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Study of greenhouse gas and nitrogen dioxide emissions into the atmosphere from the transport sector powered by diesel and compressed biomethane from OFMSW

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1. Summary of activities carried out

The activity in question focused on comparing the environmental impacts of different scenarios linked to the fuelling of heavy vehicles employed for long-distance transport. Specifically, a basic scenario (diesel fuel), a scenario for compressed natural gas (CNG), and five scenarios for compressed biomethane were taken into consideration. The biomethane scenarios were differentiated by the presence or absence of CO_2 capture during the upgrading process and for the distance between the OFMSW collection plant and the biomethane production plant. The seventh scenario represents the *best case*, that is the processes of CO_2 capture and pressurization of the methane are to be powered by biogas combustion energy instead of by the national network for energy consumption. The seven total scenarios are as follows:

1. Cabin trucks with waste collection equipment powered by diesel
2. Cabin trucks with waste collection equipment powered by compressed natural gas (CNG)
3. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, without CO_2 capture from offgas, and with a 20km distance between the OFMSW collection plant and the biogas
4. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, with CO_2 capture from offgas, and with a 20km distance between the OFMSW collection plant and the biogas
5. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, without CO_2 capture from offgas, and with a 50km distance between the OFMSW collection plant and the biogas
6. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, with CO_2 capture from offgas, and with a 50km distance between the OFMSW collection plant and the biogas
7. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, with CO_2 capture from offgas, and with a 20km distance between the OFMSW collection plant and the biogas, and biogas-derived energy

used for CO_2 capture and gas pressurization.

This study is based on a Well-to-Wheel (WTW) analysis. This type of analyses, unlike LCA analyses, does not take into consideration the manufacturing and disposal of vehicles or systems used in the production of fuels, but only the impacts linked to the production of the fuels themselves. For the choice of analysis methods, various scientific publications in peer-reviewed journals and technical reports focused on similar problems were taken into consideration, such as the comparison of fossil fuels and biofuels used in heavy vehicles (López et al., 2009; Alamia et al., 2016; Nocera and Cavallaro, 2016; Quiros et al., 2017).

To carry out the analyses, the OpenLCA software integrated with the ecoinvent 3.7.1 database was used, while the impact assessment was carried out according to the medium-term ReCiPe categories. In some cases, not covered by the database indicated and specified in the respective sections, bibliographic sources listed at the end of this report were used. The functional unit chosen is 1 MJ of fuel. This functional unit was chosen to allow an effective comparison between the different fuel systems, based on the energy content of the fuel and without taking into account the variability in efficiency of the vehicles.

In all cases, the lower heating value was used for conversions between energy units and mass or volume units. In particular, for diesel a value of 42.6 MJ/kg was used, while for CNG a value of 50 MJ/kg was used. For each scenario, the results for the Well-to-Tank (WTT) and Tank-to-Wheel (TTW) analysis are reported, as well as the summary result for the entire WTW analysis. A chapter is dedicated to comparing the results of all scenarios.

2. WTW analysis for B7 diesel trucks

In this case, the analysis focuses on vehicles powered by B7 diesel fuel, i.e. containing 7% biodiesel, commonly found in petrol stations. To carry out the analysis, emissions were modeled for the production of fossil fuel oil, to which a fraction of biodiesel, equal to 7%, was combined. For this percentage, the emissions of climate-altering gases in the TTW portion are to be considered equal to 0 because they are biogenic, while for the WTT portion an average emission value was used resulting from Directive (EU) 2018/2001 of the European Parliament and the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, calculated on the various crops used for the production of biodiesel. The value is equal to 26.38 gCO2eq/MJ.

2.1 WTT analysis

Table 1 shows the emissions for each step of the process from the well to the tank for 1MJ of low sulfur diesel fuel.

Process	**CO_2eq per MJ of diesel [g]**	**Cumulative CO_2eq per MJ of diesel [g]**	**NOx per MJ of diesel [g]**	**Cumulative NOx per MJ of diesel [g]**
Extraction	7.04	7.04	0.0034	0.0034
Transport	0.13	7.17	< 0.001	0.0034
Refining	14.56	21.73	0.0014	0.0048
Distribution	1.77	23.50	0.0241	0.0289

Table 1: WTT analysis results for diesel

2.1.1 Extraction

It refers to the production of crude oil in Libya and Algeria; however, this is similar to production in other parts of the world, including energy use and emissions: these emissions correspond to 7.04 g of carbon dioxide equivalent and 3.4 mg of nitrogen oxides per unit of MJ of diesel produced (Wernet et al., 2016).

2.1.2 Transport

To evaluate the impact of transport, we based our work on 2019 data relating to oil supplies for Italy, i.e. 72.4% coming from Africa and the Middle East, 16% from non-EU European countries (mainly Russia) and 7.8% from Central and Western Asia. A weighted average of the distances from these sources to Italy (port of Augusta) was then calculated, equal to 2073 km.

The dataset represents the transportation of liquid cargo by an oil tanker. The DWT (cargo capacity) of the oil tanker is 36,000 tonnes and is estimated to carry an average of 4,100 million tonnes/km per year for 25 years. The purpose of this dataset is to evaluate the impact of oil tanker operation, which has fuel consumption as an input; the main emissions (CO2, NOx, SOx, PM, NMVOC, CO, CH4, N2O) are calculated as weighted averages with respect to the size class of the tanker and, together with the fuel consumption, refer to current technology and take into account the average age of the fleet. Emissions at sea, emissions in controlled areas (ECA) and emissions in ports from the main engine, auxiliary engine and boiler are considered. Weighted averages of speed reduction (23%) and capacity utilization factors (48%) are applied (capacity utilization factors take into account both the load load factor and an empty trip factor). The share of voyage time and landfall time within Emission Controlled Areas (ECA) (where other fuel quality is used) is estimated at 5% and 50% respectively. Emissions other than those listed above are calculated based on the emission factors per kg of fuel consumed (Wernet et al., 2016).

2.1.3 Diesel refining

This dataset describes the operation of an average representative oil refinery located in Europe. Since oil refineries are very complex, the modeling of the actual unit process is performed in a separate refinery tool, developed by ifeu (Institute for Energy and Environmental Research, Heidelberg, Germany). The dataset is based on the outputs of a refinery model that reproduces the complexity of real plants in which the combination and sequence of processes are usually very specific to the characteristics of the raw materials (i.e. the close relationship between the composition of crude oil and products to be produced). Refineries differ not only in their configurations, process integration, raw materials, product blends, unit sizes, designs and control systems, but also in market situations, location and age of the refinery, or by environmental regulations. The basic setup of the model reflects the technical characteristics of European refineries as described in the reference document on best available techniques for refining mineral oils and gases.

The Best Available Technique Reference Document, or BREF, contains not only aggregate or weighted average numbers of emissions and energy or water consumption, but also includes the primary data of most refineries in Europe collected anonymously. This data source was complemented by various refinery-specific confidential data sets, Eurostat values (for example in the case of the mix of energy sources or process energy) and literature data. After adapting the model to the updated mass and energy flows within the European refineries, it was validated and calibrated by comparing the results with the BREF, Eurostat and European Pollutant Release and Transfer Register (E-PRTR) datasets.

The process begins with the crude oil entering the oil refinery. This includes wastewater treatment, fresh water supply (from nature), crude oil (1.14kg per kg of refined diesel fuel), product storage on the refinery grounds and energy supply. Electricity requirements are assumed to be met by the on-site generation mix (supplied internally or purchased from co-located generation entities).

The process ends with the refined petroleum products (and excess electricity and / or hydrogen, if any) leaving the refinery. Oil refineries are highly integrated multi-production production facilities in which almost every step of the process creates some co-products (Wernet *et al.*, 2016).

2.1.4 Diesel distribution

In order to assess the impact of the distribution of diesel, given the complexity of the process and the numerous variables involved, it was necessary to proceed with simplifications and assumptions. In particular, by modifying Arteconi et al. [3], it was decided to consider tankers with load capacity exceeding 32 tons and an average load of 16 tons, with EURO 6 certified emissions, which carry out an average journey of 300km (50% on motorways, 40% on other suburban roads and 10% in the city), and with a fuel efficiency of 0.623 l / km.

Fuel consumption and exhaust emissions are taken from v3.1 of the HBEFA (Handbook of Emission Factors for Road Transport) model, using data for Germany and without applying model weighting. There are more size categories used in HBEFA than in ecoinvent, so the data is grouped to fit the truck size classes used in ecoinvent. Selective Catalytic Reduction (SCR) technology is approximately 3 times more common than Exhaust Gas Recovery (EGR) as an emission reduction measure and thus the emission factors shown in the dataset are weighted to reflect this (Wernet *et al.*, 2016).

2.1.5 Biodiesel

Considering a component equal to 7% of biodiesel mixed with diesel of fossil origin, the final value of the WTT portion of this fuel is equal to 23.7 gCO2eq / MJ.(European Parliament, 2018).

2.2 TTW Analysis

For every liter of B7 fuel burned in the internal combustion engine of a heavy model vehicle, 2.62 kg of CO2 is emitted. Considering an average density for fuel equal to 0.832 kg / l, and considering the biogenic component of biodiesel equal to 0 in terms of greenhouse gas emissions, the emissions are equal to 67.68 gCO2eq / MJ.

As regards the NOx emissions, the emission factor used is 33.37 gNOx / kg (Ntziachristos and Samaras, 2020), equal to 0.783 gNOx / MJ.

3. WTW analysis for CNG trucks

The natural gas considered in this scenario is of entirely fossil origin. The entire process is modelled according to the supply chain whereby the gas is extracted in the producing countries and then transported via methane pipeline to Italy. In 2023, the main natural gas producers for Italy are, Algeria (34%, via the Transmed pipeline), Central Asia (14%, via TAP), and European producers (13%); 24% of natural gas resulted from the regasification of LNG imported mainly from Qatar and the USA.

3.1 WTT analysis

Table 2 reports emissions for each step in the production line for CNG, from well to tank. The functional unit is 1 MJ of CNG.

Process	**CO_2eq per MJ of CNG [g]**	**Cumulative CO_2eq per MJ of CNG [g]**	**NOx per MJ of CNG [g]**	**Cumulative NOx per MJ of CNG [g]**
Extraction	5.71	5.71	0.002	0.002
Refining	3.43	9.14	0.001	0.003
Transport	> 0.01	9.14	0.009	0.012
Pressurizatiom	4.78	13.92	> 0.001	0.012

Tabella 2: WTT analysis results for CNG

3.1.1 Natural gas extraction

The dataset includes data on natural gas extracted from onshore and offshore wells. Additionally, the dataset includes data on natural gas co-extracted with crude oil and wells that produce only natural gas.

3.1.2 Natural gas refining

The data set used represents natural gas refining in the Russian Federation, but it is applicable to other realities with comparable technological level. The data comes from annual reports of oil and gas producers (Gazprom, Novatek, Likoil, Rusneft) and the National Greenhouse Gas Inventory (UNFCC). Production and processing leaks are included.

3.1.3 Natural gas transportation

This process concerns the transport of natural gas through gas pipelines, and the transport of LNG by methane tankers. For gas pipelines, the energy costs of moving the gas and losses along the way are taken into account. For this study, however, methane tankers can be compared to oil tankers, described in section 2.1.2. The distances were recalculated according to SNAM data referring to 2023.

3.1.4 CNG pressurization

This data set includes the electrical demand of pressurization and that of a refuelling station, plus emissions from leaks. The initial gas pressure comes from the high-pressure network (1-5 bar). VOC emissions are calculated based on gas losses and the composition of Swiss natural gas. The energy requirement is 0.19 kWh for each kg of CNG, while the cumulative losses on all levels of the process are equal to 0.087% of the pressurized methane (Hagos and Ahlgren, 2018).

3.2 TTW analysis

For every kg of CNG burned in the engine of a model heavy vehicle, 2.47 kg of CO_2 are emitted, for a total value of 49.4 gCO_{2eq}/MJ.

As regards NOx emissions, the emission factor used is 13 gNOx/kg (Ntziachristos and Samaras, 2020), equal to 0.24 gNOx/MJ.

4. WTW analysis for compressed biomethane (bioCNG) trucks

For the following scenarios it was assumed that all anaerobic digestion, upgrading, pressurization and CO_2 capture activities took place in the same treatment plant of the organic fraction of municipal solid waste (OFMSW). The impacts for the collection of OFMSW, or for the production of waste, have not been assessed, as it is a biomass which is already waste in itself and whose production costs fall on other production lines. These scenarios, in fact, evaluate the use of waste that has, by definition, already exhausted its function (remnants and scraps of consumed food, waste from greenery management), and not the use of feedstock produced specifically for conversion into biogas and biomethane. Instead, two transport distances of the OFMSW from the collection centre to the anaerobic digestion plant were considered, equal to 20km and 50km, and the emissions deriving from the composting of an equivalent quantity of biomass, since this treatment is the one currently in use for the management of OFMSW in Italy.

Furthermore, the energy consumption for the anaerobic digestion and upgrading process was considered self-production, i.e. a larger biogas production was estimated to cover the consumption of the digester itself. For other energy-intensive processes, such as pressurization and CO_2 capture, the Italian energy mix was modelled, largely dependent on natural gas (43%), imports from the rest of Europe (17%), hydroelectric and solar (both at 9%). Scenario 7 differs in this as we wanted to model a best-case scenario in which pressurization and capture of CO_2 are also carried out in self-production, therefore with a greater production of biogas for energy purposes, as reflected by the greater impact of the anaerobic digestion process for that scenario.

4.1 WTT analysis

The emissions in g of CO_{2eq} are reported in Table 3 and Table 4 and in Table 5 and Table 6 the emissions in g of NOx for each step of the process from biomass production to the fuel tank for 1 MJ of compressed biomethane (bioCNG).

Process	**CO2eq per MJ of fuel [g]**				
Scenario	**3**	**4**	**5**	**6**	**7**
Biomass transport	0.77	0.77	1.94	1.94	0.77
Anaerobic digestion	11.38	11.38	11.38	11.38	16.44
Upgrading	2.26	2.26	2.26	2.26	2.26
CO_2 Recovery	\	-5.03	\	-5.03	-17.81
Pressurization	4.78	4.78	4.78	4.78	0.46

Table 3: CO2eq results for WTT analysis of compressed biomethane.

Process	**Cumulative CO2eq per MJ of fuel [g]**				
Scenario	**3**	**4**	**5**	**6**	**7**
Biomass transport	0.77	0.77	1.94	1.94	0.77
Anaerobic digestion	12.15	12.15	13.32	13.32	17.21
Upgrading	14.41	14.41	15.58	15.58	19.47
CO2 Recovery	\	9.38	\	10.55	1.66
Pressurization	19.19	14.41	20.36	15.33	2.12

Table 4: Cumulative CO2eq results for WTT analysis of compressed biomethane.

Process	**NOx per MJ of fuel [g]**				
Scenario	**3**	**4**	**5**	**6**	**7**
Biomass transport	0.001	0.001	0.003	0.003	0.001
Anaerobic digestion	-0.053	-0.053	-0.053	-0.053	-0.005
Upgrading	0.007	0.007	0.007	0.007	0.007
CO2 Recovery	\	0.024	\	0.024	> 0.001
Pressurization	> 0.001	> 0.001	> 0.001	> 0.001	> 0.001

Table 5: NOx results for WTT analysis of compressed biomethane.

Process	NOx cumulativi per MJ di carburante [g]				
Scenario	**3**	**4**	**5**	**6**	**7**
Biomass transport	0.001	0.001	0.003	0.003	0.001
Anaerobic digestion	-0.052	-0.052	-0.050	-0.050	-0.004
Upgrading	-0.045	-0.045	-0.043	-0.043	0.004
CO2 Recovery	\	-0.021	\	-0.019	0.004
Pressurization	-0.045	-0.021	-0.043	-0.019	0.004

Table 6: CO2eq results for WTT analysis of compressed biomethane.

4.1.1 Biomass transport

Scenarios 3, 4 and 7 involve a 20km transport of OFMSW from the collection and storage site to the anaerobic digestion plants. Scenarios 5 and 6, however, involve transport of 50km. Scenario 7 entails the transport of a greater quantity of biomass to support the production of more biogas for energy needs.

Fuel consumption and exhaust emissions are taken from v3.1 of the HBEFA (Handbook of Emission Factors for Road Transport) model, using data for Germany and without applying model weighting. There are more size categories used in HBEFA than in ecoinvent, so the data is grouped to fit the truck size classes used in ecoinvent. Selective catalytic reduction (SCR) technology is approximately 3 times more common than exhaust gas recovery (EGR) as an emissions reduction measure and therefore the emission factors given in the dataset are weighted to reflect this (Wernet et al., 2016).

4.1.2 Anaerobic digestion

The anaerobic digestion process was modeled on openLCA starting from the ecoinvent 3.7.1 database (Wernet et al., 2016). Organic waste in the current process is defined as follows: biodegradable waste from gardens and parks, food and kitchen waste from households, restaurants, caterers and shops, and comparable waste from food processing plants. It does not include sewage sludge or other biodegradable waste such as natural fabrics, paper or processed wood. Anaerobic digestion treatment is a set of processes by which microorganisms break down biodegradable material in the absence of oxygen. The treatment process produces biogas (a mixture composed mainly of methane and carbon dioxide) and residual products called solid and liquid digestate. The described process begins at the treatment site, after delivery of the treatment materials. The energy demand for operating an anaerobic treatment plant was included, as well as process emissions.

A composting process was considered as treatment of the produced digestate, the emissions of which are already included in the anaerobic digestion step. Composting treatment is a process of controlled decomposition and humification of biodegradable materials under managed conditions, which is aerobic and which allows the development of temperatures suitable for mesophilic and thermophilic bacteria following the biologically produced heat. The resulting inventory of "compost" refers to 1 kg of fresh weight of biogenic waste. The modelled process describes industrial composting. Compost is defined as humified solid particulate matter that is the result of composting, that has been sanitized and stabilized, and that confers beneficial effects when added to soil. It is used as a constituent of growing medium, or otherwise used in combination with plants (Wernet et al., 2016).

The emissions resulting from the energy needed for the composting process are however extremely low, less than 0.001 $kgCO_{2eq}$. Even taking into consideration a scenario in which the digestate is used directly in the field, the savings from the point of view of climate-changing emissions are still low, equal to approximately 0.009 $kgCO_{2eq}$ (MØller, Boldrin and Christensen, 2009).

As regards the GHG emissions avoided due to the use of OFMSW in anaerobic digestion, the impact of composting the same quantity of waste biomass was assessed. In particular, the composting of one kg of OFMSW involves the emission of 0.042 $kgCO_{2eq}$ and 0.033 gNOx (Wernet et al., 2016).

4.1.3 Upgrading

The data presented derives from information available from the manufacturer of biogas upgrade plants using membrane technologies. The biomethane leaves the plant with a pressure of 5 bar. For the composition of the gas produced, a share of more than 96 vol.% of methane is assumed. The activity begins with the biogas available at the entrance to the purification plant. The activity ends with the availability of the biomethane for transport to the gates of the purification plant. Electricity consumption and emissions represent raw gas compression, H_2S removal, gas conditioning, and methane enrichment of biogas. The production and disposal of activated carbon are neglected (Wernet et al., 2016).

4.1.4 CO_2 recovery for food use

For the scenarios in which the evaluation of CO_2 recovery is required, the recovery of 100% of the CO_2 emitted by the upgrading process was taken into consideration. During the upgrading of 1 m^3 of biomethane, 0.98 kg of CO_2 are emitted. To model the process, the capture systems of the Tecno Project Industriale were taken as a starting point (Tecno Project Industriale, 2021), while for the emissions linked to the consumption of electricity, we referred to the national energy mix as specified at the beginning of the chapter. Considering an installed power of 2.2 kW necessary for the recovery of 1 kg of CO_2, and considering that this carbon dioxide is biogenic and therefore involves a credit relating to the production of CO_2 for food use from non-renewable sources, the net saving in emission of climate-altering gases is equal to 5.02 gCO_{2eq}/MJ. NOx emission is equal to 0.024 gNOx.

4.1.5 Pressurization

For this process, please refer to section 3.1.3, as the process is exactly identical whether it is natural gas or biomethane. In scenario 7 energy consumption is self-produced, i.e. more biogas is produced in the anaerobic digestion phase to cover the energy costs of this phase.

2.1 TTW analysis

The CO_2 emissions from the combustion of biomethane in these engines are considered biogenic and therefore neutral. The only emissions that contribute to global warming in the long term are those due to methane losses, which are however very small, estimated at around 0.98 gCH4/km (Ntziachristos and Samaras, 2020). Considering a vehicle efficiency of 2.8 km/kg, the methane leak translates into 8.75 gCO_{2eq}/kg.

As regards NOx emissions, the emission factor used is 13 gNOx/kg (Ntziachristos and Samaras, 2020).

5. Comparison of scenarios

Figure 1 and Figure 2 show the comparisons of all the scenarios, with the production and consumption of one MJ of fuel as the reference point. The CO_2 component of TTW emissions for the scenarios relating to bioCNG production is reported as a credit in the WTT section, as it corresponds to CO_2 captured by plant biomass within a biogenic cycle. The only TTW emissions to be considered as having an impact from the point of view of climate alterations are those linked to methane leaks, which are however very small. The scenarios examined are:

1. Cabin trucks with waste collection equipment powered by diesel
2. Cabin trucks with waste collection equipment powered by compressed natural gas (CNG)
3. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, without CO_2 capture from offgas, and with a 20km distance between the OFMSW collection plant and the biogas
4. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, with CO_2 capture from offgas, and with a 20km distance between the OFMSW collection plant and the biogas
5. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, without CO_2 capture from offgas, and with a 50km distance between the OFMSW collection plant and the biogas
6. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, with CO_2 capture from offgas, and with a 50km distance between the OFMSW collection plant and the biogas
7. Cabin trucks with waste collection equipment powered by compressed biomethane (bioCNG) derived from urban waste, with CO_2 capture from offgas, and with a 20km distance between the OFMSW collection plant and the biogas, and biogas-derived energy used for CO_2 capture and gas pressurization.

Table 5 shows the overall results for the three components (WTT, TTW and WTW) of all the scenarios for climate-changing gases.

It is clear that, for climate-changing emissions measured as g of CO_{2eq}, the scenarios based on the use of bioCNG are the least impactful. For scenarios focused on biomethane, anaerobic digestion, upgrading and pressurization are the processes that most strongly influence the results, with anaerobic digestion having the most significant influence. Pressurization and upgrading, however, are on the same order of magnitude as oil and natural gas extraction and diesel refining.

Scenario	**WtT [gCO_{2eq}/MJ]**	**TtW [gCO_{2eq}/MJ]**	**WtW [gCO_{2eq}/MJ]**
Scenario 1	23,5	67,7	91,2
Scenario 2	13,9	49,4	63,3
Scenario 3	-30	49,4	19,4
Scenario 4	-35,1	49,4	14,3
Scenario 5	-28,9	49,4	20,5
Scenario 6	-33,9	49,4	15,5
Scenario 7	-46,1	49,4	3,3

Table 5: Total CO_{2eq} values for WTT, TTW and WTW for each scenario.

The capture of CO_2 at the biomethane upgrading step leads to significant savings in emissions, essentially counterbalancing those of the upgrading itself. The transport of OFMSW, however, always involves very limited impacts: there is little significant difference between scenarios 3 and 5, and between scenarios 4 and 6.

Figure 1: Comparison of WTW results for each scenario for CO2eq emissions per MJ of fuel.

Scenario 7 highlights how the use of biogas in self-production drastically reduces the impacts linked to climate change: the CO_2 released during the combustion of biogas is completely biogenic and therefore to be considered neutral from this point of view. The savings due to the use of a renewable and sustainable energy source surpasses the major impacts due to the anaerobic digestion of larger quantities of OFMSW.

The truly impactful emissions in the Tank-to-wheel component, however, are essentially zero for bioCNG vehicles, as the CO_2 emitted is also considered biogenic and therefore neutral. In fact, it can be noted that the WTT component of all bioCNG scenarios is considerably negative, precisely because the biogenic emissions of the TTW section are indicated as a credit in the WTT section. The only emissions considered to have an impact in the TtW phase are those, very small, due to methane losses.

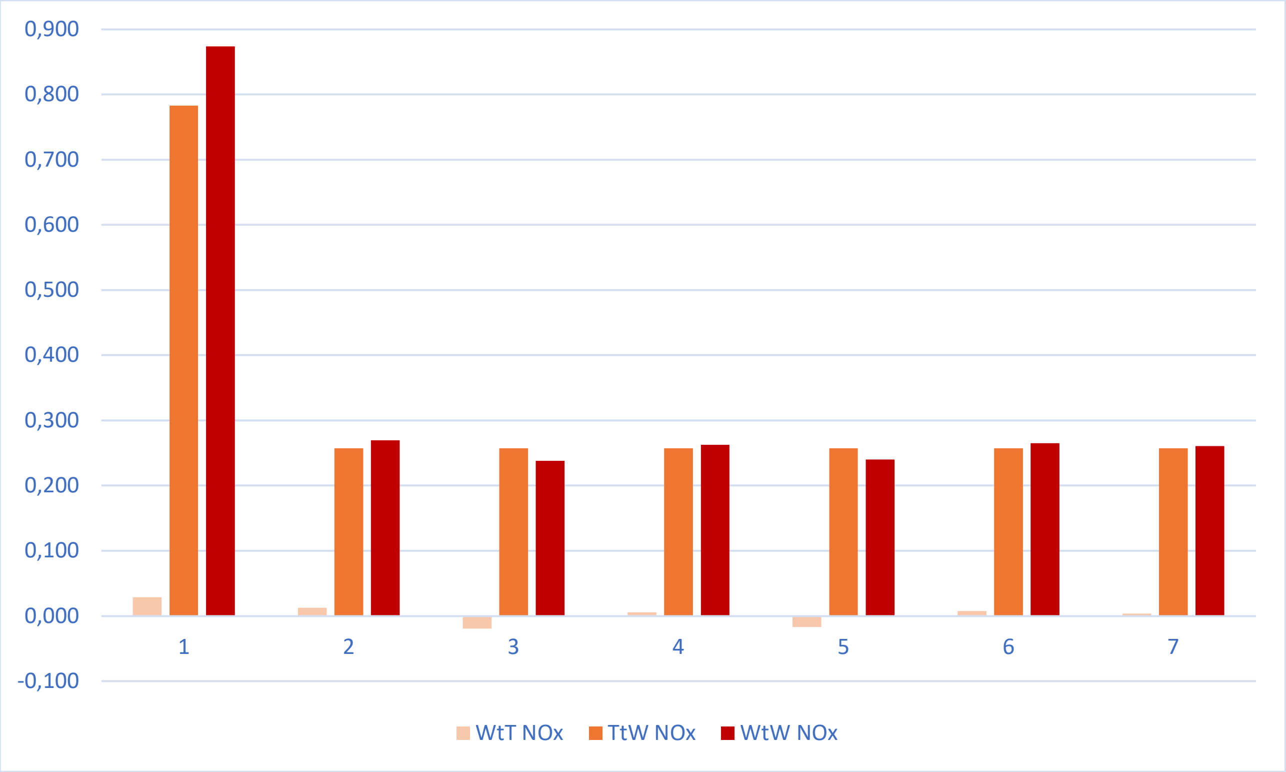

Figure 2: Comparison of WTW results for each scenario for NOx emissions per MJ of fuel.

NOx emissions are essentially the same for all methane-based scenarios, whether natural gas or biomethane. Negative emissions in some of the scenarios refer to the smaller emissions related to anaerobic digestion treatment compared to composting the same amount of waste. In any case, the TtW component is the truly determining factor in NOx emissions in this sector, and that is not influenced by the origin of the compressed gas.

In conclusion, Table 6 shows a summary of the overall results per MJ per fuel. For each scenario, the reduction compared to scenario 1, i.e. the one relating to diesel, is also reported.

As can be seen from this last chapter, even the simple switch to CNG compared to diesel has an important and positive impact on climate-changing gas emissions, equal to 25%. Compressed biomethane further stresses this reduction, bringing it to around 80% as a result of the use of a renewable feedstock whose emissions are therefore to be considered substantially neutral in the Tank-to-Wheel phase.

This phase, in fact, is the one that involves the greatest CO_2 emissions due to the combustion of the fuel, and therefore even if the production of compressed biomethane can be more environmentally burdensome than the fossil counterpart, the almost total elimination of climate-altering emissions during the operation phase of the vehicle more than compensates for this disadvantage.

Comparison	CO2eq [g]	NOx [g]
Scenario 1	91,18	0,874
Scenario 2	63,32 (-30,56%)	0,27 (-69,16%)
Scenario 3	19,36 (-78,76%)	0,238 (-72,76%)
Scenario 4	14,34 (-84,28%)	0,263 (-69,94%)
Scenario 5	20,53 (-77,48%)	0,24 (-72,51%)
Scenario 6	15,5 (-83%)	0,265 (-69,69%)
Scenario 7	3,32 (-96,35%)	0,262 (-69,99%)

Table 6: Comparison of scenarios; the baseline scenario is diesel fuel (Scenario 1)

It should also be noted that the combustion of methane, but also of any other fuel, leads to the emission of carbon dioxide regardless of the medium or technology used. On the other hand, it is always possible to optimize biomethane production technologies, for example by working on losses of methane undergoing upgrading or anaerobic digestion.

A specific note must be made regarding scenario 7, which achieves a reduction in climate-changing gas emissions of 96% compared to diesel. This scenario represents a plausible hypothesis of best practice at a local level, where a large anaerobic digestion plant for OFMSW and upgrading of biogas to biomethane, equipped with CO_2 capture from the offgas, is also coupled with a plant for pressurization of the biomethane to bioCNG and a distribution station that certainly allows the refuelling of vehicles used for waste collection and sorting operations, but also, depending on the size of the plants and productivity, of private vehicles or those linked to local public transport, thus benefitting the community itself in which the plants are located.

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