro 3 level. If we consider the 5 g/kWh NO_x and 0.1 g/kWh PM emission limit, it is clear that aftertreatment is still needed, but the blends make it possible to have smaller catalysts or less DPF regeneration cycles.

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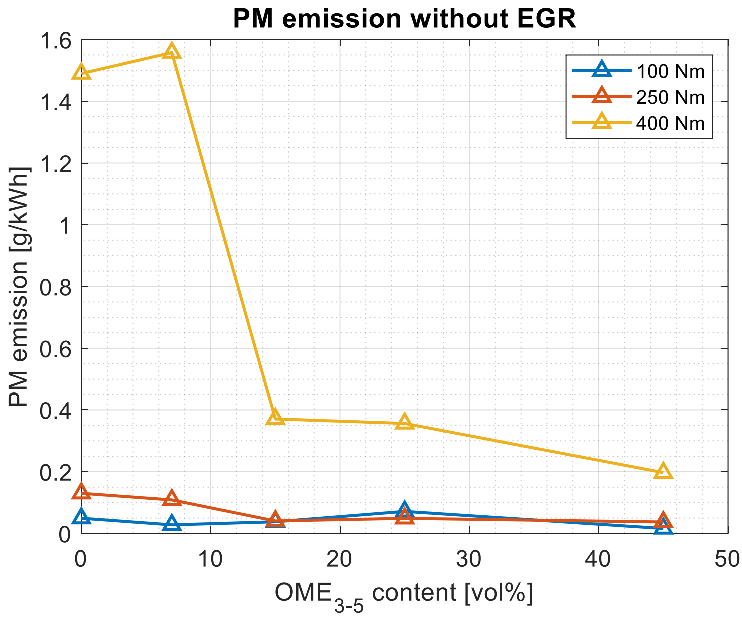

Figure 1. PM emission without EGR for the different mixtures at different loads

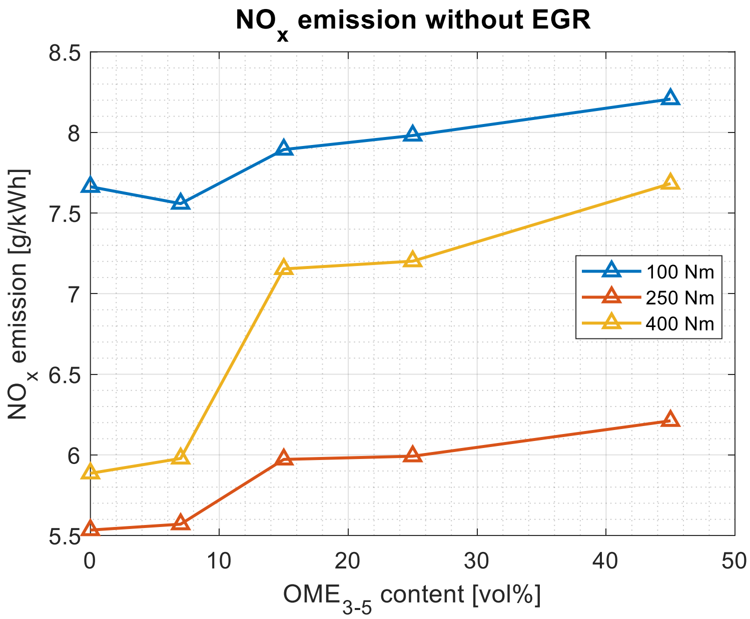

Figure 2. NO_x emission without EGR for the different mixtures at different loads

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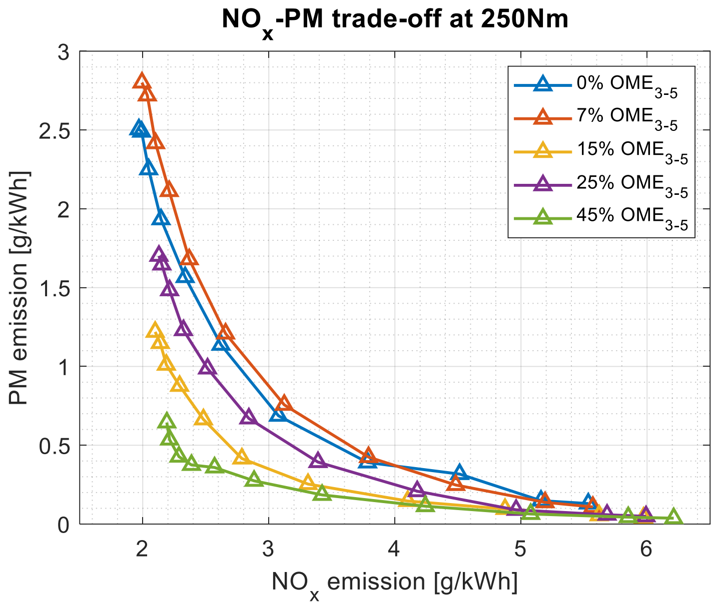

Figure 3. NO_x–PM trade-off at 250 Nm with different EGR rates for each blend

3.2. Engine performance

The engine operated at fix duty points, thus the change in the performance can be illustrated only with the fuel consumption and the efficiency from our measurement data. Figure 4 presents the brake specific fuel consumption (BSFC) as a function of the $OME_{3\text{-}5}$ content. The LHV of the blends decreases with the increasing amount of oxygen, thus more fuel is required for the same power. The rising BSFC is an expected result. However, this is not a tremendous issue, because if $OME_{3\text{-}5}$ is produced from renewable resources, than the WTW CO_2 equivalent emission is still much lower than for B7 diesel. In terms of fuel costs, this is only a problem if the production of the substance cannot be made cost-effective. The only problem is the need for a larger fuel tank.

Figure 5 shows the change in brake thermal efficiency (BTE) at different loads. Higher OME blends had major effects, the BTE increased by about 8 percentage point when 45 vol% $OME_{3\text{-}5}$ was applied. This rise is an expected result, since most authors experience it, but it is usually around only 2-3 percentage points (Liu et al., 2017b). This significant difference may be due to the estimated LHV of the used substance. LHV measurement is necessary for proper calculations.

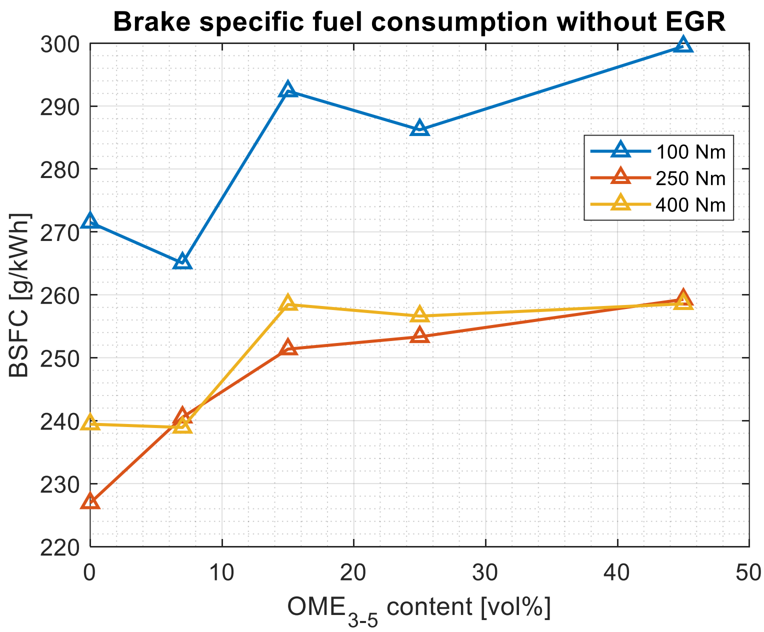

Figure 4. Brake specific fuel consumption without EGR for the different mixtures at different loads

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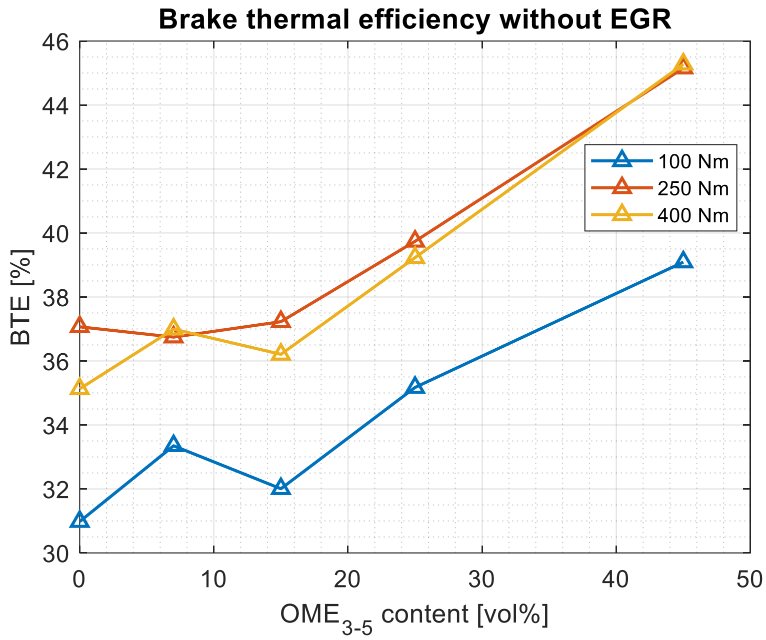

Figure 5. Brake thermal efficiency without EGR for the different mixtures at different loads

3.3. Mean combustion properties

In this section, the most important parameters of the combustion are presented. The results are the average of the measured duty cycles of each measurement case. The effects of OME_{3-5} on the peak combustion temperature is demonstrated in *Figure 6*. The fuel's rising oxygen content helps the oxidation, thus a slight temperature increase can be observed. This also has an effect on the duration of combustion (DoC), which is presented in Figure 7. The diffusion phase of diesel combustion is a slow process, because the oxygen from the air has to diffuse to the reaction zone. However, if the fuel contains oxygen, it accelerates the burning process due to the lower need for external oxygen. The measured results are in line with this expectation. At 0 and 100 Nm the combustion is already short, and the proportion of the diffusion flame is not that large, thus the DoC remains nearly the same with increasing blending ratios. In contrast, the 250 and 400 Nm curves show a non-negligible DoC diminution as the OME_{3-5} mixing ratio increases. The maximum decrease is around 5 °CA with the 45 vol% blend. In these cases, the diffusion phase is long enough to let the effects of the oxygen content prevail. The observed decrease is similar to the experiences of Liu et al. (2017a), who detected 10 °CA change in a single cylinder light duty diesel engine by adding 30 vol% OME_{3-4} to the diesel fuel.

The peak combustion pressure gradient is another important parameter (Figure 8). The values remain below 6 bar/°CA which is a common upper limit for commercial diesel engines in order to avoid damages (Yin et al., 2021). The OME_{3-5} has two main properties that affect the pressure gradient in the combustion chamber. The first is high CN, which shortens the ignition delay, thus reducing the proportion of the released heat during the premixed phase, because the fuel has less time to mix with the air. The second is the high volatility, which accelerates the mixing with air; therefore, it increases the proportion of the premixed phase, thus higher pressure gradients occur. These two contrary effects make differences in the combustion at different loads. At 0 Nm, the dose is so small that a notable part of the heat releases during the premixed phase, regardless of the little changes in the ignition delay. That is why high volatility has a more significant effect than the high CN, so the pressure gradient rises. At 100 Nm, the dose is larger, thus the heat released during the premixed phase can be effectively reduced by higher CNs. At 250 Nm, the effect becomes more significant. During the calibration of the ECU, the designers paid attention to keep the pressure gradient low as the load increases. This was achieved by retarding the SoI, which reduces ignition delay. Consequently, at 400 Nm the premixed phase is really small, and the peak combustion pressure gradient occurs at the diffusion phase. The oxygen content accelerates the diffusion flame, thus the peak pressure gradient rises slightly. This trend can be seen on the 400 Nm curve.

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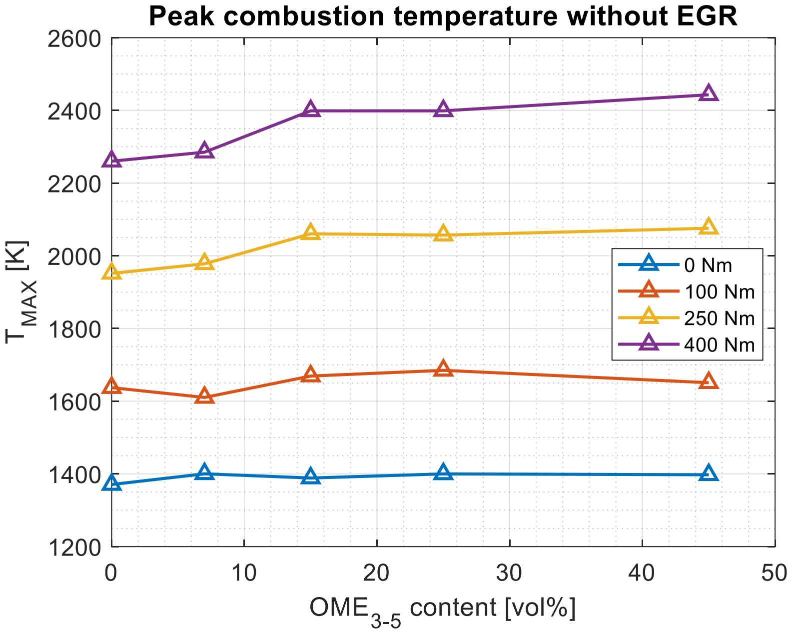

Figure 6. Peak combustion temperature without EGR for the different mixtures at different loads

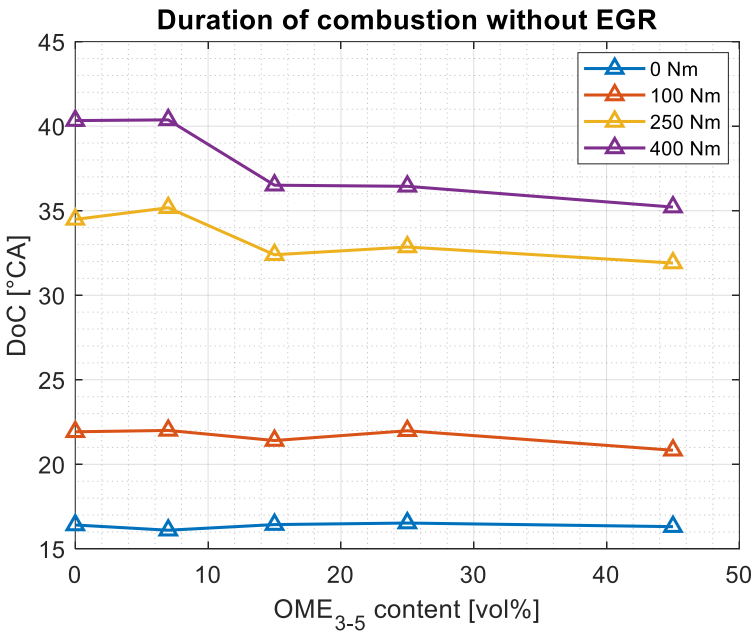

Figure 7. Duration of combustion without EGR for the different mixtures at different loads

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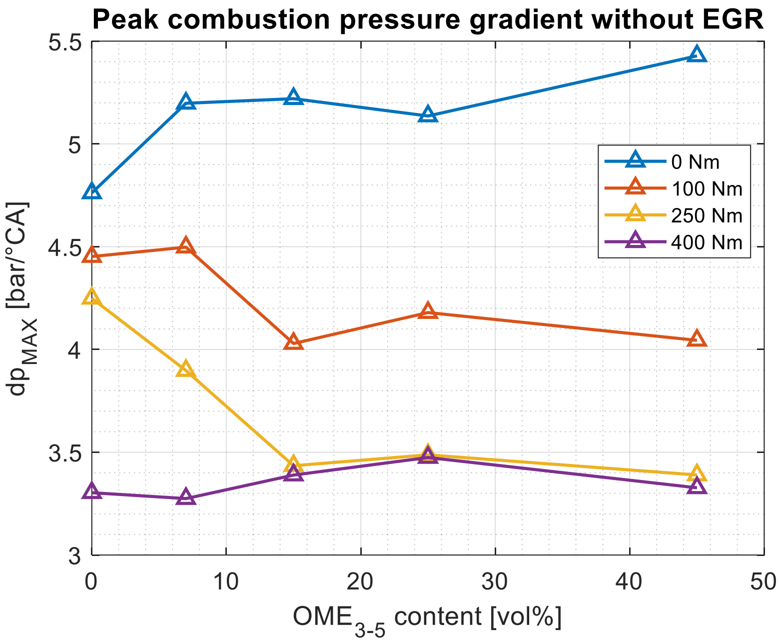

Figure 8. Peak combustion pressure gradient without EGR for the different mixtures at different loads

3.4. Heat release rates

In this section, the heat release rates (HRR) at the different loads are demonstrated, but to make them more clear, only the higher blends are plotted to the diagrams. Figure 9 shows the heat release rates of the 25 and 45 vol% blends compared to the reference pure B7 measurement at no load. It is discernable that at this small dose, the premixed phase is significant compared to the diffusion phase. The increasing OME_{3-5} content has no significant effect on it, perhaps it is slightly increased. The diffusion phase also does not indicate significant changes, but due to the rising oxygen content, the burn-out phase clearly starts earlier for the 45% blend.

The 100 Nm results presented in Figure 10 show much more influence. The combustion of higher mixing ratios starts earlier because of the shorter ignition delay, as a result of the increasing CN. This clearly reduces the proportion of the premixed phase. The diffusion phase shows a different behavior than expected. The oxygen content accelerates the combustion there, thus the peak HRRs are larger in this phase for the higher OME_{3-5} content. The 250 Nm data is similar to the 100 Nm data. The reduction of the premixed phase and the acceleration of the diffusion phase are also discernable, but the latter is not that significant. However, the 250 Nm load has longer DoC than the lower loads, thus a small acceleration can still make a notable reduction of DoC.

In the case of the 400 Nm load, only a little local maximum marks the premixed phase. However, this peak decreases because of the increasing CN. The diffusion phases are similar, but the burn-out phase starts earlier for the larger OME_{3-5} content, just like at lower loads.

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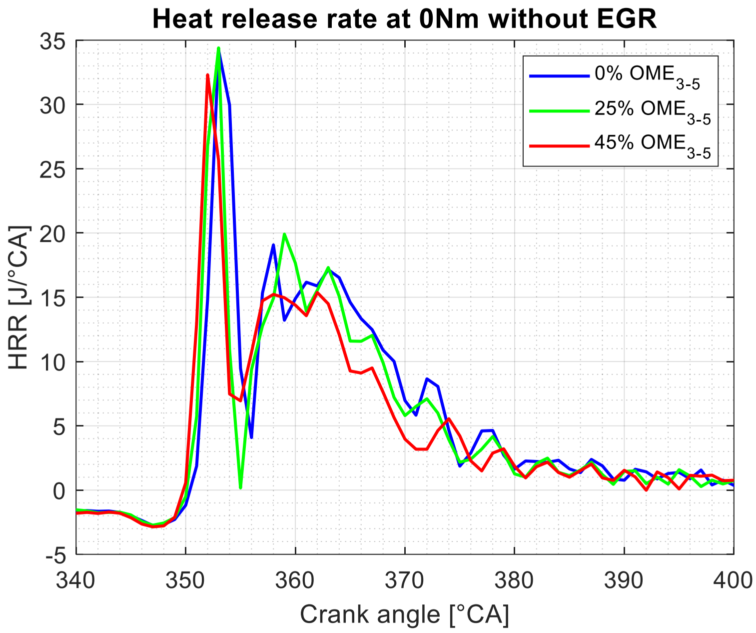

Figure 9. Heat release rate at 0 Nm load without EGR rate for different blends

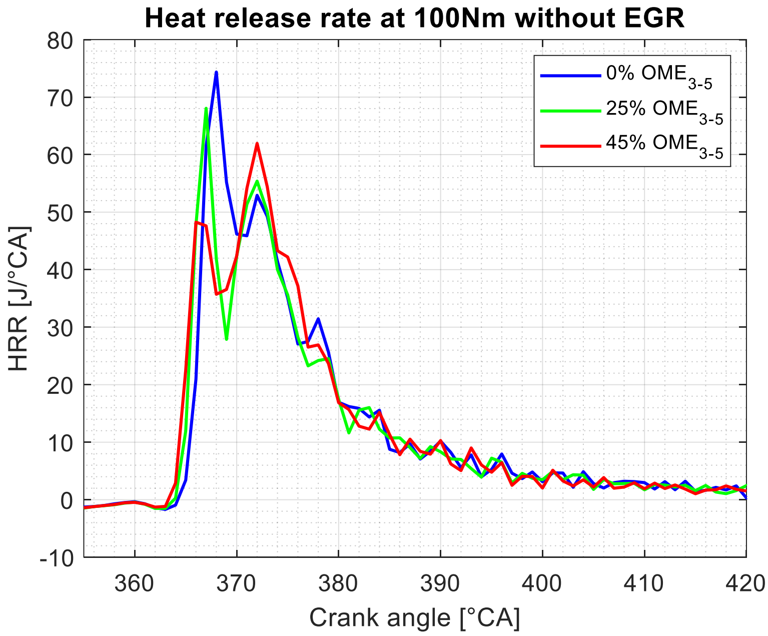

Figure 10. Heat release rate at 100 Nm load without EGR rate for different blends

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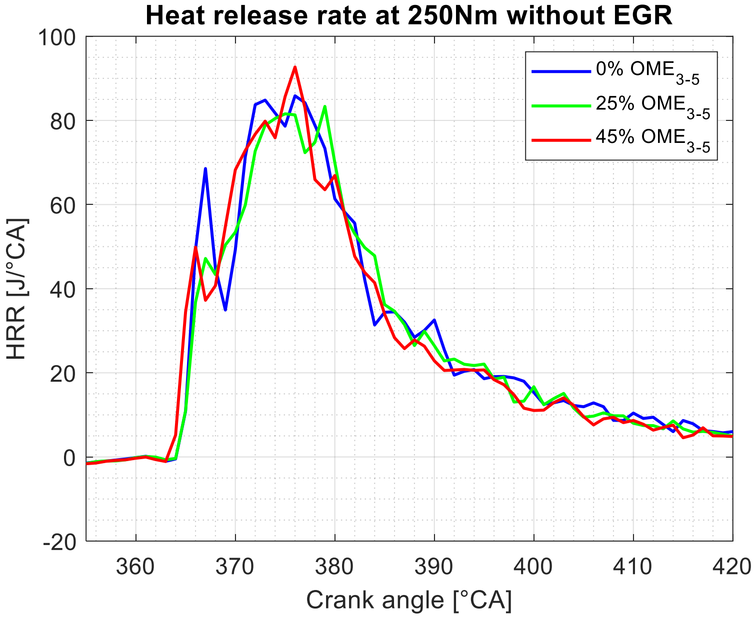

Figure 11. Heat release rate at 250 Nm load without EGR rate for different blends

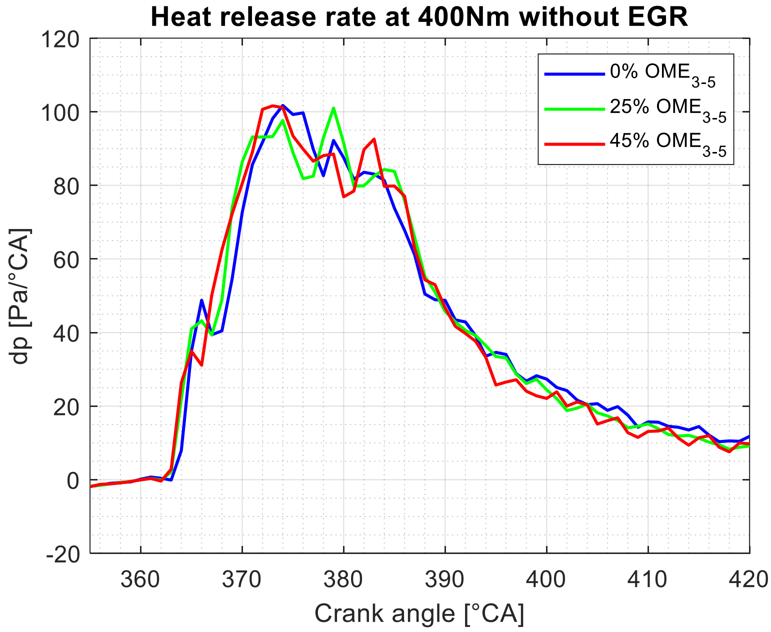

Figure 12. Heat release rate at 400 Nm load without EGR rate for different blends

4. Conclusion

OME is a promising advanced fuel which can be produced from renewable resources, thus it diminishes the WTW CO_2 emission. In addition, this oxygenate is able to reduce soot emission greatly due to its high oxygen content, the lack of C-C bonds, and the C-O bonds present in the molecule structure. This enables the use of higher EGR rates, thus the NO_x emission can also be reduced. As a consequence, this is an excellent alternative propellant for diesel engines. The combustion properties can also be improved due to the high CN of longer chain OMEs. However, there are still challenges to be solved if this fuel is to be applied at a large scale. Low LHV is a problem, because larger fuel tanks are needed. The low viscosity and the possible cavitation might damage the fuel system. Moreover, the commonly used sealing materials are incompatible with this polar fuel. Furthermore, methane and formaldehyde emissions may emerge when high EGR rates are used.

This work demonstrated the promising effects of OME_{3-5} on the combustion and emission of a medium-duty commercial diesel engine. The reason behind using OME with higher degree of polymerization was that it has superior CN, and closer

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viscosity to B7 diesel than OME_1. During the investigations, we experienced the same benefits and demerits as described in the literature. The engine-out emissions could be effectively reduced. PM emission decreased by around 70% with only 15 vol% $OME_{3\text{-}5}$ blend for medium and high loads. The maximum reduction was 86.8% with the 45 vol% mixture for the 400 Nm load. This great decrease also diminishes the NO_x–PM trade-off, so the costs of the exhaust aftertreatment can be decreased. In addition to better emissions, the BTE also increased notably, and the BSFC also increased due to the low LHV. The combustion also improved, because the high CN of the substance reduced the proportion of the premixed phase, while the oxygen content of the fuel reduced the DoC. The peak combustion temperature rose, which can also be another factor for the enhanced NO_x generation, but this can be reduced with higher EGR rates as described previously. The peak pressure gradient had different behavior at different loads, but it did not exceed the defined knocking limit. The heat release rates also substantiated that combustion started earlier due to the shorter ignition delay resulting from the higher CN. This reduced the rate of heat release during the premixed phase. The high oxygen content slightly accelerated the combustion, thus the burn-out phase started earlier.

In conclusion, the OME is a promising fuel for compression ignition engines. However, its properties should be modified with additives in order to use it in existing vehicles. Still, the incompatibility with the commonly used sealing materials remains an issue. A possible solution could be the modification of future engines to make them able to operate with high OME blends, similarly to the Swedish example with HVO.

Acknowledgements

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Abbreviations

BSFC, Brake Specific Fuel Consumption;
BTE, Brake Thermal Efficiency;
CN, Cetane Number;
CO, Carbon Monoxide;
CO_2, Carbon Dioxide;
CoHR, Center of Heat Release;
DME, Dimethyl Ether;
DMM, Dimethoxy Methane;
DoC, Duration of Combustion;
DPF, Diesel Particulate Filter;
ECU, Engine Control Unit;
EGR, Exhaust Gas Recirculation;
FSN, Filtered Smoke Number;
H_2, Hydrogen;
HC, Hydrocarbon;
HP-EGR, High Pressure Exhaust Gas Recirculation;
HRR, Heat Release Rate;
HVO, Hydrogenated Vegetable Oil;
ID, Ignition Delay;
LHV, Lower Heating Value;
NO_x, Nitrogen Oxides;
OME, Oxymethylen Ether;
PM, Particulate Matter;
SoI, Start of Injection;
WTW, well-to-wheel;

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Carbon emission trading as a climate change mitigation tool

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Abstract
Climate change has become the most urgent social and ecological problem in recent years. Now it has become a self-driving process that causes more and more problems, because it is constantly changing the climate of the different parts of the Earth. Consequently, the natural habitat of local species is diminishing, and this process rapidly decreases biodiversity. This is just one of the reasons why leaders worldwide have decided to stop this process and reverse it back to the initial stages. One of the means of achieving this is to regulate the number of harmful gases the countries can emit. The Emission Trading System was established in the EU to build a legal and supervised structure around this process.

Keywords
Carbon emission, Trading, Mitigation, Sustainability

1. Simple models– the one-point economy

Since the 1990s, most developed countries have realized that their industrial manufacturing and non-service-based production contribute to climate change. This is one side of the coin, because on the other side of production is consumption, a process in which everyone on Earth engages (Rimkus et al., 2018). The Hollywood movies made it seem cool to have loud, fast, big cars burning fossil fuels that are immensely worsening the climate. New icons like Elon Musk and other technology unicorns are shaping the industry like never before. Transportation is changing to become greener. The food industry is trying to promote goods that require less carbon emission during growth and production. What led to this point? The most important step was taken in the 1990's, to be more exact in 1997: the Kyoto Protocol (UNFCCC, 1997) entered into force in 2005. This agreement was signed by 192 bold, developed countries, claiming that they will do anything in their power to reduce climate change as much as possible (Zöldy, 2019). Some countries and associations have made bolder steps, such as the EU, announcing that they will reach a net-zero carbon emission by 2050. There is a country that is even bolder, Russia, which announced that they will reach the net-zero in carbon emission by 2025.

What does this mean in reality? How can a country reach net zero carbon emission if they are producing the same or more carbon dioxide than before? The answer for this is carbon emission trading. It works like magic, as the old saying goes. On the one hand, it is magic because no one is really changing anything while doing carbon emission trading, except paying money for companies that have the capability to sequestrate carbon from the air, or put it simply, clean their emission. Elon Musk offered 100 million dollars for someone who can come up with an idea how to clean the air and capture carbon faster and better than mother nature does (Clifford, 2021). So, this is why it is magic on the other hand, because these companies do clean the air.

Biological air filters have been known since the beginning of time. Plants that can engage in photosynthesis are capturing carbon from the air, and they make oxygen and water from it. This is the magic companies benefit from who engage in carbon emission trading (Szabó et al., 2018). There are many ways to use forests as air filters in emission trading, but the method that is getting more and more popular is trading emission with carbon credits. This method emerged when governments tightened the quotas regarding emissions and both countries and market actors had to accept it. They proposed a solution that is quick, efficient and develops rapidly, in a similar manner to production and the service segment of consumerism. Moreover, countries which cannot meet their quota boundaries can trade emission or by the leftover from other, carbon efficient countries such as Switzerland, Poland or Hungary. but consumers can also reduce their carbon footprint by purchasing offsets on the voluntary market. This article investigates both the voluntary and the obligatory part of carbon emission trading based on the relevant literature.

2. Methodology and background

This study relies on various sources on the concepts of climate change and carbon emissions trading. The aim of this literature review is to deepen the knowledge about the topic in question and about the most important tool that currently exists in the market to reduce carbon emissions as a means to mitigate climate change, highlighting its potential impact on the environment. Climate change is a change in the usual weather found in a place, e.g. average precipitation

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or average temperature for a month or a season. Climate change is not only local, but global: it is also a change in Earth's climate. Weather can change in just a few hours, but climate takes hundreds or even millions of years to change.

Since the beginning of the Industrial Revolution in 1760, people and their activities have emerged as significant factors in driving the climate on Earth, due to the tremendous negative impact caused by them, which is increasingly alarming as time passes by. Greenhouse gases (which are emitted during the combustion of fossil fuels for manufacturing, heating, land clearing, and transportation) continue to build up in Earth's atmosphere. These gases enhance the atmosphere's ability to hold in heat, which has resulted in accelerated melting of ice at the poles and of mountain glaciers and has altered reliable temperature and rainfall patterns in other parts of the world. The changes that we are witnessing in climate can have huge public health impacts, for example, floods and droughts can both impact our drinking water quality and our recreational water quality, which limits the time that we can interact with nature affecting our health and well-being.

The Paris Agreement (UNFCCC, 2015) is a landmark international accord that was adopted by nearly every nation in 2015 to address climate change and its negative impacts. The agreement aims to substantially reduce global greenhouse gas emissions, in an effort to limit the global temperature increase in this century to 2 ºC above preindustrial levels, while pursuing the means to limit the increase to 1.5 ºC. The agreement includes commitments from all major emitting countries to cut their climate pollution and to strengthen those commitments over time. The pact provides a pathway for developed nations to assist developing nations in their climate change mitigation and adaptation efforts, and it creates a framework for the transparent monitoring, reporting, and meeting of countries' individual and collective climate goals.

According to the United Nations Secretary-General, António Guterres (2021), 2021 was "the make it or break it" year. As the previous year was the second warmest year in history, the future gives us serious concerns. This means that after more than 5 years after the Paris Agreement, the situation regarding climate change just got even worse with record greenhouse gas concentrations, increasing land and ocean temperatures, sea level rise, melting ice and glacier retreat and extreme weather. In accordance with the data gathered by the National Centers for Environmental Information (NOAA), it is extremely worrying that 2020 was the second warmest year. The reason is that it was a La Niña year, which is a year where the sea surface temperature across the eastern equatorial part of the central Pacific Ocean is lower than normal, causing the global temperature to fall. That clearly did not happen, which illustrates how serious the current situation is.

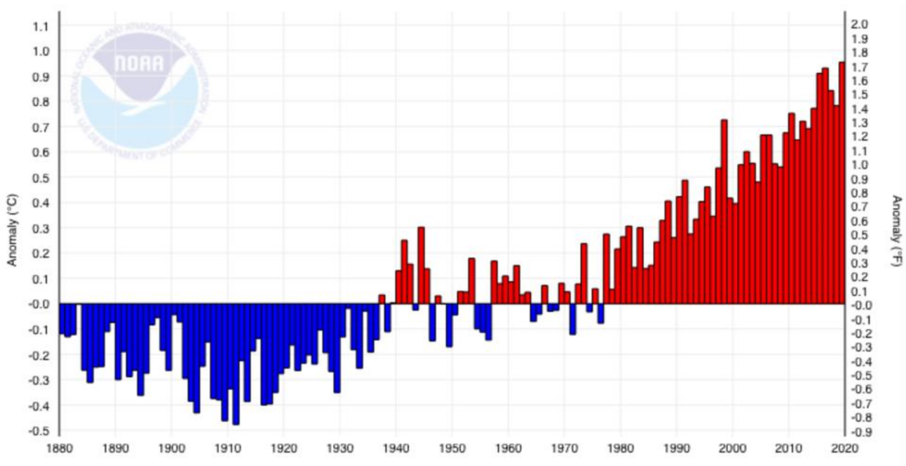

Figure 1. Global land and ocean temperature anomalies
(source: National Oceanic and Atmospheric Administration – NOAA, 2019)

Figure 1 shows the seven warmest years in the 1880–2020 record have all occurred since 2014, while the 10 warmest years have occurred since 2005. We can conclude that action must take place, otherwise, the years onward will most likely break records after records regarding global land and ocean surface temperature. With all these goals established by the Paris Agreement in mind and issues in hand, many researches have been trying to find effective ways to reduce greenhouse gases emissions.

3. –Carbon emission trading

Carbon emission trading emerged as a way for governments to try to reduce their greenhouse gas emissions, more precisely that of carbon dioxide, a crucial component in the fight against climate change. It is a market-based system that aims to provide economic incentives for countries and companies to reduce their environmental footprint. Almost all

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activities, from travel to agriculture, lead to the emission of gases such as carbon dioxide, thus contributing to the greenhouse effect responsible for climate change. Unlike voluntary offsets, where consumers can choose to pay a company to balance its carbon footprint by funding reforestation projects, as forests absorb CO_2, carbon trading is a legally binding scheme that caps total emissions and allows organizations to negotiate their allocation, hence the term "cap and trade" (Dahlan et al., 2022). The emission limits of such systems are calculated by governments and policymakers and must be compatible with their previously defined goals of limiting environmental damage. Companies that have substantially more negative impact on the environment due to their emissions, receive allowances proportionate to their historical emissions and with that, they can manage their emissions properly and effectively. For example, if a company is emitting more than their allowances offer, they will have to purchase more carbon credits in the carbon market. I exact opposite happens when they emit less than the maximum allowed, as that excess can be sold on the market.

There are many organizations that cannot sustain such reduction of their emissions for the simple reason that it would cost their businesses to produce less, resulting in an even lower profit. This is where the voluntary carbon market is useful. This proves to be a viable solution, because this method does not only help the overproducing organizations reach their net zero carbon emissions goal, but also increases social responsibility and establishes a healthy and green corporate image. Also, for the newer, small and sustainable projects, the voluntary carbon market turns out to be a huge opportunity due to its lower development/transaction costs.

Carbon credits are units of measurement that correspond to one ton of carbon dioxide equivalent (t CO_2e). They are used to calculate the reduction in greenhouse gas (GHG) emissions and their possible trade value. Based on the Global Warming Potential (GWP), all greenhouse gases are converted into t CO_2e. Therefore, the term "carbon equivalent" (or Coe) is the representation of greenhouse gases in the form of CO_2. I greater the global warming potential of a gas relative to CO_2 is, the greater the amount of CO_2 represented in CO_2e for it is. Nations that promote greenhouse gas emission reductions receive a reduction certification that will count as carbon credits. The latter, in turn, can be traded with countries that have not reduced emissions. Thus, the more a country reduces emissions in tons of CO_2 equivalent, the greater the amount of carbon credits available for trade for them is, proportionally.

The price of carbon is determined by supply and demand, with supply units capped at an acceptable level causing the cost to vary depending on whether or not companies find alternatives to pollution. By putting a price on damaging activity, the system provides a financial incentive for companies to reduce emissions while reducing the overall cost of these reductions, since the cheapest improvements are made first. In the past, there have been other "cap and trade" systems that have been successful in solving environmental problems, including one about sulfur dioxide emissions, which resulted in a reduction of acid rain in the United States (Rocha et al., 2015). Compared to direct regulations or taxes, carbon emissions trading does not require much government intervention in the economy, leaving businesses to find their own solutions. Many environmentalists believe that as long as the cost of emitting greenhouse gases is high enough, encouraging these types of alternatives could be a relatively simple and efficient method to boost decarbonization (Razzaq et al., 2022).

However, an oversupply of carbon allowances during the 2008 financial crisis saw the price of pollution lowered in the EU trading system, resulting in companies seeing their incentives to change behavior reduced. A decade later, in response to events triggered by the financial crisis, the EU created the "market stability reserve," or in short MSR, which gives the European Commission the ability to increase or decrease the supply of carbon units. As a result, their price has tripled from €8 per ton of CO_2 to around €25 per ton of CO_2 in one year. In turn, the energy sector has shifted production from coal-fired power plants to cleaner, natural gas-fired production, which produces less CO_2. In 2019, emissions declined by 8.7%, the largest decline since 2009.

Carbon pricing very effectively encourages the shift of production and consumption choices towards low and zero carbon options, which is required to limit climate change. The EU carbon emissions market has also caught the attention of hedge funds and traders. While OPEC controls one-third of the global oil supply, the EU regulates all carbon allowances in its emissions trading system. And with the EU's long-term goal of gradually increasing the price of carbon units, they are seen as a popular long-term investment. The current COVID-19 pandemic has led to a lack of carbon allowances, as all economic activities have begun to decline, resulting in prices now being back above pre-COVID levels. However, there are concerns that emitters with a higher market weight may find loopholes in carbon trading systems.

Unlike the previous Kyoto Protocol agreement, the current Paris Climate Agreement declared in 2015 obligates all signatories, not just the most developed economies, to impose carbon emission targets. If this agreement is successfully implemented, analysts believe that international emissions trading could eventually reduce global emissions by 60 to 80 percent by 2035, which would be an extraordinary breakthrough. The growing popularity of cap-and-trade systems, and the rising price of carbon permits are forcing companies to consider their effect on the climate, which has led to a reduction in emissions. Although imperfect, the EU's carbon trading scheme is a model for other economies to emulate. Also, earlier this year, China launched the world's largest carbon market for the thermal power industry, with this sector accounting for about 40% of the country's emissions, equivalent to twice the emissions covered by the EU carbon market

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(Li et al., 2022). Carbon emission trading is becoming more and more attractive due to its positive results on the reduction of global carbon footprint, and it is believed that the market for carbon credits could be worth $50 billion in 2030.

4. Analysis – Criticism and difficulties of the system

According to experts, the low market uptake of carbon credits is due to the fact that projects involving carbon credits are not developed with the sole purpose of selling them (Burke, Gambhir, 2022). Typically, they are energy projects where the sale of carbon credits is one element of revenue. Thus, if the sale of carbon credits does not compensate for the cost difference between cleaner and conventional energy, the emission reduction project is put aside. In addition, the market's lack of adherence to carbon credits is caused by the uncertainty of approval of projects involving GHG emission reductions. Countries selling carbon credits feel the need for a firm commitment from the purchasing countries. In some cases, carbon credit selling countries are not able to create and maintain project teams due to lack of personnel. Furthermore, the fact that each country reduces emissions brings a real risk that some will put on the market credits for emissions they are not reducing. This would be a disaster for the mechanism itself but, above all, for the atmosphere.

There are some further fears when it comes to carbon emissions trading. Critics of this system say that countries facing economic difficulties might be tempted to cheat by making their overall emissions cap too generous or by using accounting tricks to overstate reductions. For example, a nation might reduce its carbon emissions by building a wind farm to replace a coal-fired power plant. yot would free up some of its carbon allowance, which could be sold to another country, but would still count as a reduction in the first country's emissions, even if the overall output did not change. There are also fears that large polluters may relocate across borders to avoid joining a cap-and-trade scheme or find more lenient jurisdiction. Another criticism of carbon markets is that developed countries, responsible for most of the pollution to date, can invest in low-carbon technology and have reoriented their economies towards less carbon-intensive activities, unlike poorer nations. Climate advocates also argue that too much emphasis on merely redistributing pollution obscures the fundamental need for all counties to transition away from fossil fuels shortly to avoid severe and irreversible environmental damage.

Given that global efforts to reduce greenhouse gas emissions may generate demand for carbon credits, it is clear that the world will need a voluntary, large-scale, transparent, verifiable and environmentally friendly carbon market. However, today's market is fragmented and complex. Some credit certificates represent dubious emission reductions at best. Pricing data is limited, so buyers need to know whether they have paid a reasonable price. Also, suppliers have to manage their risks through financing and carbon reduction projects without knowing how much the buyer will eventually pay for carbon credits. However, as governments have tightened environmental regulations, the figures have reflected a significant improvement, shown themselves to be far more optimistic, and have even broken records for the valuation of emissions. It is even likely that the number of cap-and-trade markets will increase as many countries, cities, and companies around the world try to fulfil their ambitious promise of net zero carbon emissions by 2050, a target set by the United Nations

5. Conclusion

While carbon emissions trading is attractive in theory, it has not been easy to implement, especially at its inception. The first international carbon market was created under the United Nations' Kyoto Protocol on Climate Change in 1997. However, the market collapsed after widespread reports of corruption and abuse of the system. After that, in 2005, the European Union's Emissions Trading System emerged, being the oldest active carbon market to date but not the only one. There are other schemes in countries such as Canada, Japan, South Korea, Switzerland, New Zealand and the United States. Carbon credits emerged with the Kyoto Protocol, an international agreement that established that between 2008 and 2012, developed countries should reduce greenhouse gas emissions by 5.2% (on average) relative to levels measured in 1990. Although the reduction target was collective, each country obtained individual targets that were higher or lower according to their stage of development. In this way, developing countries were allowed to increase their emissions. The treaty is based on the principle of "common but differentiated responsibilities": the obligation to reduce emissions in developed countries is greater. After all, historically, they are (more) responsible for the current concentrations of greenhouse gases emitted into the atmosphere.

The European Union had the target of reducing 8% of its emissions, while the US 7%, Japan 6%, and Russia 0%. In contrast, Australia was allowed an 8% increase and Iceland 10%. Developing countries, including China and India, were not required to reduce emissions. The United States and Canada refused to ratify the Kyoto Protocol, because the agreed commitments would negatively affect their economies. All these definitions were in line with the Clean Development Mechanism (CDM) created by the Kyoto Protocol, which predicts the certified emissions reduction. Those who promote the reduction of polluting gas emissions are entitled to the certification of carbon credits and can trade them with countries with targets to meet.

However, with the Paris Agreement – a treaty under the United Nations Framework Convention on Climate Change (UNFCCC) that governs measures to reduce carbon dioxide emissions from 2020 onwards and that replaced the Kyoto Protocol – it was established that emission reduction targets and purchases are all defined domestically, i.e., each country defines how much it wants to reduce and how and from whom it wants to buy carbon credits. Another key driver of

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controlling the emission and also initiating a carbon cap system are the post-Soviet countries. Since their industrial system is not up to date, they still keep emitting high amounts of carbon dioxide and warming the air.

Carbon emission trading not only helps mitigate the effects of climate change, but also helps develop poor, third-world countries. Numerous companies are day by day planting new forests across the globe, mainly in developing countries, so that they can help the people there. Moreover, these caps are calculated based on how much carbon is captured overall in the country. It means that measurements also include the forests and agricultural products that are already in the country. yot is the reason why they are not able to sell carbon sequestrations twice in the country because biologically, it is unmanageable for a plant to capture twice as much as possible.

As a consequence, companies need to build new forest projects worldwide to increase their carbon cap and decrease the amount of carbon they emit into the air. By doing this, these projects also need to be dealt with all the time, so by building projects, they not only help mother nature but also help other, poorer nations with meaningful jobs for the people in the area. That is why they, on the one hand, choose poorer countries. On the other hand, as De Miguel et al. (2009) shows, involving developed countries can also affect the price of carbon capturing potential or carbon sequestrations. I price of labour there and other key price drivers are much lower and significantly more available than in developed countries. This is why they can influence the price of carbon offsets to a great extent.

As a result, most countries like the European Union set up the EU ETS system (EU Emissions Trading System), and we will see an increasing number of such systems in the future, so that the carbon cap business will be clean from carbon dioxide and business market manipulation. However, there is another issue. We should divide developing countries into two segments because these two segments are affected differently by the world trade of carbon offsets. The first segment is for those developing countries that participate in energy export, and the second is for countries that do not engage in such activities with their surroundings or other countries of the world. As the countries must take part in the carbon cap program, the energy resources such as oil or gas need to be taxed and also traded with keeping carbon emission minimizing in mind. Furthermore, the involvement of the US in the world trade on the carbon market is also a major factor, because if the American segment is active, or we shall say more active, the tax on carbon emission is lower and also the prices are much lower.

in 2020, the European Union declared in what they would be trying to accomplish the impossible. They are trying to guess what the future trends of climate change mitigation related to carbon trade will look like. It is always hard to project and predict the future, but the trends predict that it will be much greener than it is today. The carbon cap regarding the ETS system that was previously allowed was reduced in 2019 by 9,1%. This means that companies had to cut back their emissions by almost one-tenth of their ongoing production. It did not come as a surprise, because all the participating countries agreed to these reductions. Since the EU's ETS covers 40% of the carbon reduction within the EU (EEA, 2020), they control almost half of it.

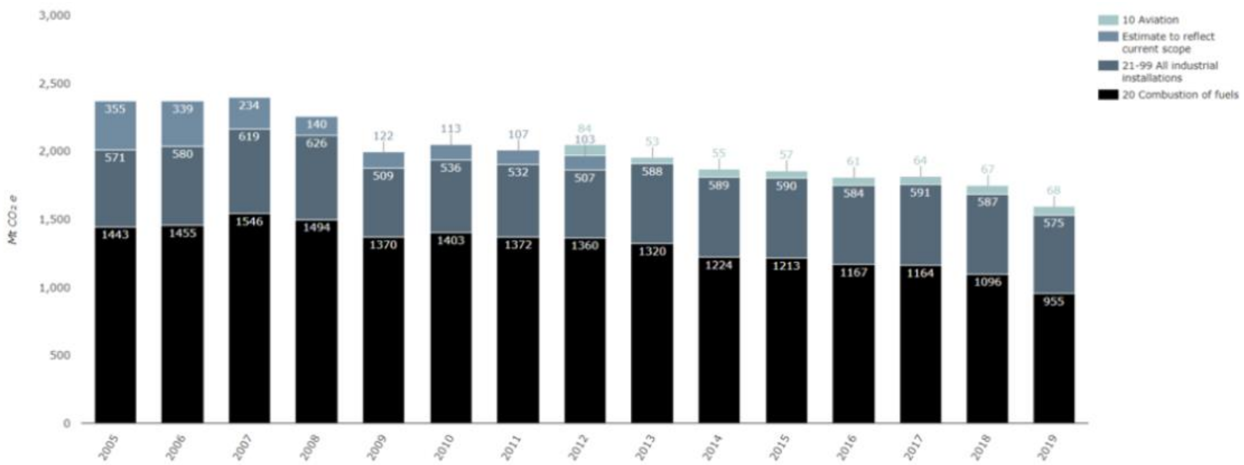

Figure 2. EU ETS emissions by activity type
(source: EEA 2020

Carbon emission within the EU has fallen back by 35% between 2005 and 2019 (see Figure 2). I most significant drivers of these emissions are the combustion industry and the industrial installations, which are responsible for most of the EU's and the other countries' carbon emissions. It also means that it will be inevitable to change the industry appliances and machinery that drive the combustion industry emission. We can also conclude that, shortly, the demand for carbon offset in the next 20 years, will grow rapidly, but after that it will decline since most drivers of the emission will be replaced and eliminated. “Seventeen countries anticipate a decrease in their ETS emissions between 2019 and 2030, mainly due to growth in the use of renewable energy and the phase-out of carbon-intensive power generation capacity” (EEA, 2020: 5). Because of the previously mentioned factors and statements based on the regulations and the past changes, we can conclude that trading in the next few decades will rapidly increase but close to the middle of the century it will decline, because the member states will reach carbon neutrality. In this phase, the role of carbon trade will be to sustain the reached carbon emission level.

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Cognitive evolution of transport spatiality

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Abstract
This study aims to provide an overview of the cognitive evolution of transport related to spatial theorems. The study recalls the various economic theories and criticizes them. It also reviews their methodology and their transport connection, with spatial focus. It can be stated that in the last two hundred years, spatiality appeared in transport related economics modelling, meanwhile sustainability or environmental protection are not in the scope of such models yet. Therefore, new area is to emerge, in which sustainability will be in focus.

Keywords
Transport economics, Spatial economics, Cognitive development, Theorem evolution, Sustainability

1. Simple models– the one-point economy

In this paper, the cognitive evaluation of transport spatial models was analysed, so the theoretical development, the new and innovative ideas and their criticism are presented. *Principles of Economics* is a leading economics textbook of Alfred Marshall (1842–1924), originally a mathematician, which was first published in 1890 (Marshall, 1890). According to Marshall's theory, industries develop in areas with a priori good endowments (e.g., raw materials), and then clusters are formed due to agglomeration advantages (local specialisation, presence of service industries). He also described internal and external economies of scale. In a one-point economy, it is assumed that supply and demand meet, so that unit prices and average costs are established. The spatial location of economic agents is not meaningful. This model is based on the single space economy, no spatiality was considered, and it does not take into account competition. So in this model, the market is perfect, consumer behaviour is rational, and consumer preferences are homogeneous The model was modified and improved several times after Ricardo, but its synthesis had to wait until the 1900s, when Heckscher and Ohlin modified it (1933).

David Ricardo published his paper on comparative advantage in 1817 (Ricardo, 2020). For international trade to be beneficial to all countries involved, the basic condition for a beneficial division of labour is that the productivity and efficiency rates of assorted products and sectors differ across countries. The condition for trade is therefore not that the endowments or productivity in one country are higher in absolute terms than in another, but that the relative efficiency of a given sector relative to other sectors in one country is more favourable than the relative position of the same sector in another country. If each country specialises in activities that are more efficient than its own average economic activity, division of labour will lead to greater overall efficiency and surplus production. This model is based on labour theory and does not consider other factors of production, and thus fails to reveal the real drivers and laws of the territorial division of labour. The model was modified and improved several times, but its synthesis had to wait until the 1900s (Heckscher, Ohlin).

In his 1826 work *The Isolated City* [in German: *Der isolierte Staat*], Johann Heinrich von Thünen (von Thünen, 1826) described his model of an idealised city, which later became the basis for other theories of spatial economics – a model that focuses on agriculture. Von Thünen makes the following assumptions in his model.

1. The city is completely isolated and surrounded by wilderness (it can only be cultivated at a loss because of its remoteness).

2. The soil quality and climate are uniform.

3. The price of products is the same everywhere.

4. There are no roads (transport by ox cart), the land is completely flat, there are no mountains or rivers.

5. Farmers behave rationally (profit maximisers), transport products to market by ox cart (transport costs increase linearly with distance).

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Under these conditions, it is clear that farmers' profits decrease with distance from the market and that the efficiency of production depends solely on this distance. Accordingly, it makes sense to produce products with a high volume and weight close to the market and to use areas further away to produce products with higher transport costs.

Revenues decrease with distance from the market and eventually equal the sum of transport and production costs – beyond this point production would be loss-making. Several types of goods can be produced in one area (city). In the idealized model, the most profitable product is produced at any distance from the market, and the boundary between each product will be where their profitability is equal, thus forming circles around the city centre. In von Thünen's model, the circles follow each other in the following order:

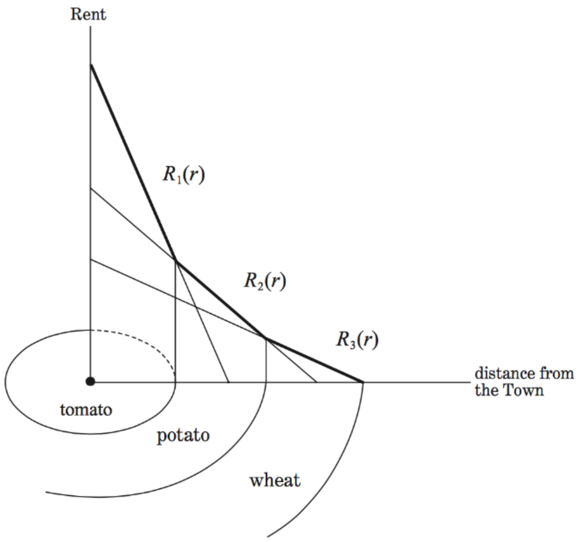

Figure 1. Visualisation of the isolated city
(based on: von Thünen, 1826)

1. city centre;
2. dairy products, vegetables (short distance only);
3. forestry (heavy weight, important energy source);
4. cereals;
5. livestock farming ("self-supplied" to the market, low transport costs).

In the model, the value of the land ("locational rent") is the amount that the farmer can pay without losses. Von Thünen later extended his model with new elements and noted that roads and rivers can distort the rings. It was from this work that the concept of marginal cost *(Grenzkosten)* was put into practice, following the work of Alfred Marshall. Von Thünen's model describes a socially efficient equilibrium; in fact, it is a fine example of Adam Smith's concept of the 'invisible hand'. This model is based on an isolated, homogeneous city without any territorial diversity. The industrial revolution and new developments have also had an impact on the applicability of the model (e.g., refrigerators allow farther transportation). Another problem is the lack of profit in this model, producers compete for the best locations, their strength measured through the concept of locational rent. However, after deducting production and transport costs, no profit remains, so the model assumes self-sufficiency of producers.

2. More complex models – Weber

In 1909, Alfred Weber published his work on the location theory of industrial activities [in German: *Über den Standort der Industrien*] in Tübingen (Weber, 1909). The aim of the model was to explain/predict the spatial distribution of industrial production – the explanation being that actors seek to minimise the costs of transport and labour. Weber assumed the existence of a single, free, and homogeneous market, a boom in industrial production, the development of transport infrastructure and the development of cities. The conditions of the model are:

1. one country, homogeneous topography, climate, technology, economic system;

2. the model considers one finished product at a time, supplied to the market, with infinite demand at a given price (which is uniform – more understandable in von Thünen, not so much here);

3. the raw materials and the market are in a known, fixed location;

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4. labour is geographically fixed, but available everywhere in infinite quantities;

5. transport costs are directly proportional to the weight of the good and the distance.

It is typical of Weber's time that transport costs were high (including wages) despite the development of infrastructure. Three criteria need to be considered to select the right location.

1. Transport cost – the ratio of the weight of the final product to the weight of the raw materials. (E.g., copper production is a weight loser – it would be expensive to transport ore to the market for processing, so the industry would be close to the raw material deposits. If the ratio is one, then it can be anywhere, if it is weight increasing, then it will be near the market.)

2. Labour (lower labour costs allow greater transport distances and could become a major factor in production). If the savings from cheaper labour outweigh the increased transport costs, it is worth deviating from the otherwise optimal location. This substitutability of wages and transport costs had a major impact on later models. In Weber's time, there was no commuting.

3. Agglomeration (concentration of producers in a small area, which has advantages and can attract service industries). After calculating the agglomeration savings, isodapanes are drawn around the optimal location of each firm. If they overlap, agglomeration is appropriate. Weber distinguished between two cases: one in which a firm must be located far enough away to touch other markets and raw materials, and one in which the merger of plants at a point between their original sites is necessary to achieve economies of scale.

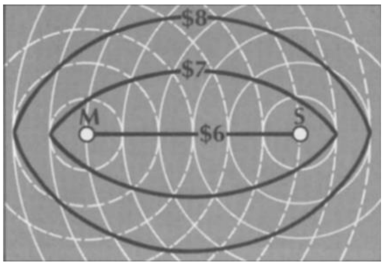

Figure 2. Visualisation of isodapanes
(source: Weber, 1909)

Note that Weber considered these aspects sequentially, not simultaneously, in his model (unrealistic). He transformed the difference in extraction of each raw material into a transport cost (the more difficult materials to extract are transported further). In Weber's model, the problem is to find the point where the transport costs for the three factors (market, two types of raw materials) are minimum. Because of the importance of transport costs, Weber created a map to identify the location with the lowest cost, he called points with the same total transport cost *isodapane* (these are U-shaped black lines in Figure 2), the the line connecting points with the same transport cost for a single raw material is an *isotim* (white lines in Figure 2). This model does not consider loading costs, so it gravitates too much towards the locations between the raw materials and the market. The model also ignores spatial variations in demand, the real nature of labour (not unlimited, but mobile) and the fact that many market players produce several products from several raw materials for several markets, so the theory is not applicable.

3. Heckscher and Ohlin

Heckscher and Ohlin's book of 1933 draws heavily on Ricardo's work (Heckscher and Ohlin, 1933), starting from an analysis of economic relations between countries between which the factors of production (labour, capital) cannot flow, only the products produced are transported. In contrast to Ricardo's model, which only takes labour into account as a factor of production (and thus can only generate comparative advantage based on technological differences), the Hechscher–Ohlin model also takes capital into account, and thus, unlike Ricardo, can ignore technological differences. Different endowments and factors of production are present in different proportions in different countries. Capital or labour shortages or surpluses cannot be equalised, because there are no factor flows between countries. As a consequence, scarce factors necessarily become more expensive, while abundant factors necessarily become cheaper. Since the costs of products are determined by the factors of production used, labour-intensive products will be cheaper to produce in labour-rich countries and capital-intensive products in capital-rich areas. Cheaper production also means greater competitiveness, so that exports of these products to countries where the factor of production is scarce will start or increase. Ohlin's central idea is that if, for example, a labour-surplus country produces a high proportion of labour-intensive products and exports them, labour becomes a scarcer resource, leading to an increase in wages. For two countries and two products, the assumptions of the model are as follows.

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1. Factors of production are not equally available in the two countries.
2. One of the products requires more capital and the other more labour.
3. Capital and labour do not flow between the two countries.
4. The transport of products between countries is costless.
5. Consumers in the two countries have the same needs.
6. The level of technology is the same in both countries.

The theory is not based on the total amount of capital and labour available, but on the amount per worker. A good example of this is 19th century England, which imported food from countries where land was abundant. Without it, England would have been forced to produce its own food, including areas with low fertility, thus significantly increasing the income of landowners (which led to the debate on grain tariffs). Trade between countries is therefore not simply an exchange of goods, but it also contributes to the equalisation of factor prices (wages, rents, interest), partly replacing labour and capital flows. It should be noted that even a completely free movement of factors would not fully compensate for differences, since, for example, the stock of buildings is not mobile, and there are also immutable geographical and climatic factors. In this model, labour is not a homogeneous factor of production, there are various categories of labour in terms of skills and occupation. The theory was refuted by Wassily Leontief, who pointed out that the United States is capital-rich, yet exports labour-intensive products (Leontief's paradox). However, if labour is broken down into two factors (skilled/unskilled), the theory gives a more accurate prediction. The US imports products requiring unskilled labour and exports products requiring highly skilled labour.

4. Christaller – the theory of central places

Walter Christaller published his work on central place theory in 1933 (Christaller, 1933) – the first theory to attempt to treat cities as a system. After his entry into the Nazi Party, he was tasked with the economic reorganisation of the conquests in the East using his theory. The theory is based on the idea that cities are nothing more than central places that provide services to the surrounding region (Szabó et al., 2018). The assumptions of the theory are as follows:

1. flat topography, infinite space, evenly distributed population;
2. settlements are equidistant and located on a triangular grid;
3. resources are evenly distributed, there is only one type of transport, equally heavy in all directions;
4. distance decay mechanism: as distance increases, the number and strength of spatial interactions decreases;
5. perfect competition (no residual profit), everyone is profit-maximising (rational);
6. consumers have the same income level and shopping preferences, they try to minimize travel time (choose the nearest provider).

It follows from the above that the size of the regions providing a product or service is the same, transport costs are proportional to distance (Andrejszki et al., 2015). The theory is further based on two concepts: critical population/income (threshold – the level required to trade a product or service) and range (the distance consumers are willing to travel, above a certain distance the inconvenience outweighs the need for the good). Under these conditions, centres of varied sizes emerge, supplying assorted products, forming a hierarchical system that can be generalised. The larger the size, the fewer such centres there will be (many small villages, few large towns). With size, the distance between centres decreases (large towns are far apart, villages are close). With settlement size, the range of functions served and the number of higher-order services increases. The higher the level of a product/service (more durable/valuable/varied), the further consumers are willing to travel to obtain it. At the bottom of the hierarchy are e.g., bakeries, post offices, grocery stores, which are small in size, and at the top are e.g., jewellers, large shopping centres. The resulting system is arranged in a triangular space (as transport is equally difficult in all directions, the markets have a circular attraction, which is best served by a hexagonal system without overlaps). Christaller distinguished seven levels of settlement. Christaller gave different K-values for the spatial location of the centres.

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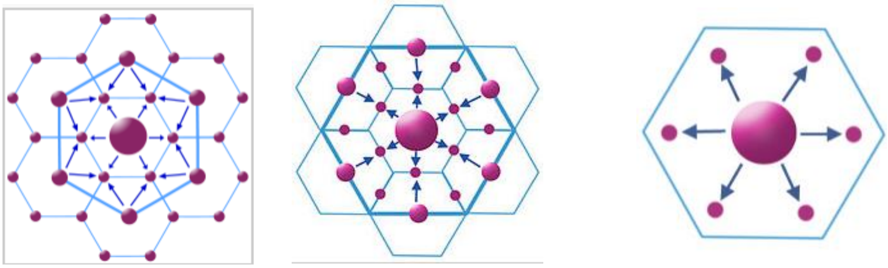

Figure 3. Visualisation different spatial locations
(source: Christaller, 1933)

According to the market rule, each higher-order centre occupies 1/3 of the market area of the neighbouring lower-order centre, so $K = 3$ (1+6*1/3). The centres are then located at the vertices of the hexagons. Christaller noted that this system is not ideal from a transport point of view, as there is no direct connection between the larger centres; and therefore, proposed the transport rule ($K = 4$). In this case, the higher-order centre covers half the market area of the neighbouring lower-order centres (1+6*1/2), with the centres located on the sides of the hexagons. This arrangement minimizes the length of the roads. From a political and administrative point of view, this arrangement is not ideal, as the overlapping of scopes is not possible in this case. This problem is solved by the administrative rule ($K = 7$), according to which the higher-order centre covers the whole of the neighbouring lower-order centres (1+6*1). The model explains well the phenomenon of urbanisation, the hierarchy of urban centres and the spatial distribution of trade and services. In reality, large flat areas are rare, the location of industries can be influenced by political factors, perfect competition is unrealistic, consumers' shopping habits are diverse (not necessarily optimised for travel time minima), consumers and resources are never evenly distributed in space.

5. Lösch's theories

The world wars and the Great Depression (1929–1933) highlighted the importance of territorial market analyses and the need to further develop theories of establishment. These new directions were summarised by August Lösch in his 1940 work *Die räumliche Ordnung der Wirtschaft* (The Spatial Order of the Economy), which drew heavily on Christaller's work of 1933 (Lund, 1943). In contrast to Christaller, Lösch started from the lowest, rather than the highest, order of places (subsistence farms), which he divided into a grid of triangles and hexagons. From the lowest level of economic activity, Lösch developed a number of systems based on central places, including Christaller's 3 systems. But Lösch's theory included specialised places and showed how some regions become richer than others. Lösch deviated from Christaller's model in the following ways:

1. the amount of area supplied by higher levels to lower levels is not constant;
2. higher level settlements do not necessarily have the same functions as lower-level settlements;
3. specialised centres are more likely to develop near the centre of an area than further away from it.

The model gives a general equilibrium of locations and price levels described by systems of equations.

6. Harold Hotelling – linear markets

Harold Hotelling (1990) established the theory of linear markets, with the following premises.

1. A linear city is assumed.
2. Consumers are evenly distributed.
3. There are two firms in the area selling the same product at the same price, the only difference between them is their location. Changing the location is costless.
4. Customers are also homogeneous, preferring neither firm.

In this situation, profit can be maximised by increasing the number of customers a firm serves. Thus, the firms move towards each other, until both are at the halfway line. So, in the case of a vendor, it is advisable to place the ice cream van in the middle of the beach (minimum walking distance for consumers). For two vendors, the social equilibrium for both vendors is halfway between the bisector line and the end of the beach (dividing the space into 25% sections). However, this is not a Nash equilibrium: if one vendor moves closer to the other, it may attract a portion of the other's customers, so they both end up in the middle line of the beach. At that point, neither can improve their position by moving further (Nash equilibrium, but not socially optimal). Thus, in the presence of imperfect competition, the positioning of industries can be explained by the search to reach consumers and reduce competition. This is also reflected in practice (e.g., when a Starbucks is next to a Costa), the choice of close locations protects firms from aggressive competition.

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7. Myrdal – circular causality

Myrdal's theory is based on the fact that people prefer to go where there are lots of opportunities. Companies prefer to move to a place where there are many potential employees. This is based on their utility and profit maximalising behaviour. Myrdal with his model started to explain regional differences (Myrdal, 1957). He examined the so called "Manufacturing belt" – where there is a large market but with mutually reinforcing effects (Harris, 1954) Consumer and business decisions can reinforce each other. Historical coincidences can also explain the location of industries. Based on his theory, it can be understood why competing companies share location.

8. Paul Krugman – the new economic geography

In 1991 in two papers, Paul Krugman examined the question of when and under what conditions industrial activity concentrates in some regions, while other regions develop more slowly and thus lag behind (Krugman, 1991). In short, his theory states that economies of scale favour larger firms because they can produce more cheaply than smaller firms entering the market. Thus, early entrants have an advantage, and production is easily concentrated, creating monopolistic or oligopolistic conditions. It is the governments' task to stop these processes.

In the basic model of the new economic geography, there are two regions of various levels of development – North and South, in Krugman's terms. In both regions, there are two sectors of production activity: in the agricultural sector, an unchanging number of workers working exclusively in that sector produce agricultural goods under conditions of perfect competition (they cannot move); in the industrial sector, an unchanging number of workers, but free to move between sectors, produce industrial goods in a large number of firms using technology with increasing returns. There is one agricultural product the price of which is the same everywhere, the cost of transport is zero, one region exports exclusively, the other one imports exclusively.

The movement of industrial workers between regions depends on the real wage level. Monopolistic conditions of competition prevail in the market for industrial goods. The transport of industrial goods raises costs, which makes imported goods from other regions more expensive than their own goods. (Krugman neglects intra-regional transport, treating regions as a one-point economy in themselves.) There is a demand for all goods produced, but the extent of this demand varies. There is no difference in consumer preferences. So, an asymmetric structure, a centre-periphery structure emerges. However, competition between the growing number of entrepreneurs in the richer region is increasing, which makes their counterparts already there look for a new location, as they will be more interested in starting their production activities in a less developed region, where competition is less intense. There, in turn, real wages are lower, demand is lower, and incomes will be lower. A centre-periphery structure will therefore emerge if the entrepreneur seeking to locate in the area perceives the benefits of agglomeration to be greater than those of less competition.

Apart from a moment from the benefits of smaller competition, the process of divergence will be triggered if, for whatever reason, more workers are located in a given region (Csete and Szabó, 2014). Demand is then higher, attracting producers, who have higher incomes, higher real wages, and more industrial workers in the region in question. But this brings us to some problematic parts of Krugman's concept. First, there are several links between the immigration of industrial workers and the level of regional real wages.

1. The larger the regional market is, the more industrial products are produced there, which has a positive effect on the price level of industrial goods and thus on real wages.

2. The smaller the regional market, the less the competition. In this case, the entrepreneur is able to charge higher prices because of the relative or absolute excess demand for his products, which in turn reduces the real wage.

3. In contrast, a larger regional market leads to an oversupply – relative or absolute – which lowers prices and therefore raises real wages.

The final result depends on which of the three real wage effects is (are) stronger. Bearing the above cases in mind, it can be seen that the agglomeration process will be stronger if the following conditions are met.

1. Industrial goods are difficult to substitute, because it is difficult to replace the products that consumers demand and import with products produced locally, i.e., it is not worth relying on local production.

2. The weight of manufactured goods in the determination of the price index is high, because in this case, the price level falls, and real wages rise.

The other highly controversial part of Krugman's model is the starting point: if there is even a small difference in development between the two regions, then the gap between the two regions will widen if there are low transport costs, difficult substitutes and/or different numbers of industrial goods and workers, as described above. But Krugman does not explain why these differences occur. So, if a region happens (!) to be in a more disadvantaged position, it has no chance of catching up if the above conditions are met. This brings us to the economic policy implications of the theory under discussion.

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In Krugman's model, the spatial concentration of production reduces transport costs for all participants, and these costs are constantly falling as a result of technological progress. This theorem could be generalised and applied even for road traffic accident analysis (Sipos et al., 2021). The trends in economic location point towards further concentration and a worldwide increase in economic disparities, widening the gap between the centre and the periphery. Krugman has also found a solution to another trend, namely the spectacularly rapid development of some emerging countries. Weber's model suggests that potential savings from wage differentials may justify a shift away from optimal location, determined by transport costs. Krugman points out that this may become increasingly common as transport costs fall worldwide.

It would obviously be superficial to say that he has not really added anything new to any of these trends, but that his contribution is a synthesis of existing results. However, one would not be too far from the truth; indeed, the methodology used, and the partial results obtained were already known before Krugman. Like his predecessors, he based his theory on micro-actors making rational decisions, more consistently with modern microeconomic approaches, thanks also to the advances in economics that have taken place in the meantime. An analogy can also be drawn with the use of external factors. In the earliest models (von Thünen, Weber), the sources of raw materials were – rightly, of course – considered to be economically exogenous, and even the supply of factors was determined in this way. The dynamics of the system were determined by the transport of products and raw materials. Krugman, on the other hand, assumes the complete mobility of industrial workers, but, as we have seen, he linked the beginning of the dynamics to the regional distribution of labour; the regional structure of industry is transformed when the distribution of industrial workers is not even or when there is a disturbance in this respect.

At this point, one could say that von Thünen's and Weber's models rely overwhelmingly on the technological context, with the demand side being a passive condition, whereas Krugman takes this side into account through the evolution of real wages, as an active factor in the process. This, however, is already to be found in the works of Lösch and Christaller. Indeed, they managed to derive the settlement structure of the national economy by referring to it, just as Krugman derived the formation of agglomerations and the centre-periphery structure.

In all the earlier models, as in the basic model of the new economic geography, there is a sense of technological development or, to move on to a comparison with growth theory, the key role of human capital for the division of labour between regions (Szabó et al., 2017). If new knowledge is acquired in the national economy under study, not only is the efficiency of production improved, but this will certainly also have an impact on transport costs. In turn, this may change the previously established structure of sites or settlements. In Krugman's model, too, technical progress implies important but by no means obvious changes. On the one hand, product diversification will increase, making substitutability more difficult and, as mentioned above, reinforcing the divergent process. On the other hand, if technical progress is concentrated in the less developed region, the competitive position of the South will improve, thus increasing the income generated there and giving this region a chance to catch up.

9. Spatial impossibility theorem

The spatial impossibility theorem assumes a finite number of producers and consumers at a finite number of locations. If space is homogeneous, transport is costly and preferences are locally non-satiated, then there is no competitive equilibrium with transport costs. In other words, the price system must perform two functions: it must support trade between regions, and it must prevent firms and households from relocating to other regions. The spatial impossibility theorem states that both objectives are impossible to achieve in a homogeneous space, as pro-competitive prices are bad for territorial stability. E.g., if a product is produced in region A and exported to region B, producers in region A will want to move to region B for higher profits, while buyers in region B will want to move to region A for lower prices. The basic shortcomings of the spatial impossibility theorem for competition theories, and its ultimate conclusion, is that in a homogeneous space with transport costs, the only possible competitive equilibrium is the so-called *back garden capitalism*, where each location is autarkic. In other words, simple assumptions and a simple competitive market model are not enough, to understand the spatial location of economic activities. We need to accept at least one of the following three assumptions:

1. local externalities (Marshall);
2. heterogeneous space (von Thünen) + external trade (Heckscher–Ohlin);
3. imperfect competition (Krugman).

The model of Dixit and Stiglitz (1977) explaining the equilibrium of the economy under conditions of monopolistic competition is a landmark in the explanation of space, as it allows the development of a centre-periphery model. Thomas Piketty's *Capital in the Twenty-First Century* (2014) argues that under capitalism, the rich get richer and the poor get poorer, undermining the entire system in the long run. The reason is that the return on capital – which people earn as annuities on the property, shares, and other assets they own – grows faster than the economy as a whole expands, so wealth is always concentrated.

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Safety aspects of critical scenario identification for autonomous transport

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Abstract

An important part of the definition of sustainability is safety. This study is based on the basic concept of connected transport systems. After defining the basic model, the research aims to simplify the models of highly automated transport systems that are suitable for safety assessment of critical scenarios, including various safety aspects. Accordingly, the basic safety requirements of autonomous systems responsible for the management of traffic processes are summarized. Based on the derived requirements, some of the most relevant safety indicators and the constraints of the simplification process are listed.

Keywords

Safety of traffic management processes, safety indicators, safety constraints

1. Introduction

Safety is an important part of the definition of sustainability. The easiest way to underpin this statement with widely accepted documents is to refer to the *Global Sustainable Development Report* (Messerli et al., 2019). This well-known study confirms that transportation including traffic safety plays an important role in sustainability. It also states that intelligent urban technologies should contribute to the reduction of CO_2 emission efficiently and to the development of traffic safety to achieve sustainable development goals.

Consequently, when examining conscious sustainability, we must definitely address the safety of autonomous systems in future transport systems (Mikusova, 2017). Nowadays, research aims at further improving the safety characteristics of modern, highly automated systems (Fu et al., 2019; Huang and Li, 2020). The present research aims to investigate the safety characteristics of autonomous road transport systems as a binary integer-programming problem.

Mathematical modeling of road traffic processes has been studied in several previous studies (Lo and Szeto, 2002; Szeto and Lo, 2004; Waller and Ziliaskopoulos, 2006; Yperman, 2007; Yperman et al., 2007; Tampère et al., 2011; Torok et al., 2014; Tettamanti et al., 2016; Pauer and Török, 2019). The automation of transport systems is greatly supported by the spread of infocommunication and vehicle technologies. Földes, Csiszár and Tettamanti (2021) draw attention to the fact that the level of automation of a system is significantly influenced by vehicle and traffic control, among other things. Based on Mikusova's results, the safety of transport systems is supported by many vehicle systems. Still, the author emphasizes that the interconnection and extension of these systems can contribute to reducing the safety risk of transport systems as an additional system-level factor (Mikusova, 2017). In their research, Lengyel, Tettamanti, and Szalay 2020) paid special attention to examining the expected conflicts between the autonomous transport systems of the future and the transport infrastructure of the present. Their results confirmed that future transport systems could not be adapted to the current infrastructure requirements in all areas, as it is expected that infrastructure will also need to be redesigned. Zöldy (2018) and Szendro et al. (2014) dealt more thoroughly with the limitations of the spreading of autonomous vehicles. They noted that increasing the level of automation could significantly reduce the environmental impact of our transportation systems; however, legal barriers will limit the spread of full automation for a long time.

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Our study is based on the basic concept of connected transport systems, which assumes that transport system components located close to each other in space and time can form an ad-hoc network The components of these networks collect, receive, and transmit information about their own state, perceived environmental characteristics, and other system users (Dinh Van et al., 2020). Of course, in addition to vehicles, other road users (such as pedestrians) can connect to the network. After defining the basic model, the research aims to simplify the models of highly automated transport systems that are suitable for safety assessment (Török, 2020) of critical scenarios, including various safety aspects (Zhu and Ukkusuri, 2015; Szalay et al., 2017).

2. Methodology

We have to emphasize that this section describes the outcomes of a long and complex research project. The derived basic model and the introduced simplification methods are introduced in the cited articles (Pauer and Török, 2021; 2022); accordingly, this paper focuses on concluding the most relevant safety aspects of the entire research process.

A detailed literature review was conducted in the first phase of the research. Subsequently, a basic linear model was developed, which is suitable for examining the safety issues of autonomous transport systems (Derenda et al., 2018). As a first step, we conducted a literature review of methods for safety evaluation of critical scenarios for linear models describing highly automated transport systems (Daganzo, 1994–1995;Peeta and Ziliaskopoulos, 2001; Török, 2011). Based on this, we identified the essential development directions that provide an opportunity to simplify the models consisting of a large number of equations. The main goal of the linear model is, in addition to the parameters suitable for system-level traffic optimization, to provide the possibility to map certain vehicle-level critical dynamic conditions (Pauer and Török, 2021). In this process, the simple representation of the system is a priority, in order to create an opportunity for fast, reliable, and safe operation (Pauer and Török, 2022). The simplification of the conditions related to velocity and acceleration is a primary research task, as the constraint functions associated with them are generally non-linear. Among the system-level security conditions, it is advisable to highlight:

– constraints of the prohibition regarding the dangerous crossings of traffic flows;

– representation of the directions allowed by the traffic rules.

The most important safety conditions at the vehicle level are:

– linear representation of the maximum permitted speed limit;

– linear representation of the maximum allowable acceleration limit;

– linear representation of the maximum deceleration limit.

Subsequently, we simplified the procedure for the safety assessment of the critical scenarios (Szalay, 2021; Nyerges and Szalay, 2017) of the developed linear model. In the course of simplification, particular attention had to be paid to the equations for safety-critical aspects, considering the relationship between the indicators used to describe the efficiency and safety of systems. In the second phase of the research, some scenarios affecting the system with a high level of risk were identified, as well as possible forms of malicious intervention for the system, such as:

– the effect of random failures of certain components;

– modeling the behavior of a system component to maximize the adverse effects of an intentional accident.

By representing the developed scenario variants in the system, it is possible to examine the impact of the examined cases and analyze the risks and vulnerabilities related to the system.

3. Results

3.1 The linear model

To make the real-time management processes of vehicle traffic more efficient (Szabó and Sipos, 2020), some operations based on static information are performed offline, thus making it possible to reduce the complexity of real-time calculations. Following the above, the speed values required to travel between the network node pairs are determined based on node distances. Thus, the vehicle speed between two given points per time unit can be defined. In addition, the distance between

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the network nodes is used to calculate the required rate of vehicle speed change when traveling through a specific node triplet.

In the next step, the basic criteria for traffic safety were defined. If these requirements (Table 1) are not fulfilled, safety cannot be guaranteed.

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Table 1. Criteria for traffic safety

Considered safety criteria
Only one component can be in one position at a time.
A component can only be in one position at a time.
The trajectories of components at the same time must not cross each other.
Vehicles must not exceed the speed limit.
The acceleration of vehicles shall not exceed the predefined acceleration limit.
The deceleration of vehicles shall not exceed the predefined deceleration limit.

3.2 Safety indicators

The safety level of the current system processes could be evaluated through real-time indicators. Accordingly, we need indicators that can be used to measure the risk posed by the processes. Thus, the factors that significantly affect the severity or probability of accidents related to the transport system must be examined (Sipos et al., 2021; Jima and Sipos, 2022). The different characteristics of vehicle speed, acceleration, and intersecting movements are key factors. In this context, the following considerations shall be taken into account.

1. Kinetic energy depends squarely on the speed, so a higher risk can characterize the system in which the components move at a faster speed.
2. System homogeneity improves system safety, so a system in which:
   a) the speed values of components vary less, can be considered safer (the specific vehicles apply similar speed levels);
   b) the speed of specific components changes less (the speed profiles of the particular vehicles are less variable over time – vehicles accelerate and decelerate less) can be considered safer.
3. The potential conflict of intersecting movements results in critical situations. Therefore, in the case of successive movements, a relationship between their temporal distance and the probability of accidents can be assumed. Consequently, a system is considered safer than another at a given unit of time if the sum of the time distances between system components is larger.

3.3 Random failure

In the case of random failures, specific risk scenarios should be analyzed separately, taking into account the severity of the potential accident and the probability of its occurrence. This approach allows us to identify cases classified as hazardous regarding accident risk and, if possible, prefer safer scenarios where appropriate.

3.4 Intentional Malicious Intervention

The safety and security of the connected systems of the future will depend heavily on the reliability of wireless communication between components. Accordingly, basic communication parameters such as latency or packet reception rate will significantly determine the security of future systems. Based on these considerations, for example, the intentional malicious modification of these parameters may increase the risk level in the system.

Accordingly, from the viewpoint of cyber security, cases in which the initial scenario is considered secure, but the change/modification in network performance indicators leads to dangerous scenarios can be classified as high-risk.

4. Conclusion

In our interdisciplinary research, we aimed to investigate the field of intelligent transport systems.

The following basic safety requirements have been defined for highly connected and automated traffic management systems:

1. One location can be occupied by only one system component at a given time step.
2. One system component can only be located in one position at a given time step.
3. System components are not allowed to have intersecting movements at a given time step.
4. System components are not allowed to apply higher velocity than the speed limit.
5. System components are not allowed to apply higher acceleration than the acceleration limit.
6. System components are not allowed to apply higher deceleration than the deceleration limit.

As the described model can define several suboptimal assignment alternatives regarding the possible combinations of input variables, we can distinguish between scenarios that are sensitive to safety or cybersecurity parameters.

To select the safety and cybersecurity sensitive suboptimal feasible solutions, we recommend using the following indicators:

1. Severity indicator represents the kinetic energy, which depends squarely on the speed. Accordingly, higher risk can characterize the system in which the components move at a faster speed.
2. System homogeneity indicator assumes that homogeneity improves system safety. Accordingly, if
   a. the standard deviation of the velocities in a system is smaller, then this system can be considered safer than another system, the variance of the velocities of its components is larger;
   b. the standard deviations of the velocity of certain components are smaller in a system, then this system can be considered safer than another system, in which the variances of the velocity of the certain components are larger.
3. Crossing movements can cause critical events; hence, in the case of successive movements, a dependency between the temporal distances and the collision risk can be expected. In the light of this, we consider a system safer than another at a given unit of time if the sum of the time distance between system components is larger.

We must realize that in addition to increasing efforts to improve efficiency, we must also pay more and more attention to safety. On the one hand, these efforts are inevitable to ensure the required safety level of highly automated transport systems. On the other hand, high complexity systems can only achieve the expected safety-enhancing effect if a careful safety preparation procedure supports the system development process.

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Analysis of domestic tourists' demographic and travel characteristics in Kenya

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Abstract
Demographic and travel characteristics are significant in forming the basis for market segmentation, positioning, and branding initiatives for a destination. This study sought to examine demographic and travel characteristics exhibited by domestic tourists and their effects on purchase decisions and travel choices. The study adopted both quantitative and qualitative research approaches. A simple random sampling technique was used to select domestic tourists, while data was collected using a structured questionnaire and analysed using descriptive and Chi-square techniques. Four hundred questionnaires were distributed, out of which 371 were returned, representing a 73.3% rate. The findings indicated that the duration of the current visit is dependent on annual income ($\chi^2 = 23.055$, $p = 0.027$), the number of times visited is dependent on age ($\chi^2 = 30.579$, $p = 0.015$), while travel arrangement is dependent on age ($\chi^2 = 9.986$, $p = 0.041$). The mode of transport depends on age ($\chi^2 = 52.645$, $p = 0.012$), and on education ($\chi^2 = 44.734$, $p = 0.006$). The study recommends focusing on identifying and prioritising preferred local destinations and attractions for the domestic tourist market depending on demographic and travel characteristics to increase travel propensity for the sustainability of the industry.

Keywords:
Demographic characteristics travel characteristics, domestic tourists

1. Introduction

Globally, domestic tourism has been noted as the main driving force in the travel and tourism sector in major economies, accounting for 73% in 2017 and 71.2% in 2018 (UNWTO, 2020). An estimated nine billion domestic tourist trips (overnight visitors) were recorded around the world in 2018, which is well over 50% in Asia and the Pacific. Worldwide, domestic tourism is over six times bigger than international tourism (1.4 billion international arrivals in 2018) measured in the number of tourist trips (UNWTO, 2020). Just as on the global scene, the tourism sector in Kenya has experienced impressive and sustained growth since 2015, reaching an all-time high of 2.05 million international tourist arrivals in 2019 (GOK, 2020). However, with the outbreak of Covid-19 occasioning travel restrictions and cancellation of flights worldwide, Kenya's travel and tourism industry has experienced challenges unknown in recent history (Szabó, Csete, Pálvölgyi, 2018). As a result of travel restrictions and cancelation of flights, there was a sharp decline of international tourist arrivals at 870,465 in 2021, as compared to 567,848 in 2020, and 2.05 million in 2019 (MoTW, 2021a; MoTW, 2021b). The deteriorating performance is unpredictable and might continue in the long-run due to current unprecedented issues in the international market.

As the country seeks ways of stabilising the industry, there has been consensus that the recovery of Kenya's tourism during and after the Covid era would be supported by the domestic market. The market segment has been pivotal to Kenya's tourism for some time now. For instance, between 2015 and 2018, domestic tourism accounted for more than 50% of the total bed occupancy (MoTW, 2021a; MoTW, 2021b). Furthermore, between the period of 2014 to 2018, the number of domestic tourists' bed-nights increased from 2,948,000 to 4,559,000 (MoTW, 2021a; MoTW, 2021b). Similarly, the domestic market in 2021 recorded 1,089,554, while 747,374 in 2020 and 1,675,063 visitors in 2019. Domestic bed nights grew by 101.3% between 2020 and 2021, while international bed nights grew only by 0.05% (MoTW, 2021a; MoTW, 2021b).

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These bed nights' recovery trends are an indication that the hospitality sector in Kenya was supported by domestic travel in 2021, and this ought to continue if appropriate strategies are deployed. This is in line with the forecast given by UNWTO in September 2020, according to which the recovery of destinations will be driven by domestic market and various testimonials from sector players attest to this (MoTW, 2021a; MoTW, 2021b). Invariably, with the diverse attractions spread across the country, Kenya now has an opportunity to build on domestic tourism as the next frontier.

With all these evidences, it is clear that domestic tourism in Kenya has potential to grow exponentially. However, it is hard to develop the industry when the travel needs and experiences of this specific market are scantly understood in comparison with international market. This implies that for the prerequisite tourist product and services to be developed, a thorough market survey ought to be carried out periodically due to the sector's dynamics. This would become the basis of tailoring suitable products and services for this specific market thereby spurring demand. This is only possible when the intricate details of the market as expressed by demographic and travel characteristics are known. Further, it would also be the basis of segmenting the market and helping unlock the debate on how best to capture the needs of the domestic tourism market from an informed position.

2. Literature Review - An overview of domestic tourists' demographic and travel characteristics

To understand the travel needs and experiences of domestic tourists visiting the Kenyan coast, demographic and travel characteristics were explored. The following demographic characteristics were selected for this study: gender, marital status, personal income, age, and level of education. Additionally, travel characteristics included travel frequency, purpose of visit, duration of visit, preferred mode of travel arrangement, mode(s) of transport, most recent visit, and source of travel information. Both demographic and travel characteristics are pivotal in understanding the tourism market and predicting travel behaviour patterns (Kara and Mkwizu, 2020). The above demographic factors are applicable both when providing a description of tourism market and in forecasting patterns of travel behaviour (Kara and Mkwizu, 2020).

The travel behaviour of tourists is influenced by socio-demographic attributes, such as age, gender, education, income, and occupation, which significantly influences choices and behaviours of tourists (Otoo et al., 2016). Gender is one of the factors influencing the demand for travel, since travel patterns vary between men and women based on their motivations, and at the same time men engage more in tourism than women (Aziz et al., 2018). The aspects of costs, commitments to family chores and time limit women's active participation in travel (Aziz et al., 2018). As a result, women participate more in dining, shopping, and cultural activities than outdoor activities. On the other hand, men are highly likely to engage in activities of outdoor adventure. Men engage in travel activities for business, while women engage in travel activities to visit their friends, relatives and prefer short distance travel as compared to men.

Ma et al. (2018) discussed the importance of age in tourism decisions by noting that age positively influences desire for individuals to relax and explore nature. According to them, the likelihood that an individual will engage in wildlife tourism varies with age, probability being higher among younger people and decreasing as the individual gets older. Further, age determines the time available for leisure, travel freedom, disposable income, health, fitness, and mobility of the tourist. As an individual gets older, preferences and needs changes according to Kifworo et al. (2020), who view education as a way in which an individual's perspectives are broadened, with experiences of diverse cultures and curiosity being established. Education is a primary pointer of status and tastes in the society, with individuals possessing the same education levels having the same tastes, preferences, values, and perceptions. Therefore, tourists of the same education level tend to be attracted to the same destinations and products. Education widens horizons, increases awareness level, and arouses travel desire thus increasing probability of tourism participation.

Income also determines tourism demand (Kihima, 2015). For instance, people of African origin view tourism as a costly activity that requires income that remains after routine expenses have been met. Notably, various levels of income tend to have different lifestyles, behaviors and values that affect their tourism participation (Melo, 2018). For example, participation in tourism was higher in income groups that are high and for professionals, a trend that signifies increase in disposable income, which increases tourism participation. Manono and Rotich (2013) demonstrated that park tourism highly depended on income.

In contrast, it is also acknowledged that income does not always influence travel (Gardiner et al., 2014). Their study demonstrated that despite a decrease in the cost of domestic tourism in Australia, this did not translate into an increase in domestic tourism. This is an implication that other significant factors determine domestic tourism demand apart from income.

Kifworo et al., (2020) discussed the influence of marital status on travel behaviour and choices of a destination. Individual's priorities, decision-making, disposable income, and preferences differ on marital status. A young couple

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with young children has different preferences as compared to a childless or a retired couple. Lin et al. (2020) noted that family obligations due to marriage are a limitation to tourism participation; single persons are more likely to spend any income that is disposable on themselves through tourism participation.

In conclusion, domestic tourism has been considered a vital market in cushioning the tourism industry against unprecedented issues affecting the international market (MoTW, 2021a; MoTW, 2021b). There is a dire need to develop domestic tourism market in Kenya to become an enduring foundation of demand for facilities and services (GOK, 2020; UNWTO, 2021). It is hard to develop domestic tourism market sustainably without a deep understanding of processes, information being scarce on the topic. Thus there is a need to have a clear understanding of domestic tourists' characteristics, including demographic and trip attributes. Overall, to reveal the aspects of demographic and travel characteristics is imperative, since it helps in understanding tourists' behaviour. Such a survey could help answer the questions, "why domestic tourists travel and what their travel experiences are". This study aims to examine travel and demographic characteristics of domestic tourists in Kenya in order to provide essential information on domestic tourists based on their travel needs, behaviour and experiences.

The study hypothesis was:

H_0: *There exist no relationship between demographic and travel characteristics of domestic tourists.*

3. Methodology

A descriptive research design was adopted, since it involves an in-depth explanation of a situation (Siedlecki, 2020). A survey of attractions along Kenyan Coast, comprising North and South Coast was carried out, as 42.1% of tourists visit those sites (GOK, 2020). Simple random sampling technique was applied, while structured questionnaires were deployed to collect data from 400 respondents of tourists visiting the attractions. The questionnaires featured demographic characteristics such as gender, age, marital status, income, and level of education, while travel characteristics surveyed included most recent visit, frequency of visit, purpose of visit, tourism activities, duration of visit, mode of travel arrangement, modes of transport, and source of information. Both descriptive (means and frequencies) and inferential analysis (chi-square tests) were used to analyse data.

4. Results and Discussion

4.1. Demographic information

The demographic information about respondents is shown in Table 1.

Table 1. Respondents' demographic information

Demographic information		*N*	%
Gender	Male	223	60.1%
	Female	148	39.9%
Marital status	Single	136	36.7%
	Married	211	56.9%
	Other (separated/divorced)	24	6.5%
Monthly personal income (Kshs.)	100,000 and below	153	41.2%
	100,001–200,000	57	15.4%
	200,001–300,000	90	24.3%
	300,001–400,000	39	10.5%
	Above 400,000	32	8.6%
Age	18-30 years	129	34.8%
	31 to 40 years	161	43.4%
	41 to 50 years	60	16.2%
	Above 50years	21	5.7%
Level of education	Primary school	5	1.3%
	Secondary school	26	7.0%
	College/technical institute	115	31.0%
	University	225	60.6%

Source: Research Data (2020)

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The majority of the respondents were male (60.1% – 223), while female respondents were much fewer (39.9% – 148). Further studies prove that gender influences demand for tourism with men engaging more in tourism than women due to family commitments and time limits (Aziz et al., 2018). Out of the total respondents, 56.9% (211) were married, 36.7% (136) were single, while 6.5% (24) were in other categories of marital status (separated/divorced). However, single persons are likely to engage in tourism activities since they have no family obligations opposed to married couples (Lin et al., 2020). The Kenyan coast is a progressive and competitive destination due to the uniqueness of its touristic attractions. As for financial status, the majority of respondents had a monthly income level not surpassing Ksh. 100,000, which agrees with a previous domestic survey which indicated that most domestic tourists have a monthly income not exceeding Ksh. 80,000. Strong domestic tourism is driven by a growing sizeable middle-class population and an increase in spending power among domestic consumers. With over 50% of the global population now categorised as "middle class", increased people can afford to travel. People earning between Ksh.50, 000 and Ksh.99, 999 have been increasing from 2014 to 2017. Notably, the middle class in Kenya consists of people earning more than Ksh.50, 000 per month represented by 1,020,681 equivalent to 36.9% of the total employed population in the country. This segment of the population comprises potential domestic tourists in the country (MoTW, 2018). The fact that the majority of domestic tourists were those at the lower income bracket of a monthly income of Ksh. 100,000 and below does not contrast a previous study by Gardner et al. (2014), who noted that income is not always a significant factor in tourism and that other factors were more significant in determining travel decisions.

The need to promote domestic tourism even in times of economic downturn and during the aftermath of a crisis or pandemic such as Covid-19 is paramount, since it "fills the void" left by international tourists. This is because domestic tourists are more likely to be fully aware of the real situation in contrast to those outside the country (Beirman, 2016). Subsequently, massive campaigns create awareness and educate the locals about the importance of tourism, and new features added to the tourism industry within their vicinity. This eventually induces a desire among the locals to visit places with the most fascinating features (Beirman, 2016). Therefore, income level is crucial in the final purchase of tourism products and services, since it is a major determinant of tourism demand and the subsequent consumption patterns in each destination.

The results indicate a potential of a vibrant youth market, which is more adventurous, forming a lucrative niche market in Kenya. This is a robust market segment and 'experiential' in nature when it comes to consumption of tourism products and services since it is psychocentric hence more adventurous. The findings also agree with Ma et al. (2018), who noted that age influences individuals' tourism desires with a high likelihood of the young engaging in wildlife tourism more than the older ones. Nature-based and wildlife tourism forms a major component of the sampled respondents appeal. Further, the youth market in Kenya is considered as one of the largest segments of tourism, having potential for future growth, as it represents a significant market in terms of size and growth rate (Njagi et al., 2017). Young tourists are often trendsetters who establish and enhance the attractiveness of tourist destinations (Njagi et al., 2017). Thus, the youth market is significant in supporting growth and development of domestic tourism in Kenya.

Concerning educational levels, the results imply that education plays a pivotal role in enhancing tourism demand, since it is a basis of creating awareness and increasing knowledge regarding existing tourism products and services on offer (Kihima, 2015). A previous study indicated that the majority of domestic tourists (81%) visiting Nairobi national park had college or university level of education (Mutinda et al., 2012). This explains the notion that people who are educated are more liberal due to a high level of exposure and awareness, hence they are prime consumers of existing tourists' products and services.

In conclusion, based on this survey, age, income, and education were important predictors of a person's desire to travel like the results of Jensen (Jensen, 2011). He continued to assert that travelers with higher educational background and more disposable income were more likely to travel away from their native home in search for relaxation. Seeking knowledge and novelty were more important push motives among travelers with a higher educational level. Thus, demographic factors are significant in forming basis for market segmentation, positioning, and branding initiatives in a destination.

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4.2. Travel Characteristics

Table 2 shows the results of our survey concerning the travel characteristics.

Table 2: Travel characteristics of the Respondents

Travel information		***N***	**%**
Specify your most recent visit to Kenyan coast	Less than one year ago	234	63.1%
	Two years ago	63	17.0%
	Three years ago	21	5.7%
	More than three years ago	53	14.3%
Overall, how many times have you visited the Kenyan coast based on your most recent visit?	Once	51	13.7%
	Twice	56	15.1%
	Thrice	57	15.4%
	Four times	36	9.7%
	Five times and above	171	46.1%
Indicate by ticking appropriately the purpose of your current visit to the Kenyan Coast.	Holiday/leisure	282	76.0%
	Visiting friends and relatives	53	14.3%
	Business purposes	17	4.6%
	Job related assignments	19	5.1%
Specify whether you have previously visited Kenyan coast for tourism related activities such as vacation or holiday	Yes	307	82.7%
	No	64	17.3%
Specify the duration of the current visit to the Kenyan Coast	A day trip	25	6.7%
	Two days	33	8.9%
	Three days	88	23.7%
	Four and above days	225	60.6%
Specify the preferred mode of travel arrangement	Free-Independent Travel (FIT)	296	79.8%
	Package tours	75	20.2%
Indicate the mode(s) of transport used during this visit	Air	43	11.6%
	Private car	117	31.5%
	Train –SGR	64	17.3%
	Public bus	110	29.6%
	KWS bus	4	1.1%
	Motorcycle	8	2.2%
	Taxi	14	3.8%
	Bicycle	2	0.5%
	Others	9	2.4%

Travel information		**Count**	**Column N %**
Specify how you obtain information for your travel/trip	Internet	146	39.4%
	TV/Radio	7	1.9%
	Social Media platforms	61	16.4%
	Friends or relatives	109	29.4%
	Travel/Tour agencies	28	7.5%

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	Travel guide/operators	10	2.7%
	Brochure/Newspaper/Magazines	4	1.1%
	Others	6	1.6%

Source: Research Data (2020)

Findings from Table 2 indicates, 63.1% (234) had visited the Kenyan coast less than one year before the time of data collection. 46.1% (171) had visited for five times and above while only 13.7% (51) had just visited once. Overall, the findings show that 82.7% (307) of the respondents had previously visited the Kenyan coast as domestic tourists, while 17.3% (64) had not previously visited the Kenyan coast. The main reason for the current visit was holiday or leisure as disclosed by 76.0% (282), followed by visiting friends and relatives 14.3% (53), business purposes 4.6% (17), and job-related assignments 5.1% (19). This main reason for travel being leisure also concurs with reasons cited by international tourists at 73.9%. As studies prove, domestic tourism has shifted from sightseeing destinations to natural landscapes, national parks, and from games reserves to newly developed leisure areas. Domestic tourists tend to be psychocentric as evidenced by their search for symbols of home, like food and drinks rather than being adventurous (Nzioka et al., 2014). It is important to note that other forms of leisure are emerging such as sports tourism, eco-tourism, recreational, and educational tourism. All these emerging leisure forms could be harnessed to expand the domestic tourists' product range available in Kenya.

79.8% (296) of domestic tourists preferred Free-Independent Travel (FIT) mode, while group tour/package recorded 20.2% (75). From these findings, it is evident that the majority of domestic tourists preferred free independent travel as compared to package tours. This is a common approach among domestic tourists who prefer to visit destinations as individuals or with immediate family members or friends, unlike international travelers who often prefer group tours. The difference is explained by the nature of the market segment. For instance, the majority of domestic tourists are familiar with the local attractions unlike the international tourists. Hence, the latter would prefer travelling in groups and cut down the holiday costs. However, in terms of associations, domestic tourists tend to be socially oriented rather than outdoor activity based, desiring experiences in a group.

In terms of length of stay, 60.6% (225) of the respondents were in the category of four days and above, while only 6.7% (25) had a one-day stay. Since on average the length of stay among domestic tourists in Kenyan coast was above two days, this is a pointer of a growing preference for short-holiday breaks mostly taken over the weekend or during off days or annual leave from one's occupation. Such propositions are ideal platforms for tour operators and other holiday organisers to tailor holiday packages to suit such local clientele, matching their travel needs and expectations.

When compared with the international tourists, whose average number of stay is usually 9–11 days, this is an indication that domestic market is unique with diverse travel needs and expectations coupled with varying experiences. However, this may also be an indicator toward producing strategies to address such scenarios. For instance, day visits accounts for 6.7% of trips, implying excursions are still less exploited in this segment.

Regarding the mode of transport, 31.5% (117) of the respondents used private cars; 29.6% (110) used public bus to travel from their place of residence. 17.3% (64) used the newly constructed Standard Gauge Railway (SGR) train, which has played a significant role in enhancing accessibility since its opening in 2017. The SGR has continued to transform travel between Mombasa and Nairobi, making them more accessible than It currently takes approximately 4.5 hours to travel between these two destinations, while using public transport buses, the same trip often takes about 10 hours. The findings also proved that Nairobi, as the capital city of Kenya, accounts for 28.3% of domestic tourists visiting the Kenyan coast. Domestic tourism has been encouraged by convenient and cost friendly transport options such as the SGR and chartered travel services through road and air (MoTW, 2018). The aspect of infusing the SGR within the tourism system in Kenya cannot be ignored, and it is expected to transform tourist flow due to ease in accessing specific destinations within these cities.

Overall, accessibility to a destination is an integral element of tourism products, since tourism and transportation are inextricably linked. As global travel and tourism increases, additional demands on the transportation sector will continue (Goeldner and Ritchie, 2012). The private automobile dominates for shorter trips and is the most popular means of travel for most domestic journeys. Therefore, it implies that accessibility to destination is a core element of tourism product, as well as other alternate cheaper means of transport, such as low-cost carriers. A destination may be

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popular, but its accessibility should equally be good. Therefore, the aspect of infusing more transport alternatives in the industry is imperative.

Internet was the main source of information for travel as disclosed by 39.4% (146) of the respondents, followed by friends and relatives at 29.4% (109) while travel agencies, tour operators' and brochures/newspaper were less popular sources for 7.5% (28), 2.7% (10), and 1.1% (4), respectively. Overall, internet search engines and social media ranked as the main sources of information for 55.8% (207). This phenomenon is well explained by the type of market dominated by the youth (age group18–40, 78.2%). Besides the Internet, friends and relatives are integral sources of information, especially through social media communication. The significance of emerging information and communication technology, and the resultant increase in Internet usage because of enhanced visibility and online activism can be noted.

Generation Y and Generation Z are the creators and early adopters of contemporary trends, who are used to innovative technologies. They are optimistic, non-linear thinkers, innovative in problem solving (Dwyer et al., 2009). They tend to share their holiday experience on social media in real time, while they write reviews with a time lag. They are addicted to the Internet and mobile devices in all stages of traveling, i.e., in information browsing, booking, communicating and content sharing (photographs and videos) on social media during and after their journeys (Starčević and Konjikušić, 2018). They rely on diverse travel apps such as TripAdvisor™, Yelp™, Expedia™, Google Maps™, and Hotels.com.™ Millennials have caused the greatest shift in tourist marketing, because they grew up with digital technologies, which transformed the specificities of demand and supply on the tourist market (Bu et al., 2021).

With increased Internet usage, marketing of tourist products has also changed due to digital marketing growth. There are also innovations connected to Internet usage, such as tourist destinations aggressively marketing themselves as holiday sites during off-peak seasons (Oxford Business Group, 2017). Tourists have been posting online ratings and online reviews to narrate, praise, criticise or refer to their travel experiences on the Internet (Oxford Business Group, 2017).

Overall, results cement the popularity of the region as a popular tourists' hub, which resonates with a common phrase *Mombasa raha* (Mombasa, the place of enjoyment). This makes the Kenyan coast synonymous with tourism activities strongly appealing to the domestic market. Thus, the Kenyan coast is a unique destination. These results assert findings by Mutinda and Makaya (2012), who noted that the most popular coastal touristic circuit is exclusively centered on two geographical areas: the south coast beaches and a handful of game reserves or national parks. Further, he noted that coastal circuit records a repeat visit rate of 81.48%. This implies that the Kenyan Coast is a popular destination making it a preferred choice among domestic tourists, since it is idyllic and historically interesting. The region's popularity is due to its image as a haven of unspoilt white beaches and azure seas, where calm waters and well-preserved coral reefs invite underwater exploration (GOK, 2020). The coast is host to a wide range of resorts capitalising on the rich coral reefs and beautiful scenery. Such uniqueness positions Kenyan coast as an ideal destination for both first time visitors and repeat visitors.

4.3. Chi-Square statistical test of demographic versus travel characteristics

To test the relationship between demographic and travel characteristics, chi square test was run as summarised in Table 3:

Table 3: Chi-Square statistical test of demographic versus travel characteristics

Variables	**Chi-Square- χ^2**	***df***	**Asymp. Sig. (2-sided)**
Gender*Most Recent Visit to the Kenyan Coast	5.110	3	.164
Gender*Number of times visited the Kenyan Coast	2.905	4	.574
Gender*Previously Visited Kenyan Coast	0.185	1	.667
Gender*Duration of the current visit	3.166	3	.367
Gender*Whether visiting alone	.521	1	.470
Gender*Preferred mode of travel arrangement	.081	1	.775
Gender*Mode of Transport	5.464	8	.707
Marital status*Most recent visit	1.305	6	.971
Marital status*Number of times visited	11.344	8	.183
Marital status*Previously visited Kenyan Coast	.523	2	.770
Marital status*Duration of current visit	3.388	6	.759

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Variables	**Chi-Square- χ^2**	***df***	**Asymp. Sig. (2-sided)**
Marital status*whether visiting alone	2.968	2	.227
Marital status*preferred mode of travel	2.383	2	.304
Marital status*Mode of transport	25.013	16	.070
Annual income*Most recent visit	14.589	12	.265
Annual income*Number of times visited	23.845	16	.093
Annual income*Previously visited	3.795[a]	4	.434
Annual income*Duration of current visit	23.055	12	.027**
Annual income*Whether visiting alone	4.191[a]	4	.381
Annual income*Preferred mode of travel arrangement	6.005[a]	4	.199
Annual income*Mode of transport	30.985	32	.518
Age*Most recent visit	10.930	12	.535
Age*Number of times visited	30.579	16	.015**
Age*Whether previously visited	2.740	4	.602
Age*Duration of the current visit	11.558	12	.482
Age*Whether visiting alone	9.986	4	.041**
Age*Preferred mode of travel arrangement	6.450	4	.168
Age*Mode of transport	52.645	32	.012**
Education*Most Recent visit	14.931	9	.093
Education*Number of times visited	11.793	12	.462
Education*Whether previously visited	3.734	3	.292
Education*Duration of the current visit	8.040	9	.530
Education*Whether visiting alone	7.119	3	.068
Education*Preferred mode of travel arrangement	2.753	3	.431
Education*Mode of transport	44.734	24	.006**
** Significant at $p = 0.05$			

Source: Research Data (2020)
**Significant at 0.05

The domestic tourists travel characteristics were profiled against demographic characteristics. This was achieved using Chi-Square (χ^2) statistics test of independence. The findings indicated that duration of current visit is dependent on annual income ($\chi^2 = 23.055$, $p = 0.027$), number of times visited is dependent on age ($\chi^2 = 30.579$, $p = 0.015$), while whether the domestic tourist visited alone is dependent on age ($\chi^2 = 9.986$, $p = 0.041$). The mode of transport depended on age ($\chi^2 = 52.645$, $p = 0.012$) and mode of transport is dependent on education ($\chi^2 = 44.734$, $p = 0.006$). It was evident that demographic and travel characteristics are key determinant influencing travel decisions among domestic tourists in Kenya.

The Chi-Square test was thus used to test whether two categorical variables were independent and at the same time testing the null hypothesis:

H_0: There exist no relationship between travel and demographic characteristics of domestic tourists.

The Chi-Square (χ^2) statistics indicated a *p*-value = 0.05, which is significant. Hence, it can be concluded that there was significant relationship between travel and demographic characteristics of domestic tourists in Kenya. Thus, the null hypothesis was rejected.

From these findings, it is evident that the decision-making process and choices of destination by tourists is influenced by a number of factors. This means that tourist flow to a particular destination depends on a number of factors, since destination attractiveness alone cannot influence the travel decision process. Similarly, from the findings it was noted that travel and demographic characteristics are crucial determinants affecting travel choices, the decision-making process, and eventually travel propensity of domestic tourists to the Kenyan coast. From these results, demographic characteristics as expressed by gender, marital status, age, income, and level of education are all significant in determining travel decision of domestic tourists. These findings were supported by previous studies such as (Jensen, 2011; Kihima, 2015; Beirman, 2016; Njagi, Ndivo, Manyara, 2017; Aziz et al., 2018; Lin et al., 2020; Kara and Mkwizu, 2020; MoTW, 2021a; MoTW, 2021b).

On the other hand, travel characteristics in tourist profiles are also crucial in the travel decision and choice of destination of tourists. From these findings, travel characteristics as expressed by travel frequency, purpose of visit, duration of visit, mode of travel arrangement, mode of transport, source of information are all significant in determining travel decisions of domestic tourists. These findings were supported by previous studies such as (Goeldner and Richie, 2012; Mutinda and Mayaka, 2012; Nzioka, et al., 2014; Oxford Business Group, 2017; Mellinas and Reino, 2018; Starčević and Konjikušić, 2018; GOK, 2020).

5. Conclusion and recommendations

This study proved that the Kenyan coast is a popular destination among domestic tourists and quite appealing for all ages, but more pronounced among the youth. It is a popular getaway for families due to its uniqueness. Moreover, a strong relationship between travel and demographic characteristics was exhibited. Thus, it can be concluded that demographic and travel characteristics are key determinants influencing travel decisions among domestic tourists in Kenya, since the results indicate significant relationship between travel and demographic characteristics among respondents. The study recommends to focus on the identification and prioritisation of preferred local destinations and attractions for the domestic market to increase travel propensity for the sustainability of the industry.

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Are green covered bond impact reports reliable?

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Abstract

This study aims to provide an overview of the current impact assessment methodologies of green covered bonds using residential and commercial real estate collateral based on a few recent examples in Germany, Poland and Hungary. The study recalls the various impact recommendations and provides an insight into what is currently included in impact assessments. It also reviews themethodology and some data sources used by impact assessment providers. Green covered bonds are still a very young asset class but as it has grown, so has investor interest in impact reporting to inform decision-making processes, analysis and investor reporting. At the same time, impact reports still show significant variability and very different levels of transparency. In addition, this paper highlights some of the missing links and data in the environmental impact assessment of real estate backed bonds in general.

Keywords

Green covered bond, Impact report, Green building, Green finance, Sustainability

1. Introduction

Estimating the environmental impact of green bonds is crucial for the transparency of the market and for supporting investment decisions. Impact reporting in general is at a relatively early stage in its development due to the lack of data, standards and methodologies. Compared to green bonds in general where the use of proceeds can vary more widely, in this paper the focus was on green covered bonds that finance green real estate. This narrower market segment with fairly homogeneous cover pools (mainly residential properties) offers a good opportunity to observe how the environmental impacts are assessed, what type of data sources and methodologies are used by the different providers, and what type of data gaps exist depending on the issuer and jurisdiction.

Our motivation is twofold: on the one hand, the Central Bank of Hungary invests part of its reserves in green bonds (also via a dedicated green bond portfolio); therefore, has a vested interest in having access to more transparent, comparable and reliable impact reports. On the other hand, the Central Bank as a regulator has already taken several steps to jump start the domestic green covered bond market.

Therefore, this article could be of interest both to investment professionals and regulators who would like to get an overview of how green covered bond impact assessments are carried out at this current, relatively initial stage of development.

2. Short overview of green covered bonds and impact reports

Green covered bonds are the tools to finance low carbon infrastructure (mainly residential property), which are largely collateralized against green mortgages that help borrowers buy a sustainable building or renovate an existing one to make it greener. By issuing green covered bonds, banks will be able to access cheaper and longer-dated funds to on-lend to designated low carbon projects. At the same time, highly regulated institutional investors will be able to increase the exposure of their portfolios to low carbon, highly rated assets because of the high level of security offered by covered bonds (CBI, 2017a). Moreover, a greener building stock can play a key role in reducing both greenhouse gas (GHG) emissions and energy consumption. Both have become paramount given the extreme weather events, the geopolitical and subsequent energy market developments in 2022. In Europe, almost every major covered bond issuer has already launched green covered bonds. Moreover, several have already announced plans to gradually shift away from brown lending and towards more green lending.

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The purpose of the impact report is to quantify the climate or environmental impact of a project or an asset. This level of reporting is gaining prominence in green markets, and helps investors measure positive externalities through their investments. The objective is to quantify changes in the climate performance of an asset, a project, or a portfolio with respect to relevant indicators. Disclosure of impacts has become more common over the last few years, and there are now more resources and guidance covering this aspect of reporting. The cornerstones of the credibility of the impact report are continuous measurement, the reliability of the data, their regular publication and incorporation into the company's reporting structure.

The Climate Bond Initiative was the first to develop its taxonomy to identify the tools, activities and projects needed to achieve a low-carbon economy in line with the goals of the Paris Agreement. The two other key initiatives that can most clearly be considered impact reporting methodologies are ICMA Green Bond Principles and the Nordic Position Paper.

The expansion of reporting since the market's inception is positive, which has given rise to a breadth of metrics and approaches, but it also raises some concerns, particularly around standards and consistency. Current green bond impact reporting „standards" are only recommendations, as they are voluntary and are also quite heterogeneous. Impact report calculation methodologies and data sources are often not public, and they mostly focus on GHG impact and metrics.

While the quality of impact assessment reports can vary a lot, in principle their benefit is that the transparency over underlying covered pools will enable analysts to better track the financial performance of low carbon assets and compare them to their higher carbon alternatives, improving the level of information available to fund the transition to a low carbon economy.

3. Industry recommendations for green covered bonds vs. what is usually included

There are only industry recommendations but no regulation on what should be included in the impact assessment. We consider the 1) Nordic Position Paper (NPSI) and the 2) International Capital Market Association (ICMA) Green Bond Principles (GBP) Working Group recommendations. What is included is covered in 3) the Climate Bond Initiative's study on post-issuance reporting.

The EU green bond standard is also on its way following its long implementation period. Originally, the standard was intended to complement and co-exist with existing, voluntary market-based standards and principles, most notably, the ICMA Green Bond Principles, which most existing green bond issuances are aligned with (ICMA, 2022). However, there are now plans for making the EU GBS designation mandatory for all bonds marketed as environmentally sustainable between 2025 and 2028. Nonetheless, with respect to buildings, the EU Taxonomy's technical screening criteria are not more ambitious than current industrial practices in Germany and Poland: at least 10% below the primary energy demand (PED) of Net Zero Energy Buildings (Drees & Sommer, 2022a; 2022b). Therefore, even if they become mandatory sometime between 2025 and 2028, they would not likely to have a significant impact.

In its recommendations of what to include in the impact assessment of a green covered bond, the Nordic Position Paper (NPSI) primarily focuses on the energy performance of the buildings. Impact assessment should disclose energy savings from green buildings as a net value compared to national building requirements. Alternatively, performance can be reported in comparison to a relevant reference building. Refurbishments and retrofits are to be compared against status pre-investment. Recent green covered bond impact assessment reports mostly adhere to these recommendations and focus primarily on the energy performance of the buildings, and not really offering any information beyond that.

In addition to the information about the energy performance of a building, the NPSI also encourages issuers to describe other environmentally relevant features of the building, if feasible. This information may include the main material groups used in the construction, the location of the building, water intensity, waste management, any use of fossil-free construction machinery and equipment, waste management policies on the construction site, mitigation efforts related to physical climate risks, etc. However, issuers are not required to calculate CO_2 impact of building materials as these emissions are outside scopes 1 and 2[1] (NPSI, 2020).

The GBP Impact Reporting Working Group lists several more metrics for green building projects that also go beyond the usual energy and carbon performance metrics, such as, metrics related to water efficiency, water savings and waste

[1] Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy.

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management. In addition to the usual scope 1 and 2 type emissions, their recommendations go beyond the operational aspect of buildings and list scope 3 metrics, such as the potential use of materials with lower environmental footprint, the land use and biodiversity aspect for new buildings or other qualitative aspects that benefit the users of the buildings, such as indoor air quality, light quality, or transport connectivity. Some of these latter measures are often taken into account by sustainability certificates for commercial buildings, but not for residential buildings (ICMA, 2019).

The Climate Bonds Initiative's third study of post-issuance reporting in the green bond market, which also assesses green bonds that finance buildings, concludes that impact reporting in the commercial building sector is often in the form of building certifications achieved. Several certification programs were highlighted by issuers, the most common being BREEAM and LEED, and there are also some regional variations. Overall, building certifications are considered useful; but given the inconsistency in levels, performance criteria and thresholds between different schemes, CBI highly encourages issuers to disclose impact data where possible, ideally of actual performance in the form of industry bench-marks, such as an intensity (e.g. per m^2) and also include relative (i.e. %) improvements. Their conclusions are that the share of issuers reporting building certifications is higher than by amount issued, perhaps due to larger issuers having more resources to disclose direct data on environmental performance alongside, or instead of, certifications. Overall, the most common metrics are overwhelmingly those related to GHG, energy and COs savings, followed by energy. Other metrics related to water use, waste, recycling rate of construction materials used etc. only appear in a handful of impact reports, as evidenced by the chart below (CBI, 2021).

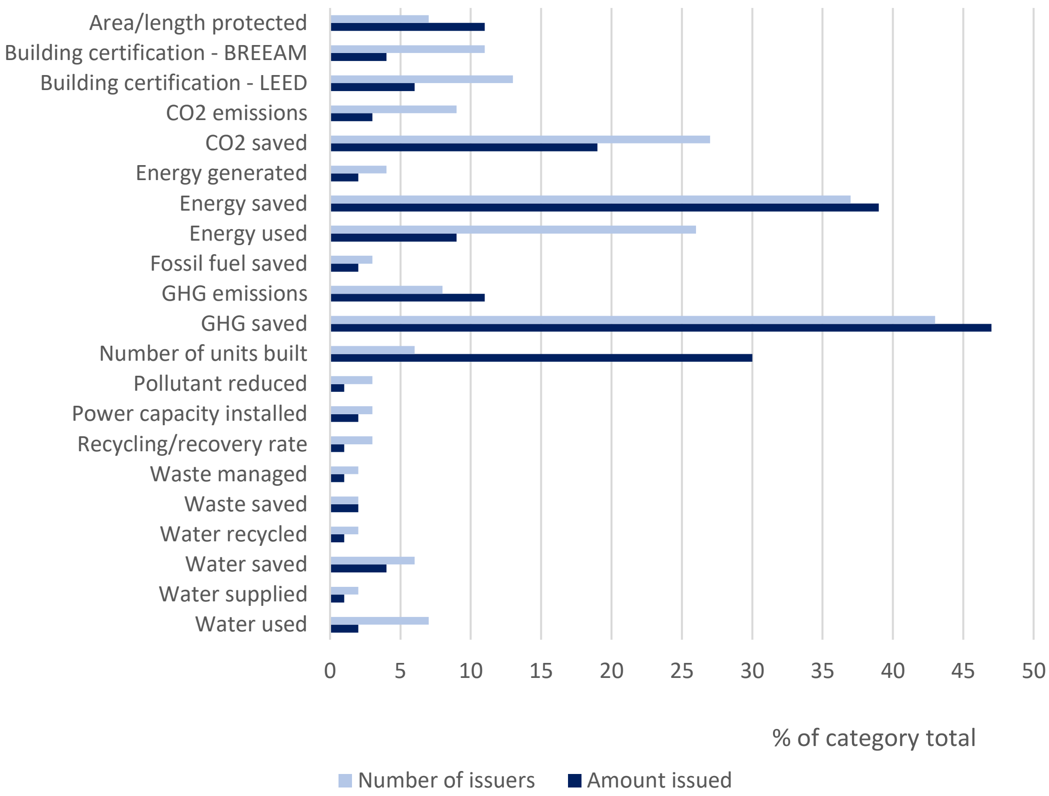

Figure 1. Metrics used in covered bond impact reports
(Source: Climate Bonds Initiative, 2021)

4. Impact assessments in practice

Green bonds are still a relatively new asset class, green bond frameworks and environmental impact assessments have only started a few years ago, with the first green covered bond (Pfandbrief) issuance in 2016 in Germany, 2019 in Poland and 2021 in Hungary with the very first impact reports just out recently.

The rationale behind impact assessments is that the financing and/or ownership of commercial and residential buildings with low energy demands avoid greenhouse gas emissions, that would otherwise have been emitted from less energy efficient buildings used for the same purpose. This is of course a point that could be argued. While the impact of a renovation project can be quite straightforward green covered bonds to a large extent finance the construction and purchase of new buildings. Where the positive environmental impact is not as obvious as these new buildings often do

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not necessarily replace older, less efficient buildings and because the construction activity itself also leads to GHG emissions. When considering the environmental impact of buildings, the most often used functional unit is avoided tons CO_2-equivalents (or CO_2e) of greenhouse gases[2] per building and share of financing (1% to 100%). As a normalized unit of comparison, tons CO_2-equivalents (or CO_2e) per million € (EUR m) financed are calculated as well. This is one of the specific green bond metrics often used by investment professionals and is an additional investment metric in addition to the traditional risk, yield etc. metrics. In fact, a green asset manager striving to make the biggest environmental impact per invested capital could rank potential investment based on the avoided tons per million euro invested.

4.1. Overview of the basic GHG impact calculation methodology

The calculation of avoided emissions for commercial and residential buildings follows a logic similar to the above mentioned one, and requires 5 crucial data inputs based on the impact assessment reports reviewed for this paper[3] (see formula below). The potentially avoided GHG emissions are estimated by taking the difference between 1) energy requirements of the building stock (benchmark value) per square meter, and the 2) energy requirements of the financed green building per square meter. In the case of a renovation, this is of course easier: the final energy demand of the two states (i.e. before and after renovation) are compared. The energy saved by buildings in kWh/m^{2}a is then multiplied by a factor specific to each market (country) that takes into account the amount of GHG or more simply CO_2-equivalent emissions required to generate one kilowatt-hour of energy for the building. This is called 3) *country-specific carbon intensity*. Finally, 4) the annual carbon emission savings per square meter are multiplied by the total floor space of the building to determine the building's total emission savings per year. It may be the case that a financial institution only finances part of the building. Then the green building's total emission savings are also calculated as a ratio of financing volume. 5) The final step is to divide the emission savings attributable to the volume of the loan, giving emission savings per EUR 1 million of financing.

1. 2. 3. 4.

$$\frac{\left[\text{benchmark}\left(\frac{kWh}{m^2a}\right) - \text{energy consumption}\left(\frac{kWh}{m^2a}\right)\right] \textbf{ x } \text{country} - \text{specific carbon intensities}\left(\frac{kg\ CO_2}{kWh}\right) \textbf{ x } \text{building area}\ (m^2) \textbf{ x } \text{financing share}\ (\%)}{\text{loan volume}\ (\text{€ mn})}$$

5.

Figure 2. The calculation methodology for the avoided GHG emissions/invested amount of a green building
(Source: NORD/LB, 2021)

4.2. Benchmark –PED for heating the building stock

One of the most important implicit assumptions behind all impact assessments is that the financed green building would replace an old, less efficient building from an operational standpoint and thus would lead to energy and GHG savings.

Energy savings of green buildings are compared to the existing building stock. There are two main approaches to calculate the PED of the theoretically replaced building and the energy savings arising from the replacement.

- One approach tries to match the type of new building with the type of the old building and use those theoretical PED numbers. This is a granular method which requires a lot of data and assumptions. One often used data source is the Tabula-Projekt.[4] It is a study which 'constructed' several generic building types and sub-types in several EU countries, based on a given construction period and the available data on energy demand. As a result, this data set provides typical final and primary energy demands for different residential building types and construction periods. In principle, each residential building of a national stock can be replaced by a generic building type of the national building type matrix. The financed buildings are then matched with the reference buildings that are sufficiently comparable. Out of the impact assessments analyzed for this study, the Wuppertal Institute mentioned using this methodology (Wuppertal Institute, 2022).

- A less granular approach uses the theoretical weighted average efficiency numbers of the national residential building stock for comparison. This type of data is also not readily available in all cases and needs to be calculated/estimated using various data sources, studies, using building occupancy types, periods of construction, residential energy performance building

[2] Wuppertal Institute (2022), The global warming potential of Greenhouse gases refers to 100 years (GWP 100a) and is calculated with the help of characterization factors for Kyoto-Gases by the IPCC (AR5). This rationale is in line with current market practices as suggested by the ICMA Green Bond Principles as well as Harmonized Framework for Impact Reporting (ICMA, 2022).

[3] Based on: Drees & Sommer (2022a; 2022b), MünchenerHyp (2021), NORD/LB (2021), Wuppertal Institute (2022).

[4] https://webtool.building-typology.eu/#bm

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codes that were applicable over the years, and finally considering any kind of statistics, often estimations thermo-modernization works done over the years. Based on such a data analysis, it is possible to estimate the building stock's primary energy demand. The result of such an exercise is shown below as an example.

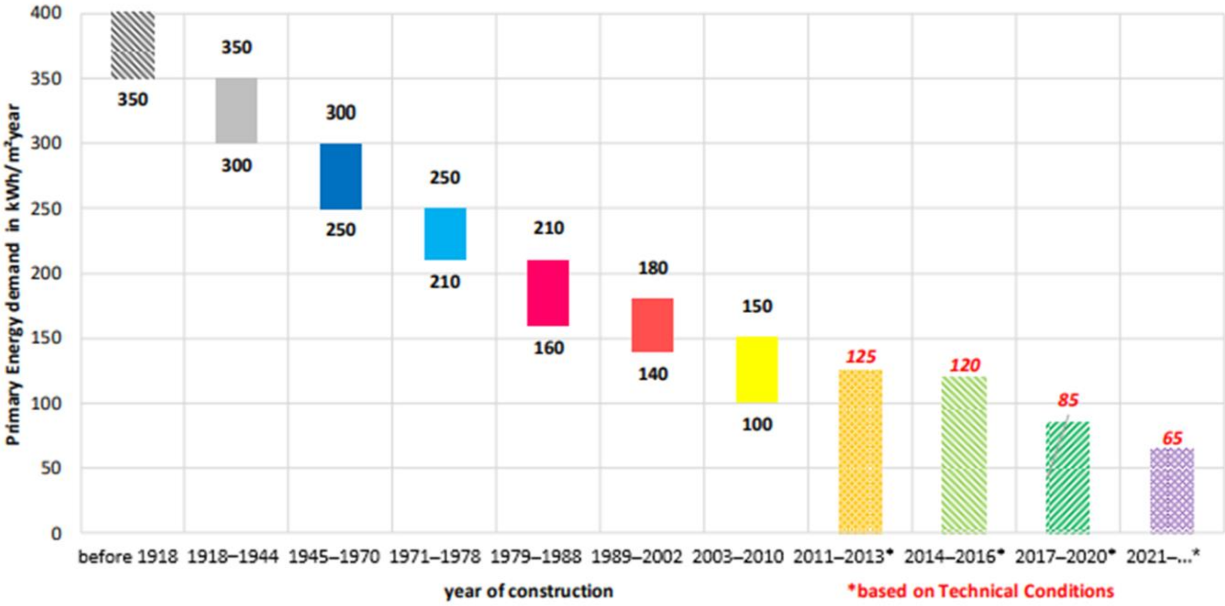

Figure 3. Poland's residential building stock - primary energy demand by year of construction and technical conditions
(Source: Drees & Sommer, 2022a)

Applying the number of buildings for each year of construction and the mean primary energy demand for the respective Polish building codes, a weighted average PED for the national residential building stock can be estimated. (These are the higher numbers in Figure 3). Furthermore, by including an estimate for any potential thermo-modernizations, the primary energy demand of the building stock is estimated[5] (the lower numbers in Figure 3). For Hungary, a similar survey of the building stock was carried out in 2013, also estimating the PED of the 15 building types in their original states at the time of construction (Nemzeti Épületenergetikai Stratégia – NFM, 2015). However, there is no available information on the thermo-modernizations over the years and what the actual weighted average PED of the building stock is currently. There are plans to conduct a fresh survey of the building stock that would provide the possibility to follow any thermo-modernizations carried out over the past decades. The impact assessments we have reviewed did not use residential building stock data,. One of the recent impact reports circumvents this question by using two collateral pools: one cover pool consists of green buildings, the other of conventional ones, the PED of both is estimated and the difference is treated as avoided emissions (OTP, 2021).

4.3. Energy consumption - PED of financed green building

Assets that are considered eligible to be included in green covered pools are green mortgage loans used for the acquisition, construction, or refurbishment of green buildings. There are also covered bonds backed by assets other than residential or commercial buildings, e.g. renewable energy power plants, ships etc. These are not covered here. The document governing green covered bond issuance is the green bond framework. A framework is set up by the issuer, while adherence to the framework is certified by external providers in what is called a *second-party opinion* (SPO), which provides investors with assurance that the bond framework is aligned to accepted market principles (ISS ESG, 2022). The issuers set up internal teams sometimes called Green Bond, Asset or Building Commission that are responsible for defining Green Bond Minimum Standards and ensure that the minimum standards required in the target markets are complied with. In the context of green bonds, the term *green building* is closely linked to energy efficiency. In December 2018, the Energy Efficient Mortgages Initiative (EEMI), led by the European Mortgage Federation and the European Covered Bond Council, published a first definition of *energy efficient mortgages*. It stipulates that if renovations lead to

[5] Calculated by Drees & Sommer (Best estimate is the full lenght of the bar charts above). In this example the estimate weighted average PED for Poland's building stock the so called benchmark is 210.6 kWh/m²year for the year 2019.

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a decrease in energy demand or consumption of at least 30% for the mortgage loan financing, this renovation must be considered energy efficient. In summer 2019, the Association of German Pfandbrief Banks (vdp) member banks agreed on a common minimum standard that includes different approaches and gives certainty to green covered bond investors concerning what they can expect when they invest in a green German covered bond (Pfandbrief), independently of the issuer. Commercial and residential properties can be eligible by meeting at least one of several other criteria (Sustainabonds, 2019). For example: commercial properties whose sustainability certificates are ranked in an established provider's top categories; residential properties assigned to energy class B or better, or with energy demand no greater than 75kWh/m^2. Renovations or refurbishments resulting in a reduction in energy consumption or demand of at least 30% are also eligible or buildings that are in the top 15% of the national stock regarding energy consumption/demand – in line with the Climate Bonds Initiative (CBI) and the EU Taxonomy. The Climate Bond Initiative (CBI) definition of low carbon buildings only accepts the 15% with the lowest carbon intensities in a regional market. City-baselines developed by the CBI are trajectories that also include the term of a green bond financing green buildings (CBI, 2020). The longer the term of the bond, the lower is the maximum allowed carbon intensity. This approach aims to ensure that a green, energy efficient building represents the top 15% in its local market at least until the maturity date of the bond. Although these criteria and minimum standards are important steps to increase the harmonization of green building definitions, they still leave room for different approaches and qualities.

Table 1. Common minimum standards for green buildings in Germany
(Source: Environmental Finance, 2020)

<table>
<tr><th>COMMERCIAL REAL ESTATE</th><th>RESIDENTIAL REAL ESTATE</th></tr>
<tr><td>New construction financing:
– At least the statutory energy standards for new buildings at the time of financing</td><td rowspan="2">New construction/acquisition of existing properties:
– Energy efficiency class B or better, or
– Energy demand no greater than 75kWh/m2 or,
– Projects co-financed by KfW funding programs for energy efficient construction or renovation, or
– Top 15% of national residential property stock with regard to energy consumption/demand</td></tr>
<tr><td>Acquisition of existing properties:
– Compliance with comparative values published by the German Federal Ministries for Economic Affairs and Energy, and for the Environment, Nature Conservation, Building and Nuclear Safety on 7 April 2015, or
– Sustainability certification top category (LEED, BREEAM, DGNB, etc.), or
– Top 15% of national commercial property stock with regard to energy consumption/demand</td></tr>
<tr><td>Renovation/refurbishment:
– Reduction in energy demand/consumption of at least 30% and
– New energy demand/consumption in line with EU climate objectives</td><td>Renovation/refurbishment:
– Reduction in energy demand/consumption of at least 30%, and
– New energy demand/consumption in line with EU climate objectives</td></tr>
</table>

An asset is categorized as a Green Building if the applicable standards are fulfilled at the time of inclusion in the Green Bond portfolio. The primary energy demand or consumption (warmth) should be used for valuation if the use of renewable energy reduces the primary energy demand or consumption to below the final energy figure. In the case of commercial buildings, compliance with the thresholds is proven by energy performance certificates (EPC) which the bank asks its borrowers to provide as an integral part of the loan origination process. In addition, the bank asks its customers for sustainability certificates issued by known institutions, such as LEED, BREEAM, DGNB and HQE. In order to be eligible for the green finance portfolio, these have to reach a certain minimum (NordLB, 2021). In target markets outside Germany, issuers already follow the CBI top 15% rule of the national building stock. The identification is based on the

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primary energy demand. Another possibility is if the building is already a "Nearly-Zero-Energy-Building", as a standard for all new buildings is compulsory since 2021, for public buildings already since 2019. This standard describes a building that has a very high energy performance. Near-zero or very low energy demand should be met to a very significant extent (min. 25%) by energy from renewable sources, including energy from renewable sources produced on-site or nearby (European Commission, 2010). For the financed „green" buildings, maximum primary energy demand metrics are derived by considering all of the green building definitions above by Green Bond, Asset or Building Commission at each issuer. These serve as performance limits (maximum values) for financing both commercial and residual buildings. For example, for German green residential buildings, depending on the year and the bank, a maximum primary energy demand of between 55–75 kWh/ m^2/year has been used lately as defined by several issuer's framework.

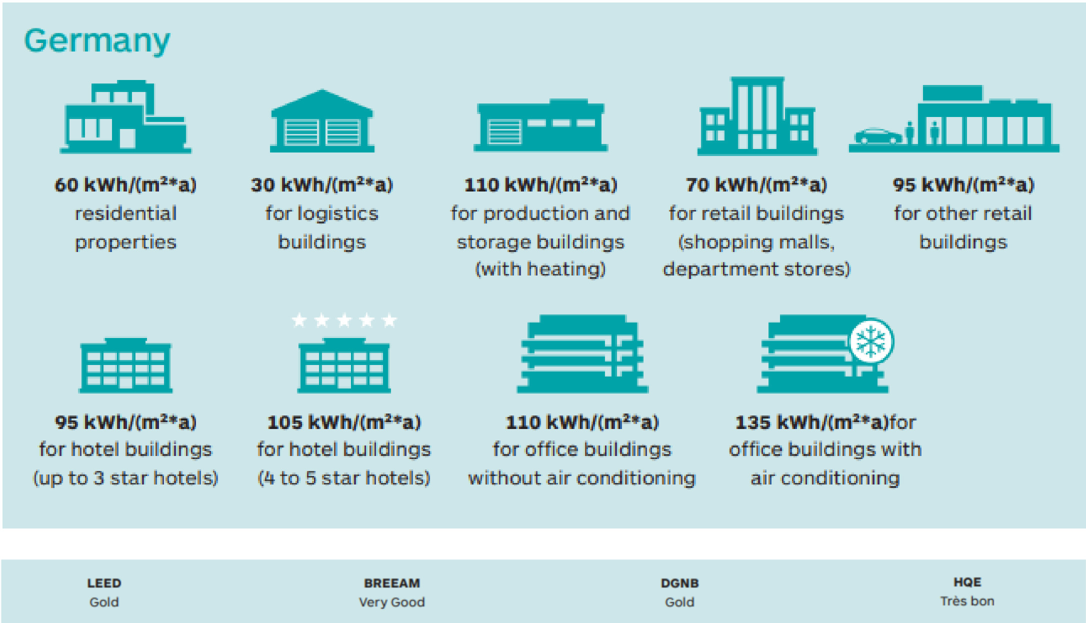

Figure 4. PED for various green buildings at a German green covered bond issuer
(Source: NORD/LB, 2021)

In the case of Polish green residential buildings, the thresholds also differ depending on whether it is a new building, a renovation, or an acquisition. The various cases are detailed below with the maximum threshold for PED between 58.8 to 63 kWh/a/m^2/year in case of a newly built nearly zero-energy building, while can be as high as 85 to 95 in the case of an acquisition, according to the green bond framework of the PKO BANK HIPOTECZNY, which would still represent the top 15% of the national building stock.

Economic activity	Screening Criteria	Residential Single-Family	Residential Multi-Family
7.1 Contruction of new buildings	**Nearly Zero-Energy Building** Primary energy demand minus 10%	At least 10% lower than the requirements for the primary energy demand of the "Nearly Zero-Energy Building" standard (NZEB). Based on the "Energy Performance of Buildings Directive" (EPBD), the NZEB-standard is implemented in Technical Condition 2014 requirements.	
Built 01/01/2021 or newer	Indicative reference values:	PED ≤ 63 kWh/(m^2 year)	PED ≤ 58,8 kWh/(m^2 year)
7.2 Renovation of existing buildings	**Major Renovation** Cost optimal level	The building renovation complies with the applicable requirements for major renovations as defined int the EPBD, based on the cost optimal level as defined in Technical Condition 2014.	
Built before 31/12/2020	**Property Upgrade** Relative improvement ≥ 30% in primary energy demand	Relative improvement in primary energy demand ≥ 30% in comparison to the performance of the building before the renovation. Reductions through renewable energy sources are not taken into account.	
7.7 Acquisition and ownership of buildings	**Top 15%** of the national existing building energy code	Technical condition TC 2017 or newer	
Built before 31/12/2020	**Top 15%** of the national existing building energy stock	PED ≤ 95 kWh/(m^2 year) FED ≤ 67,7 kWh/(m^2 year)	PED ≤ 85 kWh/(m^2 year) FED ≤ 60,6 kWh/(m^2 year)

Table 2. Polish residential buildings
(Source: PKO BANK HIPOTECZNY, Drees & Sommer, 2022a)

In Hungary, green residential buildings would also have to meet similar criteria. In order to qualify as a green building, the building should meet at least one of the criteria below, according to the green bond framework of the UniCredit

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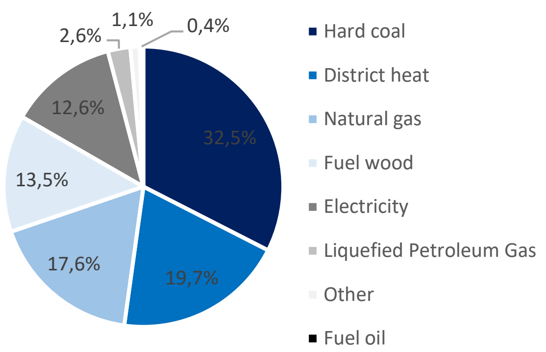
Bank: 1) Buildings with Energy Performance Certificate (EPC) class 'A' (before 1st of January 2016) or class 'AA' (after 1st of January, 2016). The exact PED was not explicitly defined. 2) The energy performance (PED) of the building is within the top 15% of the Hungarian building stock. In 2020, the threshold was estimated to be 118 kWh/m^2/year using CBI's methodology, which is expected to linearly decline to 0 by 2050[6] (Ritter, 2021). 3) Implementation of energy efficiency solutions or renovations in the buildings, which lead to a 30% increase in the energy efficiency of the building, or results in at least a two-step upgrade in EPC compared to the baseline before the renovation.

To sum it up, green definitions of issuers consider the same screening criteria (CBI and the EU Taxonomy) in all three jurisdictions, but the PED of new residential buildings in Germany (55–60 kWh/m^2/year) and Poland are already quite low. Using the top 15% of the national building stock criteria would enable banks to finance buildings with a PED of 55-75 in Germany, 85-95 in Poland and around 100-118 kWh/m^2/year in Hungary (UniCredit, 2021; OTP, 2021). These regional differences in particular for new buildings are expected to decline over time, the EU regulation on NZEB is also acting in that direction.

4.4. Carbon emissions intensity

National Residential Mean Carbon Emissions Intensity calculation takes into account the composition of primary energy sources used in the national energy mix (these are the weights), which are multiplied by the standard CO_2-Emissions factors of the respective energy inputs.



Energy Type	Carbon Emission Equivalent ($kgCO_2/kWh$)
Hard coal	0,354
Natural gas	0,202
Fuel wood	0,403
Liquefied Petroleum Gas	0,249
Municipal Wastes (non-biomass fraction)	0,330
Wood (non-sustainable forestry)	0,403
Fuel oil	0,279

Figure 5. Composition of energy inputs

Table 3. Standard CO_2-Emissions factors

(Source: Drees & Sommer, 2020)

Applying the carbon emissions equivalents (GHG intensity) to the weighted average of energy inputs, the "national residential mean carbon emissions intensity" is calculated.[7] Using this number and multiplying that with the national primary energy demand of the building stock, the amount of national residential mean carbon emissions is calculated.

Data sources used for GHG intensities in the various impact assessments range from various studies and a multitude of sources.[8] These sources vary by the issuing country and the impact assessment provider, inevitably leading to less transparency and lack of standardization. The main issue is the lack of a uniform data source.

Therefore, a green mortgage can have fairly different GHG impact depending on the factors listed and described above. Differences are more significant in the building stock of these countries, with the building stock of Germany having the

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[6] This threshold has been calculated together with CBI and the National Bank of Hungary, Eligible Residential Building – Hungary, 2021.

[7] Drees & Sommer (2022a): In the case of Poland, the national residential mean carbon emissions results in: 0.385 $kgCO_2/kWh$. Using this number and multiplying that with the national primary energy demand of 210.6 kWh/m^{2}year × 0.385 $kgCO_2/kWh$, we come to the national residential mean carbon emissions result: 81.0 $kgCO_2/m^2$year.

[8] Wuppertal Institute (2022): GHG intensity of district heating refers to oekobau.dat data for Germany, cited in the DGNB framework for climate-neutral buildings and locations (DGNB, 2020: 61). All other intensities are drawn from the Covenant of Mayors (CoM) default emission factor document, provided by the European Commission (European Commission, 2017).

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lowest GHG impact, having gone through the most thermo-modernization. There are also significant differences in the GHG intensities, the highest relative emitter is Poland, where the share of coal in the energy mix is the highest. While the PED of new buildings has already showed some convergence. In terms of impact per invested amount, the markets with the lower average real estate prices can offer a higher impact for the amount invested.

5. Challenges

Impact assessment is still primarily centered around GHG emissions. In the number of impact reports reviewed for the purpose of this article, the sole focus was on greenhouse gas emissions avoidance. There was only one assessment that had data on the share of new vs. refurbished buildings in the cover pool (NordLB), which could be an important input for analyzing the potential environmental impact of new construction vs. refurbishments. There is no mentioning of other scope 1 and 2 type of emissions, such as water efficiency, savings, waste management etc. There was no mentioning of scope 3[9] metrics, such as the potential use of materials with lower environmental footprint, the land use and biodiversity aspect for new buildings or other qualitative aspects that benefit the users of the buildings, such as transport connectivity. There are two main reasons for the lack of such data. The assessments reviewed here were either related to residential or mixed-use cover pools, where this type of data is either not available or could not be aggregated, although for newer commercial buildings, this type of data should be available in the certificates (such as Breem, Leed etc.) This is broadly in line with the findings of the Climate Bonds Initiative's third study of post-issuance reporting in the green bond market. (CBI, 2021)

Data quality and availability is a limiting factor in the quality of impact assessments. While ideally the energy performance of each building in the cover pool should be available to the issuer and to the impact assessment provider, that is sometimes not the case. Data quality can vary on a case-by-case basis, depending on the issuer, pool, building type, assessment provider, country etc. The quality of the cover pool data is usually not disclosed, only mentioned specifically in one impact assessment.

A typical example for a data challenge is when the PED of the financed buildings is not known. In one particular example, the impact assessment provider employed a conservative estimate to correct for the missing data and applied the maximum allowed PED within the green bond framework (MünchenerHyp, 2021). In a low number of cases, other data may be missing, or the building type may not fall into the typology of existing buildings. When no suitable reference building can be selected, the lowest PED for buildings in stock (conservative estimate) are used. In other cases, more important data, such as the floor area may be missing, which can be estimated from the value estimate and the total costs per square-meter of all other buildings in the sample in order to ensure a conservative estimate. The chart below is a rare example detailing the data quality of the German residential and commercial cover pool available to the impact assessment provider. While the methodology given by the Wuppertal Institute is one of the most detailed and transparent ones, it shows that data quality, even in the case of office buildings and German residential buildings, can be an issue requiring a number of assumptions (Wuppertal Institute, 2022). Some impact assessment providers emphasize that their assumptions and calculations use conservative estimates for the avoided GHG emission potentials. For example, the energy savings in the actual buildings compared to buildings in stock are expected to be larger than shown in the impact assessment. In terms of overall accuracy, the lack of data for electricity use leads to less accurate results.

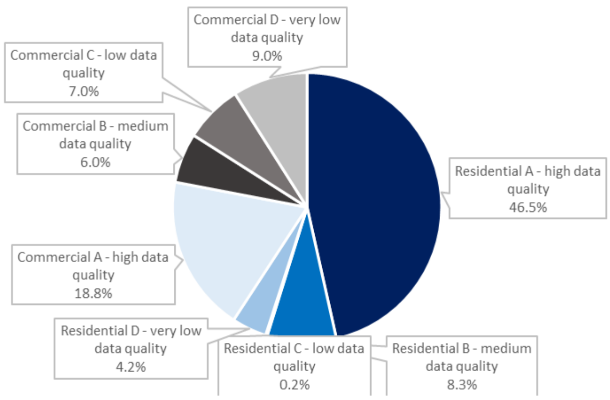

Figure 6. Data challenge example – MünchenerHyp porfolio analysis
(Source: MünchenerHyp, 2021)

[9] Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions

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For residential impact assessments, there are various data sources, studies available for the PED of the national building stock. However, even in the best of cases, these are geographically fragmented, in some cases quite outdated with e.g. the impact of thermo-renovations not included. There are also various data gaps; and therefore, most jurisdictions impact assessment providers must come up with their own estimates, using various assumptions. While PED data on the cover pool is of better quality in Germany, there are still significant data gaps. More significant data gaps appear to be in Hungary, where data is incomplete both for the primary energy demand (PED) of the cover pool and that of the building stock. The former is expected to improve rapidly, as mortgage banks are now aware of the data required for impact assessment reports and will likely increase their efforts to collect and store any related data, such as the environmental certificate of the financed buildings (CBI, 2017b).

Another challenge is that the EU pays more and more attention to GHG emissions caused by construction and renovations, but these barely appear in the impact reports. The renovation wave plays a key role in upgrading existing buildings and making them more energy efficient, and it will be an important element in achieving a climate-neutral EU by 2050. Many studies have shown that extending the life cycle of a building has a lower environmental impact than new construction and demolition. By avoiding or delaying the use of new materials in buildings, circular economy-based approaches to renovation can help to reduce embedded greenhouse gas emissions and contribute significantly to achieving climate neutrality (European Commission, 2020).

6. Conclusions

Green covered bonds are still a relatively new asset class, green bond frameworks and environmental impact assessments have only been around for a few years, with the first green covered bond (Pfandbrief) issuance in 2015 in Germany, 2019 in Poland and 2021 in Hungary (with the very first impact reports just out recently).

The green bond market and impact assessments overall have come a long way in a relatively short period of time, with every major covered bond issuer having issued at least one green bond, set up a green bond framework and have commissioned an environmental impact assessment.

Notwithstanding, there are a lot of areas for improvement, such as a need for much better, more granular data, as well as more transparency on the data front in the impact assessment reports. There are significant data challenges that impact assessment providers need to tackle. It would be best if they did that in an open and transparent manner, disclosing what is missing, where they had to fill data gaps and make assumptions.

It would also be welcome to have more transparency on how environmental impact is measured and calculated. More unified and better data sources would be welcome, potentially on a pan-European level. Focus should be broadened to beyond GHG emissions to include other scope 1 and 2 but also scope 3 building emissions that are already included in several impact reporting recommendations.

While many believe that the green covered bond market and impact assessments may have a significant impact on how the real estate sector evolves, the authors of this article are of the view that the push from bond investors alone will not be sufficient to force a further radical greening of the real estate sector. Stricter but also sensible regulation potentially far out in the future may be needed to provide further impetus (similarly to cars), a case in point is the EU regulation for Net Zero Energy Buildings. Similarly, there are also initiatives to limit and measure other emissions, increase savings, and use building materials and technologies with lower carbon footprints.

A sustainability revolution is required that would go beyond and encompass sustainable architecture. A lot of complex technologies can be avoided if engineering design properly balances regional environmental impacts and building materials with the potential of technology. According to the theoretical architect Lebbeus Woods (Manaugh 2007), fundamental changes in the architecture of the future cannot take place until humanity changes its current sociological model, and this change must have regional diversity to be sustainable. The architecture of the future must reduce the carbon footprint of construction and operation, while providing flexibility that adapts to the functional needs arising from changing social and sociological influences during the building’s lifetime (Cognitive Sustainability in Cognitive Sustainability, 2022).

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