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JEC Well-To-Wheels report v5

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context

Concawe
Environmental Science for European Refining

eucar
EUROPEAN COUNCIL FOR AUTOMOTIVE R&D

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Contents

Abstract

JRC (the Joint Research Centre of the European Commission), EUCAR and Concawe have updated their joint evaluation of the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options, first published in December 2003. As an update of the previous version, the objectives of JEC WTW v5 are to establish, in a transparent and objective manner, a consensual Well-to-Wheels energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2025 and beyond. This versions updates the technologies investigated and applies a common methodology and data-set to estimate WTW emissions.

This WTW version 5 concentrates on the evaluation of energy and GHG balances for the different combinations of fuel and powertrains, in road transport. The current version 5 investigates, for the first time, the heavy duty segment, thus expanding the scope of the previous versions of the study.

Foreword

Notes on version number:

This is version 5 of this report replacing version 4a published in January 2014. The changes and additions to this version from version 4a are numerous and described in detail in the complementary reports JEC WTT v5 (See Appendix 3) and TTW v5. Some of the most relevant for the JEC WTW v5 report are:

- The base year for this Well-to-Wheels evaluation is 2015/2016 with a time horizon of 2025+;
- Expansion of the scope beyond Passenger Cars towards Heavy Duty vehicles (HDV). A complete assessment for two different configurations have been conducted: rigid trucks used in regional delivery mission (Type 4) & tractor semitrailer combination for long haul (Type 5).
- Definition of criteria to guide the selection of fuel pathways (WTT) for the WTW integration (e.g. Technology Readiness and Commercial Readiness Levels per type of fuel production technology).
- Addition of new sections presenting a comparative analysis per fuel and powertrain for the two different timeframes considered, aiming to help readers understand the variability in the WTW results.
- New visualization of the detailed results, deepening into the WTW GHG and energy expended results by decoupling the contribution of both WTT and TTW elements, for each type of fuel/powertrain combination, and showing the variability for the selected WTT pathways and time horizons.

Acknowledgements

This JEC Consortium WTW study was carried out jointly by experts from the **JRC** (EU Commission's Joint Research Centre), **EUCAR** (the European Council for Automotive R&D), and **Concawe** (the refining European association for environment, health and safety in refining and distribution), assisted by experts (W. Weindorf) from Ludwig-Bölkow-Systemtechnik GmbH (LBST), AVL and FVT.

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Executive Summary

1. *What is the scope of the JEC WTW analysis?*

The JEC consortium is a long-standing collaboration between the European Commission's **J**oint Research Centre, **E**UCAR (the European Council for Automotive Research and development) and **C**oncawe (the European oil companies' association for environment, health and safety in refining & distribution).

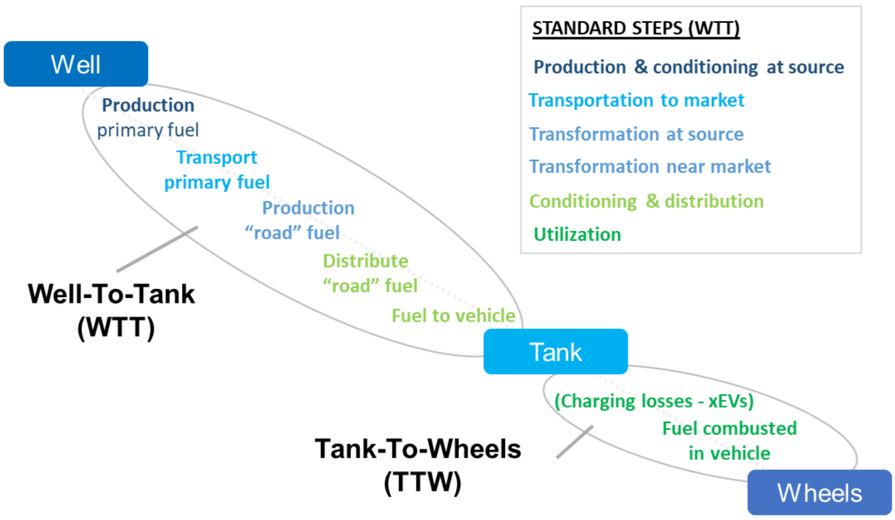
This JEC WTW v5 integration:

- Includes a selection of fuel and powertrain combinations for the current and 2025+ timeframe. The WTT pathways integrated have been decided based on a list of criteria explained in section 2.5 of the WTW report[1]
- Allows the reader to access additional comparisons, referring back to the individual WTT and TTW reports.

This WTW version 5 concentrates on the evaluation of energy and GHG balances for the different combinations of fuel[2] and powertrains in road transport. The current version investigates the heavy duty sector for the first time, expanding the scope of the previous versions of the study beyond the passenger car sector.

It is worth noting that the JEC WTW study is based on Life Cycle Assessment, but does not aim to be a full LCA. In light of the agreed scope of the study, JEC WTW does not consider energy and the emissions involved in building the facilities, the production of the vehicles, or other end of life aspects. JEC WTW v5 concentrates on fuel production and vehicle use stages, which are recognized to be the major contributors to lifetime energy use and GHG emissions nowadays.

Figure 1. Scope of the JEC WTW analysis (Energy expended and CO_{2eq})



Energy use and GHG emissions are associated with both fuel production and vehicle use; hence it is only by considering the whole pathway that the overall impact of fuel and vehicle choices can be seen.

[1] The comparison on WTT feedstock/conversion routes has been focused at pathways ready or close to commercial scale (Technology Readiness Level > 6). Therefore, the comparison excludes some novel pathways with the potential to achieve lower GHG emissions than the routes presented as minimum in this version of the WTW report.

[2] The term "fuel" refers to the energy required to fuel a certain powertrain and, thus, includes both liquid and gaseous fuels as well as electricity.

The aim of JEC WTW has been to evaluate the impact of fuel and/or powertrain substitution in Europe, on global energy usage and GHG emissions balance, i.e. taking into account induced changes derived by fuels substitution[3]. This is particularly relevant for fuels produced from biomass, where careful consideration of co-products is essential for accurate modelling, and where use of land to produce crops can have large implications for agriculture around the World. The evaluation of individual pathways calls for sound comparison of the various options from a variety of angles. JEC WTW endeavours to shed some light on this topic, by answering the questions:

- Which kind of combinations of fuel and powertrains will be more likely to represent current and 2025+ road sector? and which of these exhibit the best environmental performances?
- Which is the impact of the selected feedstock/fuel production pathway, on the final WTW performance?

The WTW energy and GHG figures combine the WTT expended energy (i.e. excluding the energy content of the fuel itself) per unit energy content of the fuel (LHV basis) (g $CO_{2eq}/MJ_{\text{final fuel}}$), with the TTW energy consumed by the vehicle per unit of distance covered.

The energy figures are generally presented as total primary energy expended, regardless of its origin, to move the vehicle over 1 km on the test cycle. These figures include both fossil and renewable energy. As such, they describe the energy efficiency of the pathway. Results for all pathways considered in the study are summarised in Sections 3.2 for Passenger Cars and Section 4.2 and 5.2 for Heavy Duty (Type 4 and 5 respectively).

As in previous versions, the marginal approach has been applied in the WTT to the refining of fossil crude, natural gas and biofuel processing pathways while average emissions have been estimated as a proxy for EU electricity and crops cultivation. The JEC WTT v5 report includes a detailed section comparing attributional and consequential CO_2 allocation methods to refining products (focus on gasoline and diesel). This suggests JEC readers and LCA practitioners do not directly apply JEC results without taking into consideration the methodological approach chosen. In JEC v5, the different experiences from automotive and petroleum/refining industries have been put to use. As a general conclusion, a study conducted by an external party confirmed that both modelling principles, attributional and consequential [EUCAR 2020], are scientifically sound in its domain of validity and applicability. Therefore, carbon intensities of fuels can be calculated by following attributional or consequential modelling principles, depending on the specific goal & scope defined and the decision on the context being applied, see ISO 14040/44 and European Commission's ILCD Handbook. Considering this, due to the scope of the JEC WTW analysis, JEC WTT data is based on a consequential approach and the following Table 1 aims to illustrate how results can be affected by different methodological allocation choices:

[3] To complement the analysis, JEC WTT v5 report includes a detailed section comparing attributional and consequential CO_2 allocation methods to refining products (focus on gasoline and diesel). Therefore, JEC readers and LCA practitioners are advised to not directly apply JEC results without taking into consideration the methodological approach chosen.

Table 1. Summary. Refinery allocation results based on extended literature review[4]

	Consequential “Marginal” (gCO_{2eq}/MJ)			**Attributional “Average” ($g\ CO_{2eq}/MJ$)**			
	JEC (1) (Concawe)		JRC paper (2017)	Aramco paper (4)		JRC paper(2)	Sphera (2020)
	JEC v4 (1)	**JEC v5 (3)**	JRC (2)	Standard mass allocation	Customized allocation (4)*	EN (2)	Mass & Energy
Gasoline	7	**5.5**	5.8	10.2	7.6	5.7 - 5.8	9.6
Diesel	8.6	**7.2**	7.2	5.4	6.8	5.8 -	3.4

It is of utmost importance to remark that, while the JEC-WTT (and the derived WTW) values follow a consequential approach, for Attributional-LCAs, the average values shall be used. It is thus fundamental, before using the data provided in JEC, to consider the goal and scope of the analysis carefully.

2. Pathways selection criteria

Due to the major revision conducted in the JEC v5 reports, both on WTT (>250 resource to fuel pathways modelled) and TTW (>60 powertrain combinations), the number of potential routes to be combined in the WTW analysis has increased considerably since the last version (> 1500 possible combinations). This led to the need to define an appropriate way to present the results. Therefore, a number of WTT pathways have been selected to show the variability of the conversion routes, due to different feedstocks or processes modelled, deriving a comparative analysis between alternatives.

In order to select the relevant WTW combinations, a series of criteria have been applied to filter the WTT pathways. Symbols have been defined to highlight the pathway characteristic (see Table 2):

[4] Sources: (1) JEC WTW studies (2014) Version 4; (2) Moretti, C et al. (2017) (JRC) Analysis of standard and innovative methods for allocating upstream and refinery GHG emissions to oil product; (3) JEC WTW studies (2019) version 5; (4) Gordillo, V et al. (2018) Customizing CO_2 allocation using a new non-iterative method to reflect operational constraints in complex EU refineries; (4)* Customized reallocation, influencing Hydrogen production from catalytic reforming and vacuum distillation; (5) Sphera values [EUCAR 2020]

Table 2. WTT selection criteria for WTW integration

Criteria to select pathways		**Icon**
Reference fuel for comparison	Conventional fuel: the alternative can be compared against (e.g. regular diesel).	
GHG emissions - Max **(Maximum value - gCO_{2eq}/MJ)**	Value close to the maximum allowed GHG Emissions, according to RED recast. As a general rule, WTT pathways with significantly higher GHG Emissions are not included in the comparison[5].	
GHG emissions - Min **(Minimum value - gCO2eq/MJ)**	The route offering the minimum WTT GHG emissions. This value, along with the maximum route mentioned above, determine the WTT range of the production routes explored towards a final fuel.	
Representative pathway	Selected pathway for the final fuel. Chosen by consensus within the JEC as example of one of the commercially available routes depending on the case (e.g. most frequent in Europe, higher share in the current mix, etc.).	
Special interest	Selected examples of interesting new pathways/ feedstock.	
Technology Readiness Level	TRL > 6 (*)	(no icon)

Note. (*) In this WTW report we have focused on WTT feedstock/conversion routes at or close to be ready for commercialization. Therefore, WTT pathways with Technology Readiness Level (TRL) <6 have been excluded for the present WTW comparison (For additional comparisons, we would suggest the reader to refer back to the individual WTT and TTW reports where all the results for individual pathways/powertrain modelled are detailed).

3. Results

When the JEC WTT and TTW v5 results are combined, factors such as the conversion pathways chosen, the feedstock/resource used, together with the specific powertrain technology in the 2015/2025+ timeframe have a strong impact on the final results.

Therefore, results are presented in two different ways in this version of the JEC WTW v5 report, for both Passenger cars and Heavy Duty (Type 4 and 5): GHG emissions (CO_{2eq}/km) and energy expended (*MJ/100km*):

a) Detailed results

- This subsection presents detailed results for each type of fuel/powertrain combination, expanding on the WTW GHG and energy expended results, obtained by decoupling the contribution of both WTT and TTW elements (showing the variability for the selected WTT pathways and time horizons). The details are grouped in:
    a. Internal Combustion Engines (ICEs) – Liquid fuels
    b. Internal Combustion Engines (ICEs) – Gaseous fuels
    c. Electricity driven powertrains (xEVs)
    d. Fuel Cell Hydrogen Electric Vehicles (FCEV)

[5] *It is worth noting that REDII and JEC use different allocation criteria. Therefore, REDII limits have been used only as guidelines to filter the pathways, and not as strict thresholds.*

b) Comparative analysis:

- Aiming to help readers understand the variability in the WTW results due to the feedstock/fuel production route chosen, and the powertrain technology for the time-frame explored in the study (2015 / 2025+) with different test cycles. For that purpose, two type of comparative charts are produced:
  - **Fuel comparison:** these charts show, for the main selected powertrain technologies, the variability due to the use of different type of fuels (and within a fuel, the representative selected pathway and the range as defined in Appendix 1).
  - **Powertrain comparison:** in these charts, the impact of modifications in the main powertrain technologies through, for example different levels of hybridization or battery sizes, are explored for each type of fuel and its representative feedstock/conversion pathway.

As an important general consideration and regardless of the sub-segment considered (Passenger Cars or Heavy Duty), it is worth noting that the electricity and Hydrogen use in transport sector is, in terms of GHG emissions saving, determined by the pathway of electricity production. At least for the transitional phase towards road electrification when power for vehicles is taken from the grid, this can lead to either an increase or a reduction in emissions compared to the baseline depending on the electricity source used for that purpose (which is out of the scope of this JEC study). If the system reacts to this increased demand by increasing the production from fossil sources (e.g. Coal), the overall net effect might be an increment in the GHG. On the other hand, a substantial uptake of electrical energy for the road sector may act as a driver for increasing the share of renewable energies, in the EU mix. These issues are country specific and time specific (as production is a non-steady process by definition) and, as mentioned, considerations like these are not included in the present JEC study. For this reason, the improvement in country electricity mixes can only be used as a proxy for deriving a back-of-the-envelope evaluation.

Similarly to electricity used as a fuel, and from a mere GHG reduction perspective, the use of hydrogen fuel cells may not lead to any advantages, if the electricity used is not from carbon neutral source. This is valid either for direct production of electricity as well as if it is the displaced amount of electricity is replaced in the electrical system by a non-carbon neutral source. As e-fuels production is based on electricity, the above-mentioned considerations can be extended to these cases. Greening the EU grid mix indeed helps also in greening the road sector, but not necessary with a proportional correlation.

In this Executive summary, as an illustrative example of the types of informative charts included throughout the whole JEC WTW v5 report, the *comparative analysis / powertrain comparison* charts are presented here (for both Passenger Cars and Heavy Duty – Type 5). Some of the main conclusions extracted from the whole analysis conducted are also summarized hereafter.

3.1 Passenger Cars

Fuel comparison:

Generally speaking and regardless the timeframe considered (2015/2025+):

- All the alternative fuels analysed offer a better WTW performance than conventional oil based gasoline/diesel when used in Internal Combustion Engines (DISI/DICI). There are some exceptions, such as the gasification of coal to produce synthetic diesel (as the carbon source is fossil). It is worth mentioning that, although the refining industry is currently moving towards further energy efficiency improvement and GHG reduction (WTT) and further reductions are expected by 2030, these improvements have not been modelled in the current version of the JEC WTW v5.
- Specific pathways, such as alternative fuels based on waste cooking oil (WOHY1a) offer significant WTW performance improvements (e.g. in terms of energy expended) than conventional oil based gasoline/diesel.
- Most of the modelled alternative fuels lead to a higher energy use, when applied to Internal Combustion Engines (DISI/DICI). In spite of this lower energy performance, it has to be noted that in case of renewable fuels a large part of the energy expended is renewable, thus leading to lower GHG emissions.

Electricity and Hydrogen:

- These energy vectors have the potential to offer low CO_2 emissions, comparable with the bio liquid/gaseous' representative pathways selected for the analysis. The use of renewable electricity for xEVs and FCEV offer one of the lowest WTW intensive combinations, similar to the use of biomethane and syndiesel (e-fuels) in DICI.
- When energy expended is considered, the use of renewable electricity for xEVs offers one the lowest energy intensive combinations.
- Interestingly, PHEV technology (when powered with the EU mix and conventional gasoline/diesel) shows a similar CO_2 emission pattern than the one related to the use of FCEV in 2015 (Hydrogen produced through conventional natural gas reforming route). These differences increase towards 2025+, in favour of the BEVs/PHEVs/REEVs alternatives (if no low-CO_2 intensive hydrogen is used).

Other issues worthy of note:

- This comparison includes the effects of the in the test cycle change: from 2015 (NEDC) to 2025+ (WLTP). This partially offsets the potential WTW benefits.
- The fuel production considers state–of-the-art technology of fuels already or close to be commercialized at scale in the market.
- Availability issues are not included in the scope of JEC WTW v5[6].

Powertrain comparison:

For gasoline/DISI type of engines:

- Generally speaking, the hybridization of ICEs offers an effective option to reduce fuel consumption, up to ~25% (better performance in gasoline than diesel powertrains) when focused on non-plug-in HEVs (excluding PHEVs), and therefore an option to lower emissions.
- For gasoline engines, the combination of high compression rates with a high octane gasoline (102 RON) offers a similar GHG performance than DICI (diesel), vehicles when approaching 2025+.
- Regarding the contribution of alternative fuels, ethanol, MTBE and specially bio-ETBE routes show a higher energy use than traditional fossil fuels (up to a factor of 2 in the case of bio-ETBE). However, in case of renewable fuels the energy use mainly consists of renewable energy and, therefore, they show interesting WTW GHG reductions (up to 2/3rds in the case of bio-ETBE).

LPG fuelled DISI deems to offer a ~15% WTW GHG and energy expended reduction versus pure DISI in 2015, slightly increasing its potential benefits significantly when approaching 2025+ (~9%).

Regarding diesel-like powered engines, the selected fuel pathways:

- Offer routes to lower the GHG emissions of conventional DICI in 2015 from ~50% up to 85% (bio and synthetic diesel pathways – synthetic diesel understood here as *BTL* - biomass/waste derived fuels). The full hybridization technology *per se* does not offer as significant GHG reductions when compared with the mild hybridization one.
- Lead to higher WTW energy use than the crude oil based pathways except HVO (up to 2.7 times compared to crude oil based diesel if OME from waste wood is considered) but lower WTW emissions.

The xEVs technology:

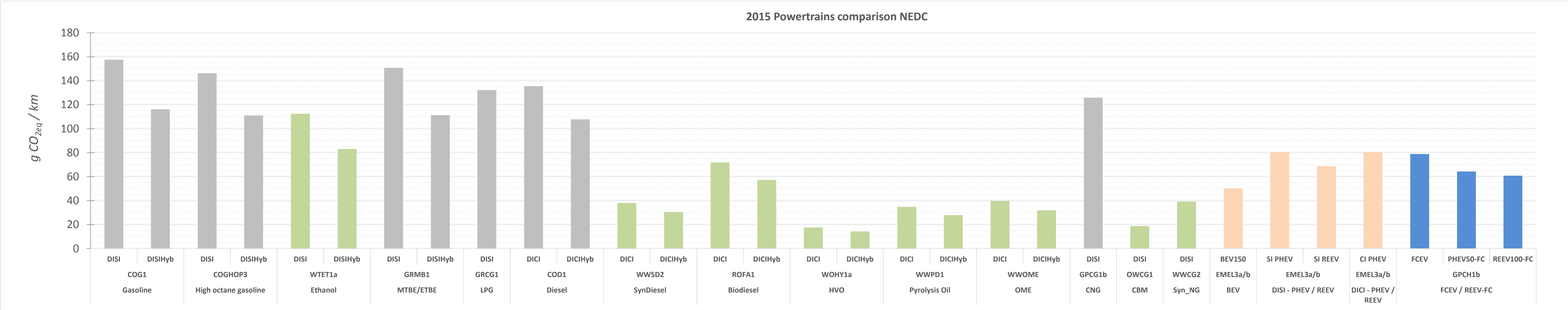
- Is expected to improve significantly towards 2025+ (including battery size increase).
- In 2015, FCEV and PHEV/REEV offer similar WTW results (~15% better performance of the latter versus FCEV).
- The difference increases when approaching 2025+ mainly due to the less CO_2 intensive electricity mix used in 2030 for the selected pathways (the combination of FCEV and PHEV/REEV in the same powertrain offers similar results than DISI/DICI PHEV/REEV especially as the % of the time being driven in e-mode is expected to increase). This has to be read as a proxy for this comparison with the big caveat around the real impact due to the marginal country specific electricity production routes.

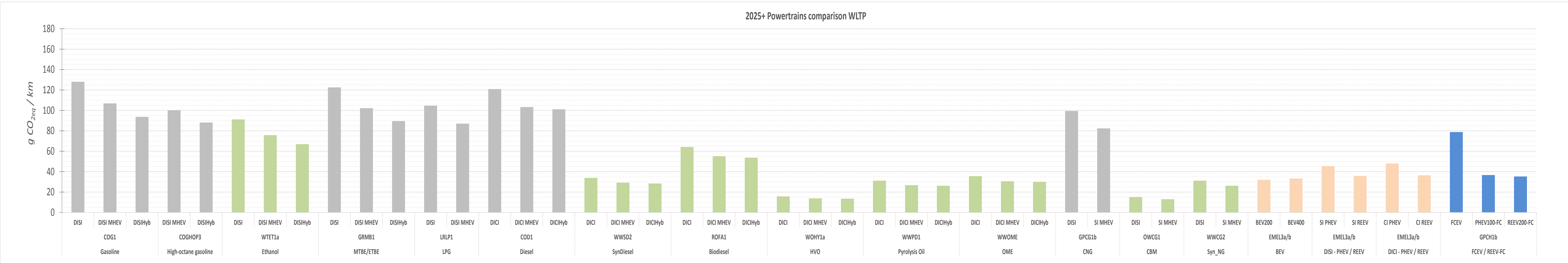
General additional remarks:

[6] These kind of considerations are addressed in JEC-Alternative Fuel Study.

- From all combinations of fuel/energy carriers and powertrains explored in this WTW report, the HVO pathway with the DICI Hybrid technology (waste as feedstock) and the use of CBM in a SI MHEV represent the lowest GHG routes.
- From the energy expended point of view, the HVO pathway with the DICI Hybrid technology (waste as feedstock) and the use of electricity from the electricity mix in a BEV represent the lowest energy intensive routes in 2015 and 2025+ respectively. For 2025+ the energy use for the combination of Hydrogen from natural gas steam reforming and electricity from the electricity mix used in PHEV-FC/REEV-FC as well as the SI REEV and CI REEV are close to that of the BEV.

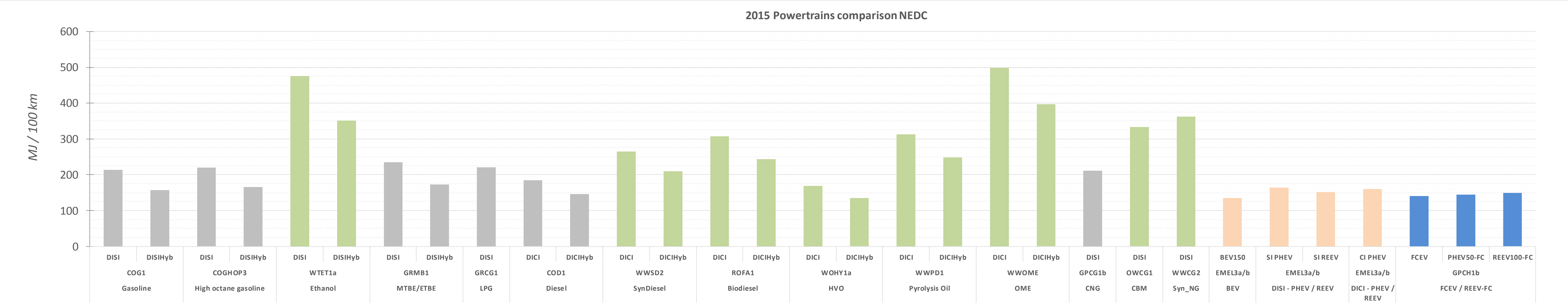
Figure 2. Passenger Cars - WTW powertrain comparison (2015 – NEDC / 2025+ WLTP) - GHG emissions[7]

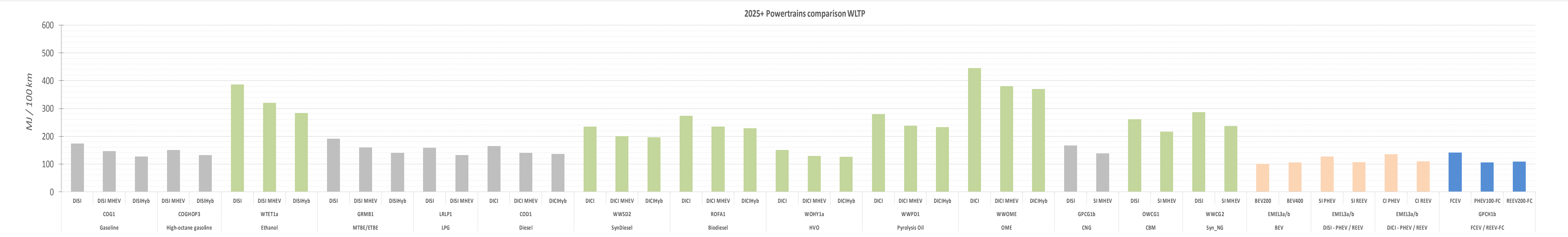




[7] Note. It is important to highlight that while NEDC test cycles was applied to 2015 powertrains, WLTP is included in the 2025+ scenario. This change in the test cycle towards more real driving emissions is partially offsetting part of the GHG emission reduction due to fuel efficiency measurements achieved in the powertrain technologies. Besides this, it is worth reminding the reader about the use of the representative pathway for each fuel. The different ranges per type of energy carrier are extensively covered in the JEC WTT v5 report.

Figure 3. Passenger Cars - WTW powertrain comparison - Energy expended



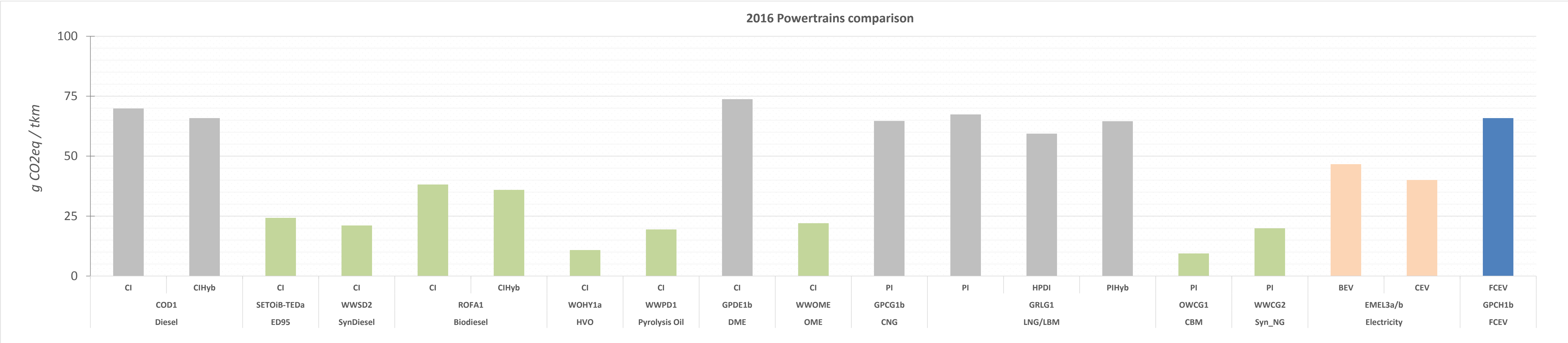


3.2 Heavy Duty – Type 5.

For Heavy Duty, the same analysis approach used for Passenger Cars has been used. Type 5 results are reported here, giving a good representation of the analysis carried out (similar for Type 4). The following conclusions can be highlighted:

- The hybridization of ICEs offers an effective option to reduce fuel consumption, up to ~7%.
- Regarding diesel-like alternatives, the selected fuel pathways offer routes to lower the GHG emissions of conventional Direct Injection Compression Ignition (CI) in 2016 from ~50% up to 85% (bio and synthetic diesel pathways).
- High pressure direct injection (HPDI) engines offers energy savings of about 20%, when compared to diesel CI engines and leading up to about 12% lower GHG emissions in 2016 and in 2025+ compared to SI engines with the same fuel.
- The xEVs technology is expected to improve significantly towards 2025+, and the EU electricity mix is presented here as theoretical proxy, as mentioned earlier.
- From all combinations of fuel/energy carriers and powertrains explored in this WTW report, the HVO pathway with the CI technology (waste stream used as feedstock) and the use of compressed biomethane (CBM) in a Port Injection Positive Ignition (PI) hybrid represent the lowest GHG intensity routes.

Figure 4. Heavy Duty – Type 5 – JEC WTW v5 powertrain comparison - GHG emissions



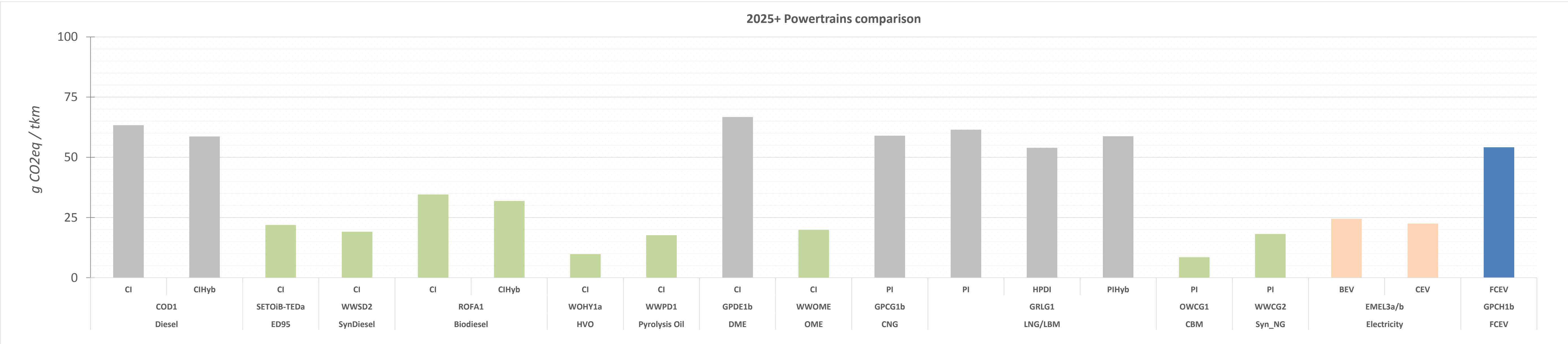
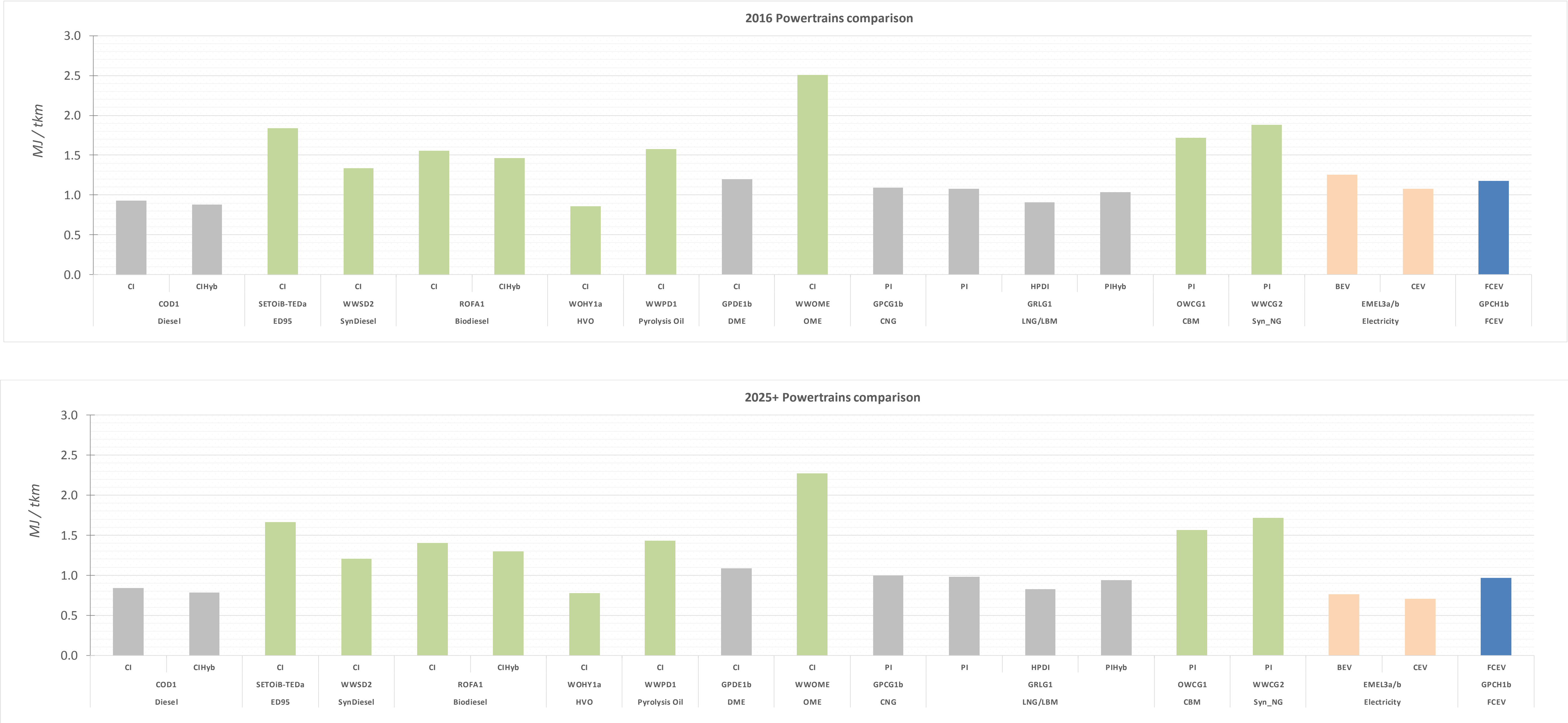


Figure 5. Heavy Duty – Type 5 – JEC WTW v5 powertrain comparison - energy expended



1 Introduction

JRC (the Joint Research Centre of the European Commission), EUCAR and Concawe have updated their joint evaluation of the Well-to-Wheels energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options, first published in December 2003. As an update of the previous version, the objectives of JEC WTW v5 are:

- establish, in a transparent and objective manner, a consensual Well-to-Wheels energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2025 and beyond;
- update the technologies investigated;
- apply a common methodology and data-set to estimate WTW emissions;
- have the outcome accepted as a reference by all relevant stakeholders.

This WTW version 5 concentrates on the evaluation of energy and GHG balances for the different combinations of fuel and powertrains, in road transport. The current version 5 investigates, for the first time, the heavy duty segment, thus expanding the scope of the previous versions of the study.

It worth noting that the JEC WTW study is not a Life Cycle Assessment. Despite the fact that JEC WTW largely relies on a LCA methodology, it does not consider energy or the emissions involved in building the facilities and the vehicles, or other end of life aspects. In light of the agreed scope of the study, JEC WTW concentrates on fuel production and vehicle use stages, which are recognized to be the major contributors to lifetime energy use and GHG emissions nowadays.

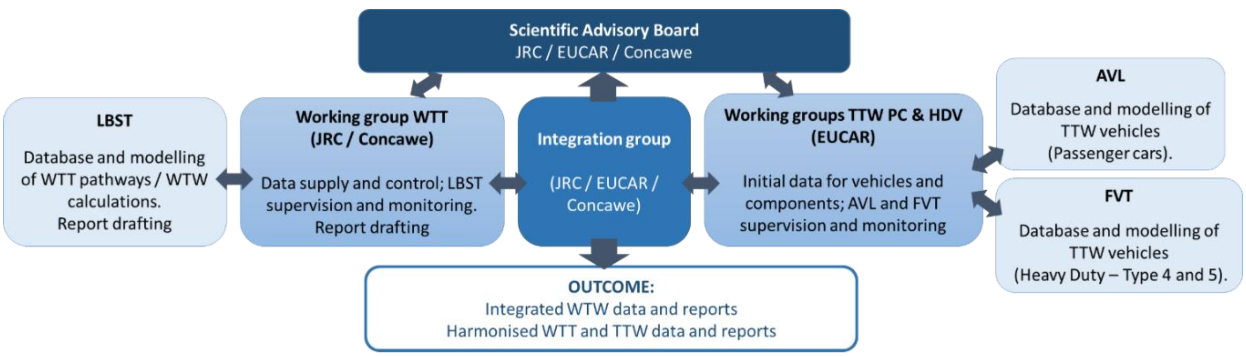
Regulated pollutants have only been considered in so far as all plants and vehicles considered are deemed to meet all current and already agreed future regulations.

With the development of recent European specific legislation on the introduction of alternative fuels, issues about the availability of alternative fuels and penetration of non-conventional powertrains in the market have been receiving a lot of attention and generated a lot of debate. These aspects are not included in the scope of the JEC WTW report and are addressed in another publication of the consortium: the JEC *Alternative fuels study*.

Additionally, no attempts have been made to estimate the overall "benefit/cost for society", such as health, social or other speculative areas.

This study was undertaken jointly by the Joint Research Centre of the European Commission, EUCAR and Concawe supported by the structure illustrated in the diagram below:

Figure 6. JEC Supporting Structure.



- The “Well-to-Tank” Working Group was coordinated by Concawe/JRC assisted by Ludwig-Bölkow-Systemtechnik GmbH (LBST), a consultancy firm with a proven track record in WTW assessment, and which had a major involvement in previous work by General Motors [GM 2002] and the German Transport Energy Strategy Partnership (TES). JRC directorate C (Directorate C - Energy, Transport and Climate) provided a major contribution to the biofuel pathways characterization.
- The “Tank-to-Wheels” Working Group was coordinated by EUCAR. EUCAR supplied the vehicle data, the engines energy efficiency maps and adaptation procedures. The simulation code adaptation and the simulated fuels-vehicle assessments were contracted to the AVL GmbH for the Passenger Cars segment and to Forschungsgesellschaft for Internal Combustions Engines and Thermodynamics mbH (FVT)[8] for the Heavy Duty analysis.
- JRC contributed to an ADVISOR / AVL Cruise comparison (see JEC TTW v5 reports).
- The WTW Integration Group was led by a JEC subgroup chaired by JRC and supervised by a Scientific Advisory Board representing the three partners.

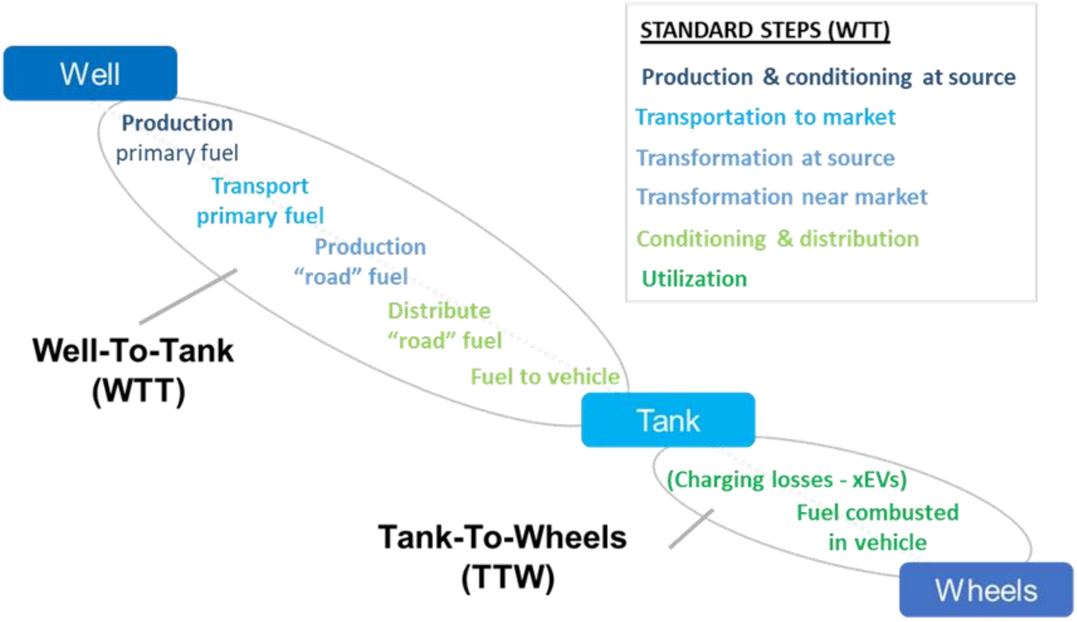
[8] The *Forschungsgesellschaft* for Internal Combustions Engines and Thermodynamics mbH (FVT) is a spinoff of the Institute for Internal Combustions Engines and Thermodynamics (IVT) at the Graz University of Technology (TU Graz). There is a close cooperation between the two institutions which is based on sharing the staff and infrastructure to a large extend.

2 Scope, methodology, definition and structure

2.1 Scope

The following figure summarizes the scope of the JEC WTW analysis and highlights how both fuel production pathway and powertrain efficiency impact GHG emissions as well as total and fossil energy use.

Figure 7. Scope of the JEC WTW analysis (Energy expended and CO_{2eq})



Energy use and GHG emissions are associated with both fuel production and vehicle use; hence it is only by considering the whole pathway that the overall impact of fuel and vehicle choices can be seen. Well-To-Wheels analysis is essential to assess the GHG and energy impact of future fuel and powertrain options, and it is the result of the integration of two complementary JEC steps: the *Well-To-Tank* and the *Tank-To-Wheels* components. The WTW merges the analyses of the individual fuel production pathways and powertrain, for both Passenger Cars and Heavy Duty.

The WTW report describes: the results of the Well-To-Wheels (WTW) integration for the fuel/vehicle combinations considered, including an overall assessment of the energy required and the GHG emitted per unit distance covered. The related methodologies and findings are fully documented and discussed in the companion "Well-To-Tank" and "Tank-To-Wheels" reports. The main assumptions are summarised in section 2 of this report.

The study is forward-looking, as it aims to provide information to guide future choices of fuel and vehicle technologies towards the 2025+ timeframe.

The aim of JEC WTW has been to evaluate the impact of fuel and/or powertrain substitution in Europe, on global energy usage and GHG emissions balance, i.e. taking into account induced changes in the rest of the world. This is particularly important for fuels produced from biomass where careful consideration of co-products is essential for a complete picture, and where use of land to produce fuel crops can have implications for agriculture around the world. The evaluation of individual pathways calls for sound comparison of the various options from a variety of angles. JEC WTW endeavours to shed some lights on this topic, by answering the questions:

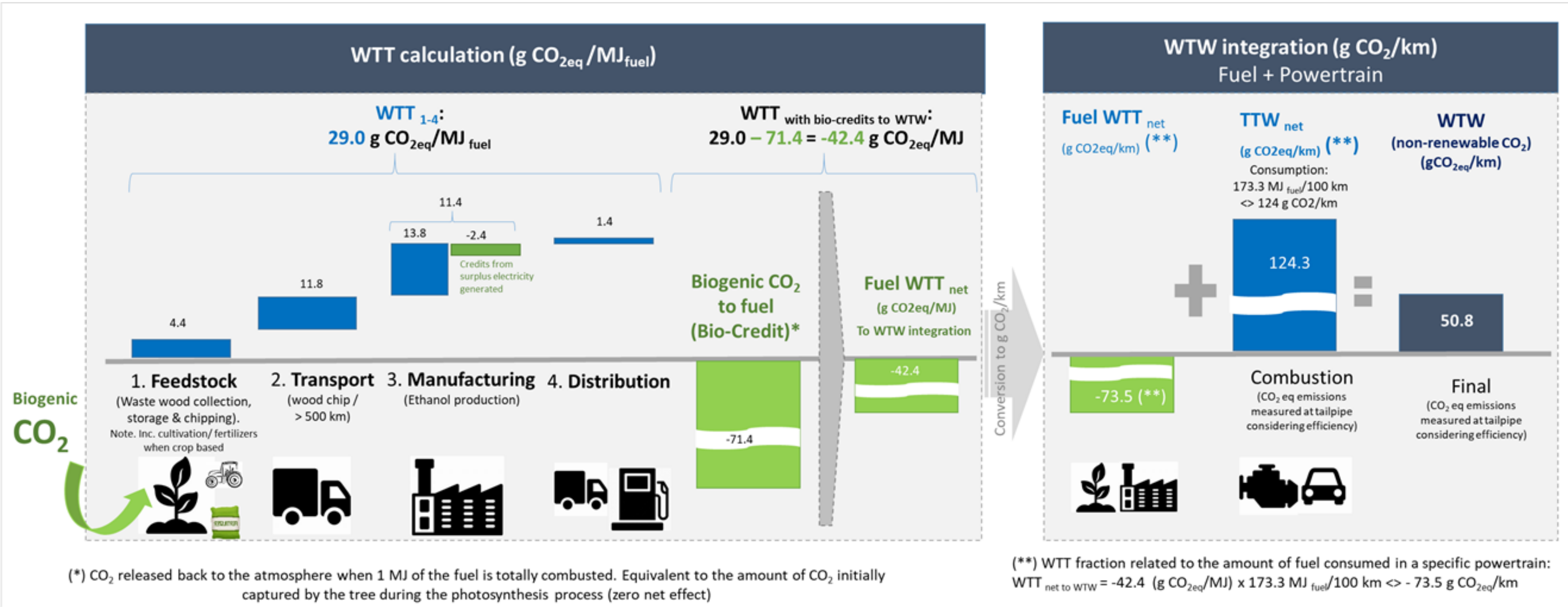
- Which kind of combinations of fuel and powertrains will be more likely to represent current and 2025+ road sector? And which of these hold the best environmental performances?
- Which is the impact of the selected feedstock/fuel production pathway, on the final WTW performance?

Amongst the various data sources, the ones judged the most appropriate and reliable in line with the scope of JEC have been selected. Some assumptions, such as the set of minimum driving performance criteria, are real and tangible; while others, relating to emerging technologies, extrapolated to 2025+, are more affected by JEC experts' judgment. In any case, the choices made are referenced, justified and documented. The details of the calculations have been to the largest possible extent included in the appropriate appendices and workbooks, so to allow readers to access not only the results but also the basic data and the main calculation assumptions.

Data sources are referenced in the WTT and TTW reports and in the Workbooks but with a few exceptions are not generally repeated in this WTW integration document.

For illustrative purposes, the following chart attempts to guide the reader through the link between the WTT calculations (production routes), and the integration with the TTW values. Through a selected example, the chart details the rationale behind the calculations included in the WTT individual spreadsheets and in the WTW integration file.

Figure 8. CO_2 equivalent – Well-To-Wheels calculations - Simplified chart. Example.
(Wood based pathway (Ethanol – WWET1b) + Gasoline DISI technology 2015)



Note. As detailed in JEC WTT v5 report (Section2.9.4), the WTT figures included in the JEC WTT report reflect the net energy requirement and related emissions required for the production of 1 MJ of fuel (WTT_{1-4} of the example above). In case of bio-based feedstocks, the bio-credits will be taken into consideration into the WTW calculations (where the impact of the combustion of the fuel in a specific engine is assessed).

Other aspects such as feedstock availability, required infrastructure or other considerations have not been addressed in this study as they are out of the JEC WTW v5 scope.

2.2 WTW and LCA Methodologies

JEC WTW study estimates the energy use and GHG emissions in the production of a fuel and its use in a vehicle. The term 'Well-To-Wheels' has been chosen for this process for fuels from all sources, because although the term is most applicable to conventional crude oil resources, it is widely used and understood.

Despite the fact the JEC WTW is based on a broader Life Cycle Assessment (LCA) methodology, it focuses on energy and GHG performance. This methodological choice is justified in light of the goal of the study.

In the past, the JEC consortium has been asked why the energy use and GHG emissions in the production and end of life disposal of the vehicle and fuel production/distribution facilities are not considered, so to move toward a full Life Cycle Analysis.

It is worth noticing that LCA is a broad methodology, typically used to account for the many environmental impacts of an industrial process; this could include energy and GHG (as in the WTW) but also the consumption of all the materials needed for the production process, water requirements, emission of many kinds of pollutants (liquid, gaseous etc.), and presenting results on a potential wide set of impact categories. Despite the interest for a full LCA approach, much wider sets of data are required; moreover, calculations tend to be more complex and results are often less transparent and less comparable. In particularly for new processes, where system boundaries are often less defined, and data scarce, the resulting full LCA studies can lead to controversial results.

All that considered, and in light of the main aim of JEC study, the Well–To-Wheel (made of WTT plus TTW) approach has been preferred. Several analysis have been carried out in the past e.g. [MIT 2008], [Baumann 2012] including vehicle production and end of life disposal and a recent VehicleLCA project commissioned by DG CLIMA is in the final step towards publication at the time of drafting this JEC WTW v5 report. Overall, the results generally indicate that vehicle production and end of life disposal make a significant, but fairly constant, contribution to the overall lifetime performance. For example, in a mid-sized US car the GHG emission contribution is estimated in 2035 to be 21-24 g CO_{2eq}/km for Gasoline, diesel and hybrid vehicles including PHEV, compared with total emissions for these vehicles from 109 to 178 g CO_{2eq}/km. The MIT study predicts that for fuel cell and battery vehicles the GHG emissions for vehicle production and disposal could rise to 30-31 gCO_{2eq}/km. For informative purposes, an attempt to expand the WTT to include LCA for selected pathways – still focusing on energy use and GHG emissions – is being conducted and will be published as an Appendix of this JEC WTW v5 in due time. It is also relevant to remark that the JEC WTT v5 assesses the incremental emissions (marginal approach) associated with the production of a unit of alternative fuel, with respect to the current status of production. This marginal approach has been chosen as being instrumental to:

- guide judgements on the potential benefits of substituting conventional fuels/vehicles with a specific alternative.
- for future fuels: understand where the additional energy resource would come from.

As in previous versions, the marginal approach has been applied to refining of fossil crude, natural gas and biofuel processing pathways while average emissions have been estimated as a proxy for EU electricity and crops cultivation (since estimating incremental increases in crop output is challenging and controversial). In all the cases, the report is also forward-looking and considers state-of-the-art technology to support future choices. Note that, for fuels from biomass origin, the GHG balance figures presented do not include emissions caused by land use change. Despite the potential impact it may have on the final values, both direct and indirect land use changes (DLUC and ILUC) have not been accounted for in this exercise, mainly because of the high uncertainties in the methodology for estimation (a wide discussion about this issue is available in JEC WTT v5 Appendix 5).

Additionally, results from JEC WTT v5 are different from the values contained in the Renewable Energy Directive recast (2018/2011/EU) (See section 2.10 of the JEC WTT v5). Although JEC WTT v5 shares the input dataset for biomass-related pathways, which have been provided by EC-JRC, the methodology is different. In particular for the co-products, Renewable Energy Directive (RED) recast values used energy allocation for convenience of use by economic operators. Thus, the RED recast values cannot be directly compared with the ones presented in this report.

To complement the analysis, this JEC WTT v5 report includes a detailed section comparing attributional and consequential CO_2 allocation methods to refining products (focus on gasoline and diesel). JEC readers and LCA practitioners are therefore asked not to directly apply JEC results without taking into consideration the methodological approach chosen. In JEC v5, the different experiences from automotive and petroleum/refining industries have been put to use. As a general conclusion, a study conducted by an external party confirmed that both modelling principles, attributional and consequential, are scientifically sound in its domain of validity and applicability. Therefore, carbon intensities of fuels can be calculated by following attributional or consequential modelling principles, depending on the specific goal & scope defined and decision context being applied, see ISO 14040/44 and European Commission's ILCD Handbook[9]. In this context, due to the scope of the JEC WTW analysis, JEC WTT data is based on a consequential approach and the following Table 3 aims to illustrate how results can be affected by different methodological allocation choices:

Table 3. Summary. Refinery allocation results based on extended literature review[10]

	Consequential "Marginal" (g CO_{2eq}/MJ)			**Attributional "Average" (g CO_{2eq}/MJ)**			
	JEC (Concawe)		JRC paper (2017)	Aramco paper (4)		JRC paper	Sphera (2020)
	JEC v4 (1)	**JEC v5 (3)**	JRC (2)	Standard Mass allocation	Customized allocation (4)*	EN (2)	Mass & Energy
Gasoline	7	**5.5**	5.8	10.2	7.6	5.7 - 5.8	9.6
Diesel	8.6	**7.2**	7.2	5.4	6.8	5.8 – 6	3.4

It is of utmost important to remark that, while the JEC-WTT (and the derived WTW) values follow a consequential approach, for A-LCA average values shall be used. It is thus fundamental, before using the data provided in JEC, to consider the goal and scope of the analysis carefully.

Finally, the values in this report, even though they apply a forward-looking approach through the marginal approach, remain focused on a product-basis comparison and do not include detailed modelling of possible scale-driven consequences or market-mediated effects on other sectors of the economy. Therefore, the results can provide a useful guide but should not be used for large-scale, strategic policy decisions[11].

[9] https://eplca.jrc.ec.europa.eu/

[10] Sources: (1) JEC WTW studies (2014) Version 4; (2) Moretti, C et al. (2017) (JRC) Analysis of standard and innovative methods for allocating upstream and refinery GHG emissions to oil product; (3) JEC WTW studies (2019) version 5; (4) Gordillo, V et al. (2018) Customizing CO_2 allocation using a new non-iterative method to reflect operational constraints in complex EU refineries; (4)* Customized reallocation, influencing Hydrogen production from catalytic reforming and vacuum distillation; (5) Sphera values [EUCAR 2020]

[11] https://ec.europa.eu/jrc/en/science-update/life-cycle-assessment-environmental-impacts-bioeconomy

2.3 Well-To-Tank. Summary.

In this version of the WTW v5, different fuel/energy carriers have been modelled. Both the methodology and the results are briefly discussed in the following sections (the full report can be found in the following link https://ec.europa.eu/jrc/en/jec/publications).

2.3.1 Methodology (WTT)

This part of the study describes the process of producing, transporting, manufacturing and distributing a number of fuels suitable for road transport powertrains. It covers all steps from extracting, capturing or growing the primary energy carrier to re-fuelling the vehicles with the finished fuel (Steps 1 to 4 in Figure 8) without including the biogenic credit for biofuels (which are considered in the WTW integration). The results presented in the WTT figures are the calculated energy use and GHG emissions for each future fuel pathway (all details of assumptions and calculations are available in the *WTT report* and its appendices [JEC WTT v5]).

We briefly discuss below some basic choices that have been made, especially regarding the methodology applied, which have a material impact on the results:

Selection of pathways modelled

It is important to emphasize that, as an energy carrier, a fuel must originate from a form of primary energy, which can be either contained in a fossil feedstock or fossil material, or extracted from renewables (solar energy, biomass or wind power). Generally, a given fuel can be produced from a number of different primary energy sources. The number of conceivable fuels and fuel production routes is very large and we have included all fuels and primary energy sources that appear relevant for the foreseeable future (>250 pathways in total included in the JEC WTT v5). While we have tried to be as exhaustive as possible, certain combinations considered less relevant in terms of their commercial readiness level have been left out for the integration stage.

The database is structured in such a way that new data from scientifically established changes, progress, or new applications can be easily taken into account in future updates. The following matrix summarises the main combinations of primary energy and finished fuels that have been included.

Table 4. Well-to-Tank resource to Fuels pathways - Version 5

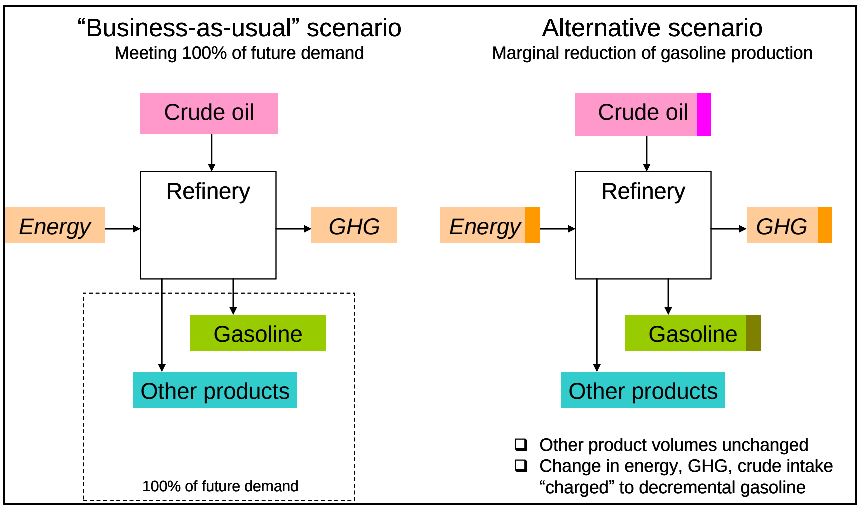
Technology		Gasoline, Diesel (2017 quality)	Gasoline E10 / Gasoline High octane	Synthetic gasoline (Pyrolysis-based Naptha)	Diesel B7 (2017 market blend)	Synthetic diesel	Synthetic diesel (Pyrolisis-based diesel)	DME	OME	Ethanol	Methanol	MT/ETBE	ED95	FAME / FAEE	HVO	CNG	CBG	SNG	LNG	LPG	Hydrogen (Comp., liquid)	Electricity	Heat
Crude oil extraction		X	X		X								X									X (5)	X (6)
Crude oil refining		X	X		X								X									X (5)	X (6)
NG extraction & processing				X	X	X	X	X	X		X	X (3)		X	X	X			X	X (3)	X	X	X
Anaerobic digestion for biogas generation																	X		X (2)			X	X
Pressing and solvent extraction of vegetable oil					X									X	X								
Plant oil refining					X									X									
Esterification					X									X									
Saccharification of lignocellulosic biomass										X													
Fermentation to produce ethanol			X							X		X	X	X									
Fermentation to produce bio-isobutylene												X											
Gasification						X		X	X		X							X	X (7)		X	X	
Pyrolysis				X			X																
Steam reforming of NG				X			X								X						X (1)		
Partial oxidation of NG						X (1)																	
Combined reforming of NG					X			X (1)	X		X	X		X									
Hydrocracking						X																	
Hydrotreating				X		X	X								X								
Oligomerization						X																	
Methanation																		X	X (7)				
Synthesis	Methanol				X	X			X		X	X		X									
	DME					X		X															
	Olefin					X																	
	Fischer-Tropsch					X																	
	Formaldehyde								X														
	Methylal								X														
	Trioxane								X														
	OME								X														
	MTBE											X											
	ETBE											X											
Liquefaction	Hydrogen																				X		
	Methane																		X				
	LPG																			X			
Power station	Wind, PV, hydro					X			X									X	X		X	X	
	Thermal power																				X	X	
	Nuclear power																				X	X	
CHP plant																					X	X	X
Heating plant																							X
Water electrolysis	Low temperature (AEL/PEMEL)					X			X									X			X		
	High temperature (SOEC)					X																	
Direct air capture of CO2						X																	

Note.
(1) With / Without CCS
(2) Biogas
(3) Associated with natural gas production
(4) EU and US sources
(5) Heavy Fuel Oil
(6) Heating oil / Diesel
(7) Bio-SNG or bio-LNG

Marginal approach

The ultimate purpose of this study is to guide those who have to make a judgement on the potential benefits of substituting conventional fuels by alternatives (see section 2.2). It is clear that these benefits depend on the incremental resources required for alternative fuels and the incremental savings from conventional fuels saved. Therefore, a marginal methodology has been used when allowed by available data (see Figure 9 below).

Figure 9. Impact of a marginal reduction of conventional gasoline demand



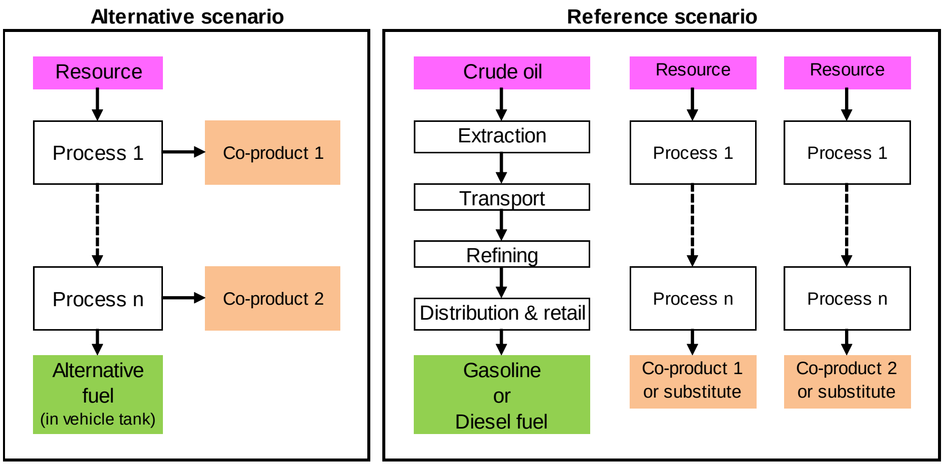
Co-products

Besides the marginal methodology used, our JEC methodology considers also that many processes produce not only the required fuel product but also other streams or "co-products". This is the case for biofuels from traditional crops such as bio-diesel from rapeseed. In line with the philosophy described above we endeavoured to represent the "incremental" impact of these co-products as well. This implies that the reference scenario includes either an existing process to generate the same quantity of co-product as the alternative-fuel scenario, or another product which the co-product would realistically replace.

The implication of this logic is the following methodology (Figure 10):

- All energy and emissions generated by the process are allocated to the main or desired product of that process.
- The co-product generates an energy and emission credit equal to the energy and emissions saved by not producing the material that the co-product is most likely to displace.

Figure 10. Co-product credit methodology



In most cases, co-products can conceivably be used in a variety of ways and we have included the more plausible ones. Different routes can have very different implications in terms of energy, GHG or cost and it must be realised that economics rather than energy use or GHG balance are likely to dictate which routes are the most popular in real life.

The last important remark regarding the WTT methodology is that, in the case of biofuels, no DLUC or ILUC (Direct / Indirect Land Use Change) emissions have been included (see JEC WTT v5 Appendix 5 for more details on this subject).

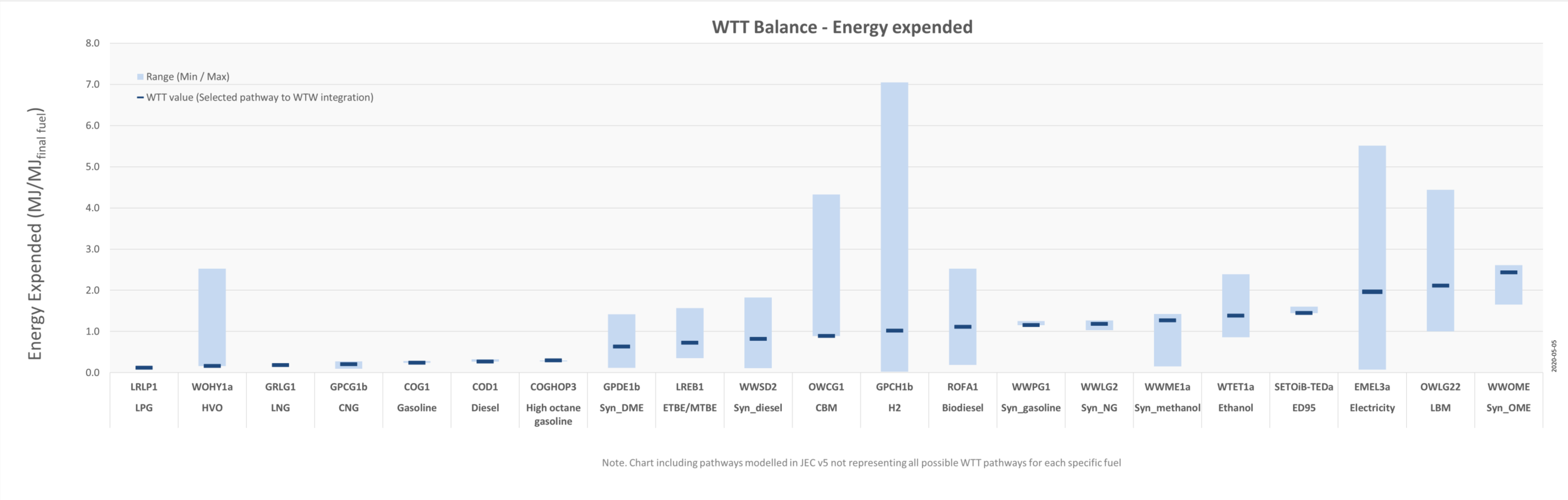
2.3.2 Results (WTT)

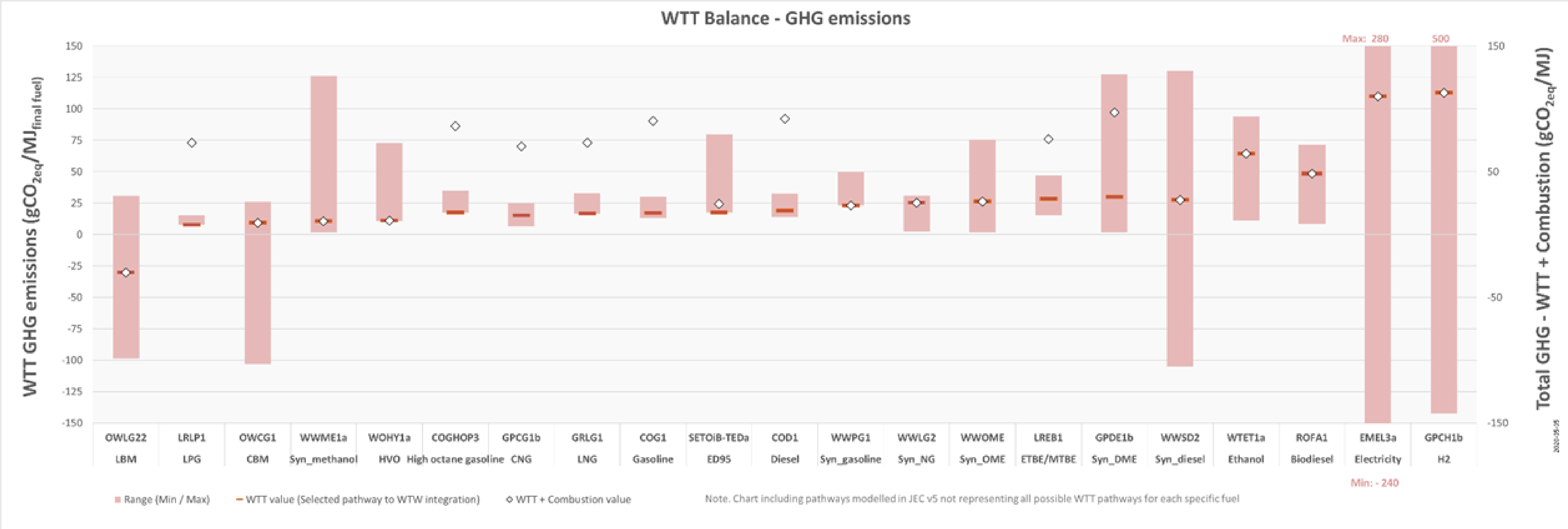
What are the main results in terms of WTT Energy expended and GHG emissions?

As presented along the JEC WTT v5 document, the variability among the more than 250 different pathways modelled is significant in terms of WTT energy expended and GHG emissions when compared with conventional fuels. Factors such as the conversion pathways chosen and the feedstock/resource used have a strong impact on the final results. As a summary, the fuel comparison figures (Figure 11) aims to show the WTT Energy expended and GHG range per type of fuel (e.g. fossil, CNG (Compressed Natural Gas), DME (DiMethyl Ether), etc.) including the range (min/max) and a representative pathway for each of the conversion routes modelled.

For each specific final fuel, the minimum and maximum values represent the variability within the existing production pathways. The most "representative" pathway has been selected mainly on the base of techno-economical evaluations and in line with RED II criteria; these representative pathways are those used for the WTW integration (more details on the selection criteria are detailed in section 5 of the JEC WTT v5 report – Comparative analysis as well as in the Appendix 1 of this JEC WTW v5 report):

Figure 11. Comparison among the WTT values (Energy expenditure and GHG emissions) for some investigated fuel production pathways.





Notes

(1) For each fuel, the width of the bar represents the minimum and maximum values from the pathways modelled in this JEC WTT v5. Within the range, the thick line represents the pathway selected as representative of the specific fuel – consistent with the JEC WTW v5 report (code included above as a reference). For the high octane gasoline pathways the wheat-to-ethanol pathway WTET5 (biogas from DDGS for internal energy supply) instead of the representative wheat-to-ethanol pathway WTET1a (NG boiler) has been used for admixture. The difference for the WTW GHG balance for high octane gasoline pathway COGHOP3 (variant with the highest ethanol share) amounts to about 2%.

(2) The WTT figures included in this JEC WTT report reflect the net energy requirement and related emissions required for the production of 1 MJ of fuel (see section 2.9.4). In case of bio-based feedstocks, the bio-credits will be taken into consideration into the WTW calculations (where the impact of the combustion of the fuel in a specific engine is assessed).

(3) Due to the consequential nature of the LCA approach applied according to the goal and scope of JEC WTT v5 the values shall not be used in attributional LCA context.

(4) The report includes representative pathways / routes but additional technologies (not included in this version 5) are already in development. Therefore, the comparison of various WTT routes has been conducted among the modelled JEC pathways which differ depending on the type of fuels and the routes to produce them. E.g. whereas we have considered a very extensive range of primary energy sources for some fuels/energy carriers (e.g. electricity, hydrogen), for others, only some initial examples of potential sources/pathways have been chosen for illustrative purposes (e.g. DME). This issue should be factored in when comparing the ranges for different fuels.

(5) In case of electricity negative GHG emissions occur for electricity from biogas from liquid manure due to credits for avoided CH4 and N2O emissions from avoided storage of untreated liquid manure

From the analysis of the results, the following general conclusions can be drawn:

- In terms of WTT energy required for fuel production, among fossil-based fuels, the representative pathways for LPG, LNG and CNG resulted more energy efficient than conventional crude oil based ones.
- Among the pathways with high-energy input, the most WTT energy-intense ones resulted from the electricity (when EU mix is considered), liquefied bio-methane (LBM) and synthetic OME.
- A number of pathways offer the possibility to achieve negative WTT emissions: e.g. LBM/CBM (liquefied/compressed bio-methane) and electricity and hydrogen, when produced from biogas due to the avoided CH_4 and N_2O emissions[12,] and production of synthetic diesel from biomass when coupled with CCS processes (a portion of CO_2 absorbed from the crops is not released but permanently stored in underground geologic formation- see section 3.5 of JEC WTT v5).
- It is important to point out that for biomethane negative emissions are a result of a reduction of GHG emissions compared to a reference use (e.g. avoided CH4 emissions). In case of bio-CCS, if CO_2 is permanently sequestered, then that pathway is actually increasing the C-sink and it is actively removing carbon from the atmosphere (both pathways actively mitigate climate change, but one is reducing emissions, the other is increasing a sink).
- It is worth noting that the wide variability, observed in some pathways such as for HVO, CBM/LBM, H_2 and electricity, is heavily dependent on the conversion route/feedstock chosen which have a significant impact on the final expended energy and GHG emissions.
- Additionally, it is important to highlight that general conclusions about the most favourable routes, both in terms of GHG emissions and energy consumption minimisation can be derived only when the whole WTW analysis is taken into account, as the powertrain efficiency strongly impact the results (expressed in terms of g CO_{2eq}/km, including the efficiency of the different powertrains). As an initial proxy, the total GHG emissions including combustion is also included in the WTT related chart.

Within each of the categories and when the WTT energy and GHG emissions are compared:

- Fossil: A number of "representative" fossil based pathways such as CNG/LNG or high octane gasoline can offer lower GHG emissions routes than conventional gasoline and diesel, while lower energy intensities are mainly reached by the gaseous fossil fuels. One reason for the slightly lower GHG emissions for high octane gasoline is the admixture of bio-components.
- It is worth remarking, that results for gasoline and diesel are based on the consequential LCA methodology used in JEC. The Concawe refinery model calculates marginal CO_2 intensities induced by a marginal change, e.g. demand in petroleum products, around the European refinery operations calibrated for the reference year (2010) in terms of refinery configuration, price of crude oil, other feedstocks supply, petroleum product demand and specifications, as well as processing capacities. Due to the consequential nature of the LCA approach applied according to the goal and scope of JEC WTT v5 the values shall not be used in a pure attributional LCA context. An attributional LCA approach follows other modelling criteria. This is why this JEC WTT v5 report includes a detailed section comparing attributional and consequential CO_2 allocation methods [reference to section 2.3.2 in the JEC WTT v5 study].
- Crop derived fuels: the newly added bio-ETBE route involving ethanol and isobutene from sugar beet shows interestingly low GHG emissions, when compared to Ethanol from other sources than sugar beet (wheat except WTET4a/b, barley, and corn) or HVO/Biodiesel routes, but with higher energy demand. Compared to the associated ethanol pathway the GHG emissions for the ETBE route are higher.
- Wood: selected pathways for synthetic diesel, DME and hydrogen are the ones with the potentially lowest WTT GHG emissions[13]. Negative emissions can be achieved in the pathways implementing CCS.
- Biogas: biogas from manure as feedstock for hydrogen production shows promisingly lower WTT emissions than CBM or LBM pathways, but with significantly higher energy requirements. Significant negative emissions can be derived from routes involving biogas from manure due to the avoided CH_4 emissions. This is the reason why biogas to hydrogen routes involving biogas from manure show lower WTT GHG emissions than the CBM and LBM ones although the energy

[12] It has to be noted that the negative GHG emissions for biomethane from manure only can be taken into account as long as there are farms where storage of untreated manure is applied.

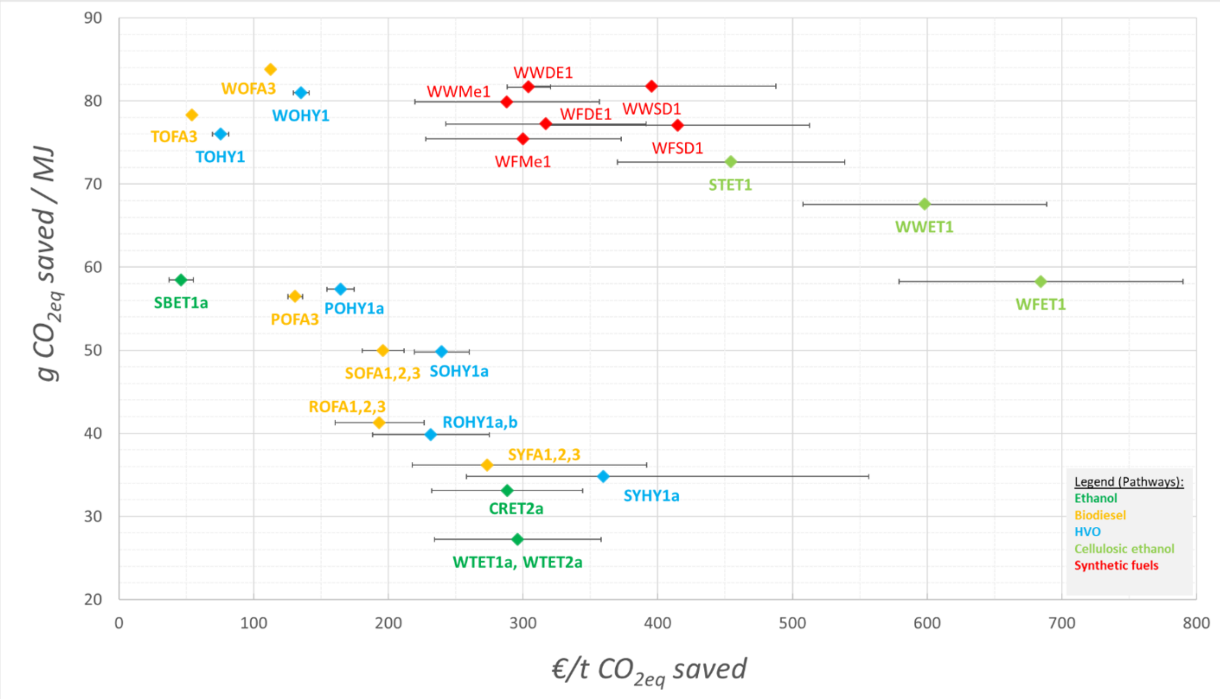
[13] Impacts on forest C-stocks and sinks is not included in this analysis

requirement is higher. It is important to note that this substitution approach is valid under the current assumption that the methane would be released to the atmosphere if not used as fuel. Alternative technologies could also reduce the fugitive methane emissions and, thus, for comparisons to such a case, the current pathway calculations would have to be adjusted accordingly.

- Electricity and H_2: regarding electricity and Hydrogen, it is worth noting that they should be primarily considered as energy carriers, with environmental performances determined by the primary source used for their production. More precisely, the use of electrical energy in the transport sector is, in terms of GHG emissions saving, determined by the pathway of power production. At least for the transitional phase towards road electrification when power for vehicles is taken from the grid, this can lead either to an increase or a reduction in emissions compared to the baseline depending on the electricity source used for that purpose (out of the scope of this JEC study). If the system reacts to this increased demand by increasing the production from fossil sources (e.g. Coal); the overall effect might be an increase in the overall GHG. On the other end, a substantial uptake of electrical energy for the road sector may act as a driver for increasing the share of renewable energies in the EU mix. These issues are country specific and time specific (as production is a non-steady process by definition) and, as mentioned, considerations like these are not included in the present JEC study. For this reason, the improvement in country electricity mixes can only be used as a proxy for deriving a back-of-the-envelope evaluation.
- e-fuels: as e-fuels production is based on renewable electricity, the above-mentioned considerations can be extended to these cases. As detailed in JEC WTT v5 section 3.9, this route is an example of Carbon Capture and Utilisation (CCU) in a highly energy and capital intensive process with high CO_2 abatement potential versus their equivalent fossil-based fuels.

Beyond the technical assessment, the WTT report analyses and quantifies the production and the related GHG savings costs for the main conventional and advanced biofuels, produced in Europe. Focusing the analysis on the pure cost of saved CO_2, Figure 12 shows that using biofuels is today a more expensive solution with respect to fossil fuels, if compared with other mitigation options (e.g. EU-ETS):

Figure 12. Cost of GHG savings for the investigated production pathways in 2014-2016



Note 1. Synthetic fuels included in the WTW integration refer to BTL (Biomass-To-Fuels) pathways.
Note 2. The total production costs are simply given by the sum of capital costs (CAPEX), cost of feedstocks and operational costs (OPEX). A capital charge rate of 12% has been used, representing a return on investment of about 8% without accounting for a profit tax, which returns to the EU. A 20% uncertainty range on the capital investment was also applied.

2.4 Tank-To-Wheels. Summary

In this version of the WTW v5, both Passenger Cars and Heavy duty vehicles have been assessed, with a different combination of energy carriers and powertrains. Both the methodology and the results are briefly discussed in the following sections (the full report can be found in the following link [JEC TTW v5]).

https://ec.europa.eu/jrc/en/jec/publications

2.4.1 Passenger cars (PC)

2.4.1.1 Methodology (TTW - PC)

The Tank-To-Wheel analysis described in the JEC TTW v5 report includes several different fuel–powertrain configurations for conventional[14] (i.e. “ICE-only”) as well as electrified (i.e. “xEV”) powertrain variants. These variants are considered for 2015 (including technologies in the market in the years 2013 up to 2017) to represent the current state-of-the-art in automotive industry and for 2025+ (to give an outlook on the future technical development of passenger cars) based upon the likely market-average technology development expected by EUCAR and AVL experts.

Aligned with the previous section, a summary of some of the key assumptions made and the methodology applied is described below:

Methodology

- For the passenger cars calculations, a common vehicle platform representing the most widespread European segment of passenger vehicles (C-segment compact 5-seater European sedan) was used.

[14] Non-electrified vehicle variants driven by an ICE only are subsequently named as “conventional”. This excludes Hybrid vehicles, which fall into the xEV category.

- All conventional or xEV variants are derived from this reference based on protection of pre-defined vehicle performance criteria. The xEV variants include definitions of appropriate powertrain topologies and system architectures, educated estimations of Hybrid functionalities and operational strategies, and powertrain components including optimized layout and a proper mass balance.
- For detailed investigation, all variants are modeled in the system simulation tool AVL CRUISE which is a development from the ADVISOR vehicle simulation tool use in earlier versions of the study. Data, models and strategies have been discussed and mutually agreed between the EUCAR Task Force and AVL to ensure a high quality of results.
- Key to the methodology was the requirement for all vehicle configurations to comply with a set of minimum performance criteria relevant to European customers while retaining similar characteristics of comfort, driveability and interior space. Also, the appropriate technologies (engine, powertrain and after-treatment) required to comply with pollutant emission regulations in force at the relevant date were assumed to be installed.

It should be noted that all investigated powertrain variants only represent theoretical vehicle configurations and do not correlate to any existing vehicle or brand. However, the definitions made try to ensure, that the investigated powertrain variants provide a representative overview about todays and expected future automotive technologies and their impact on GHG emissions in European C-segment passenger cars.

Powertrain configurations modelled

In the JEC TTW v5 report, chapter 3 and 4 introduce the fuels and powertrain configurations covered in this TTW study:

- Conventional powertrains include the Internal Combustion Engine (ICE) technologies of Direct Injection Spark Ignition, e.g. Otto engine (DISI) and Direct Injection Compression Ignition, e.g. Diesel engine (DICI).
- Electrification of conventional powertrains is covered in terms of a 48V Mild Hybrid Electric Vehicle (MHEV), a Hybrid Electric Vehicle (HEV), a Plug-In Hybrid Electric Vehicle (PHEV) and a Range Extender Electric Vehicle (REEV).

The 48V MHEV, only considered for 2025+, in principle shows the same functionality as the HEV, but represents a simpler approach compared to the dedicated HEV development.

- Additionally, pure electric powertrains like Battery Electric Vehicle (BEV) and Fuel Cell driven Electric Vehicle (FCEV) are investigated.

A description of all analysed combinations of these powertrains with corresponding fuel variants for 2015 and 2025+ is given in chapter 6. The methodology used for the simulation study is described in chapter 5. The detailed description of investigated powertrain configurations and their component specifications for 2015 variants is given in section 3.1, and for 2025+ variants in section 3.2 (JEC TTW v5).

Fuel and powertrain combination (TTW)

Table 5. Automotive fuels and powertrain combinations

EUCAR V5: 2015 Investigation Matrix	2015 Powertrain Variants										
	DISI	DICI	Hybrid DISI	Hybrid DICI	PHEV50 DISI	REEV100 SI	PHEV50 DICI	BEV150	FCEV	PHEV50 FC	REEV100 FC
Gasoline (E5)	■		■		■	■					
Gasoline E10 market blend	■		■		■	■					
Gasoline high RON (var. 1)	■		■		■	■					
Gasoline high RON (var. 2)	■		■		■	■					
Diesel (B0)		■		■			■				
Diesel B7 market blend		■		■			■				
LPG	■										
CNG	■										
E100	■		■		■	■					
FAME (B100)		■		■			■				
DME		■		■			■				
FT-Diesel*		■		■			■				
HVO*		■		■			■				
Electricity					■	■	■	■		■	■
Hydrogen (CGH2)									■	■	■

EUCAR V5: 2025+ Investigation Matrix	2025+ Powertrain Variants														
	DISI	DISI MHEV	DICI	DICI MHEV	Hybrid DISI	Hybrid DICI	PHEV100 DISI	REEV200 SI	PHEV100 DICI	REEV200 DICI	BEV200	BEV400	FCEV	PHEV100 FC	REEV200 FC
Gasoline (E5)	■	■			■		■	■							
Gasoline E10 market blend	■	■			■		■	■							
Gasoline high RON (var. 1)	■	■			■		■	■							
Gasoline high RON (var.2)	■	■			■		■	■							
Diesel (B0)			■	■		■			■	■					
Diesel B7 market blend			■	■		■			■	■					
LPG	■	■													
CNG	■	■													
E100	■	■			■		■	■							
FAME (B100)			■	■		■			■	■					
DME			■	■		■			■	■					
FT-Diesel*			■	■		■			■	■					
HVO*			■	■		■			■	■					
Electricity							■	■	■	■	■	■		■	■
Hydrogen (CGH2)													■	■	■

* EN15940 synthetic diesel standard to allow optimized engines

Note.

Matrix of fuel-powertrain combinations investigated in the current TTW study; some of the variants modelled in powertrain simulation in detail while some others are derived from them based on their fuel properties. All variants are considered for 2015 and 2025+ except the following: MHEV and REEV CI are considered for 2025+ only, and BEV 2025+ is defined in two different range variants.

Details:

All conventional variants DISI and DICI are equipped with a 55L standard size fuel tank for 2015. This is reduced to a 35L fuel tank for 2025+ to ensure a comparable driving range for the more efficient future powertrains. All HEV, PHEV and REEV (Gasoline only) variants are equipped with a 55L standard size fuel tank for 2015. In case of 2025+, to ensure a comparable driving range for the more efficient future powertrains, this is reduced to a 35L fuel tank for MHEV and HEV, and further reduced to a 28L fuel tank for PHEV and a 21L fuel tank for REEV 2025+. Hydrogen fuel tank systems represent Compressed Gaseous Hydrogen (CGH2) technology. In both 2015 and 2025+, the fuel tank capacity is assumed to 4kg, which gives a driving distance well above the 500km minimum criterion. All FC variants are simulated based on a generic tank system of 90kg. Battery sizes for 2015 and 2025+ are 30, 50 and 90 kW for HEV, PHEV and BEV respectively. The complete vehicle specifications can be found on section 3.2.1. Main vehicle specifications of the JEC TTW study for passenger cars.

Terminology:

DISI: Direct Injection Spark Ignition | **DICI**: Direct Injection Compression Ignition
HEV: Hybrid Electric Vehicle | **MHEV:** Mild Hybrid Electric Vehicle (48v)
PHEV: Plug-In Hybrid Electric Vehicle | **REEV**: Range Extender Electric Vehicle
BEV: Battery Electric Vehicle | **FCEV**: Fuel Cell driven Electric Vehicle
LPG: Liquefied Petroleum Gas | **CNG**: Compressed Natural Gas
FAME: Biodiesel (B100) | **DME**: DiMethyl Ether
FT-Diesel: Paraffinic diesel (EN15940) | **HVO**: Hydro-treated Vegetable Oil

Note.

BEV range: 150km (2015), 2 variants (2025+) 200km and 400km

PHEV EV range: 50km (2015), 100km (2025+)

REEV EV range: 100km (2015), 200km (2025+)

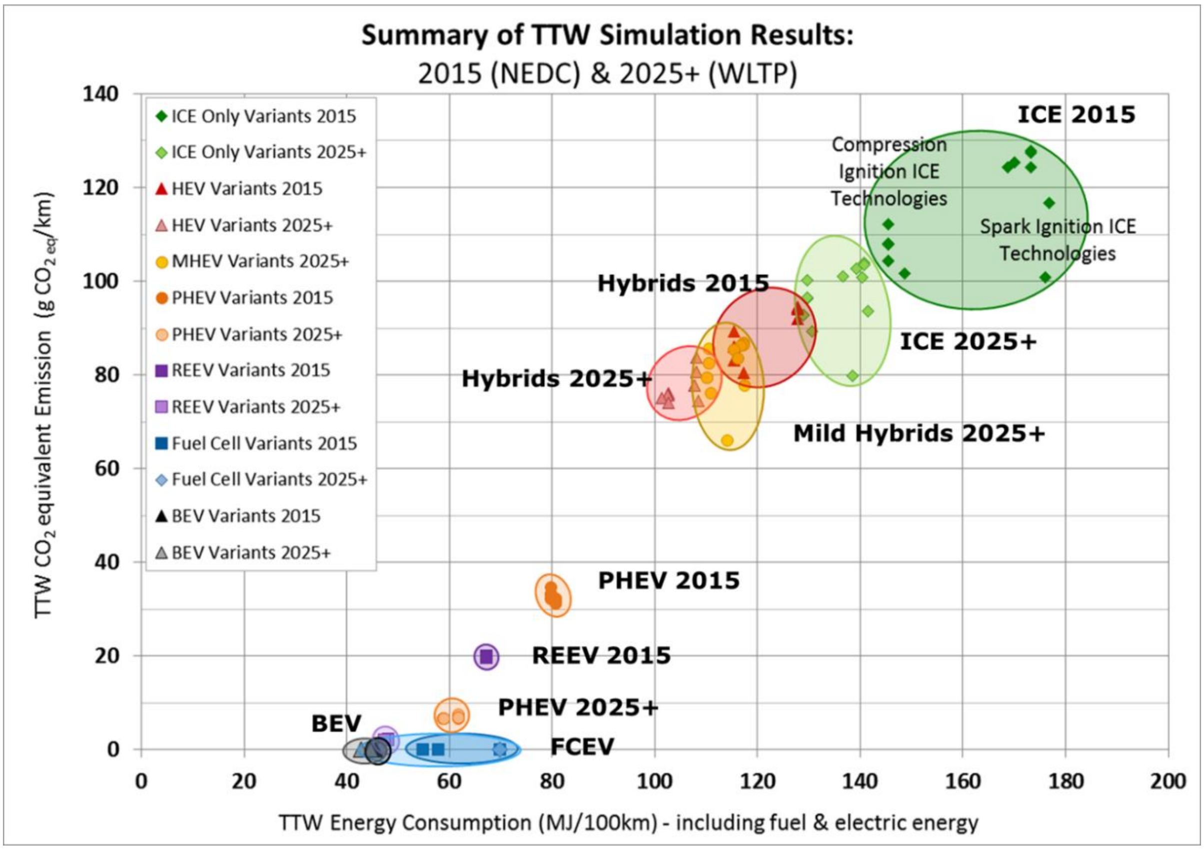
Based on the above, it is important to highlight that:

- The model vehicle is simply a comparison tool and is not necessarily deemed to represent the European average in terms of fuel consumption.
- The results relate to compact passenger car applications, and should not be generalized to other segments such as Heavy Duty or SUVs.
- No assumptions or forecasts were made regarding the potential of each fuel/powertrain combination to penetrate the markets in the future. In the same way, no consideration was given to availability, market share and customer acceptance.

2.4.1.2 Results (TTW - PC)

In the following overview diagram, all results are summarized in terms of CO_2 equivalent emission and energy consumption for 2015 and 2025+ variants:

Figure 13: Summary of TTW Simulation Results for 2015 (NEDC) & 2025+ (WLTP) Variants; note that electric energy consumption includes charging losses



It is worthy of note that:

- Due to improvements in future powertrain technology, as well as with the support of fuel quality, ICE powered vehicles will continue to deliver TTW GHG emission reductions and energy savings compared to the 2015 baseline. Future Diesel-type engines will keep energy efficiency benefits.
- Hybridisation (Mild (48v) and Full-Hybrids) will deliver additional reductions in both domains (gasoline and diesel).
- Additional GHG and energy consumption reductions can be achieved with deeper electrification, i.e. PHEV, REEV as well as FCEV and BEV powertrains. However, the main differentiator between PHEV and REEV is battery size rather than ICE integration.

2.4.2 Heavy Duty Vehicles (HDV)

2.4.2.1 Methodology (TTW – HDV)

In this part of the TTW study, typical figures for fuel consumption (FC), CO_2 and CO_2-equivalent emissions as well as energy consumption of current and future propulsion and fuel configurations for heavy duty vehicles (HDV) have been assessed.

A summary of some of the key assumptions made and the methodology applied is described below:

Methodology

- All vehicle concepts considered have been analysed for the model years 2016 and 2025, whereby 2016 models are representing the state of the art on the European market for the individual application purpose. Vehicle specifications for 2025 are based on a technology assessment of future improvements. For xEV concepts, it is at the moment not possible to identify typical vehicle configurations as these systems are currently a new technology under development for HDV. As a consequence, xEV vehicle specifications and related results as elaborated in the present study shall been understood as examples for these new technologies.
- Simulation of vehicles which are driven by an ICE only have been performed with the software Vehicle Energy Consumption Calculation tool (VECTO), the tool which is also used for the CO2 certification of HDV in the EU. Electrified propulsion systems have been simulated with the model PHEM15 as these propulsion concepts are not covered in the current VECTO version.

Powertrain configuration modelled

The following two HDV configurations have been analysed:

- Rigid truck with 18 tons gross vehicle mass rating (GVMR) designed for use in regional delivery mission ("group 4 vehicle")16
- Tractor-semitrailer combination with 40 tons GVMR designed for use in long haul mission ("group 5 vehicle")
- The analysed HDV configurations are either driven with a conventional internal combustion engine (ICE) or an electrified propulsion system (xEV). ICE only configurations include the technologies:
- Direct Injection Compression Ignition (CI)
- Port Injection Positive Ignition (PI)
- LNG High Pressure Direct Injection Compression Ignition (HPDI)

Fuel and powertrain combination (TTW)

- For CI engines the fuels Diesel B0 (fossil), B7 (7%v FAME) and B100 (100% FAME) as well as DME, ED95, OME and Paraffinic Diesel were considered.
- For PI engines CNG and LNG were analysed.
- The electrified propulsion systems include: Hybrid electric vehicle (HEV), Battery electric vehicle (BEV), Catenary electric vehicle (CEV) and Hydrogen Fuel cell (FCEV).
- In the case of FCEV, the tank system is compressed hydrogen at 700 bar.
- For a full description of powertrain specifications, please see section 4.3 Propulsion systems in the JECT TTW report for Heavy-duty vehicles.

[15] Passenger car and Heavy duty Emission Model, developed at the Institute for Internal Combustion Engines and Thermodynamics at the Graz University of Technology

[16] Labelling of vehicles by „group" refers to the method as applied in the European Regulation for CO_2 certification of Heavy Duty Vehicles [EU, 2017]

Table 6. Investigated fuel and powertrain configurations and simulated vehicle groups

Powertrain / Fuel	ICE CI (Diesel)	ICE PI (Gasoline)	ICE CI +HEV	ICE PI +HEV	BEV	FCEV	CEV (electric road)
Diesel B0	Both						
Diesel B7 market blend	Both		Both				
DME	Both						
ED95	Both						
Electricity					Both		Both
Biodiesel (B100)	Both						
Paraffinic Diesel	Both						
CNG		Both		Group 4			
Hydrogen						Both	
LNG (EU mix.)	Both	Both		Group 5			
OME	Both						

Notes.
(1)Colour code implies "Both" for Type 4 & 5.
(2) The vehicle/powertrain configurations are:

- **ICE**: Internal Combustion Engine
- **CI**: Compression Ignition (Diesel)
- **PI**: Port Injection
- **HEV**: Hybrid Electric Vehicle
- **BEV**: Battery Electric Vehicle
- **FCEV**: Fuel Cell driven Electric Vehicle
- **CEV**: Catenary Electric Vehicle (electric road)[17]
- **DME**: Di-Methyl-Ether
- **ED95**: Ethanol based fuel for diesel engines
- **CNG**: Compressed Natural Gas
- **OME**: Oxy-methylene-ethers

Based on the above and as for the passenger car section, it is important to highlight that:

The model vehicle is simply a comparison tool and is not necessarily deemed to represent the European average in terms of fuel consumption.

The results relate to configured Heavy Duty vehicles in defined applications, and should not be generalized to other vehicles and applications in the same segment, or even different Heavy Duty segments, LDV, PCs or SUVs.

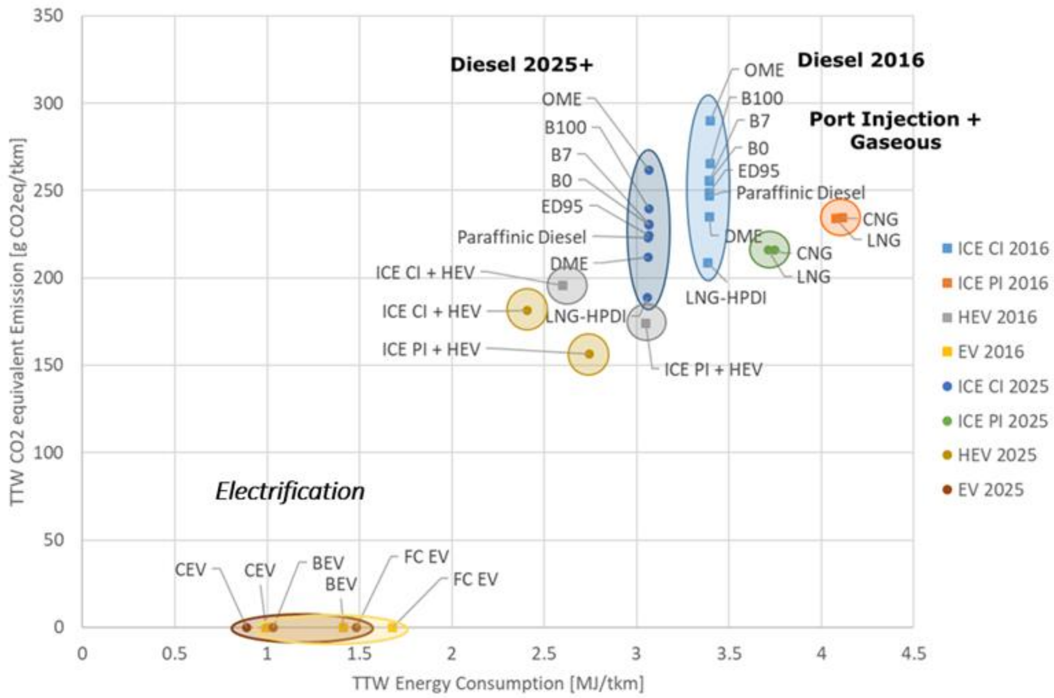
No assumptions or forecasts were made regarding the potential of each fuel/powertrain combination to penetrate the markets in the future. In the same way, no consideration was given to availability, market share and customer acceptance.

2.4.2.2 Results (TTW – HDV)

Figure 14 and Figure 15 give a summary on the results on transport specific figures (i.e. per tonne-kilometre) for energy consumption and TTW CO_2-equivalent emissions. The main conclusions on the comparison of different propulsions systems drawn from these results are given in chapter 7 of the JEC TTW v5 report:

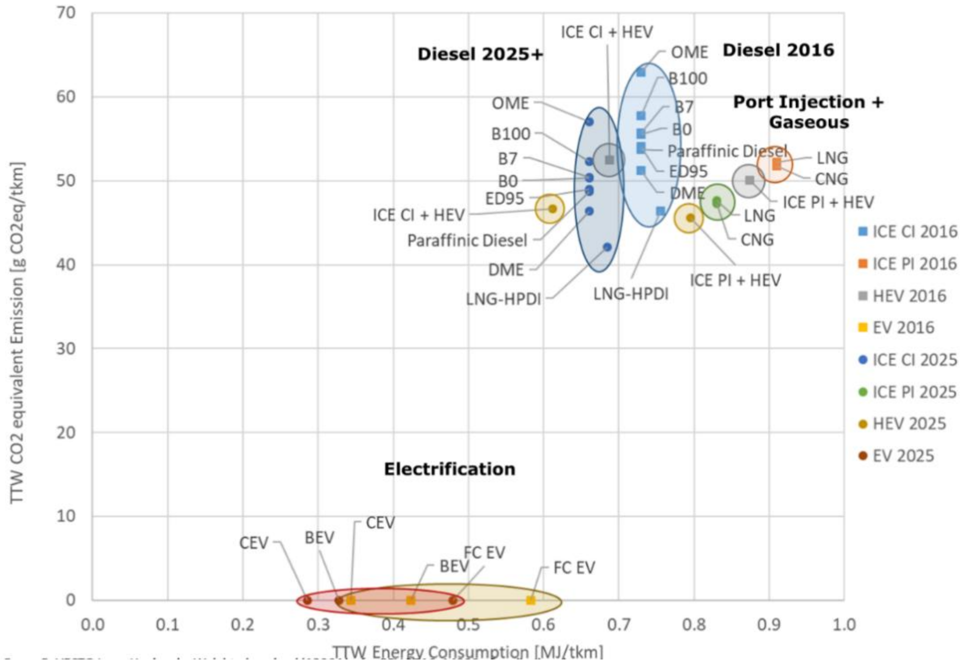
[17] The overhead infrastructure has ~10% losses due to air resistance of the pantograph (approx. 0.1 kWh/km for Type 5 vehicle) additional to the JEC TTW v5 reported values (As more detailed information becomes available, these losses will be integrated in JEC WTW v6).

Figure 14. Summary results vehicle group 4 (Regional Delivery)



Group 4; VECTO Urban-Delivery cycle; Weighted payload (2650 kg)
Analysed propulsion systems do vary in performance criteria like operating range, payload capacity or fuelling time

Figure 15. Summary results vehicle group 5 (Long Haul)



Group 5; VECTO Long-Haul cycle; Weighted payload (13064 kg for BEV 2016; 14290 g for all others)
Analysed propulsion systems do vary in performance criteria like operating range, payload capacity or fuelling time

Based on the TTW results, some relevant comments can be derived:

- Future ICE technologies and alternative fuels will continue to deliver GHG & energy savings.
- Diesel CI engines have about 20% lower energy consumption than the PI gasoline engines.
- Hybrids provide significant energy and GHG reduction.
- Fully electric and fuel cell alternatives offer zero TTW GHG emissions and significantly higher energy efficiency, up to 2.5 times for catenary electric vehicle (CEV[18], electric road).

2.5 WTW integration and selection of pathways

2.5.1 WTW integration. Approach.

The Well-To-Wheels integration is presented in the following sections where the results of selected fuel pathways (WTT) and powertrains (TTW) are combined to estimate the energy and GHG balances for different alternatives.

The WTW energy and GHG figures combine the WTT expended energy (i.e. excluding the energy content of the fuel itself) per unit energy content of the fuel (LHV basis) (g CO_{2eq}/MJ $_{final\ fuel}$), with the TTW energy consumed by the vehicle per unit of distance covered (for passenger cars, the NEDC/WLTP cycle expressed as MJ/km factors is used whereas for Heavy Duty vehicles, the energy consumption is based on VECTO and PHEM simulation and expressed in terms of MJ/km and MJ/tkm. In both Passenger cars and Heavy Duty vehicles, the TTW energy consumption is converted into g CO_{2eq}/km (or tkm) through the characterized fuel emission).

The energy figures are generally presented as total primary energy expended, regardless of its origin, to move the vehicle over 1 km on the test cycle. These figures include both fossil and renewable energy. As such they describe the energy efficiency of the pathway.

Total WTW energy (MJ/100 km) = (MJ TTW energy / 100 km) • (1 + MJ WTT total expended energy / MJ fuel))

For fuels of renewable origin, fossil energy expended in the pathway has been also evaluated: illustrating the fossil energy saving potential of that pathway compared to conventional alternatives.

Fossil WTW energy (MJfo/100 km) = (MJ TTW energy /100 km) • (λ + MJ WTT fossil expended energy / MJ fuel)

λ = 1 for fossil fuels, 0 for renewable fuels

GHG figures represent the total grams of CO_2 equivalent emitted in the process of delivering 1 km of vehicle motion on the NEDC cycle.

WTW GHG (g CO2eq/km) = TTW GHG (g CO2eq/km) + (MJ TTW energy /100 km)/100 • WTT GHG (g CO2eq/ MJ fuel)

Results for all pathways considered in the study are summarised in Sections 3.2 for Passenger Cars and Section 4.2 and 5.2 for Heavy Duty (Type 4 and 5 respectively).

Beyond this considerations and for the electricity driven powertrains (e.g. Battery or Catenary electric vehicles), it is worth noting that, although the same WTT and TTW terminology is used, this refers to *Well-To-Low voltage* until the point where electricity is effectively used to drive the powertrain and, from there, Low voltage-to-Wheels (medium voltage in the case of CEVs – See Figure 7 in Section 2.1.).

[18] Note that ~10% of additional losses in the overhead infrastructure would need to be considered (as a proxy). Currently not included in the JEC TTW v5 report.

2.5.2 Selection of pathways

Due to the major revision conducted in the JEC v5 reports both on WTT (>250 resource to fuel pathways modelled) and TTW (>60 powertrain combinations), the number of potential routes to be combined in the WTW analysis has increased considerably since last version (> 1500 possible combinations). This led to the need of finding an appropriate way to present the results. Therefore a number of WTT pathways have been selected to show the variability of the conversion routes, due to both different feedstock and processes modelled, deriving a comparative analysis between alternatives.

In order to select the relevant WTW combinations, a series of criteria have been applied to filter the WTT pathways. Symbols have been defined to highlight the pathway characteristic:

Table 7. WTT selection criteria for WTW integration

Criteria to select pathways		Icon
Reference fuel for comparison (*)	In this context, conventional fuel refers to fossil fuels the alternative can be compared against (e.g. regular 100% fossil diesel or CNG for comparison purposes).	
GHG emissions - Max(**) **(Maximum value - gCO_{2eq}/MJ)**	Value close to the maximum allowed GHG wmissions, according to RED recast. As a general rule, WTT pathways with significantly higher GHG emissions are not included in the comparison.	
GHG emissions - Min **(Minimum value - gCO2eq/MJ)**	The route offering the minimum WTT GHG emissions. This value, along with the maximum route mentioned above, determine the WTT range of the production routes explored towards a final fuel.	
Representative pathway	Selected pathway for the final fuel. Chosen by consensus within the JEC as example of one of the commercially available routes depending on the case (e.g. most frequent in Europe, higher share in the current mix, etc.).	
Special interest	Selected examples of interesting new pathways/feedstock.	
TRL	TRL > 6 (***)	(no icon)

Note 1 (*). It worth remarking that fuels at pumps are derived by a blend of processed fossil and bio-feedstock. According to the Renewable Energy Directive (2009/28/EC) mandatory targets, a 10 % share of energy has to come from renewable sources in transport energy consumption in European Union by 2020. For 2025+ timeframe the RED II targets increases to an overall minimum target of 14% of renewable energy for the transport sector. In order to facilitate the estimation of potential feedback of substituting fossil based fuel with bio-derived, in this JEC WTW v5 analysis no blends are considered for comparison.

Note 2 (**). REDII methodology for calculating default values, and therefore maximum allowed GHG emission differs from JEC WTT, for some methodological aspects. For this reason, REDII limits have been considered as a guideline for filtering out some pathways with very high GHG emissions.

Note 3. (***) In this JEC WTW report we have focused on WTT feedstock/conversion routes at or close to be ready for commercialization. Therefore, WTT pathways with Technology Readiness Level (TRL) <6 have been excluded for the present WTW comparison (For additional comparisons, we would suggest the reader to refer back to the individual WTT and TTW reports where all the results for individual pathways/powertrain modelled are detailed).

Note 4. In the JEC TTW v5 report, only certain "main fuels" were directly simulated. However, in the JEC WTW report, additional combination of WTT and TTW values for different fuels (not covered explicitly in the TTW section) were presented. In these cases, a simple conversion has been applied starting from the energy use reported in the TTW v5 report for a similar fuel and adjusting the CO_2 emissions by considering the different CO_2 emission factor of the new fuel (e. g. LNG consumption in the TTW report allows to calculate LNG and LBM values in the WTW report, to name only a few).

When these criteria are applied, the selected WTT pathways per fuel cluster (i.e. ethanol, biodiesel) are effectively limited to ~5 routes and integrated, when applicable, to both Passenger Cars and Heavy Duty TTW results. This implies no differentiation between the segments where the fuels are consumed **(Appendix 1** includes the detailed list of the selected WTT pathways per individual fuel once the selection criteria have been applied).

2.5.3 Fuel properties

As a summary of the properties of the fuel used for the integration of the Well-To-Wheels pathways and the Tank-To-Wheels ones are detailed in the Table 8:

Table 8. Summary of fuel properties used for the Well-To-Wheels integration (Liquids)

Fuel	Density	RON / CN	LHV	Elemental composition of Carbon	CO_2 emission factor (Fuel combustion [Note])	
	kg/m^3	---	MJ/kg	%m	g/MJ	kg/kg
Gasoline 2016 (E0)	743	95	43.2	86.4	73.4	3.17
Gasoline 2016 (E5)	746	95	42.3	84.7	73.3	3.10
Gasoline E10	748	95	41.5	82.8	73.3	3.04
Gasoline High Octane. Case 1 (100 RON)	761	100	42.4	84.8	73.3	3.11
Gasoline High Octane. Case 2 (102 RON / E5eq)	759	102	42.4	84.8	73.3	3.11
Gasoline High Octane. Case 3 (102 RON/ E10eq)	759	102	41.6	83.3	73.4	3.05
Pyrolysis-based Naphtha	745	95	43.2	86.4	73.4	3.17
Ethanol	794	108	26.8	52.2	71.4	1.91
Methanol	793	132	19.9	37.5	68.9	1.37
MTBE	745	118	35.1	68.2	71.2	2.50
ETBE	750	119	36.3	70.6	71.3	2.59
Diesel (B0)	832	51	43.1	86.1	73.2	3.16
Pyrolysis-based Diesel	832	51	43.1	86.1	73.2	3.2
Diesel B7 market blend	836	53	42.7	85.4	73.4	3.13
FAME	890	56	37.2	77.3	76.2	2.83
ED95	820	n. a.	25.4	49.4	71.3	1.81
FT Diesel	780	70	44.0	85.0	70.8	3.12
HVO	780	70	44.0	85.0	70.8	3.12
OME	1067	84	19.2	43.5	83.3	1.60

Note) CO_2 emission factor refers to the emissions released during the total combustion (full oxidation) of the carbon contained in the fuel molecules (expressed per MJ (or kg) of a certain fuel burnt). Therefore, the factor is not linked to the production process but to the chemical composition, carbon content, of the fuel itself.

Estimation of CO_2 emissions from fuel combustion for a given fuel can be summarised as follows:

CO_2 emissions from fuel combustion = Fuel consumption * CO_2 Emission factor.

In the case of fuels from biogenic origin (biofuels), the emissions during combustion can be offset (net zero) as the carbon released during combustion is equal to the carbon captured by the plant/tree during its growing process). See Figure 8.

Table 9. Summary of fuel properties used for the Well-To-Wheels integration (Gases)

Fuel	Density	RON / CN	LHV	Elemental composition of Carbon	CO_2 emission factor (Fuel combustion)	
	kg/ m³i.N.*	---	MJ/kg	%m	g/MJ	kg/ kg
DME (liquefied via pressurisation at 288.15 K)	670	55	28.4	52.2	67.3	1.91
LPG (liquefied via pressurisation at 288.15 K)	550	**	46.0	82.4	65.7	3.02
CNG (EU mix piped NG)	0.780	**	46.6	70.8	56.1	2.60
CNG (2016 Mix)	0.782	**	46.6	71.3	56.2	2.62
CNG (2030 Mix average)	0.782	**	46.8	71.7	56.2	2.63
H-CNG (2016)	0.775	**	48.0	73.5	56.2	2.69
H-CNG (2030)	0.775	**	48.0	73.5	56.2	2.70
CNG (Russian NG quality)	0.727	**	49.2	73.9	55.1	2.71
CNG (upgraded biogas)	0.752	**	46.1	71.3	56.7	2.61
LNG (EU mix. 2016/2030)	0.798	**	49.1	75.6	56.4	2.77
LNG (Upgraded biogas 2016/2030)	0.716	**	50.0	74.9	54.9	2.74
Shale gas	0.727	**	49.2	73.9	55.1	2.71
Hydrogen (CGH2 & cCGH2)	0.090***	#	120.0	0.0	0.0	0.00
Liquid Hydrogen			120.0	0.0	0.0	0.00

Notes:
*) All values are related to standard conditions according to DIN 1343 (0.1013 MPa; 273.15 K) & ISO 2533 (288.15 K);
**) can vary significantly;
***) 0.084 kg/m³ @ 288.15 K (as indicated in the TTW report). The pressure of the CGH2 at the refueling station amounts to 88 MPa. CGH2 is stored in the vehicle at a pressure of maximum 70 MPa at 15°C.
The pressure of the CNG in the stationary CNG storage at the refueling station amounts to 25 MPa. CNG is stored at a pressure of maximum 20 MPa in the vehicle at 15°C.

Additional components:

- AdBlue CO_2 emission factor: 0.24 kg/kg

2.5.4 European biofuel mix: weighted average of GHG emissions (2017 / 2025+)

For comparison purposes, this section presents a weighted everage of GHG emissions (from an elaboration of the related feedstocks JEC WTT v5 values) of the mix of ethanol, biodiesel and HVO used or expected to be used in Europe, in two different timeframes: a scenario deemed to be representative of the current situation (based on 2017 data) and some estimate for a potential 2030 mix.

The weighted values presented in the Table 10 consider two contributing factors:

1. the shares of the feedstock used for the EU ethanol, biodiesel and HVO production
2. the shares of the most representative WTT sub-pathways estimated on the basis of JEC experts' judgment.

It is worth remarking that the assumptions made to estimate the GHG emissions of biodiesel and HVO (detailed in Appendix 2) have been made with the sole purpose of calculating an average WTW, for these two alternative fuel classes. This exercise, functional to the goal of JEC WTW, it is to be considered as an estimate, and it does not aim to represent an accurate analysis of the future European market.

Table10. Summary ethanol, biodiesel and HVO EU mix

<table>
<tr><th>gCO_{2eq}/MJ</th><th colspan="2">2017</th><th>2025+</th></tr>
<tr><td>Ethanol - EU mix</td><td colspan="2">52</td><td>44</td></tr>
<tr><td>Biodiesel – EU mix</td><td>39</td><td rowspan="2">37*</td><td>39</td></tr>
<tr><td>HVO – EU mix</td><td>30</td><td>27</td></tr>
</table>

* 83% is biodiesel and 17% is HVO on the basis of USDA, 2018

Note. **Appendix 2** describes the assumptions considered for the above estimate.

3 Passenger cars

As presented along the JEC WTT and the TTW v5 documents, the variability among the more than 250 different pathways modelled and the different powertrains is wide when compared with conventional fuels, both in terms of energy expended and GHG emissions. Factors such as the conversion pathways chosen, the used feedstock/resource, together with the specific powertrain technology in the 2015/2025+ timeframe have a strong impact on the final results.

As a summary, this section includes the results of the JEC WTW integration in terms of GHG emissions (CO_{2eq}) and energy expended covering:

Sub-section 3.1. Comparative analysis aiming to help readers understand the variability in the WTW results due to the feedstock/fuel production route chosen, and the powertrain technology for the two time horizons explored in the study (2015 / 2025+). For that purpose, two type of comparative charts are produced:

- Fuel comparison: these charts show, for the main selected powertrain technologies, the variability due to the use of different type of fuels (and within a fuel, the representative selected pathway and the range as defined in Appendix 1).
- Powertrain comparison: in these charts, the impact of modifications in the main powertrain technologies through, for example different levels of hybridization or battery sizes, are explored for each type of fuel and its representative feedstock/conversion pathway.

Sub-section 3.2. Presents detailed results, deepening into the WTW GHG and energy expended results by decoupling the contribution of both WTT and TTW elements, for each type of fuel/powertrain combination (showing the variability for the selected WTT pathways and time horizons). The details are grouped in:

- Internal Combustion Engines (ICEs) – Liquid fuels
- Internal Combustion Engines (ICEs) – Gaseous fuels
- Electricity driven powertrains (xEVs)
- Fuel Cell Hydrogen Electric Vehicles (FCEV)

3.1 WTW integration. Comparative Analysis

The comparison of the different fuels/energy carriers are described in the following charts.

Figure 16. WTW fuel comparison (2015 – NEDC / 2025+ WLTP) - GHG emissions

Note. The charts above include selected pathways modelled for the JEC WTW v5 integration (not representing all possible WTW fuel and powertrain combinations following the criteria explained in section 2.5.2). Additional promising low-CO_2 intensive pathways, not available at commercial scale yet (Technology Readiness Level < 6), have not been included in this WTW comparison but all detailed data are available in the JEC WTT v5 report for the reader to conduct their own in-depth assessment.

Conclusions:

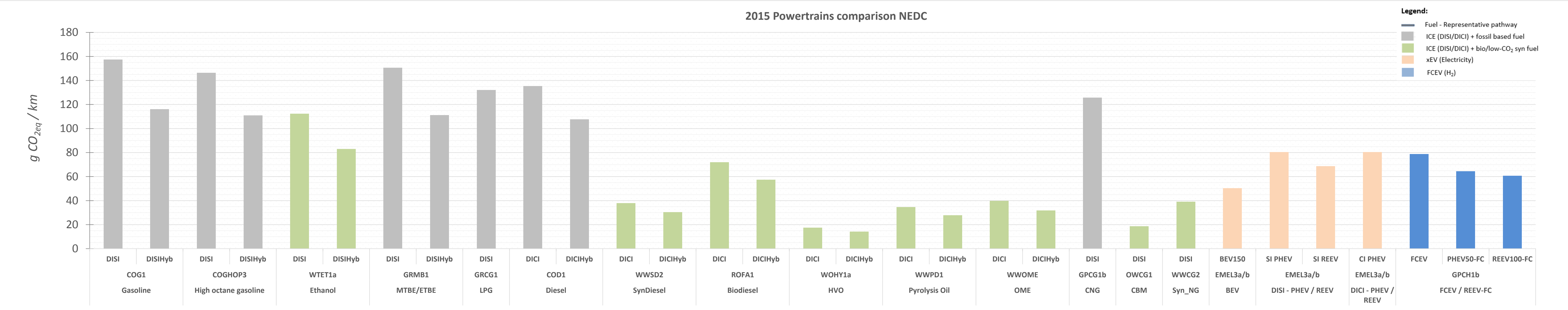
Regardless the timeframe considered (2015/2025+), almost all the alternative fuels analysed offer a better WTW performance than conventional oil based gasoline/diesel when used in Internal Combustion Engines (DISI/DICI). Some exceptions are present, such as the gasification of coal to produce synthetic diesel.

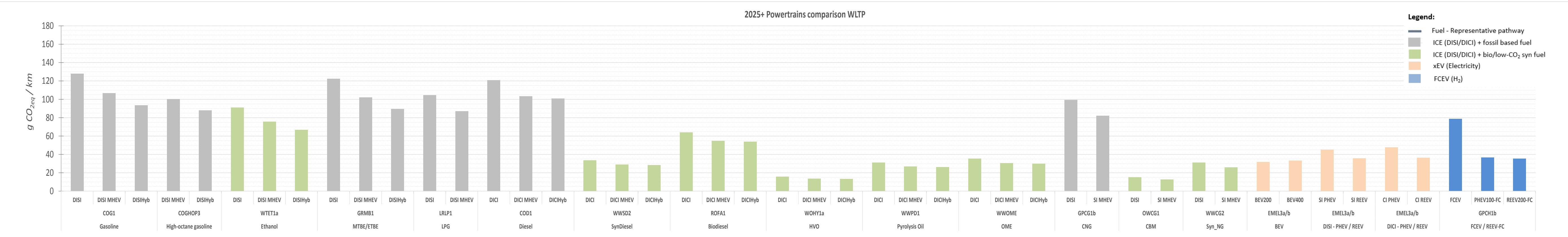
Electricity and Hydrogen have the potential to offer low CO_2 intensive alternatives comparable with the bio liquid/gaseous' representative pathways selected for the analysis. The use of renewable electricity for xEVs and FCEV offer one the lowest WTW intensive combinations similar to the use of biomethane and syndiesel (e-fuels) in DICI.

Interestingly, PHEV technology (when powered with the EU mix and conventional gasoline/diesel) shows a similar CO_2 intensive route than the use of FCHEV in 2015 (Hydrogen produced through conventional natural gas reforming route) but the differences increase towards 2025+ in favour of the BEVs/PHEVs/REEVs alternatives (if no low-CO_2 intensive hydrogen is used).

It is worth noting that: (1) this comparison includes the effect of the change in the test cycle from 2015 (NEDC) to 2025+ (WLTP) partially offsetting the potential WTW benefit. (2) the fuel component considers state –of-the-art technology of fuels already or close to be commercialized at scale in the market. (3) Availability issues are not included in the scope of JEC WTW v5.

Figure 17. WTW powertrain comparison (2015 – NEDC / 2025+ WLTP) - GHG emissions





Conclusions:

- Generally speaking, the **hybridization** of ICEs offers an effective option to reduce fuel consumption, up to ~25% (better performance in gasoline than diesel powertrains) when focused on non-plug-in HEVs (excluding PHEVs).
- For **gasoline/DISI** type of engines, the combination of high compression with a high octane gasoline (102 RON) offers a similar performance than DICI (diesel) vehicles when approaching 2025+. For the high octane gasoline pathways the wheat-to-ethanol pathway WTET5 (biogas from DDGS for internal energy supply) instead of the representative wheat-to-ethanol pathway WTET1a (NG boiler) has been used. The difference for the WTW GHG balance for high octane gasoline pathway COGHOP3 (variant with the highest ethanol share) amounts to about 2%. Regarding the contribution from alternative fuels, ethanol, MTBE and specially bio-ETBE routes show interesting WTW GHG reductions (up to 2/3 in the case of bio-ETBE).
- **LPG** used in DISI engines deems to offer a ~15% WTW GHG reduction versus pure DISI in 2015, slightly increasing its potential benefit when approaching 2025+.
- Regarding **diesel**-like alternatives, the selected fuel pathways offer routes to lower the GHG emissions of conventional DICI in 2015 from ~50% up to 85% (bio and synthetic diesel pathways – synthetic diesel understood here as *BTL* - biomass/waste derived fuels). The full hybridization technology *per se* does not offer as significant GHG reductions versus the mild hybridization one.
- The xEVs technology is expected to improve significantly towards 2025+ (including battery size increase). In 2015, FCEV and PHEV/REEV offer similar WTW results (~15% better performance of the latter versus FCEV. The difference increases when approaching 2025+ mainly due to the less CO_2 intensive electricity mix used in 2030 for the selected pathways (the combination of FCHEV and PHEV/REEV in the same powertrain offers similar results than DISI/DICI PHEV/REEV especially as the % of the time being driven in e-mode is expected to increase. In the case of H_2, a combination of different pathways has not been assessed in this WTW v5 (as a H_2 2025+ mix).
- From all combinations of fuel/energy carriers and powertrains explored in this WTW report, the HVO pathway with the DICI Hybrid technology (waste as feedstock) and the use of CBM in a SI MHEV represent the lowest GHG intensive routes.
- As in the previous chart, it is important to remark that while NEDC test cycles was applied to 2015 powertrains, WLTP is included in the 2025+ scenario. This change in the test cycle towards more real driving emissions is partially offsetting part of the GHG emission reduction due to fuel efficiency measurements achieved in the powertrain technologies.

Figure 18. WTW fuel comparison (2015 – NEDC / 2025+ WLTP) - energy expended

Conclusions:

Energy use does not necessarily correlate with GHG emissions and vice versa.

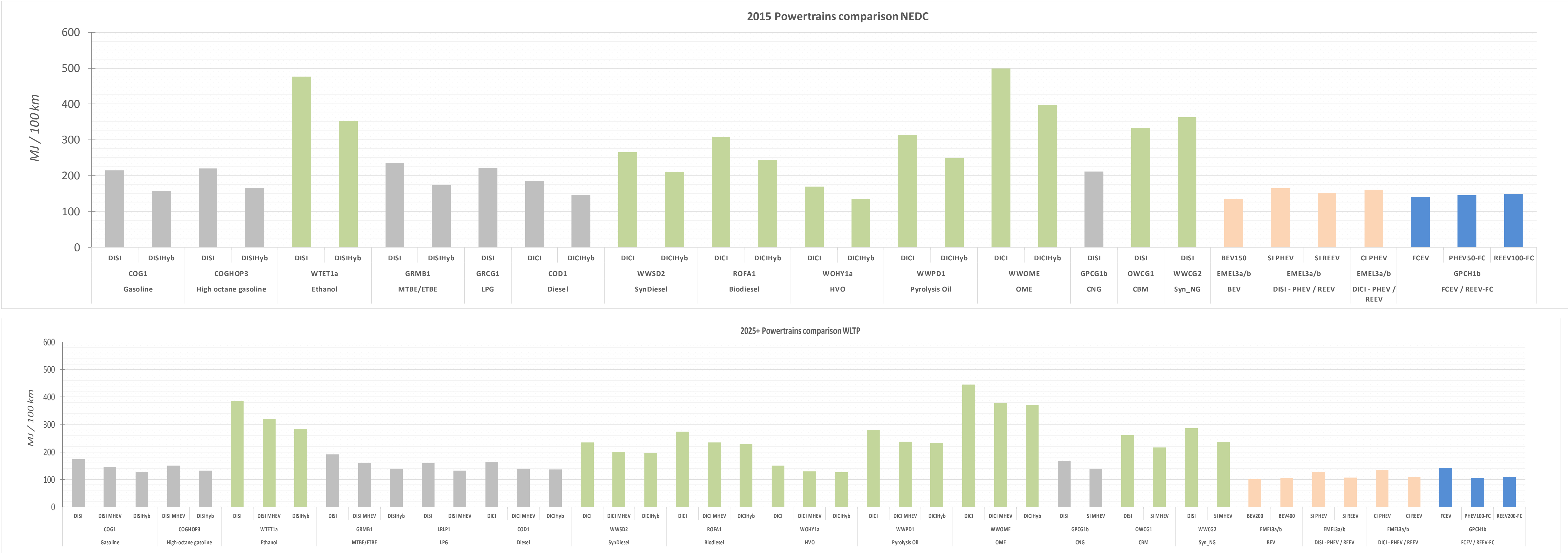
Regardless the timeframe considered (2015/2025+), alternative fuels based on waste cooking oil (WOHY1a) analysed offer a better WTW performance than conventional oil based gasoline/diesel. Most of the alternative fuels lead to a higher energy use when used in Internal Combustion Engines (DISI/DICI). It has to be noted that in case of renewable fuels a large part of the energy expended is renewable leading to lower GHG emissions.

Electricity and Hydrogen have the potential to offer low energy intensive alternatives comparable with the bio liquid/gaseous' representative pathways selected for the analysis. The use of renewable electricity for xEVs offers one of the lowest energy intensive combinations

Interestingly, BEV technology (when powered with the EU mix) shows a similar energy use than the use of FCEV in 2015 (Hydrogen produced through conventional natural gas reforming route) but the differences increases towards 2025+ in favour of the BEVs alternatives.

It is worth noting that: (1) this comparison includes the effect of the change in the test cycle from 2015 (NEDC) to 2025+ (WLTP) partially offsetting the potential WTW benefit. (2) the fuel component considers state –of-the-art technology of fuels already or close to be commercialized at scale in the market.

Figure 19. WTW powertrain comparison (2015 – NEDC / 2025+ WLTP) - energy expended



Conclusions:

- Generally speaking, the hybridization of ICEs offers an effective option to reduce fuel consumption, up to ~25% (better performance in gasoline than diesel powertrains)
- For **gasoline/DISI** type of engines, the combination of high compression with a high octane gasoline (102 RON) offers a similar performance than DICI (diesel) vehicles. Regarding the contribution from alternative fuels, ethanol, MTBE and specially bio-ETBE routes show a higher energy use (up to factor 2 in the case of bio-ETBE). However, in case of renewable fuels the energy use mainly consists of renewable energy. It is worth mentioning that, although the refining industry is moving towards an energy efficiency improvement and GHG reduction (WTT) in 2030, this improvement has not been modelled in the current version of the JEC WTW v5.
- **LPG** used in DISI engines deems to offer a ~14% reduction of WTW energy use versus pure DISI in 2015, and a 9% reduction of energy use when approaching 2025+.
- Regarding **diesel**-like alternatives, the selected fuel pathways lead to higher WTW energy use than the crude oil based pathways except HVO (up to 2.7 times compared to crude oil based diesel if OME from waste wood is considered).
- The xEVs technology is expected to improve significantly towards 2025+ (including battery size increase).
- In 2015, FCEV and PHEV-FC/REEV-FC offer similar WTW results. The results changes (PHEV-FC/REEV-FC up to 25% lower energy use than FCEV) when approaching 2025+ (mainly due to the higher share of wind and solar power in the electricity mix used in 2030 for the selected pathways. As described in the box text below, this has to be read as a proxy for this comparison with the big caveat around the real impact due to the marginal country specific route).
- From all combination of fuel/energy carriers and powertrains explored in this WTW report, the HVO pathway with the DICI Hybrid technology (waste as feedstock) and the use of electricity from the electricity mix in a BEV represent the lowest energy intensive routes in 2015 and 2025+ respectively. For 2025+ the energy use for the combination of hydrogen from natural gas steam reforming and electricity from the electricity mix used in PHEV-FC/REEV-FC as well as the SI REEV and CI REEV are close to that of the BEV.
- As in the previous chart, it is important to remark that while NEDC test cycles was applied to 2015 powertrains, WLTP is included in the 2025+ scenario. This change in the test cycle towards more real driving emissions is partially offsetting the GHG emission reduction due to fuel efficiency measurements achieved in the powertrain technologies.

Some additional comments:

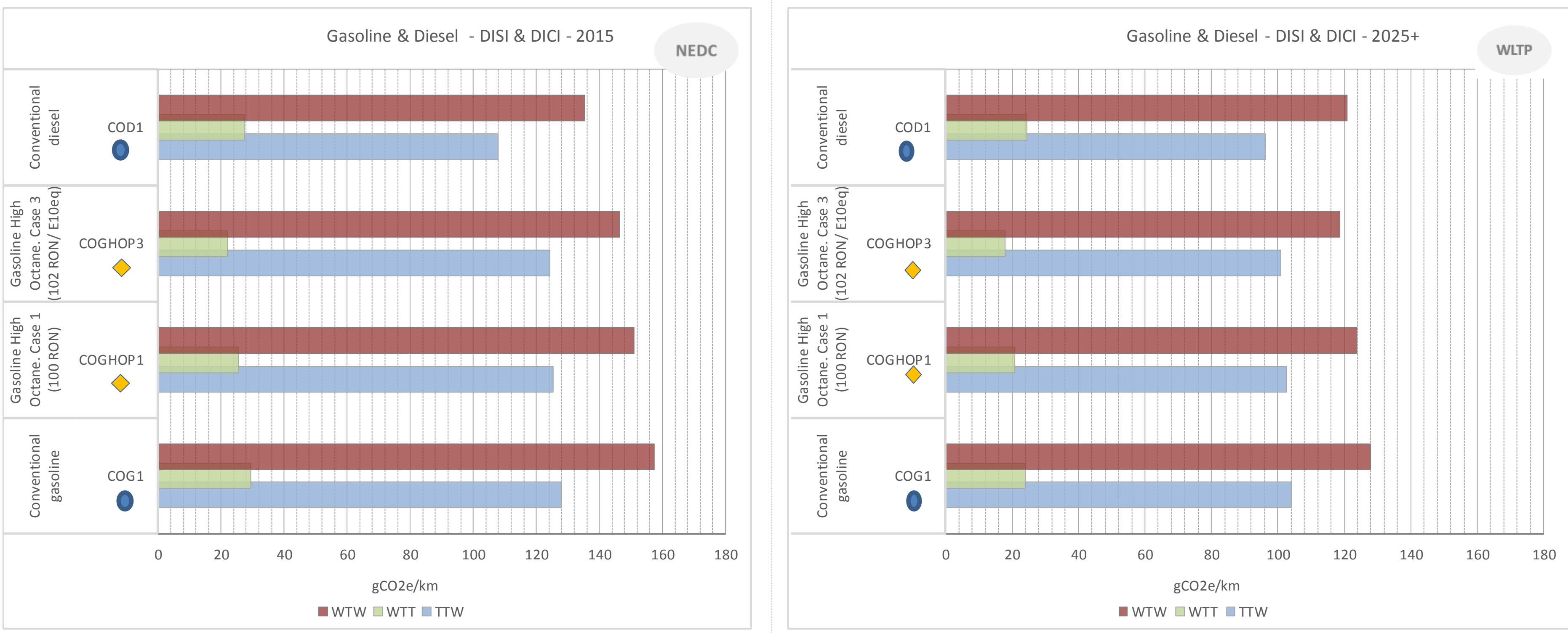
- Regarding electricity and Hydrogen, it is worth noting that, their use in transport sector is, in terms of GHG emissions saving, determined by the pathway of power production. At least for the transitional phase towards road electrification when power for vehicles is taken from the grid, this can lead either an increase or a reduction in emissions compared to the baseline depending on the electricity source used for that purpose (out of the scope of this JEC study). If the system reacts to this increased demand by increasing the production from fossil sources (e.g. Coal); the overall effect might be an increment in the overall GHG. On the other end, a substantial uptake of electrical energy for the road sector may act as a driver for increasing the share of renewable energies in the EU mix. These issues are country specific and time specific (as production is a non-steady process by definition) and, as mentioned, considerations like these are not included in the present JEC study. For this reason, the improvement in country electricity mixes can only be used as a proxy for deriving a back-of-the-envelope evaluation.
- Similarly to electricity used as a fuel, and from a mere GHG reduction perspective, the use of hydrogen fuel cells may not lead to any advantages, if electricity used is not from carbon neutral source.
- e-fuels: as e-fuels production is based on electricity, the above-mentioned considerations can be extended to these cases.
- Greening the EU grid mix indeed helps also in greening the road sector, but not necessary with a linear correlation.

3.2 WTW integration. Detailed results

3.2.1 Internal combustion engines (ICE) & Liquid fuels

3.2.1.1 Conventional Gasoline & Diesel (Fossil based) & High Octane gasoline

Figure 20. Conventional fossil based gasoline & diesel - GHG emissions (g CO_{2eq}/km)



The WTW analysis shows that:

- Conventional **gasoline** (100% fossil) in DISI technologies is expected to be subjected to relevant improvements in term of efficiency. Despite of the impact of the change in the test cycle (WLTP) in 2025+, the consumption figures for 2025+ are lower than in 2015 and further reductions are expected by applying mild and full hybridization (e.g. hybrid technology can reduce emissions up to ~25% versus conventional DISI). In 2025+, mild hybrids are expected to become available reaching ~15% reductions versus DISI 2025+ technologies, emission reductions are approaching ~27% when full hybridization is implemented.
- Regarding the **differences between DISI and DICI**, the 2015 technology shows ~15% better WTW performance of a Diesel ICE vehicle versus the equivalent Gasoline ICEs (~10% in the hybrid cases favourable to diesel hybrid DICI). When approaching 2025+, the state-of-the-art technologies are deemed to reduce the differences down to ~2% (still in favour of diesel MHEV) but shifting the trend towards a more efficient gasoline hybrid in 2025+ (~8% better than eq. Diesel DICI Hyb). The use of high octane gasoline (102 RON) in high compression engines/hybrid technology increases this difference (up to 10%) and ~20% versus DICI Hybrid in the same 2025+ horizon.

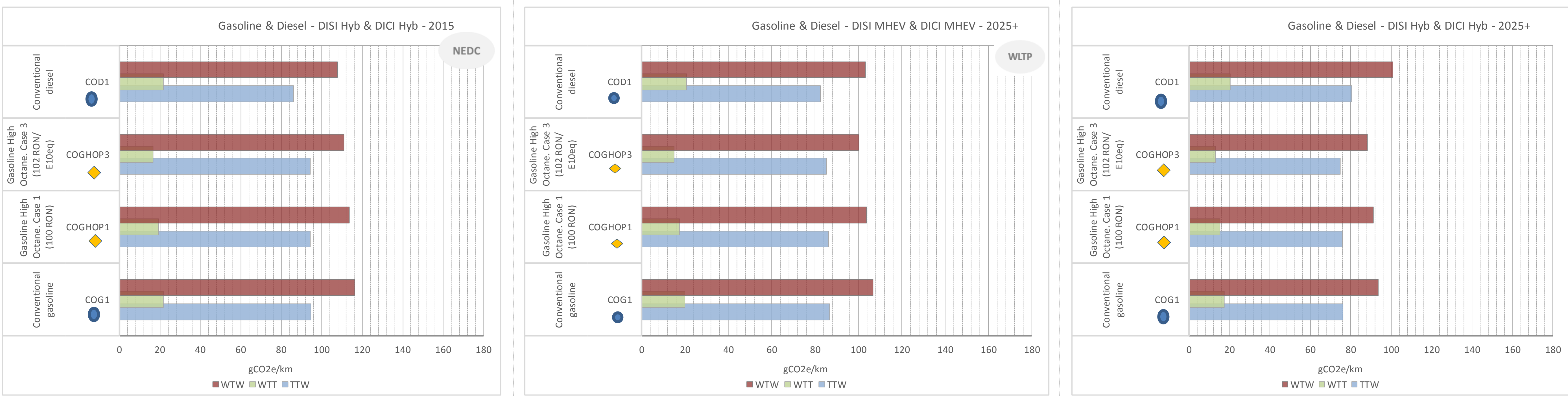
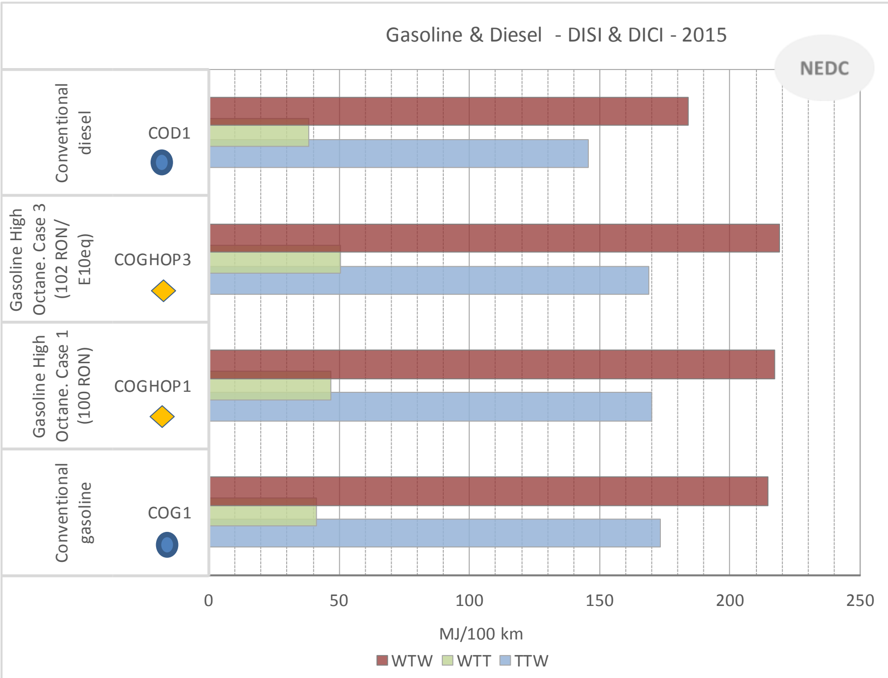
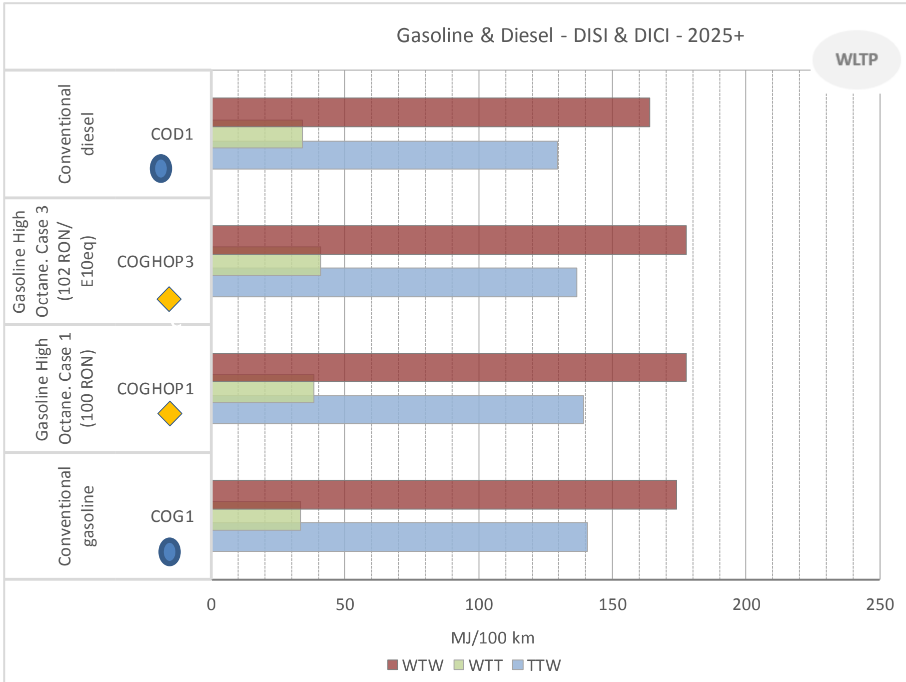


Figure 21. Conventional fossil based gasoline & diesel – Energy expended (MJ/100 km)



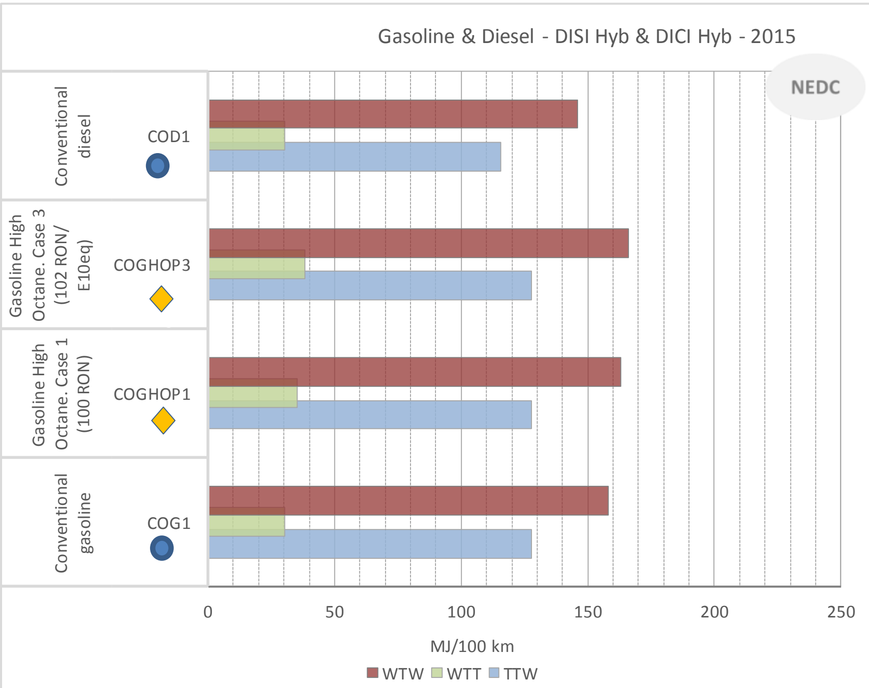


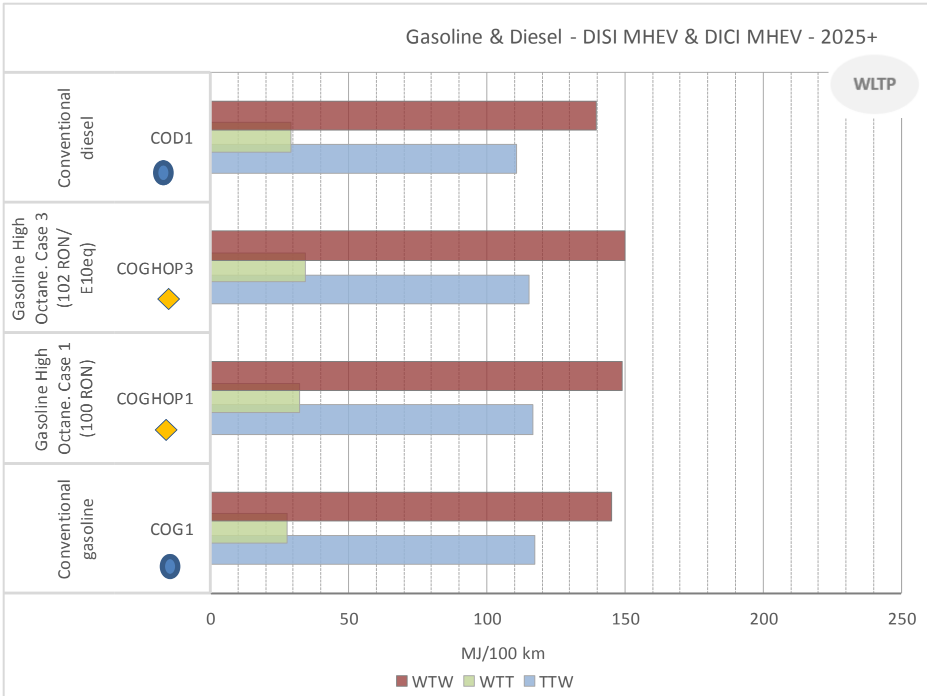
Energy use does not necessarily correlate with GHG emissions and vice versa. The high octane gasoline pathways lead to slightly higher (1 to 2%) energy use than the WTW pathways involving conventinal pathways although the GHG emissions are lower (7 to 12% compared to conventional gasoline). The reason is that high octane gasoline contains biomass derived blending agents which have a higher energy consumption for manufacture but lower GHG emissions due to the renewable share.

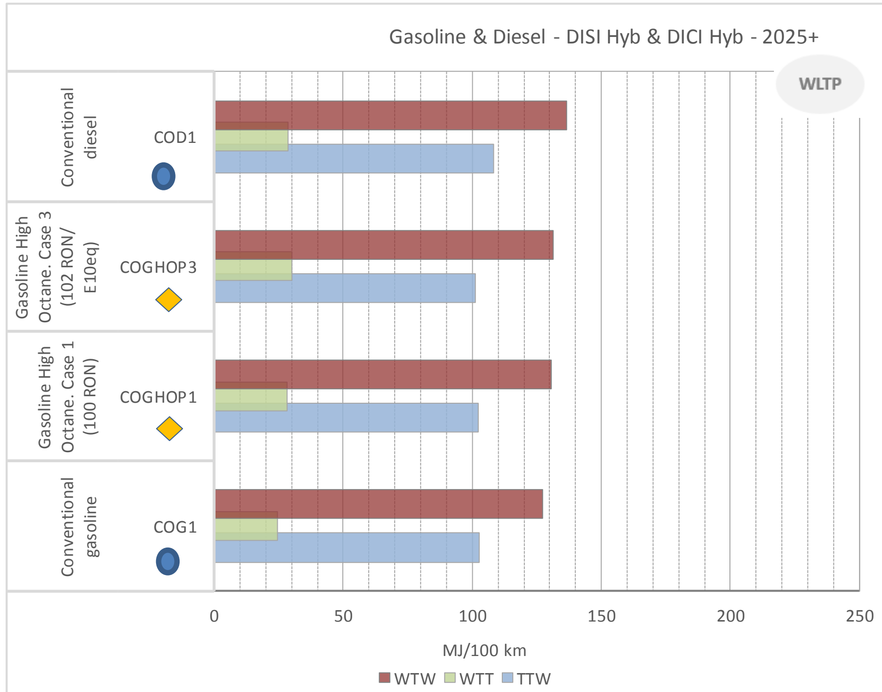
Hybridisation of gasoline engines leads to energy savings of 26 and 27% in 2015 and 2025+ respectively, mild hybridisation to about 17% compared to non-hybridised gasoline engines in the same time horizon. Hybridisation of diesel engines leads to energy savings of about 21% in 2015 and some 17% in 2025+ (mild hybridisation: 15% energy saving in 2025+).

The energy use generally decreases towards 2025+ due to improvement of the engine efficiency.

Although the refining industry is moving towards an energy efficiency improvement and GHG reduction (WTT) in 2030, this improvement has not been modelled in the current version of the JEC WTW v5.

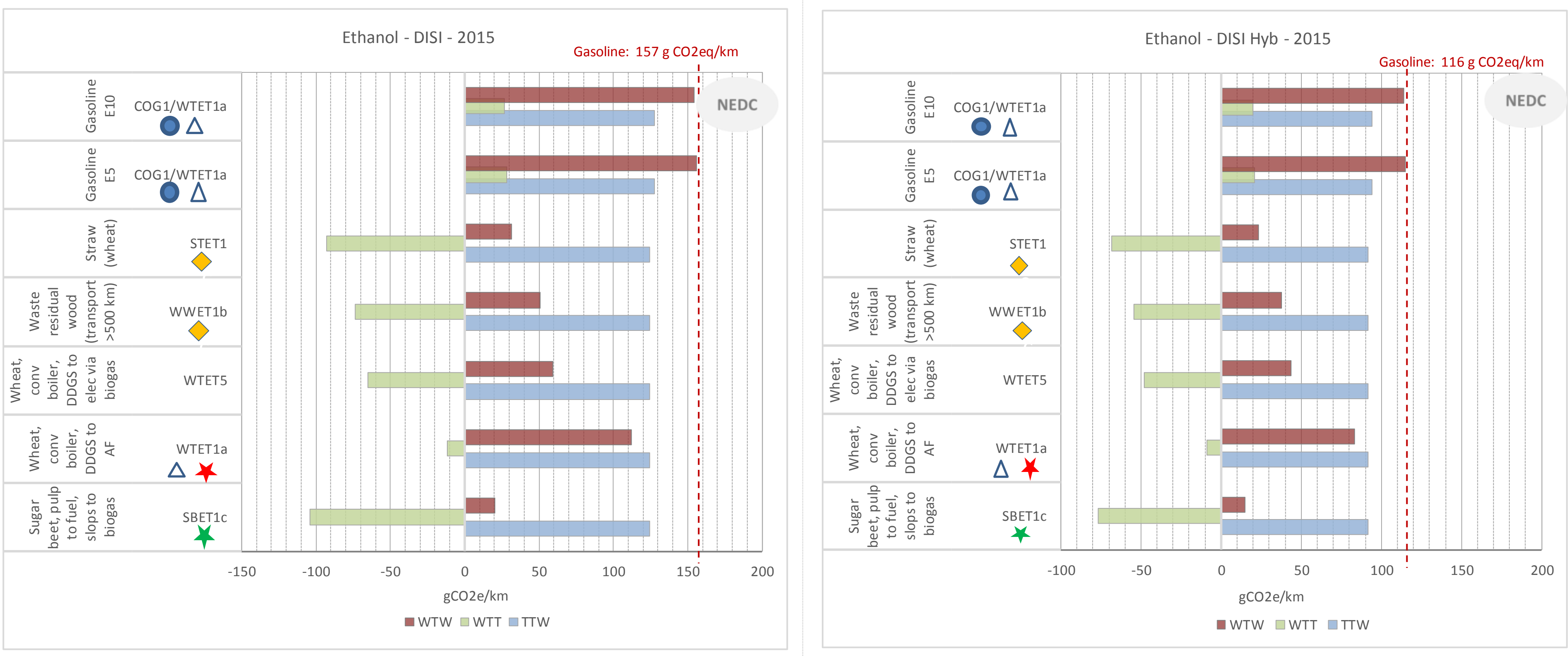






3.2.1.2 *Ethanol (E100) & Ethanol blends (E5/E10)*

Figure 22. Ethanol & Ethanol blends - GHG emissions (g CO_{2eq}/km)



Ethanol can be produced from many different feedstocks leading to WTW GHG emission savings varying from 30 up to ~90%, versus conventional gasoline (100% fossil). Among the selected as the most relevant ones, the best performance is related to pathways where process by-products are valorised in the production cycle, to reduce energy demand.

Interesting GHG savings can be achieved using residues and wastes, as residual wood and straw. For example, when waste wood based pathways are explored, pure ethanol (E100) used in a DISI engine could perform ~70% better WTW than a conventional gasoline engine regardless the year and level of hybridization considered.

Currently, gasoline with different ethanol blends is available in the European Market. E5 (5%v ethanol) and E10 (10%v) ethanol are included as a reference of the WTW impact of this blend versus 100% fossil-based gasoline (limited impact).

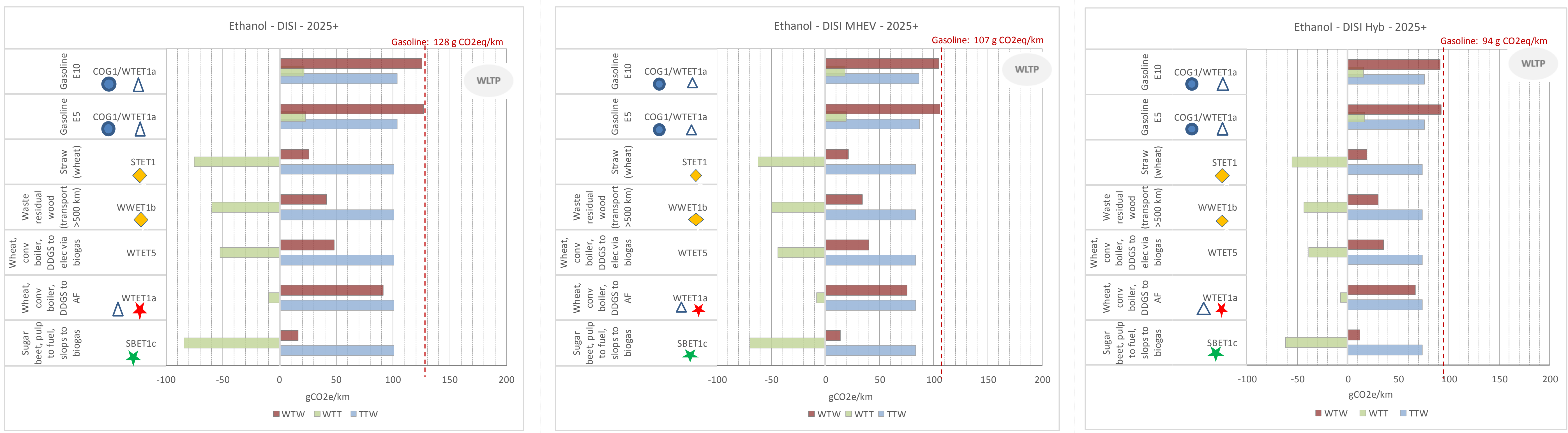
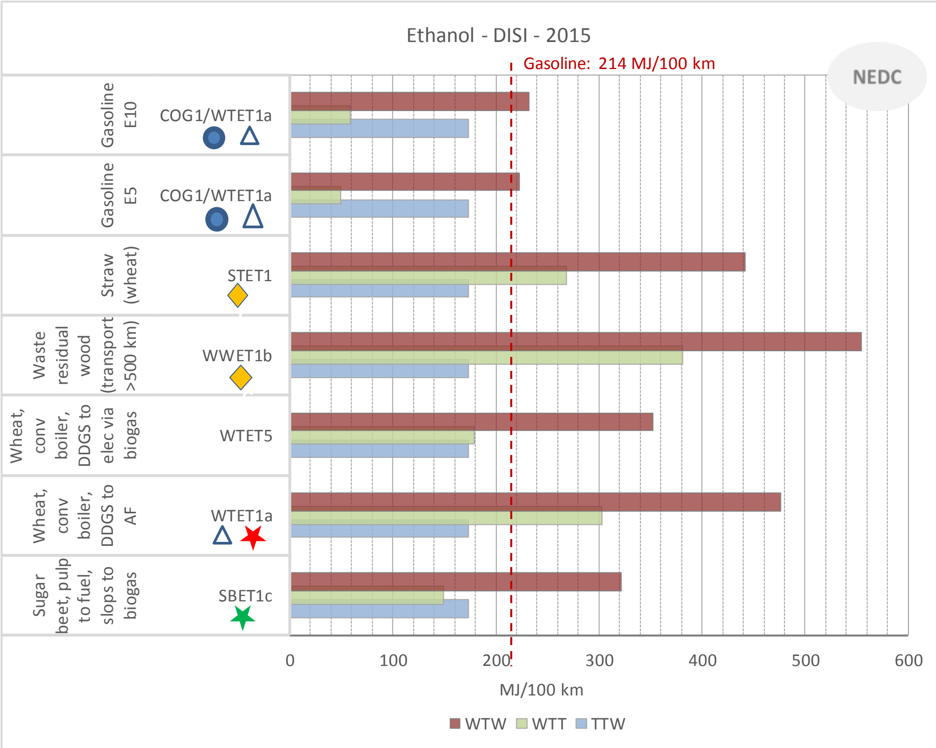
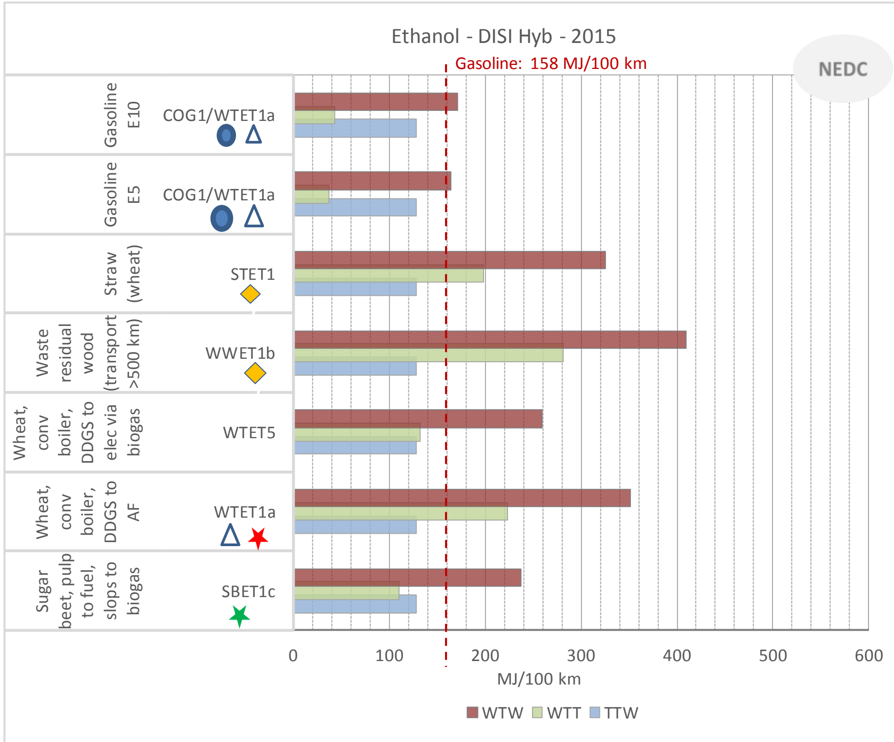


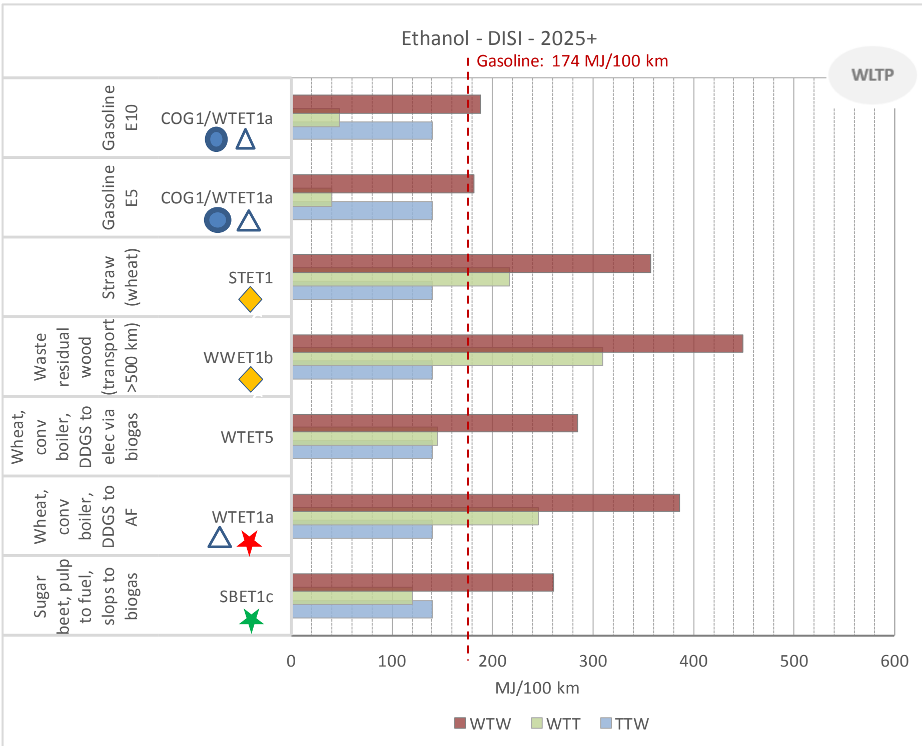
Figure 23. Ethanol & Ethanol blends - Energy expended (MJ/100 km)

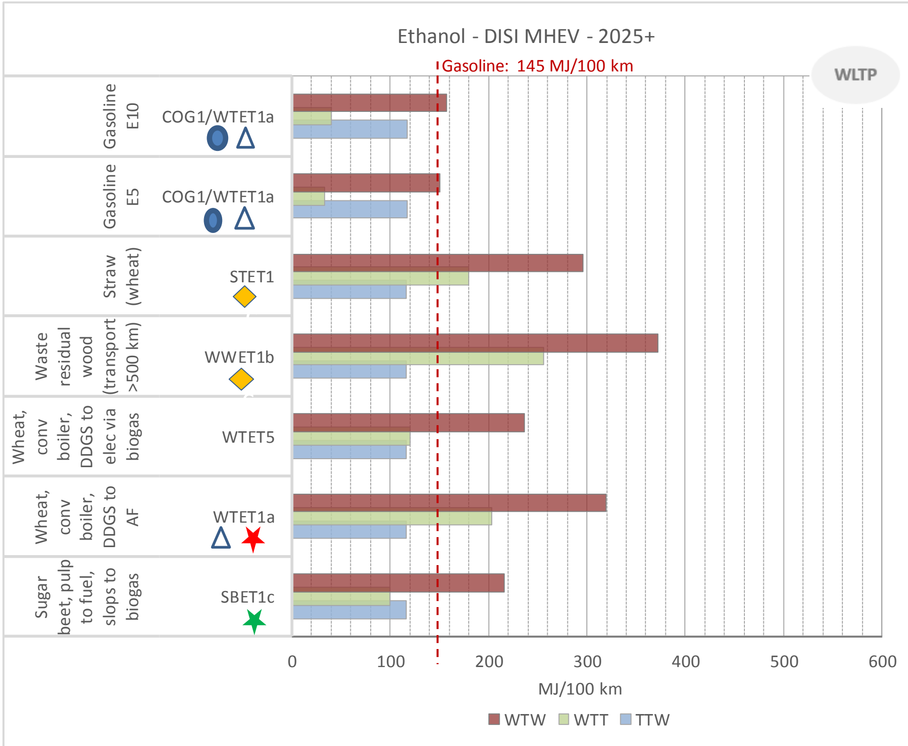


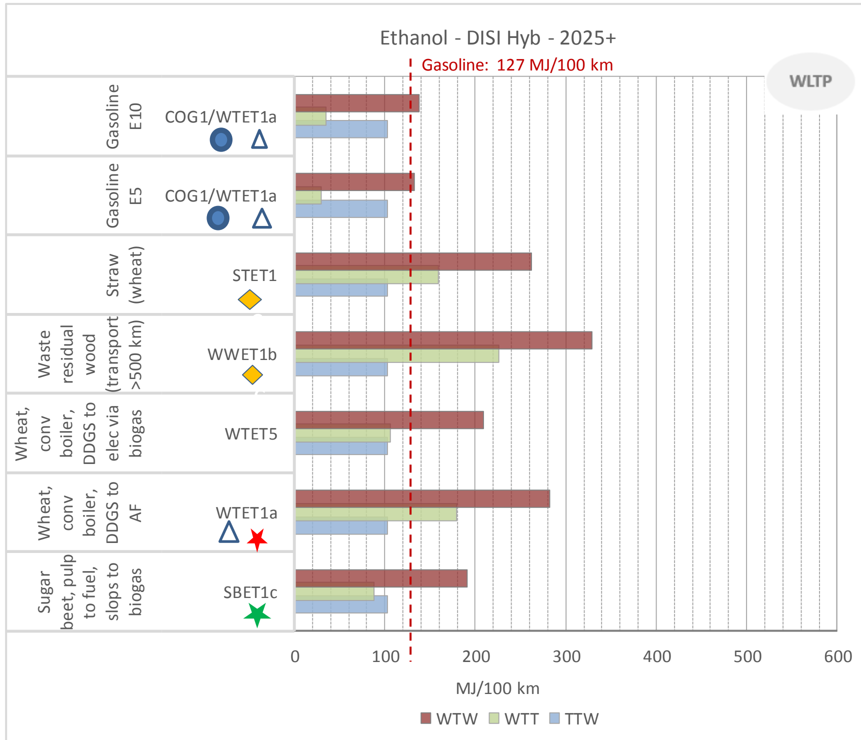


The energy use for pathways involving biomass-derived fuels is generally higher than that for pathways involving conventional gasoline (100% fossil)

Ethanol from wood chips from waste wood (WWET1b) leads to the highest WTW energy use (approximately 2.6 times of that for gasoline fueled ICE vehicles. Although the WTW energy use is the highest the WTW GHG emissions are significantly lower than those for conventional gasoline fueled vehicle with the same drivetrain (approximately one third of those of conventional gasoline used in the same drivetrain).

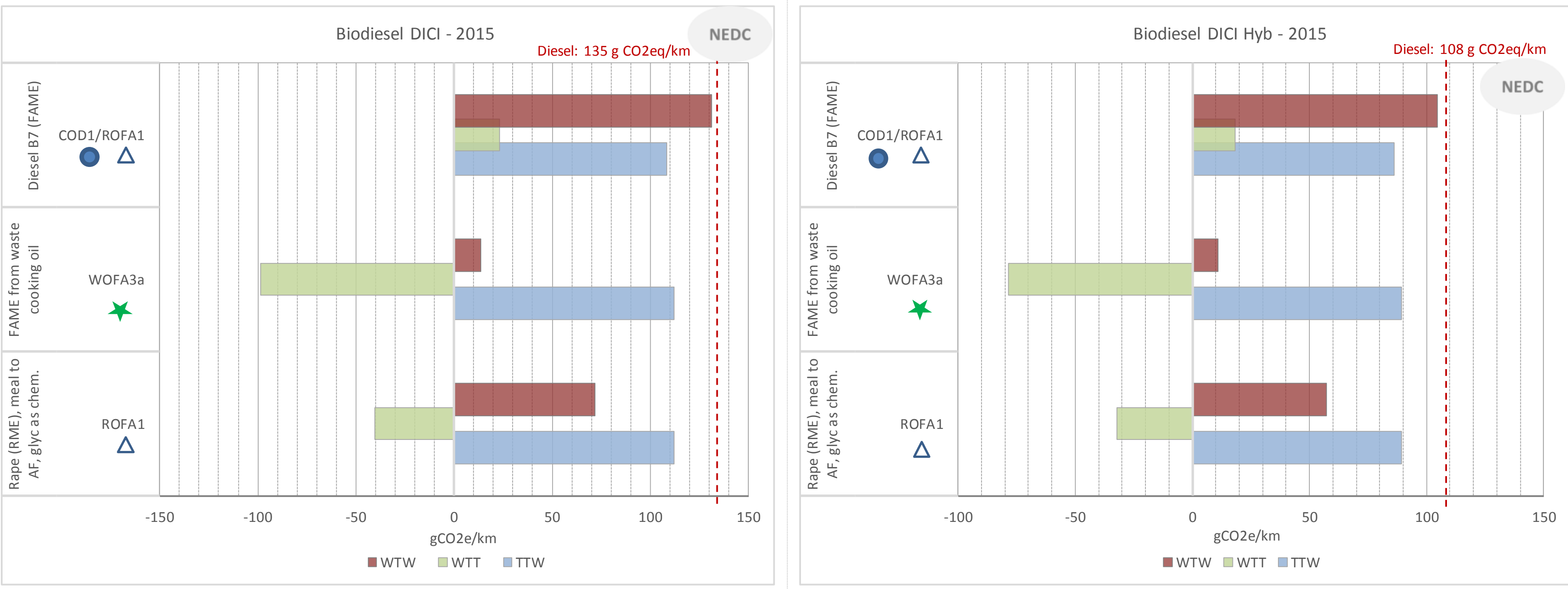






3.2.1.3 Biodiesel (B100)

Figure 24. Biodiesel - GHG emissions (g CO_{2eq}/km)



Biodiesel is manly produced by lipid feedstock. The potential GHG saving offered by the use of biodiesel are strongly linked to the nature of the feedstock, varying from ~50%, versus equivalent fossil diesel DISI in the case of rape seed oil, up to ~90% when waste oil routes are explored regardless the year and the level of hybridization considered.

As for the ethanol case, interesting GHG savings can be achieved using residues and wastes, as waste cooking oil.

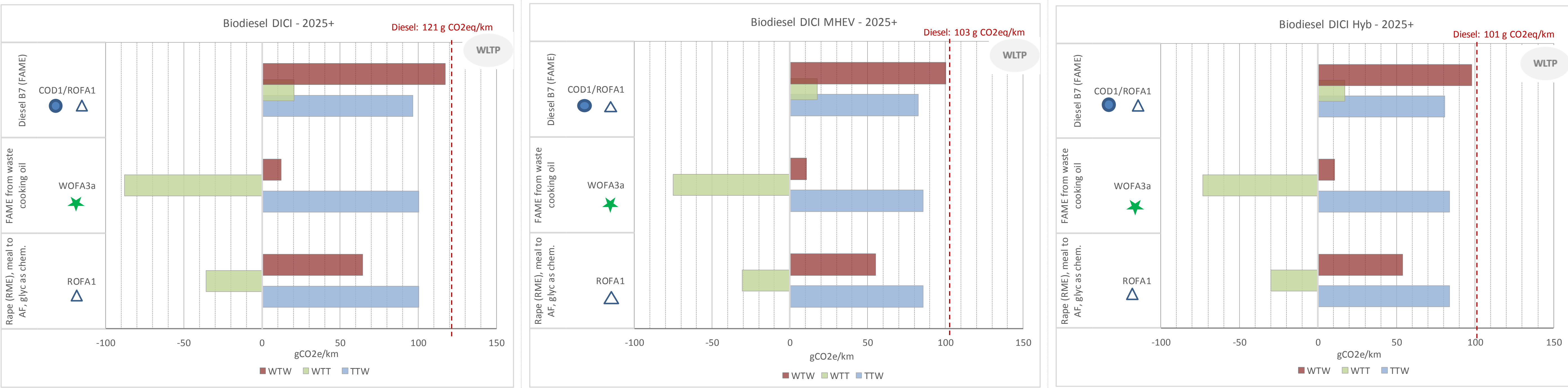
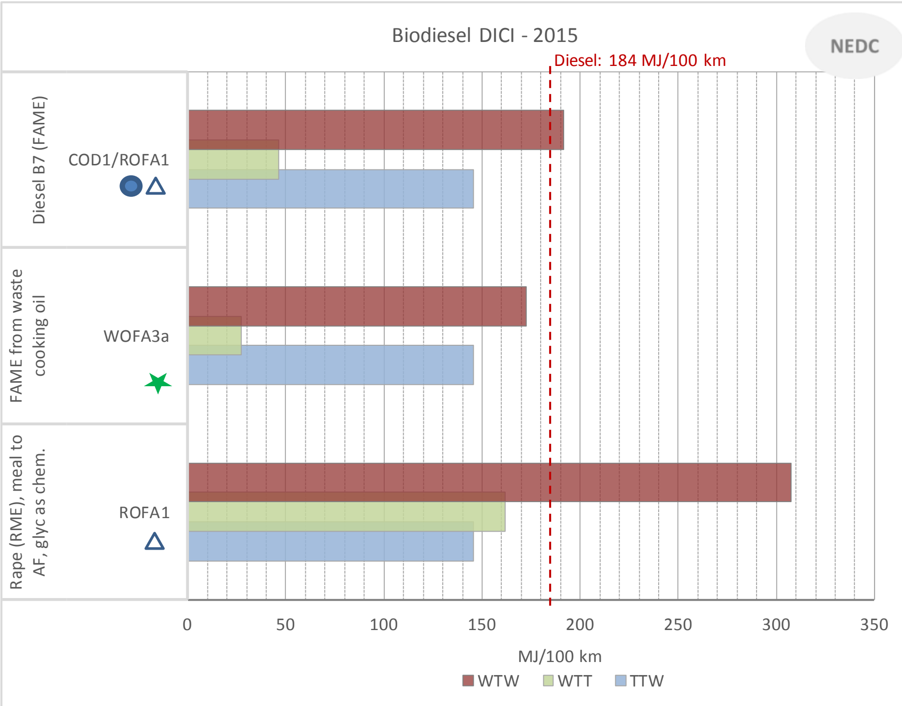
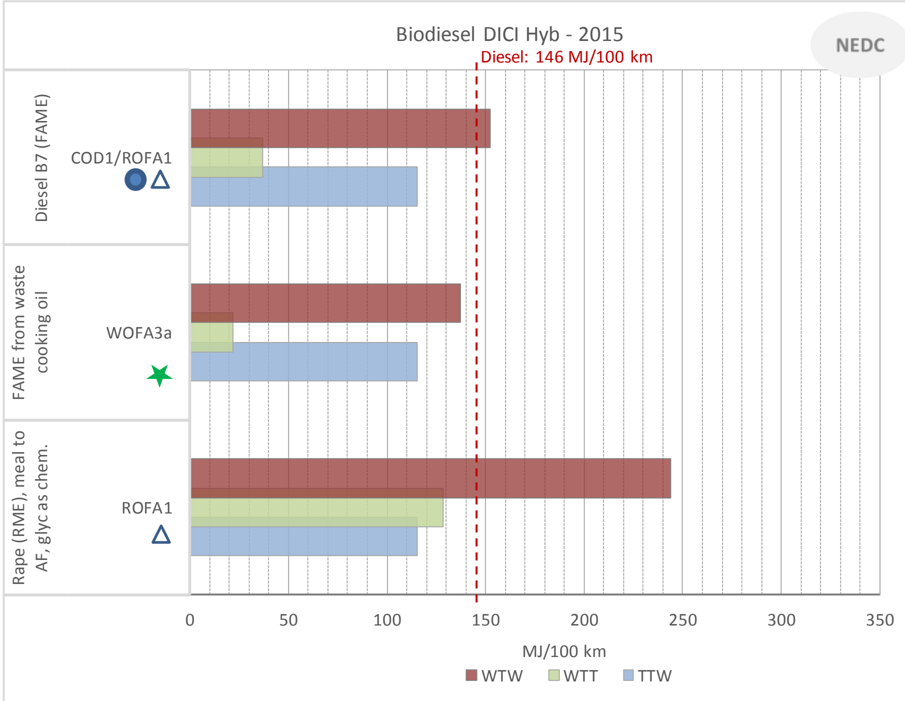


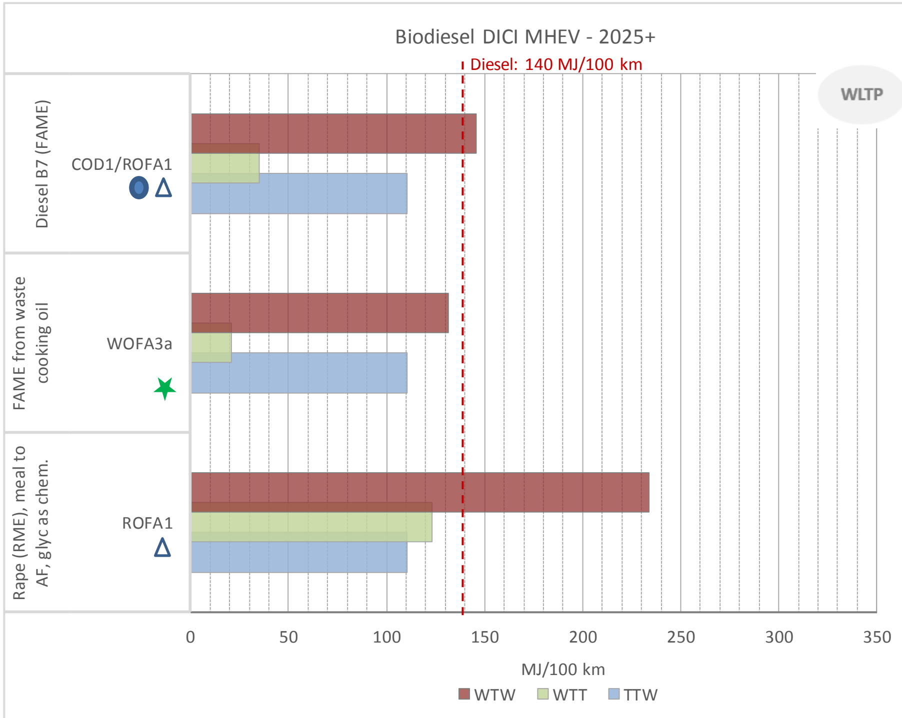
Figure 25. Biodiesel - Energy expended (MJ/100 km)

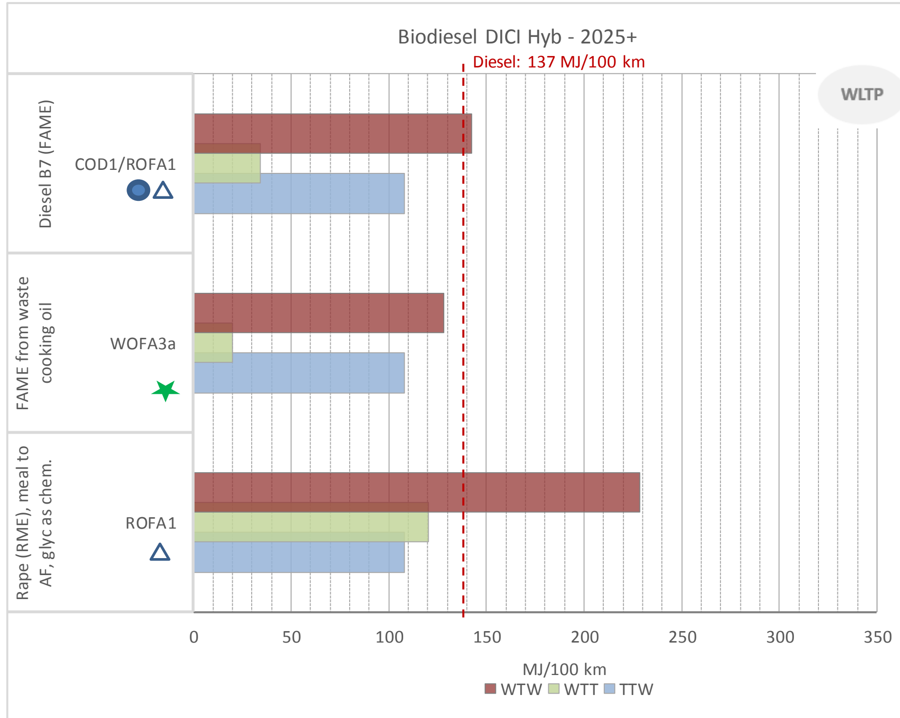




The energy use for pathways involving biomass-derived fuels is generally higher than that for pathways involving conventional diesel (100% fossil) except biodiesel (FAME) from waste cooking oil.

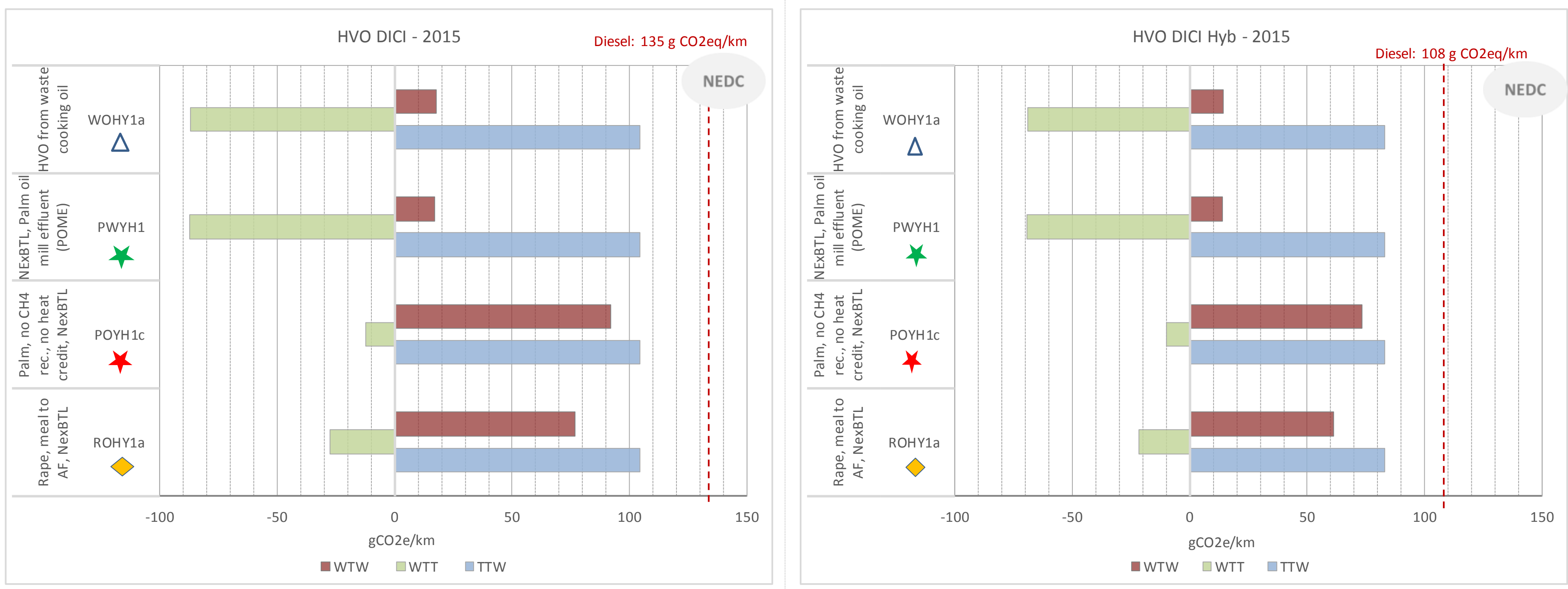
The WTW energy use for biodiesel from rapeseed is about 67% higher than that of conventional diesel used in the same drivetrain.

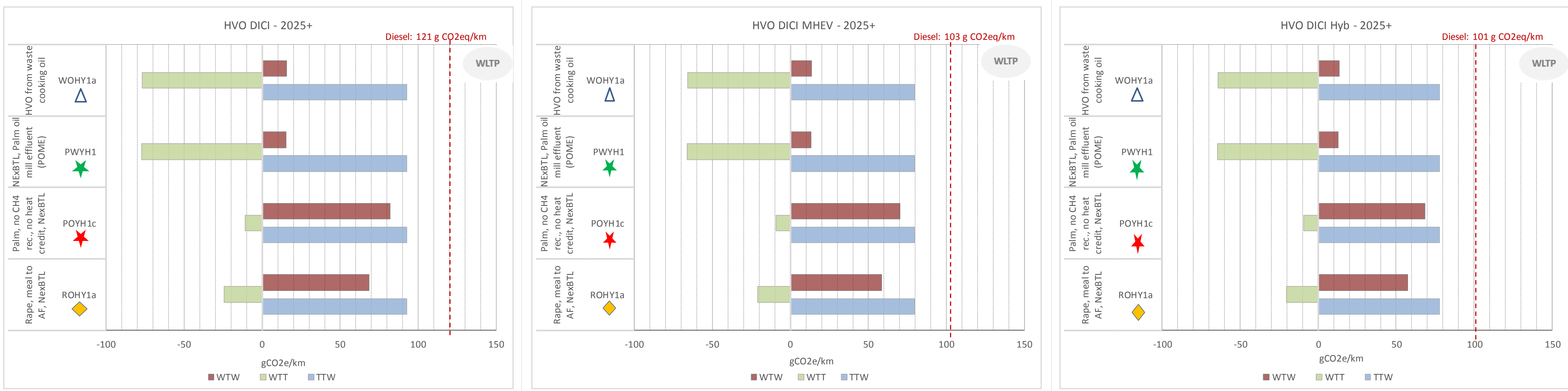




3.2.1.4 HVO

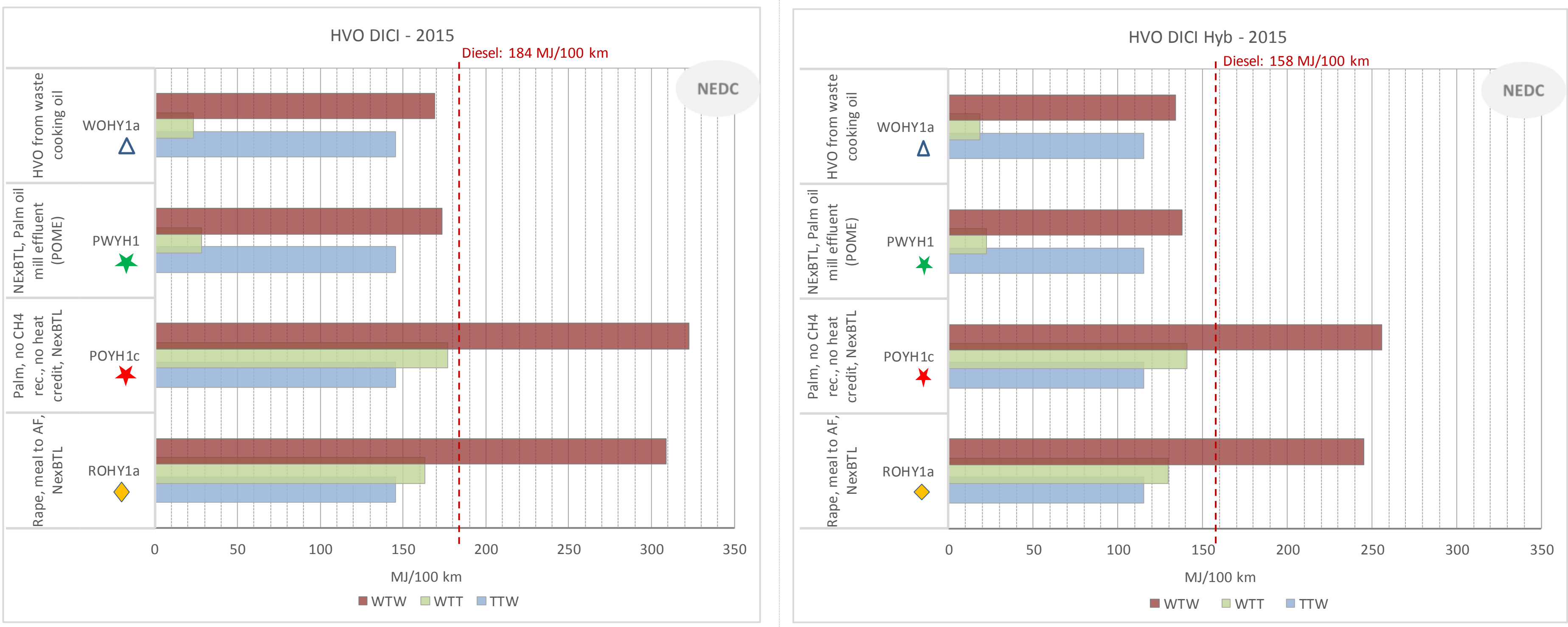
Figure 26. HVO - GHG emissions (g CO_{2eq}/km)





As the feedstocks used for **HVO** production are mainly the same of the biodiesel, the potential GHG savings are strongly linked to the nature of them with the benefit of HVO being a drop-in fuel and thus, not limited by blending walls. Similarly, high GHG savings can be achieved using residues and wastes, as waste cooking oil (ranging from ~30% to ~90% WTW GHG savings depending on the feedstock used with similar results regardless the test cycle and powertrain technology used in 2015/2025+ horizon)

Figure 27. HVO - Energy expended (MJ/100 km)

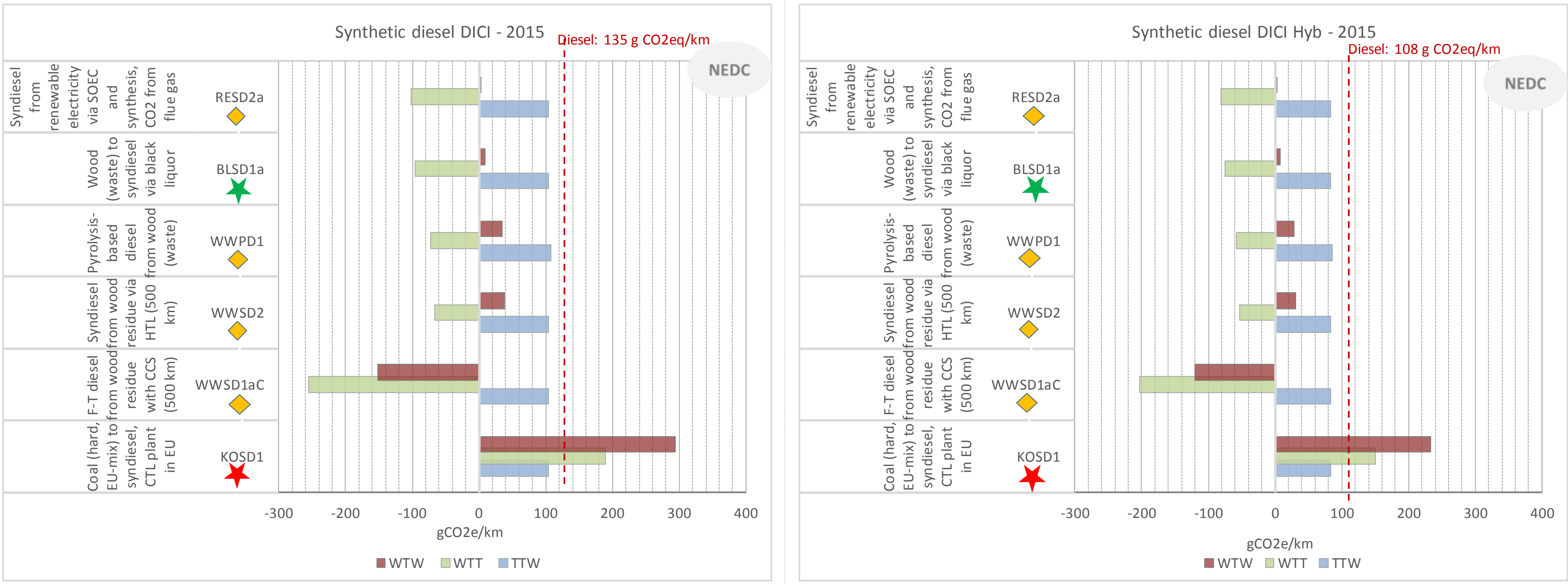


HVO from waste cooking oil (pathway WOHY1a) and HVO from palm oil mill effluent (pathway PWYH1) leads to a lower WTW energy use than that of conventional diesel (100% fossil) used in the same drivetrain.

However, it is important to remark that for the sole purpose of this exercise, HVO produced from palm oil mill effluent show a low energy use (and low GHG emissions), mainly due to the assumption that palm oil extracted from the waste water is treated as waste, and not as a product from the oil mill.

3.2.1.5 *Synthetic Diesel*

Figure 28. Synthetic diesel - GHG emissions (g CO_{2eq}/km)



Being a synthetic mix of molecules optimized to result in very similar properties to regular fossil derived product, **synthetic diesel** offers the advantage of being a drop-in fuel, easily usable in standard infrastructures, and powertrains.

GHG performances of synthetic diesel production and use are mainly determined by the primary source of energy used for its production (WTT). When produced from coal, synthetic diesel does not offer any advantages (even doubling the associated GHG emissions), if compared with regular fossil diesel

Benefits can be achieved through Fischer-Tropsch (FT) conversion process, using residual feedstock, such as: waste wood, black liquor, pyrolysis oil derived from wood waste, or via power-to-liquid using renewable electricity. In these cases, the potential saving offered by using synthetic diesel can be remarkable. As interesting pathways, e-fuel route combined with DICI vehicles (RESD2a) approach zero WTW emissions when renewable electricity is used while negative WTW emissions could be obtained in the case of wood residue coupled with CCS (BECCS schemes) These latter pathways are not commercially available in the moment of writing this report.

Note. Regarding the e-fuel route, as CO_2 is considered as a waste in the JEC WTT v5, there is no difference between direct air capture (DAC) or flue gases pathways.

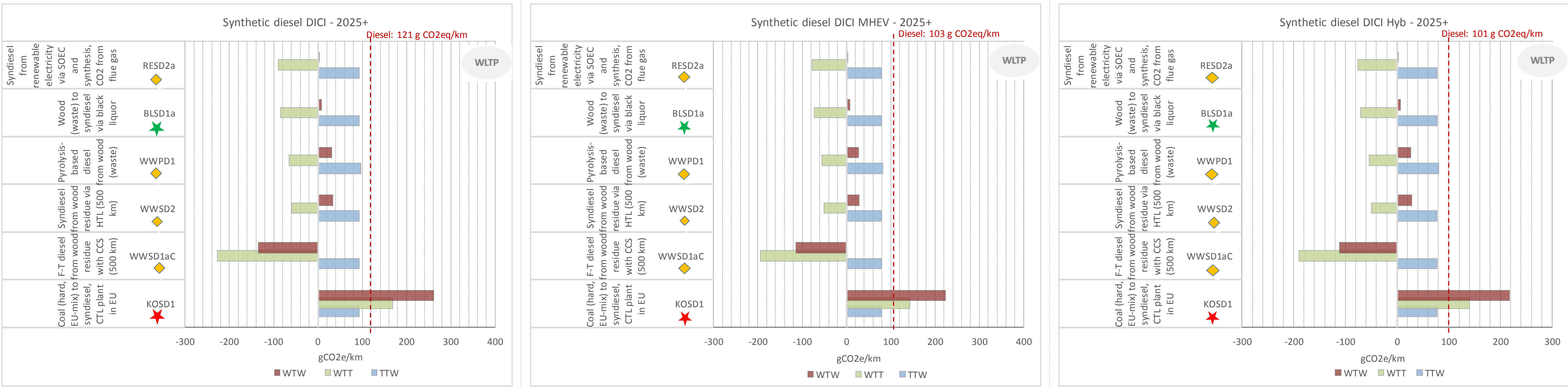
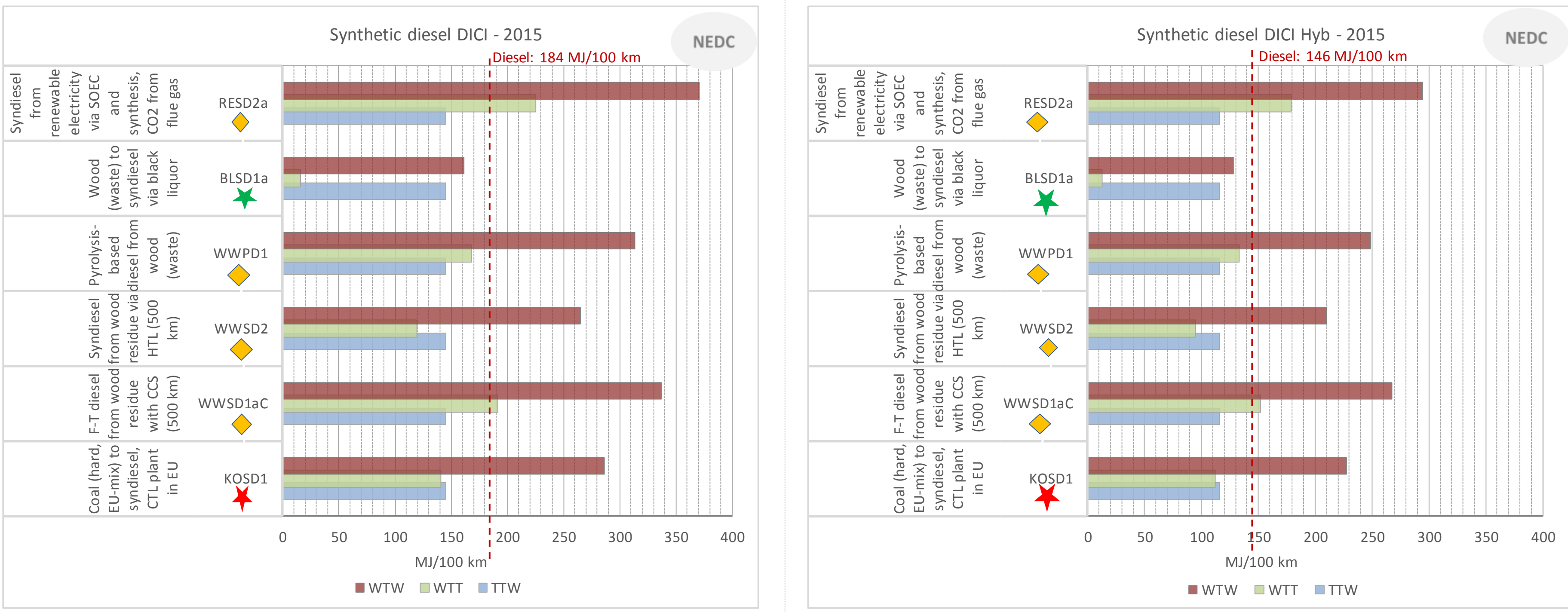
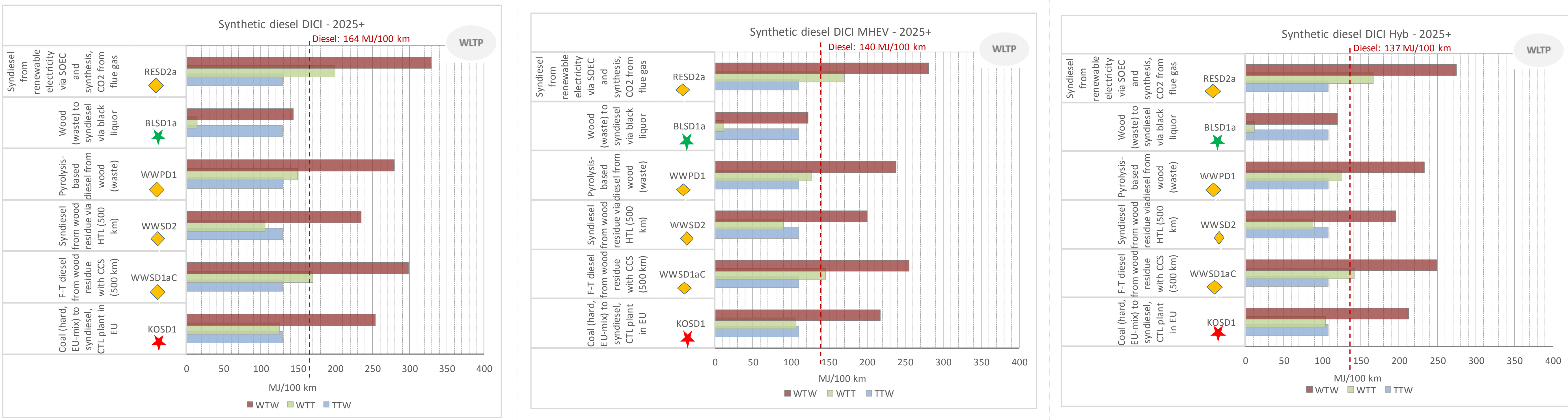


Figure 29. Synthetic diesel - Energy expended (MJ/100 km)



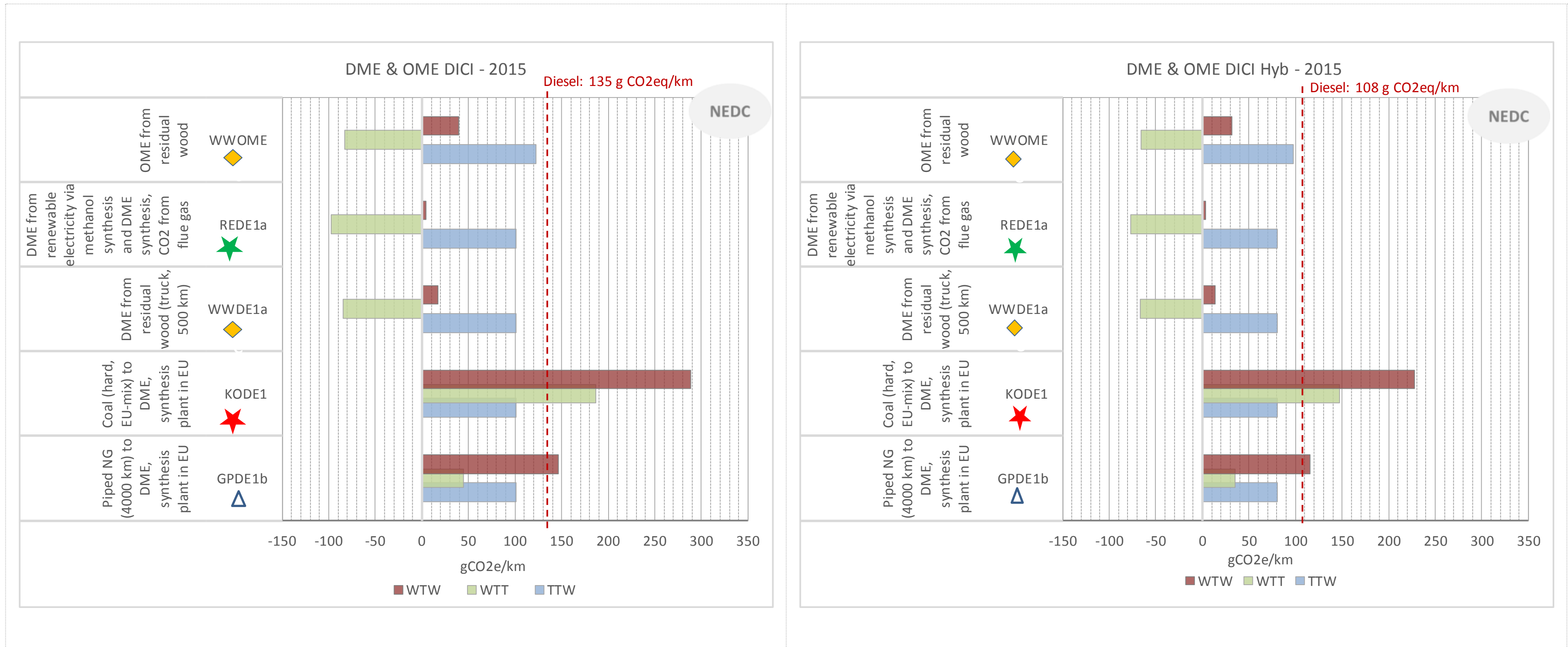
The WTW energy use for the renewable fuel pathways is generally higher than that for conventional diesel (100% diesel) with the same powertrain except synthetic diesel from black liquor (pathway BLSD1a) although the GHG emissiosn are lower. The energy use for synthetic diesel from renewable electricity via high temperature steam electrolysis and downsream synthesis (pathway RESD2a) is about two times that of conventional diesel but the GHG emissions are nearly zero.

Synthetic diesel from coal (pathway KOSD1) also leads to a higher WTW energy use (~55% more than conventional diesel) but simultaneously about two times higher GHG emissions than conventional diesel in the same drivetrain.



3.2.1.6 DME and OME

Figure 30. DME / OME – GHG emissions (gCO_{2eq}/km)



GHG performances of DME and OME production and use are mainly determined by the primary source of energy used for their production.

When produced from coal, DME does not offer any advantages (even resulting in increasing the GHG emissions WTT), if compared with regular fossil diesel

Benefits can be achieved using residual feedstock, such as: waste wood or via power-to-DME using renewable electricity. In these cases, the potential saving offered by using DME and OME can be remarkable (reaching zero emissions in the case of e-DME (REDE1a). It is worthy of note that the GHG emissions from the supply of OME from waste wood are significantly higher than those for DME from waste wood due to the lower efficiency of OME production compared to DME production.

Both of them can be used in dedicated compression ignition engines.

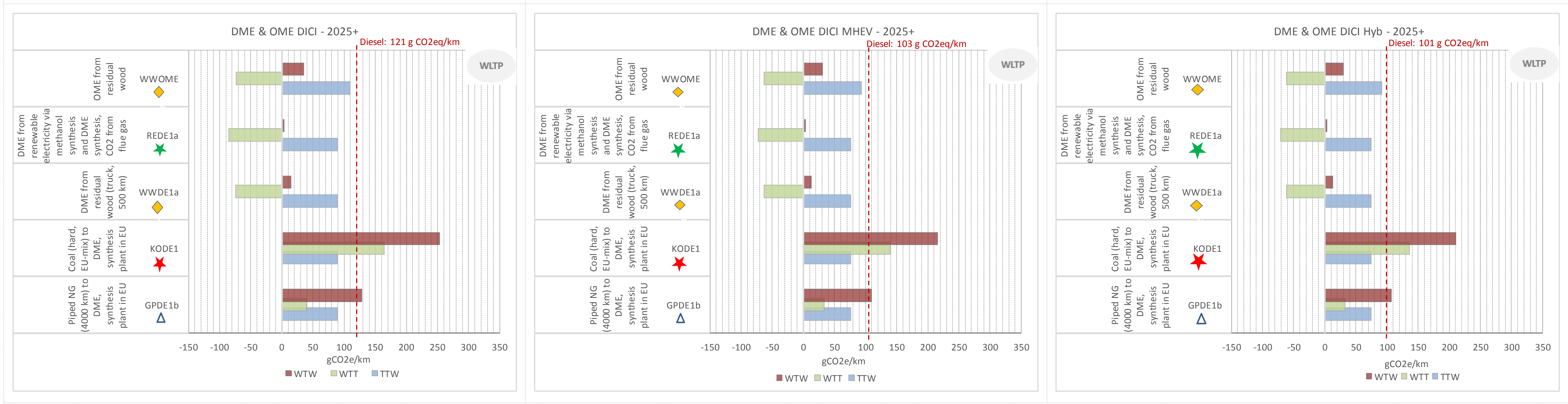
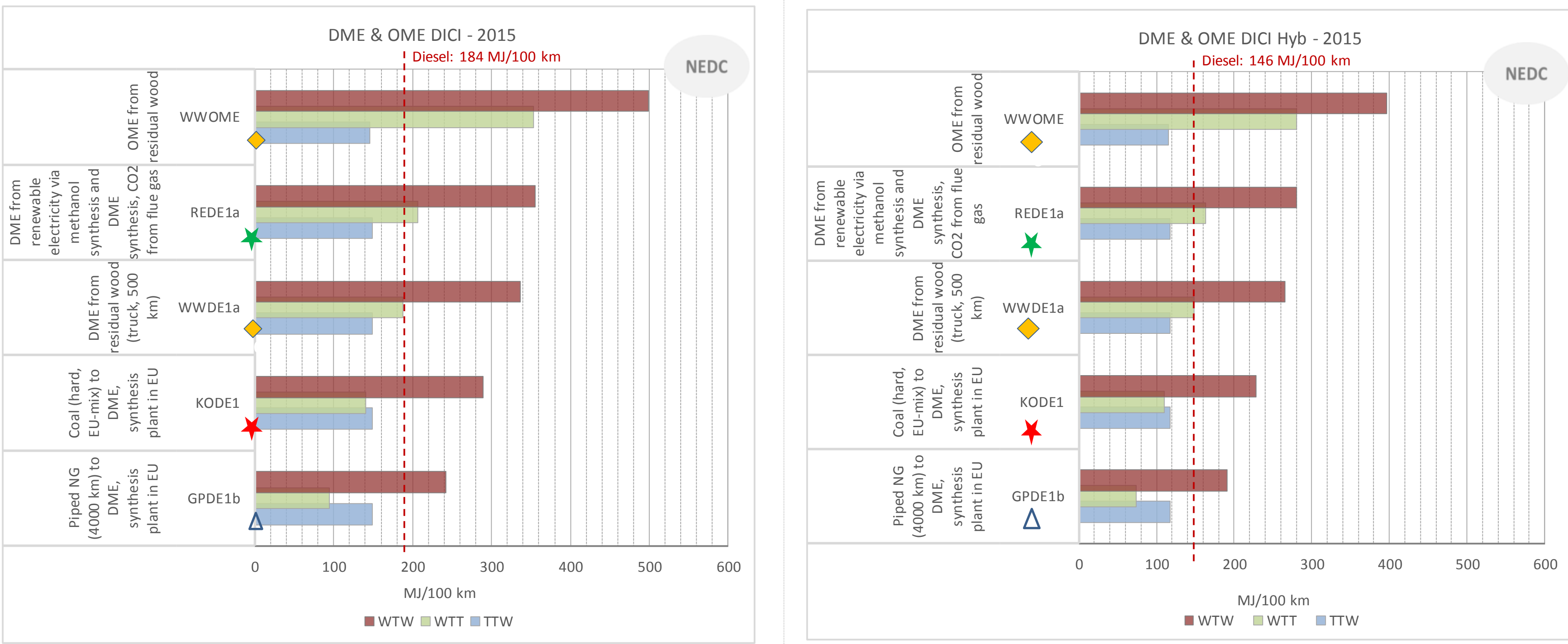


Figure 31. DME / OME - Energy expended (MJ/100 km)

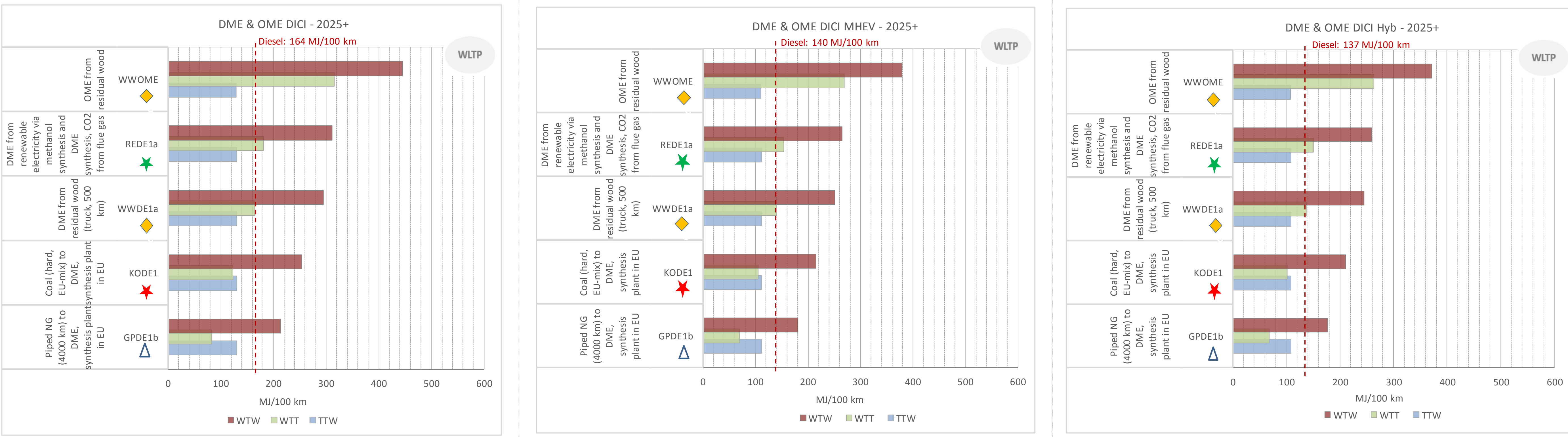


The WTW energy use of OME from waste wood (pathway WWOME) amonts to approximately 2.7 times that of conventional diesel (100% fossil) in the same drivetrain.

The WTW energy use of DME from low temperature water electrolysis with downstream synthesis (pathway REDE1a) amounts to approximately two times that of conventional diesel in the same drivetrain but nearly zero GHG emissions.

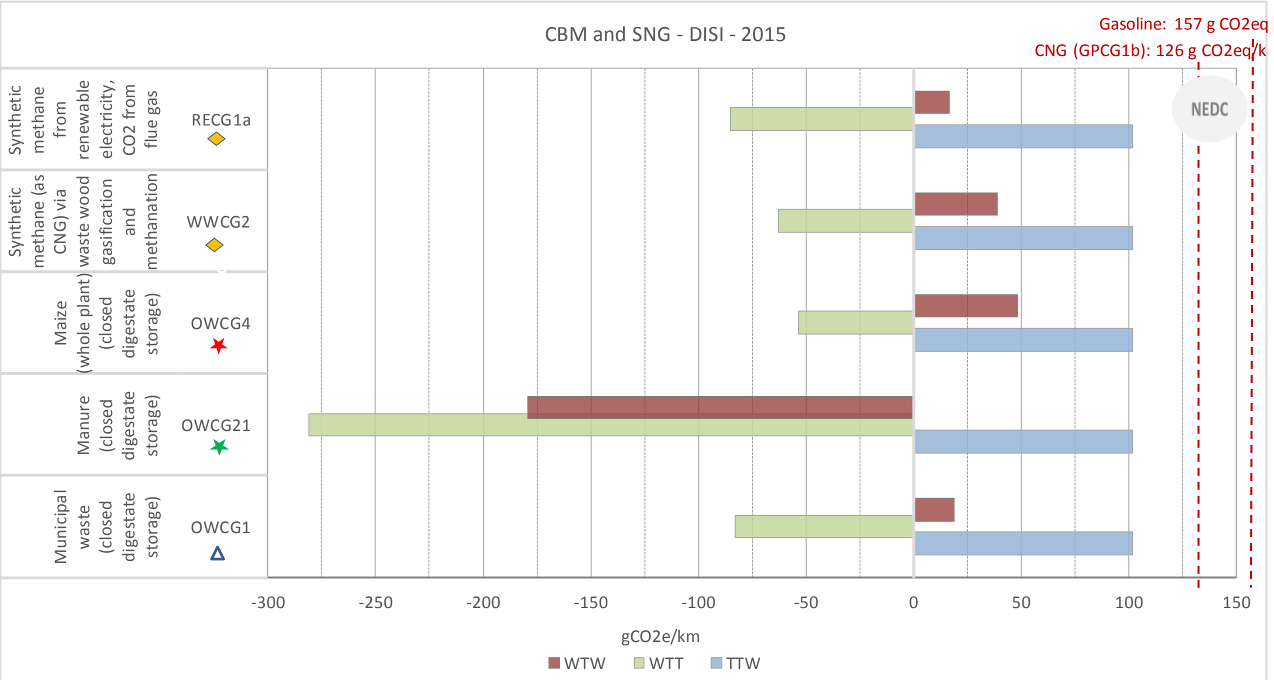
DME from coal (pathway KOSD1) also leads to a higher WTW energy use (~56% more than conventional diesel) but simultaneously about two times higher GHG emissions than conventional diesel in the same drivetrain.

DME from natural gas (pathway GPDE1b) leads to higher WTW energy use (~31% more than conventional diesel) than conventional diesel in the same drivetrain but similar GHG emissions.



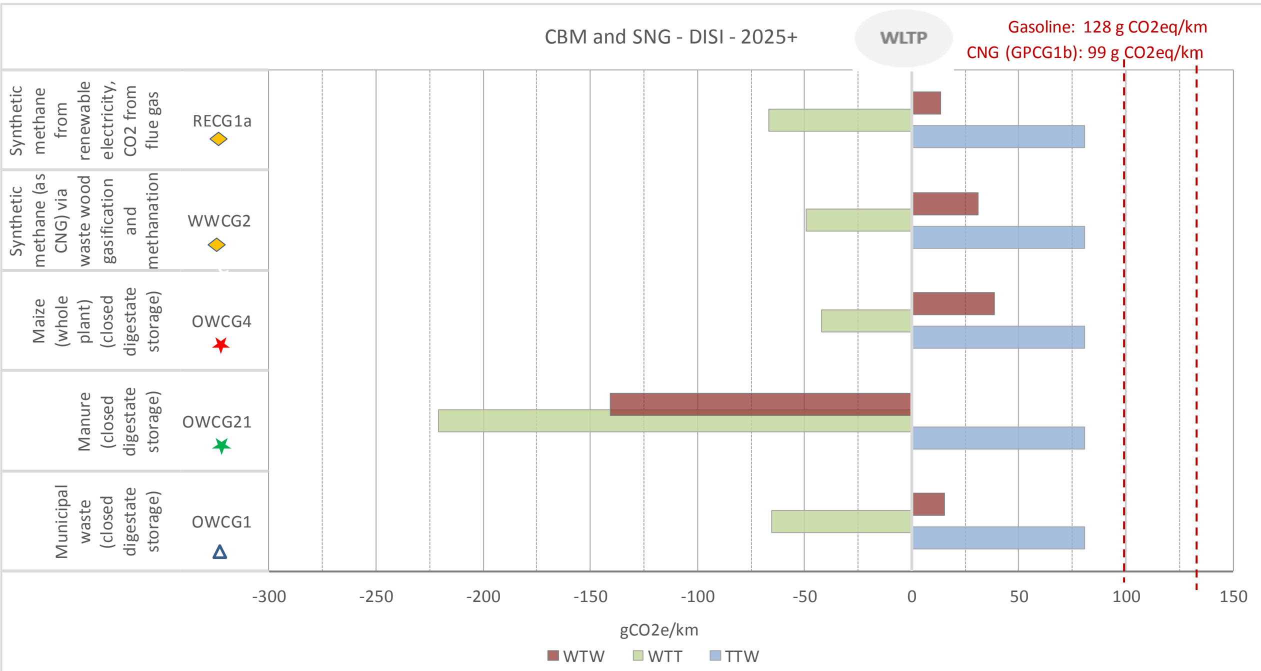
3.2.2 Internal combustion engines (ICE) & Gaseous fuels (Bio and synthetic methane)

Figure 32. Bio and synthetic methane - GHG emissions (gCO_{2eq}/km)



Conclusions (WTW):

- Considering the GHG saving potential, **gaseous fuels** offer significant advantages, with respect to fossil derived fuels (~85% less WTW versus conventional gasoline in 2015/2025+) without significant WTW differences between the bio or synthetic fuel pathways included in the comparison (with the exception of manure). Referring to the representative pathways as example (OWCG1) and the 2025+ timeframe, the results show ~30% less TTW emission than DISI technology in ~35% when mild hybridization is applied).
- The main advantages are related to the WTT part, as credit for the avoided CH_4 emission from manure is considered as negative values due to the replacement of untreated manure storage. It has to be noted that the negative GHG emissions for biomethane from manure only can be taken into account as long as there are farms where storage of untreated manure is applied.



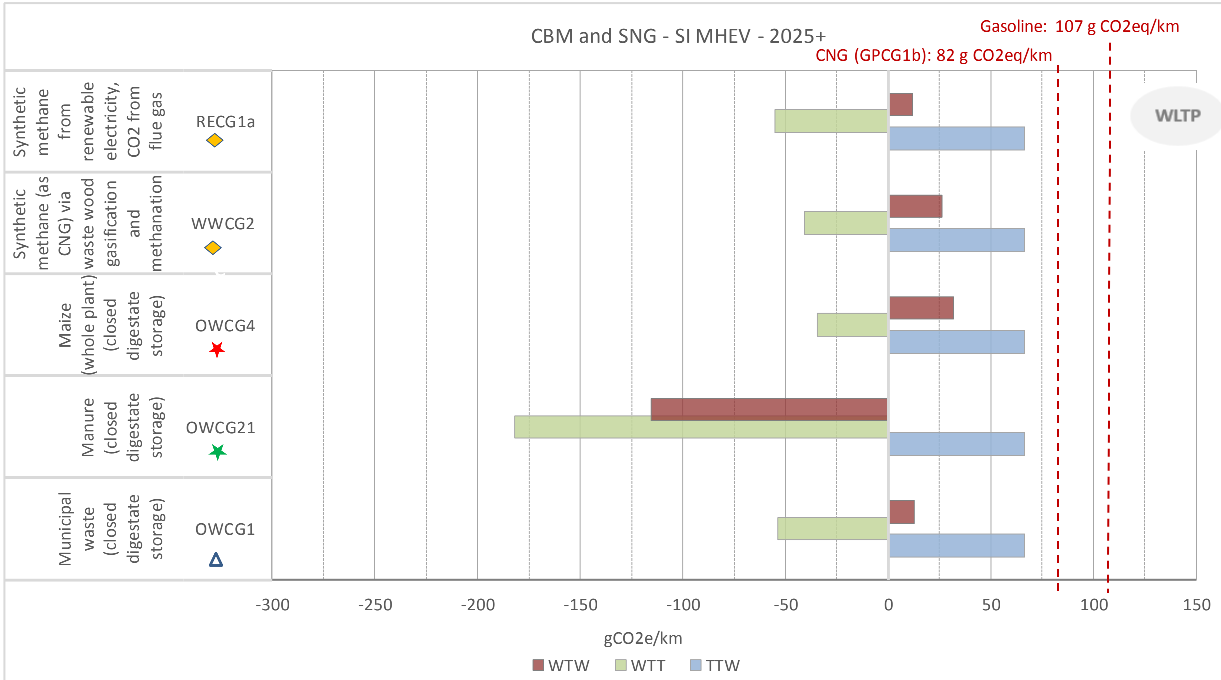
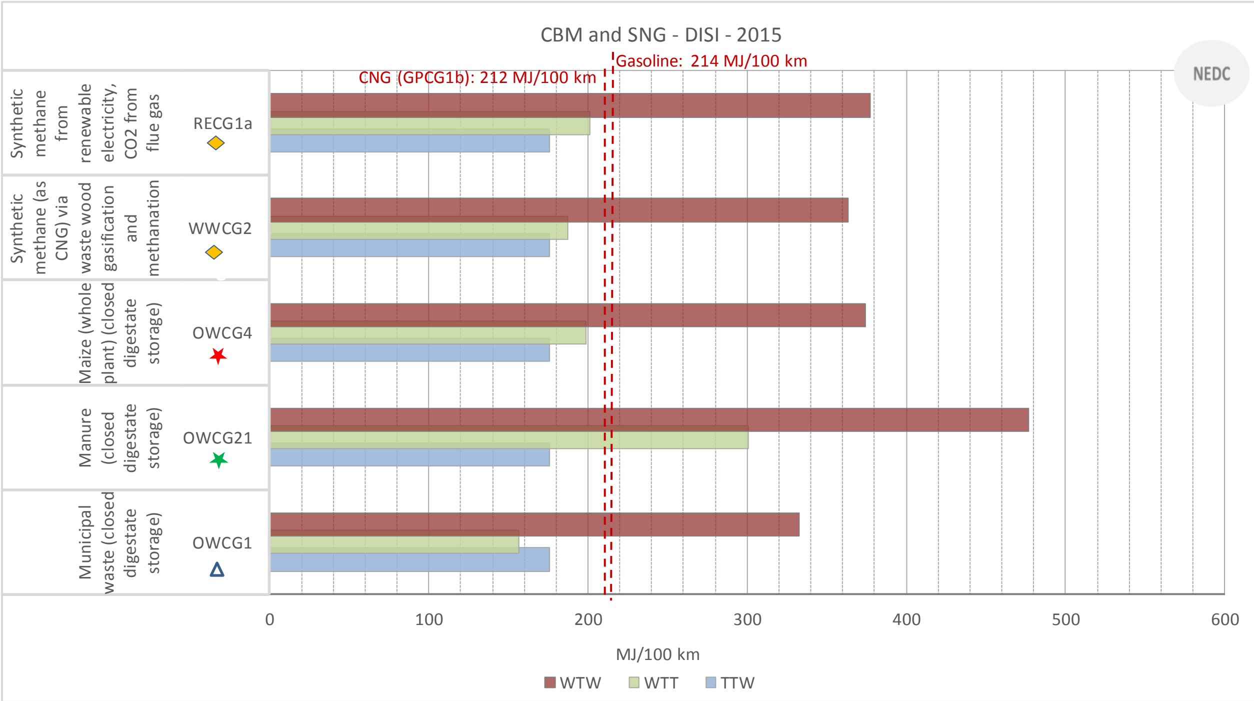
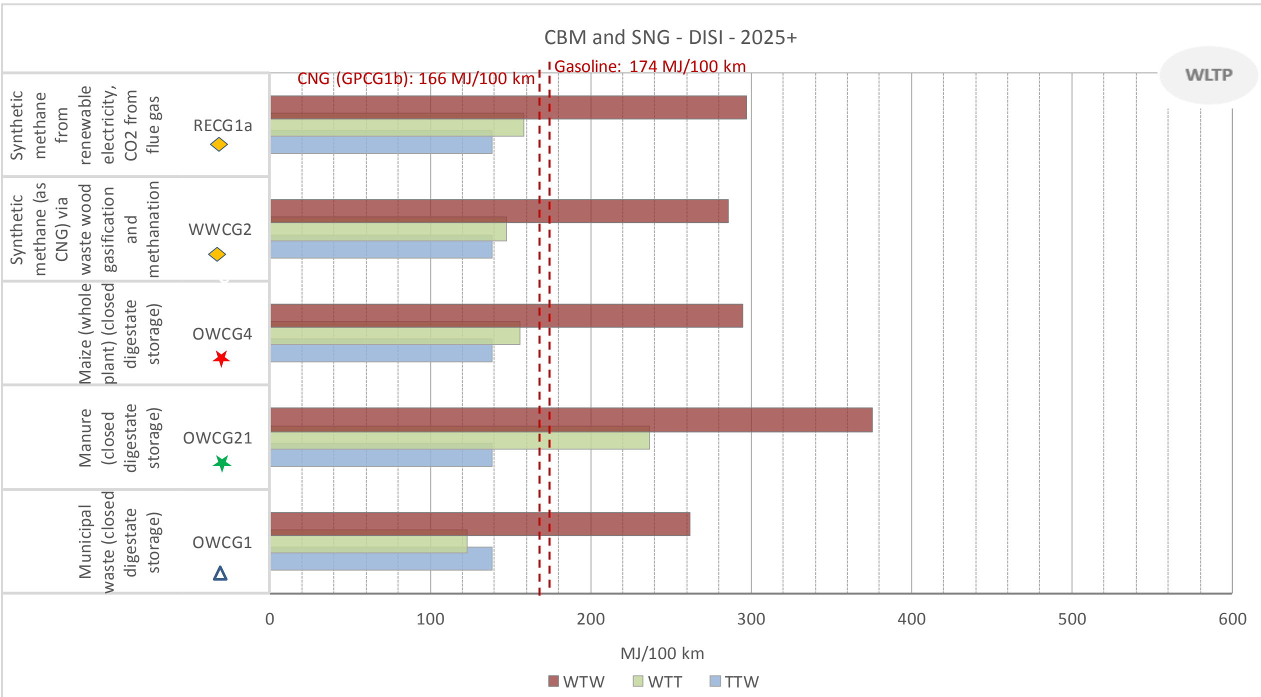
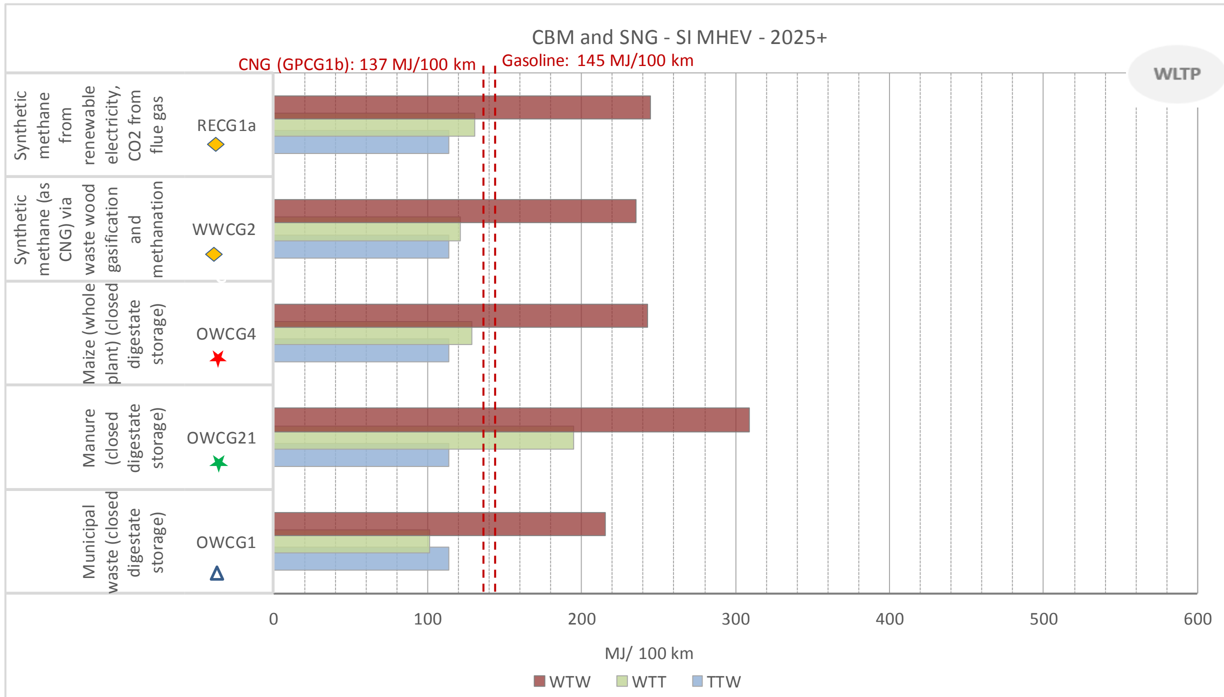


Figure 33. Bio and synthetic methane - Energy expended (MJ/100 km)



The WTW energy use for the renewble fuel pathways is generally higher than that for conventional gasoline (100% fossil) in a comparable drivetrain, due to the higher energy demand for processing, but the GHG emissions are typically lower. The highest WTW energy use has CBM from biogas from manure (pathway OWLG21) due to the relatively low energy conversion efficiency of the fermenter related to the dry matter LHV of the wet manure.

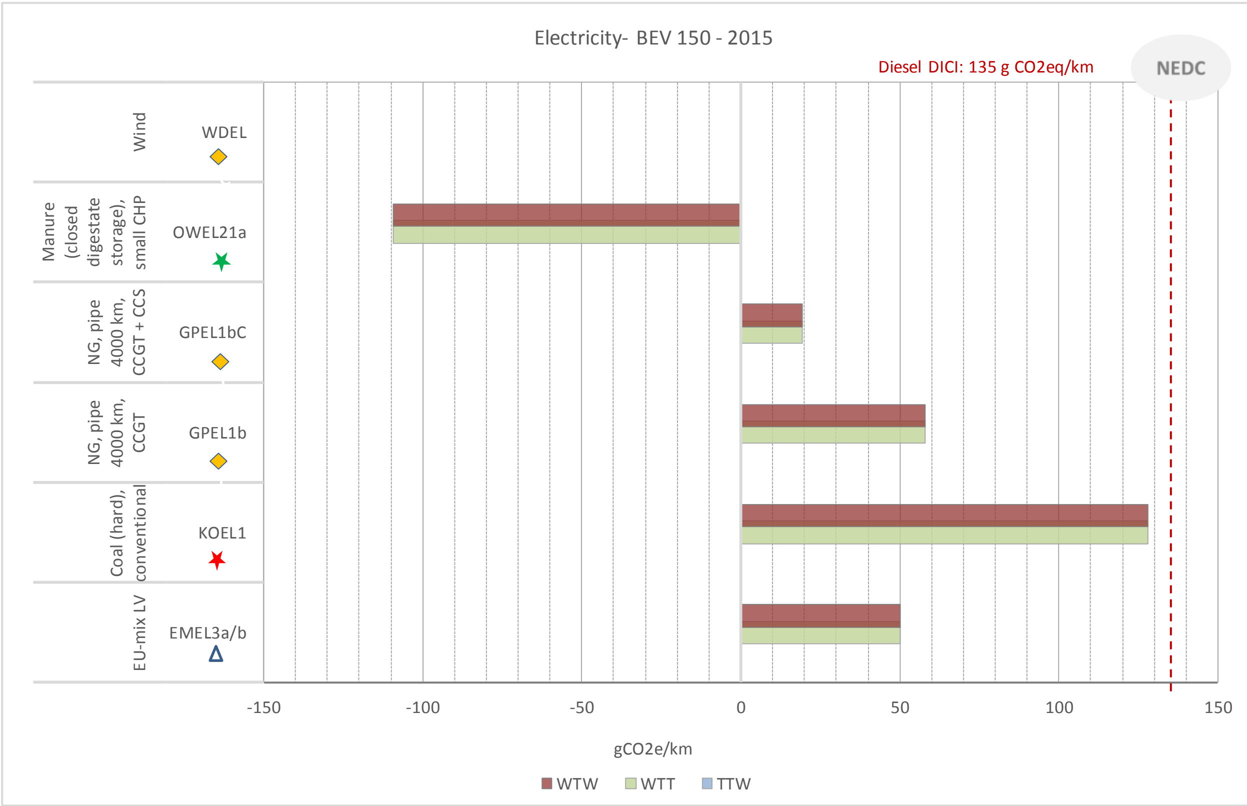


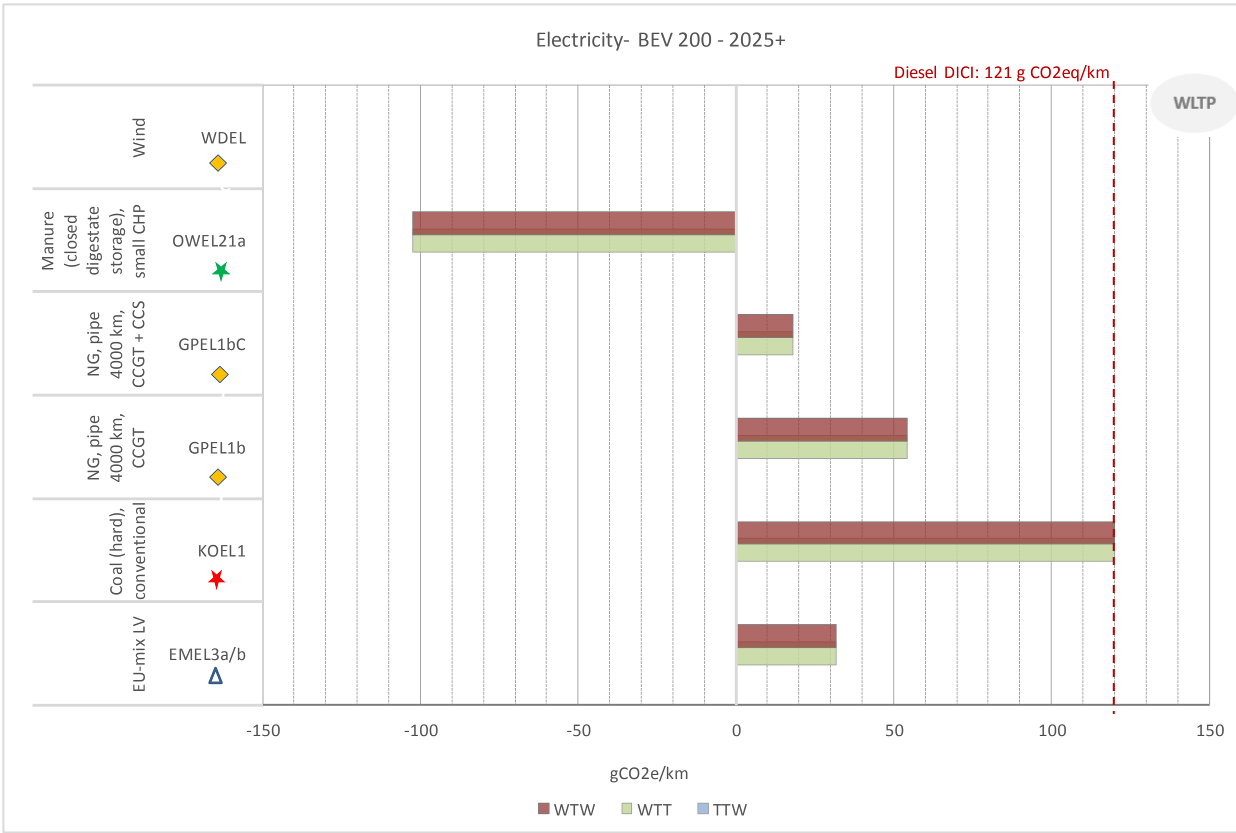


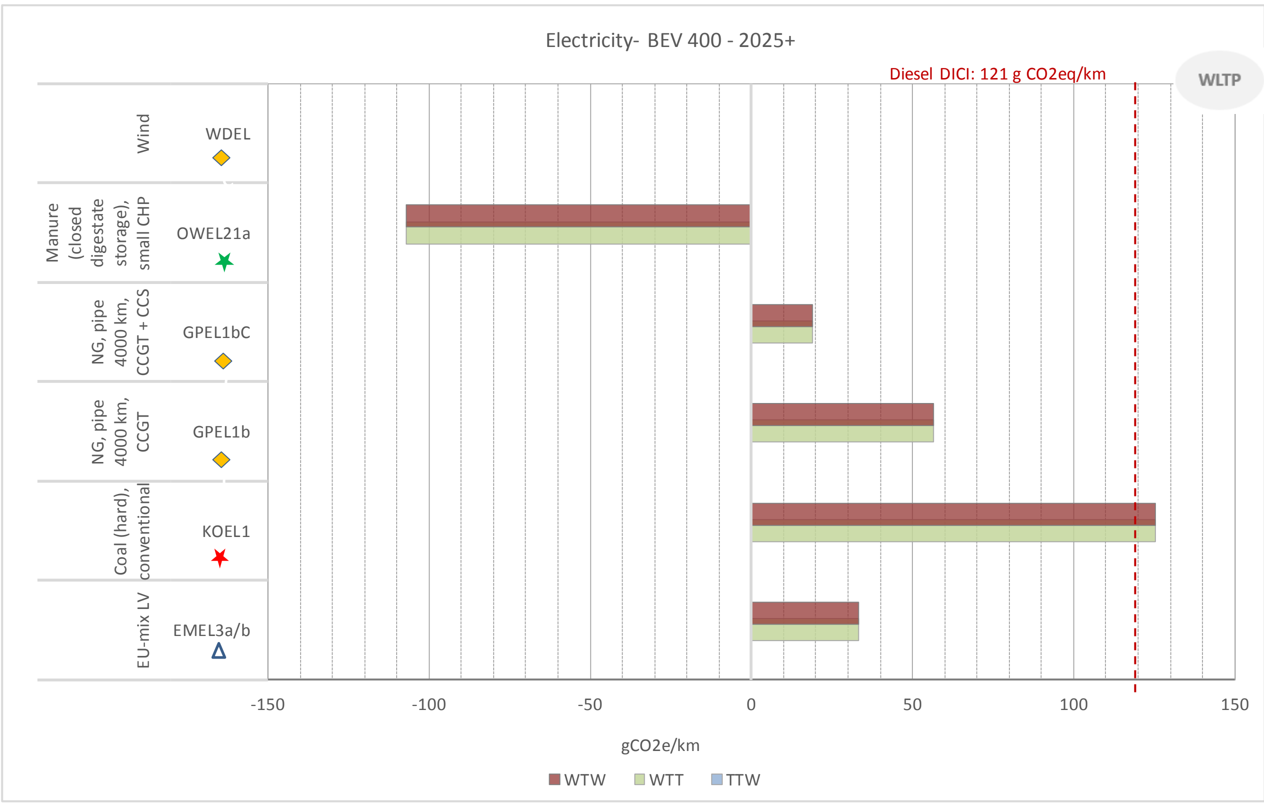
3.2.3 Electricity driven powertrains

3.2.3.1 Battery Electric Vehicles (BEVs)

Figure 34. BEVs - GHG emissions (g CO_{2eq}/km)





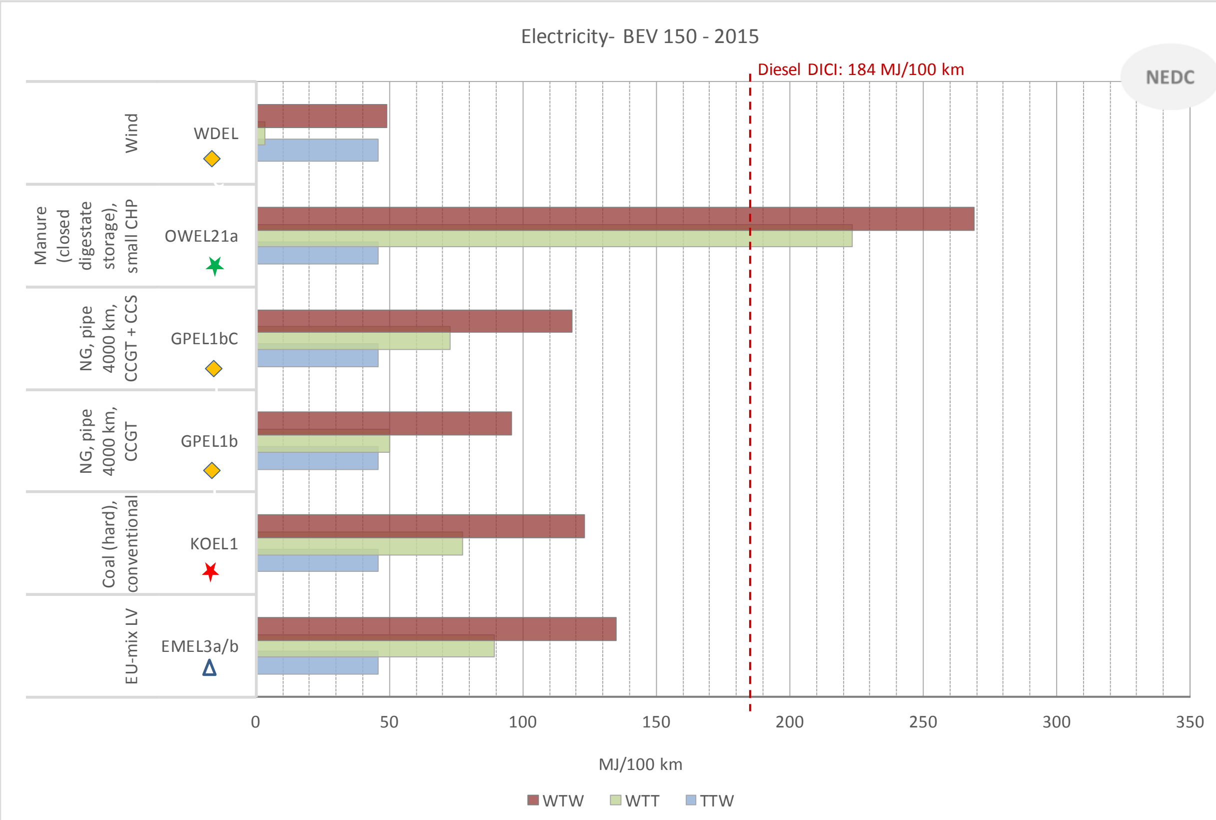


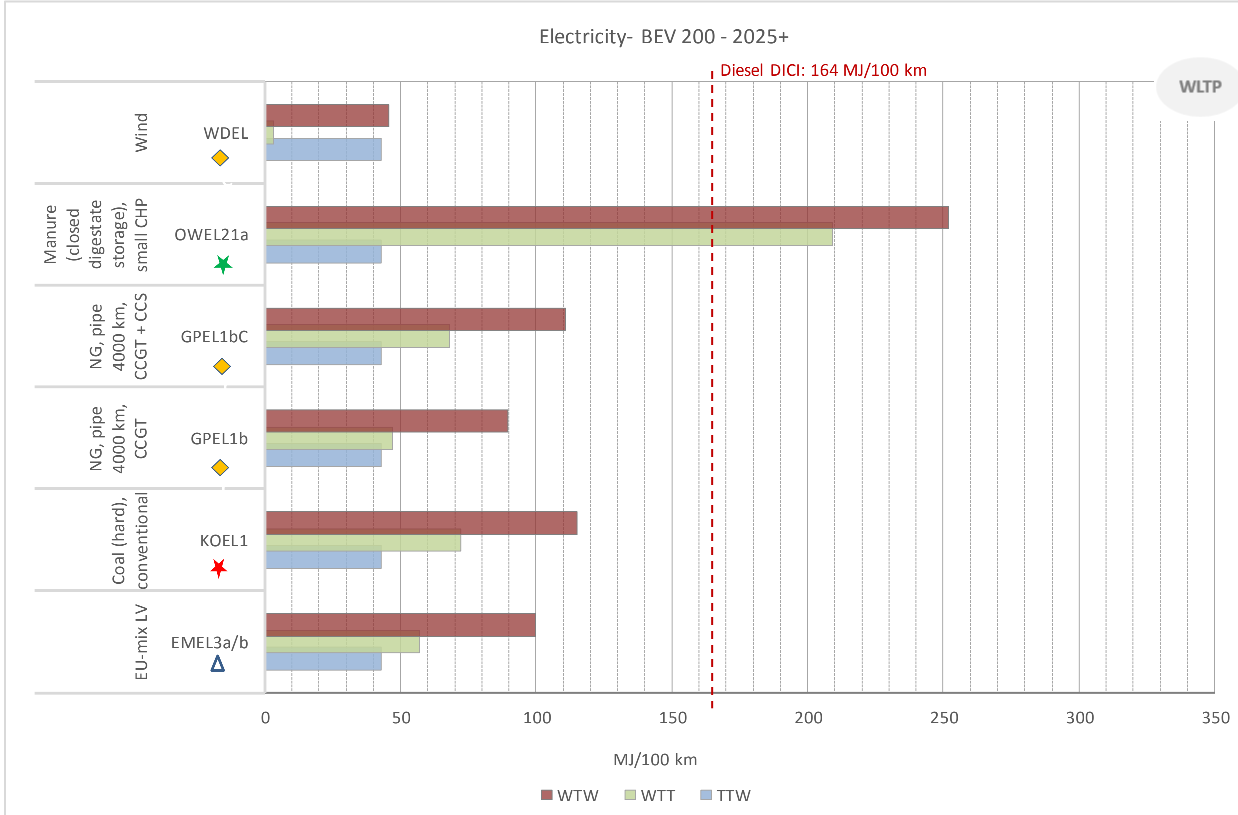
Battery electric vehicles (BEV) show lower GHG emissions for all selected electricity pathways than a similar passenger car with DICI engine fueled with conventional crude oil-based diesel, except in case of coal electricity combined with a BEV with 400 km range (potentially resulting in negative WTW emissions when biogas from manure is used as the electricity source due to the avoided CH_4 emissions as mentioned earlier in the report).

When looking into the 2025+ powertrain technology and referring to the EU-mix as an example, the WTW values improve ~40% due to the higher efficiency of the electric engine. The impact of the range of the battery (increasing from 100 km in 2015 to 200 or 400 km in 2025+) is almost negligible.

It is worth noticing that considering electrical energy used in road transport, as made from the EU mix, may not represent real emissions. This because when taken from the grid, the additional MJ required for road is unlikely to be produced from the mix. Country by country, the grid is expected to react in different way, but most likely adjusting the demand by supplying energy from fossil sources, i.e. natural gas (at least in the short term). Despite EU mix is used as a proxy for comparative purposes, any conclusion about the GHG saving related to the greening of the EU electricity mix may not well represent the reality.

Figure 35. BEVs – Energy expended (MJ/100 km)

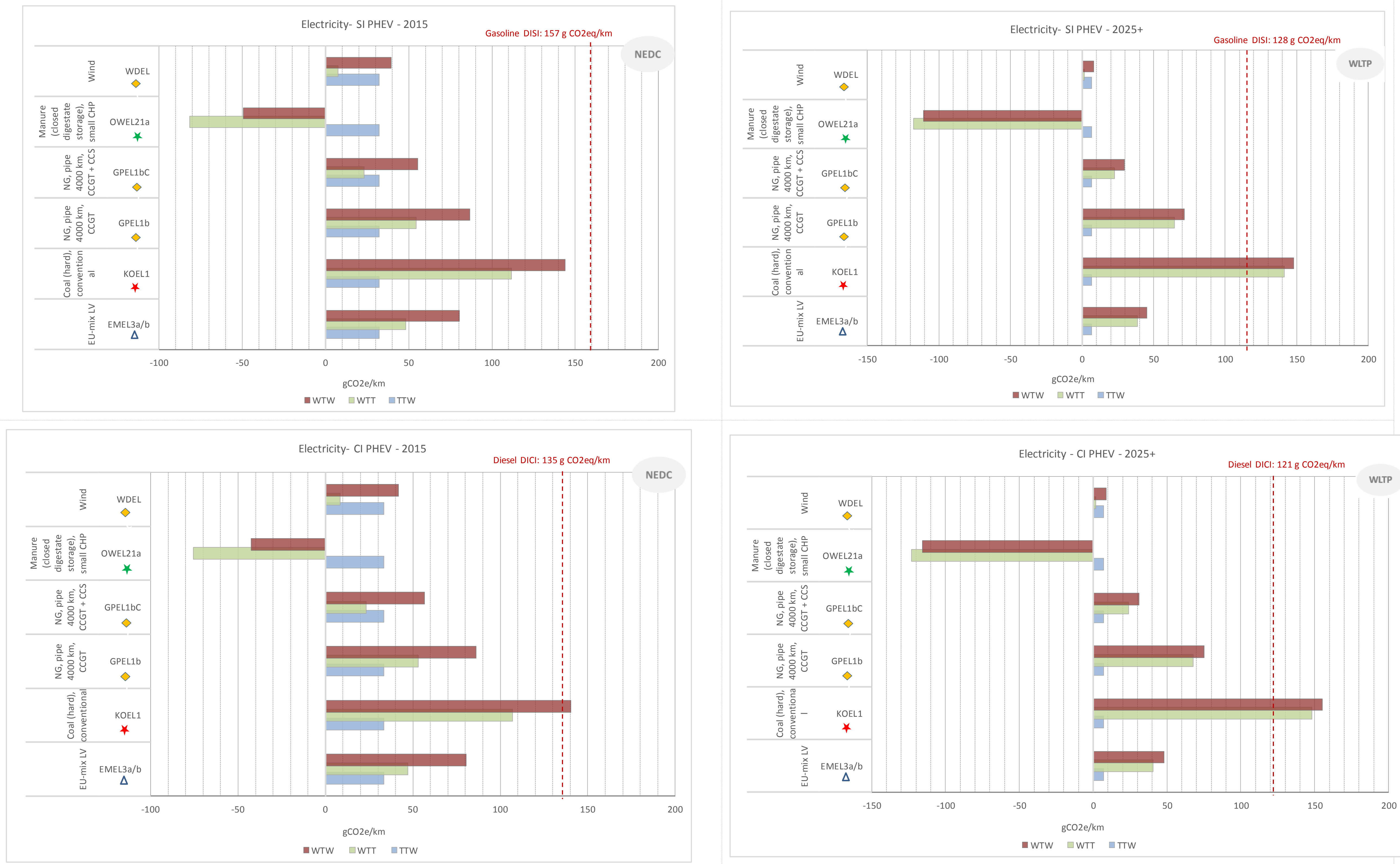




Generally, energy intensity is not a good measure for GHG emissions, as the latter depends on the carbon intensity of the specific feedstock. For example the conversion of renewable electricity to synthetic diesel via power-to-liquid and its use as transportation fuel leads to a high WTW energy use although the WTW GHG emissions are low.

3.2.3.2 Plug-in Hybrid Electric Vehicles (PHEVs)

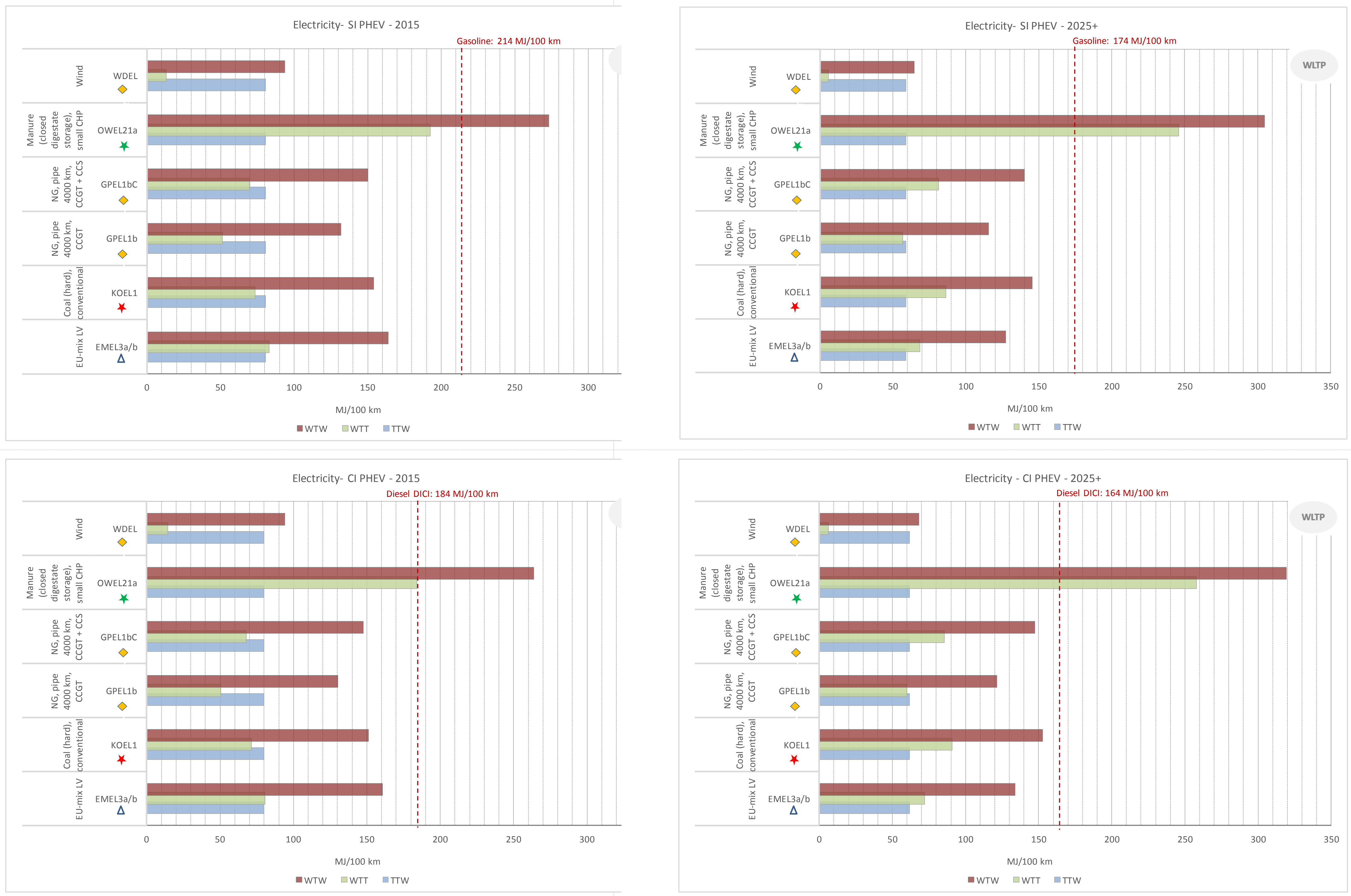
Figure 36. PHEVs - GHG emissions (g CO_{2eq}/km)



Both SI and CI PHEV show lower GHG emissions than conventional gasoline and diesel ICE (100% fossil) except in case of coal electricity (especially for time horizon 2025+).

The engine technology is expected to improve significantly towards 2025+. As a proxy, the EU electricity mix is explored and, for that theoretical scenario, the WTW intensity is reduced by ~40% (EMEL3a/b), offering a slightly better WTW performance for the gasoline SI PHEV combination than the diesel one.

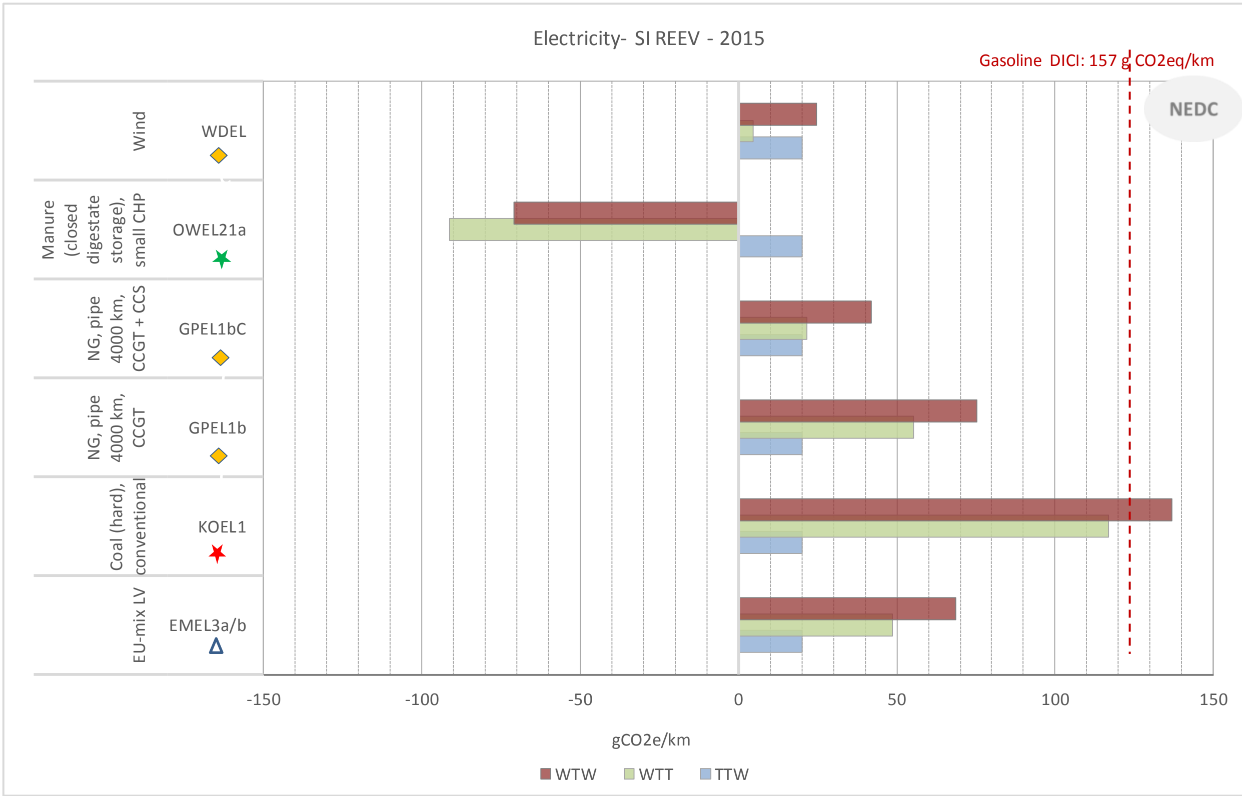
Figure 37. PHEVs - Energy expended (MJ/100 km)

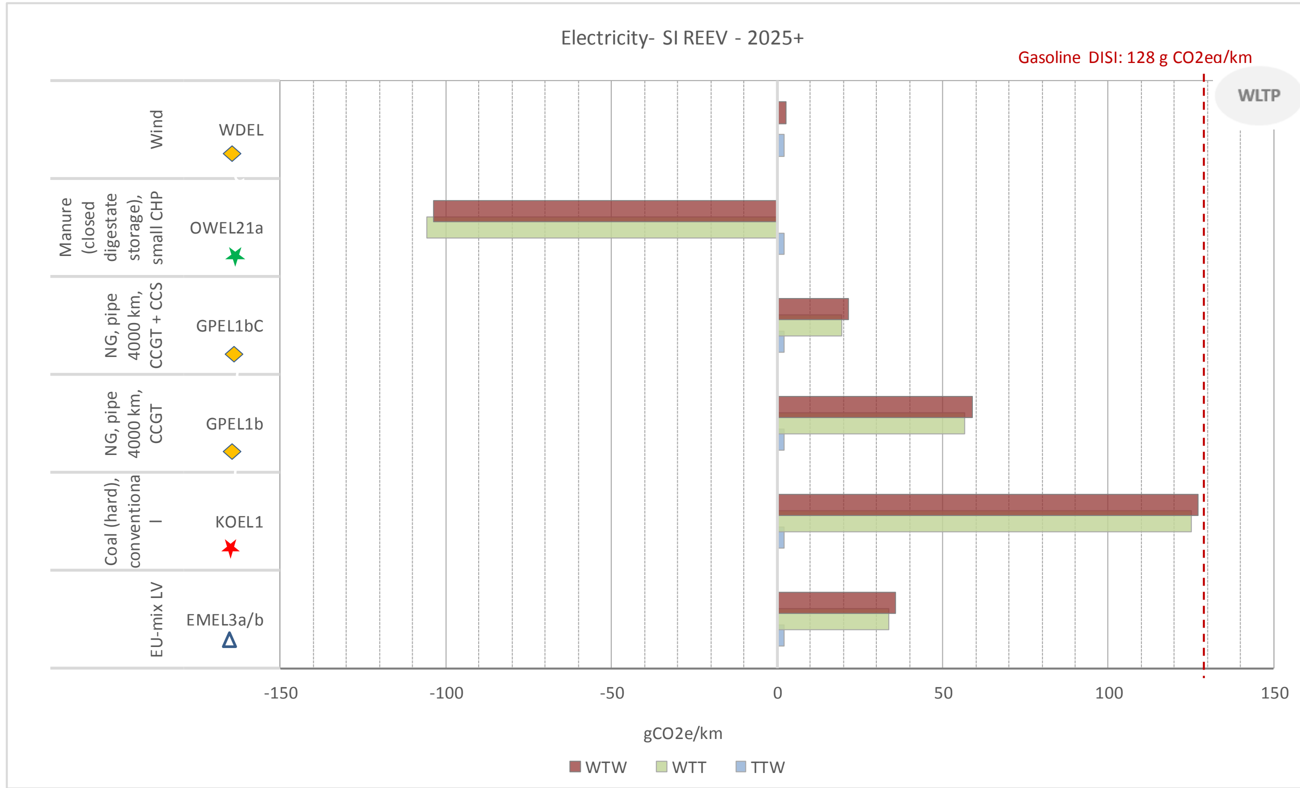


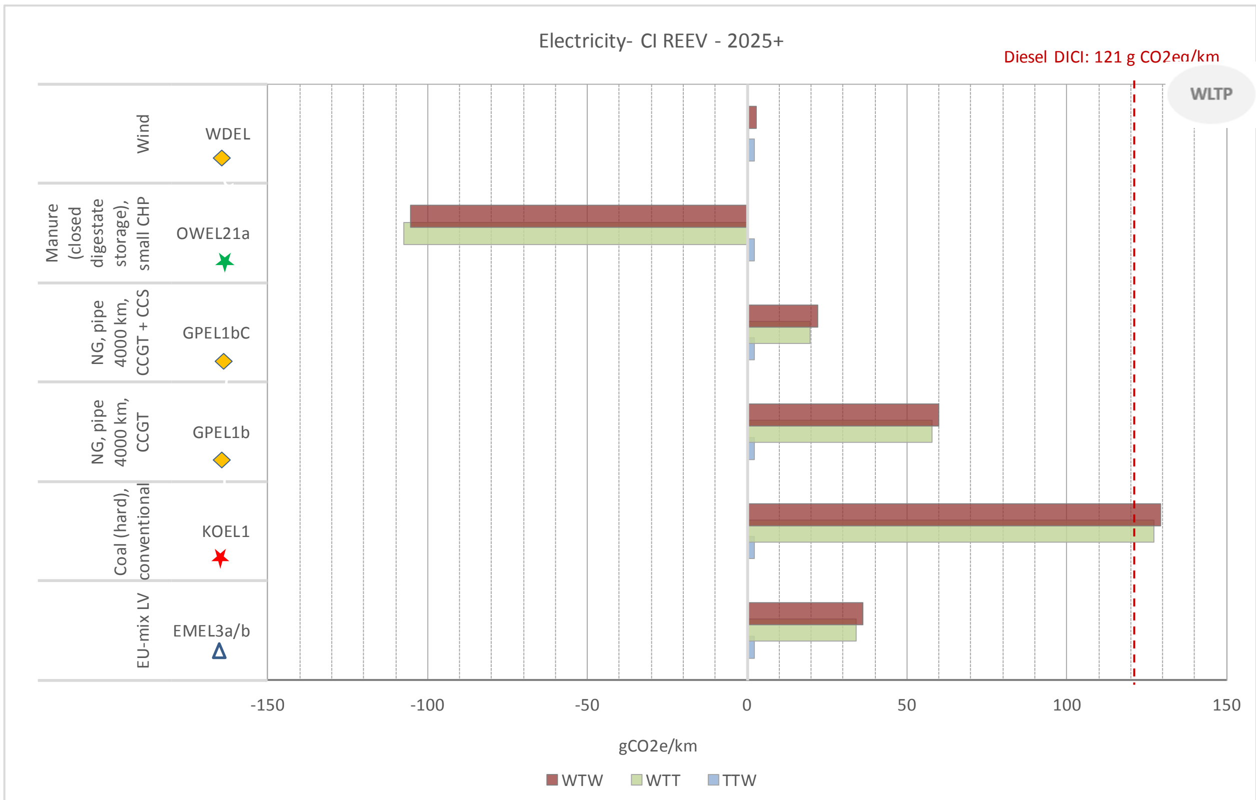
The driving cycle (NEDC for 2015 and WLTP for 2025+) defines the parameters that have been used as a reference to estimate PHEV consumption. However, it is worth mentioning that these cycles do not necessarily reflect the real use of PHEV in electric mode.

3.2.3.3 Range Extender Electric Vehicles (REEVs)

Figure 38. REEVs - GHG emissions (g CO_{2eq}/km)

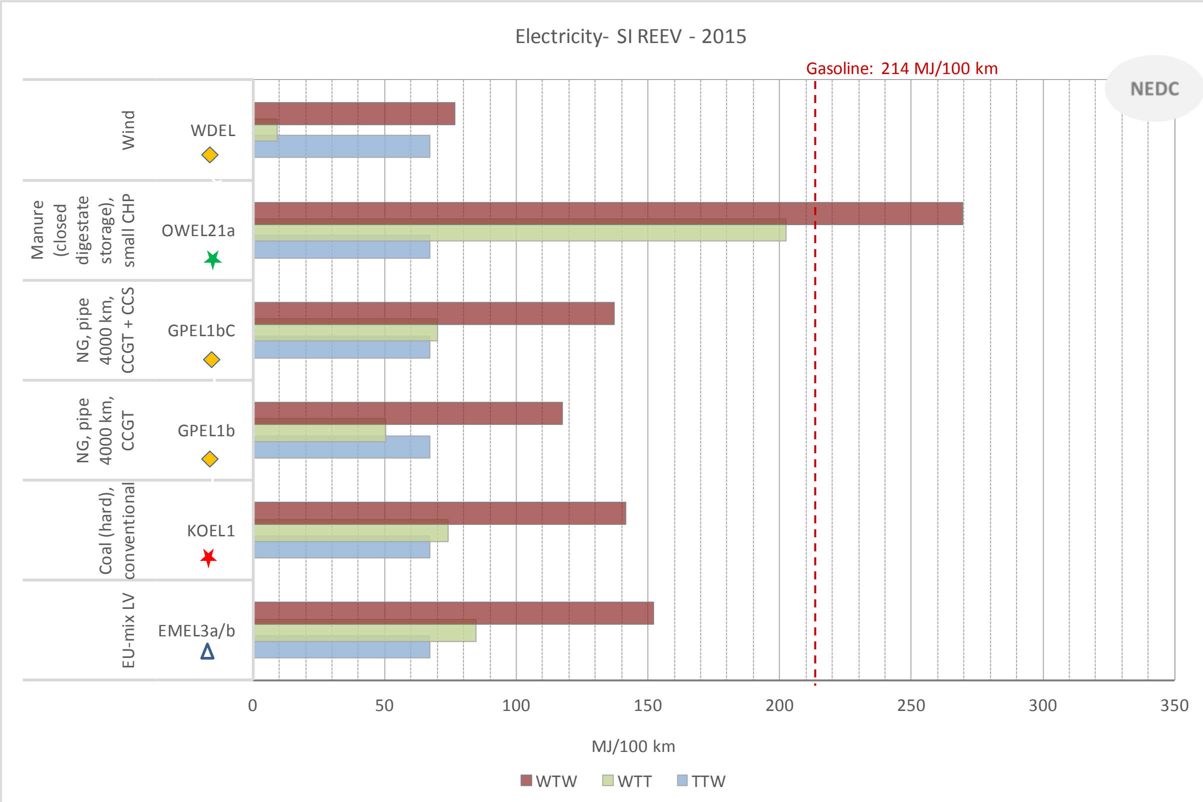


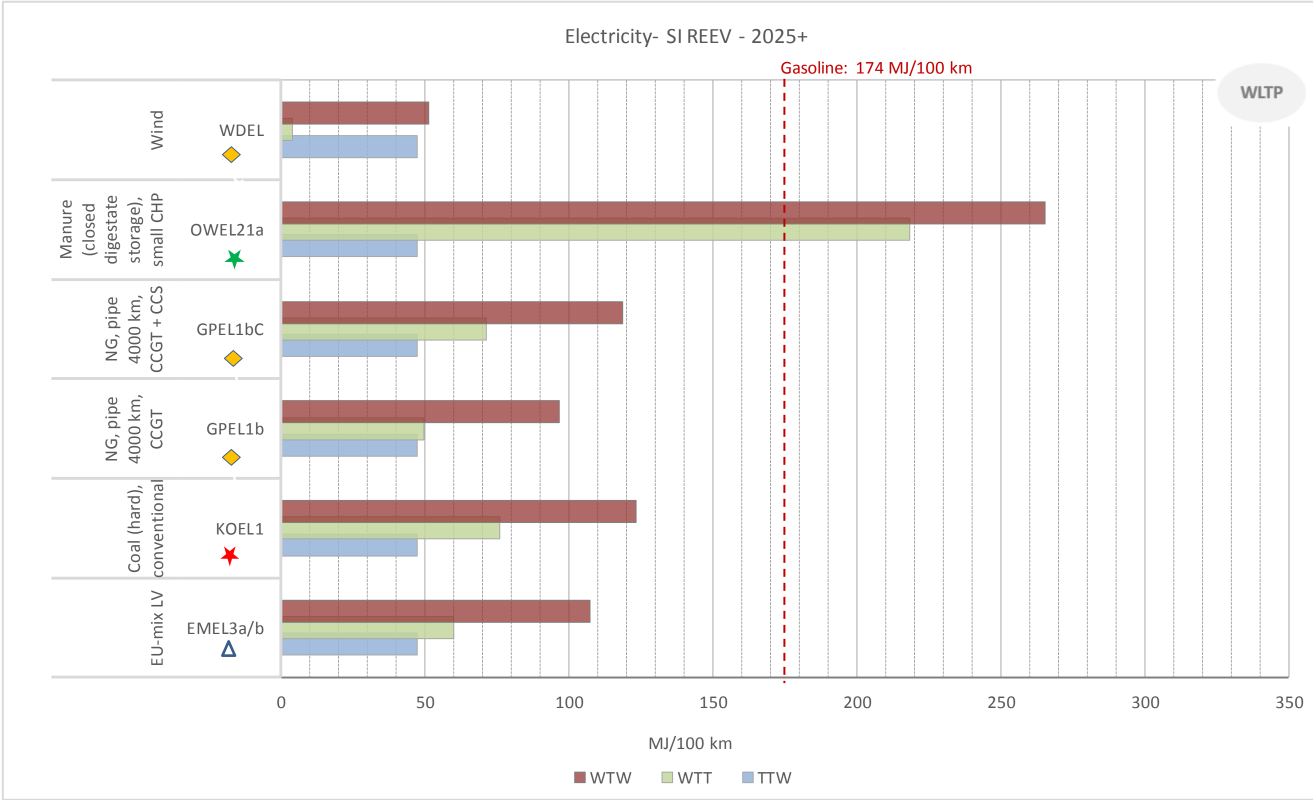


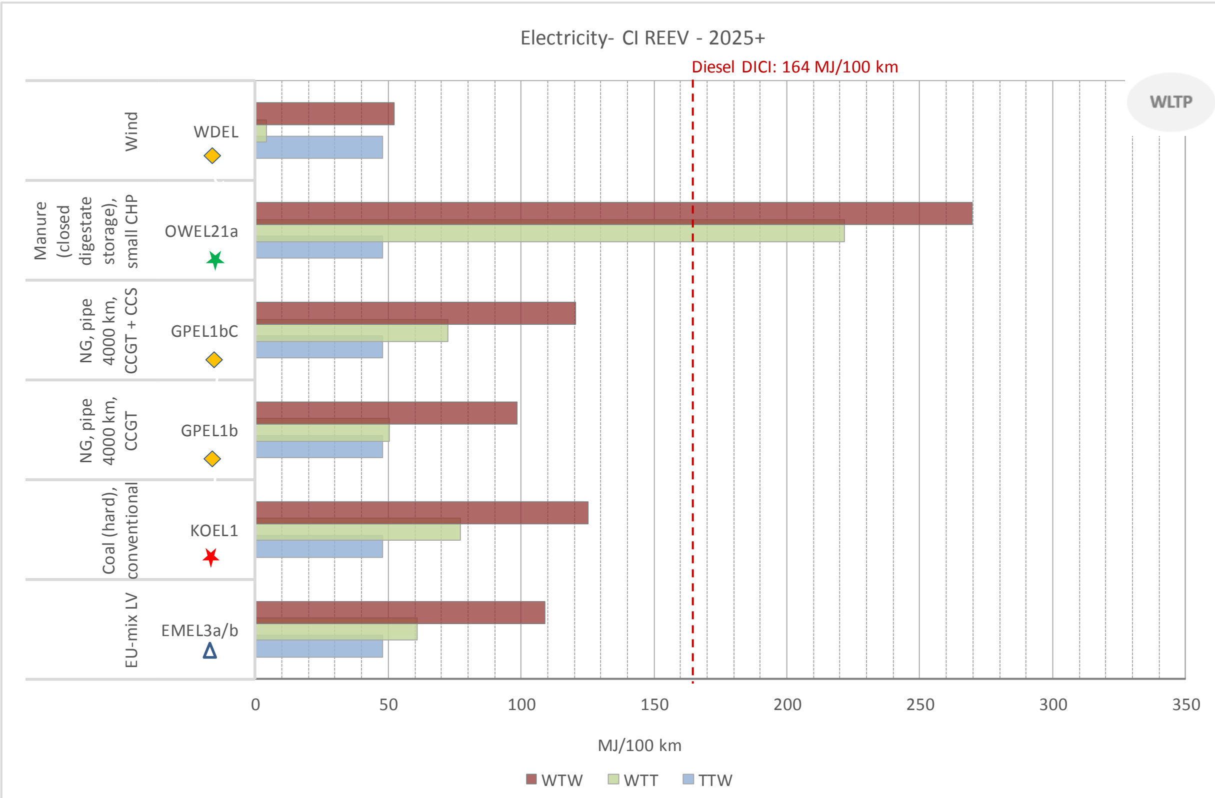


As for the PHEV comparison, SI and CI REEV show similar results with lower GHG emissions than the fossil gasoline/diesel comparison for almost all of the selected pathways. The combination of the improved engine technology with the lower CO_{2eq} emissions in the EU mix offers also similar level of WTW reductions (~50%).

Figure 39. REEVs - Energy expended (MJ/100 km)



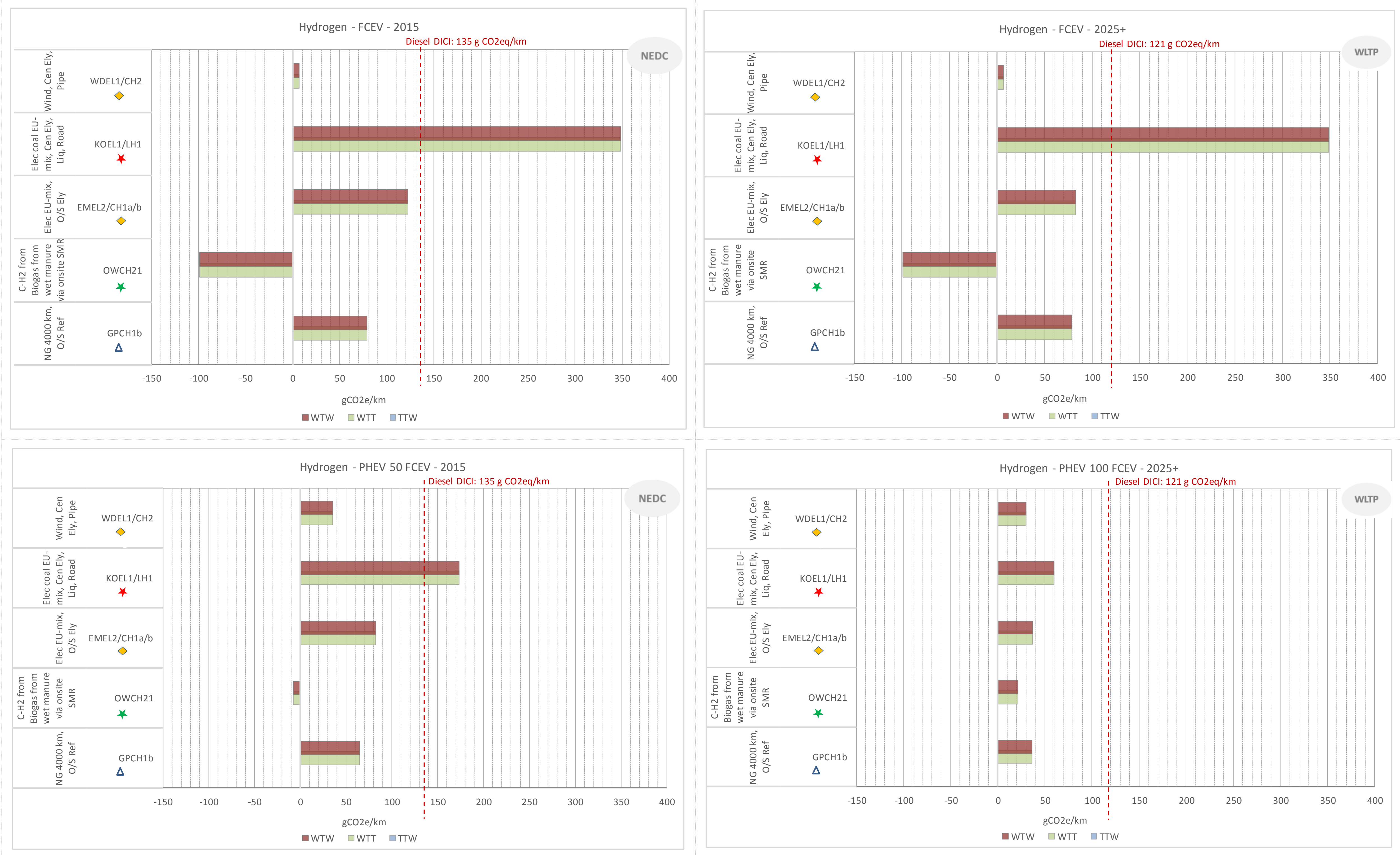




Due to the high efficiency of the drivetrain the WTW energy use is generally lower than that of ICE with conventional gasoline and diesel as fuel except for electricity from biogas from manure.

3.2.4 Fuel Cell Hydrogen Electric Vehicles (FCEVs, PHEV FCEVs & REEV FCEVs)

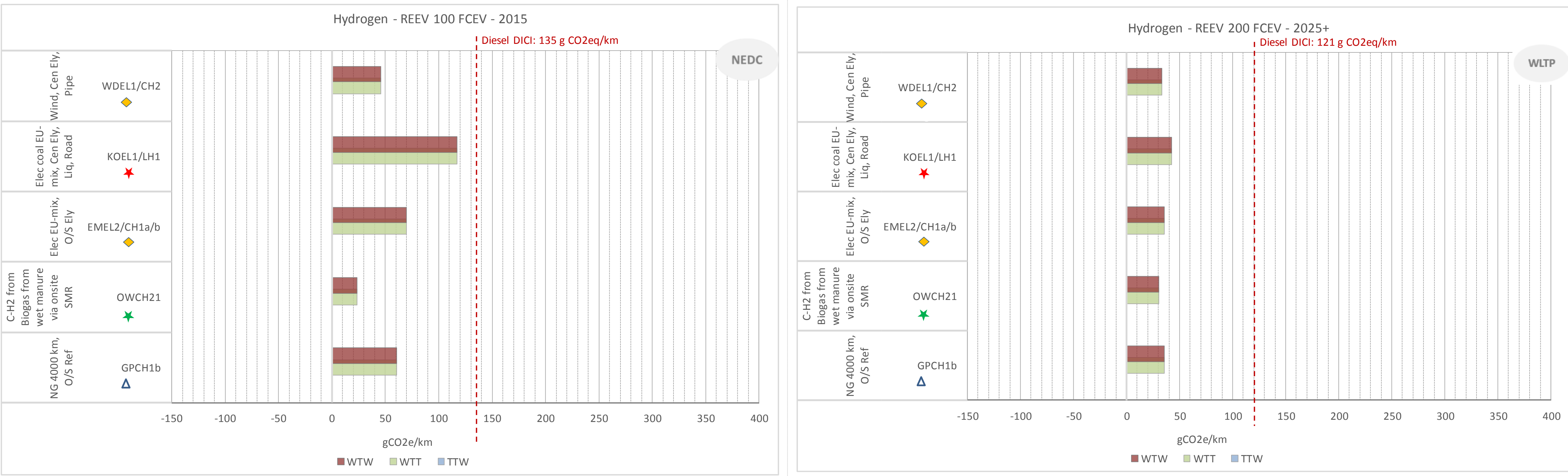
Figure 40. FCEVs, PHEV - GHG emissions (g CO_{2eq}/km)



Except in case of electrolysis using coal electricity with downstream hydrogen liquefaction, FCEV show lower GHG emissions than the conventional diesel ICE (100% fossil).

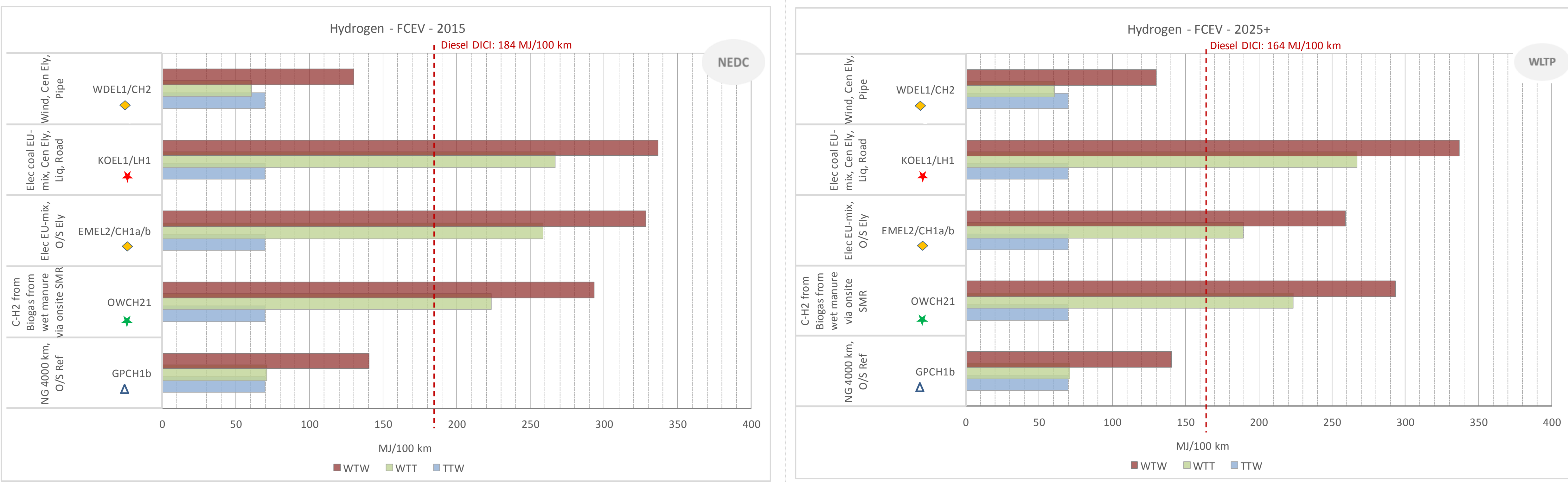
In case of the PHEV 100 (range of the battery 100 km) FCEV the GHG emissions are lower than those of the diesel DICI for all selected pathways. The reason is that the PHEV are often operated at BEV mode.

Figure 41. REEV FCEVs – GHG emissions (g CO2eq/km)



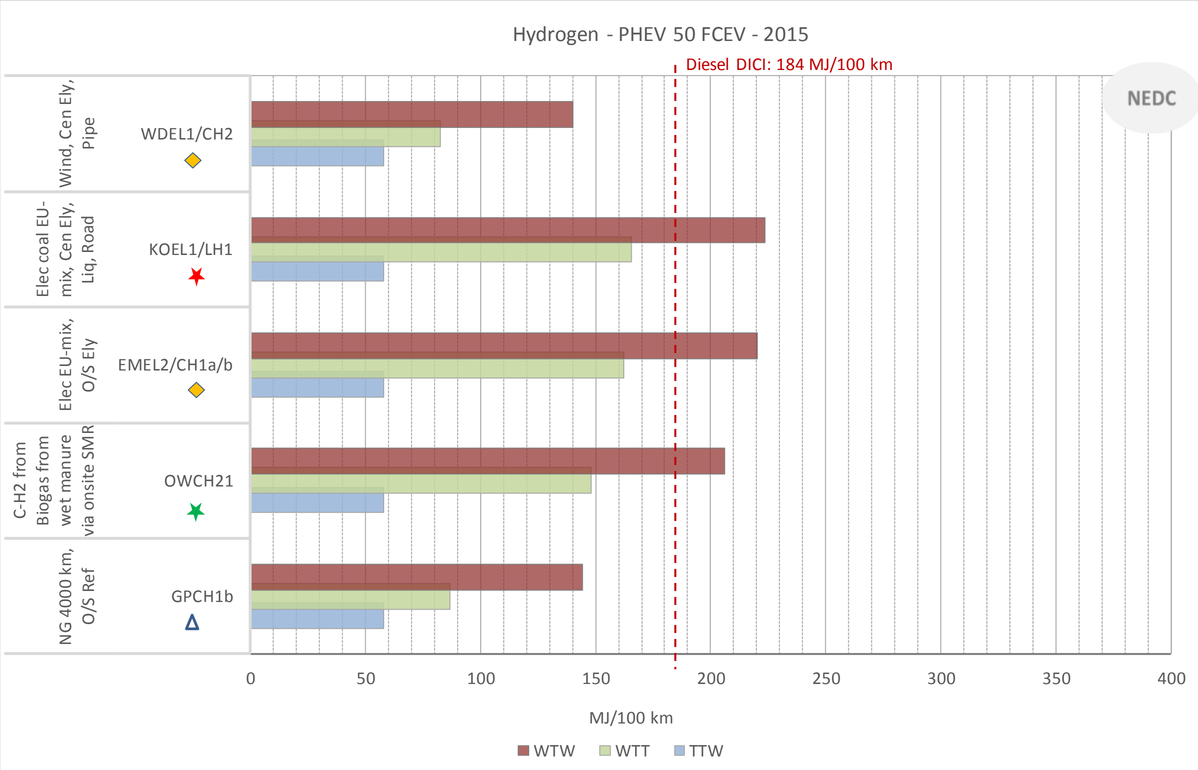
In case of the REEV FCEV the GHG emissions are lower than those of the diesel DICI for all selected pathways. The reason is that theseare often operated at BEV mode.

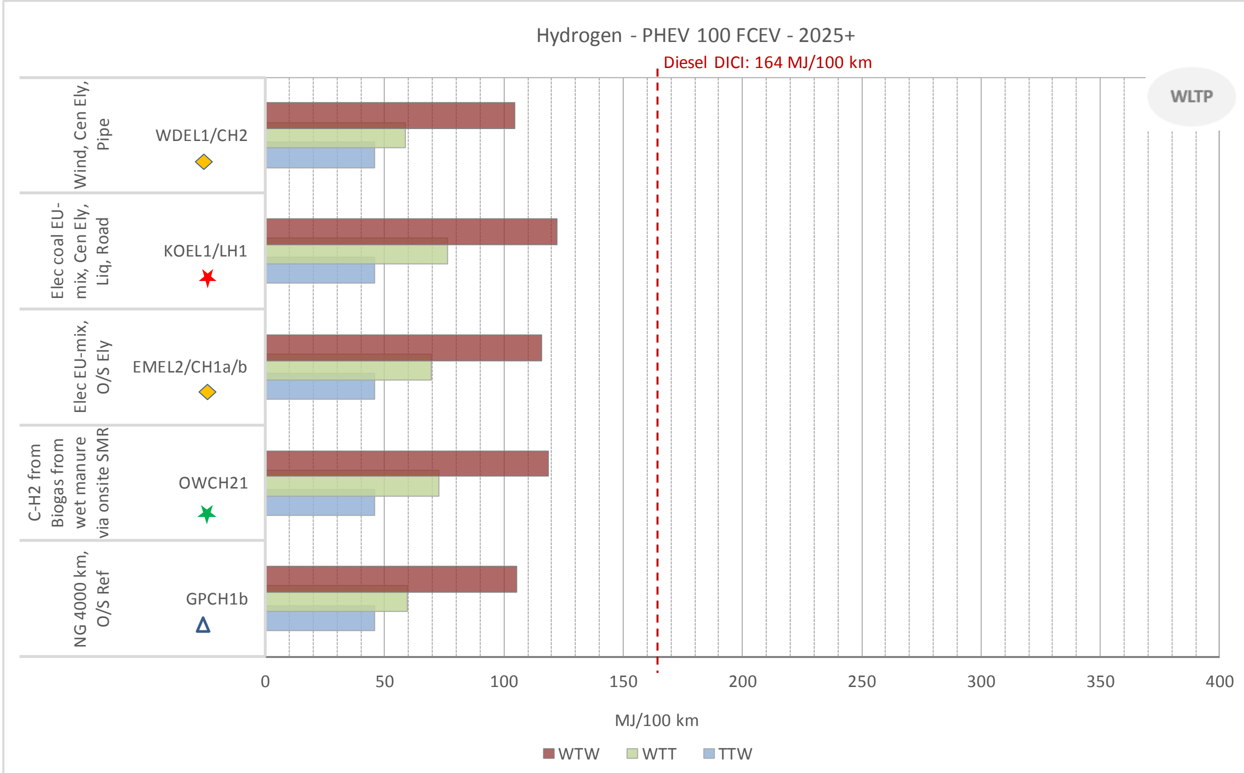
Figure 42. FCEVs – Energy expended (MJ/100 km)



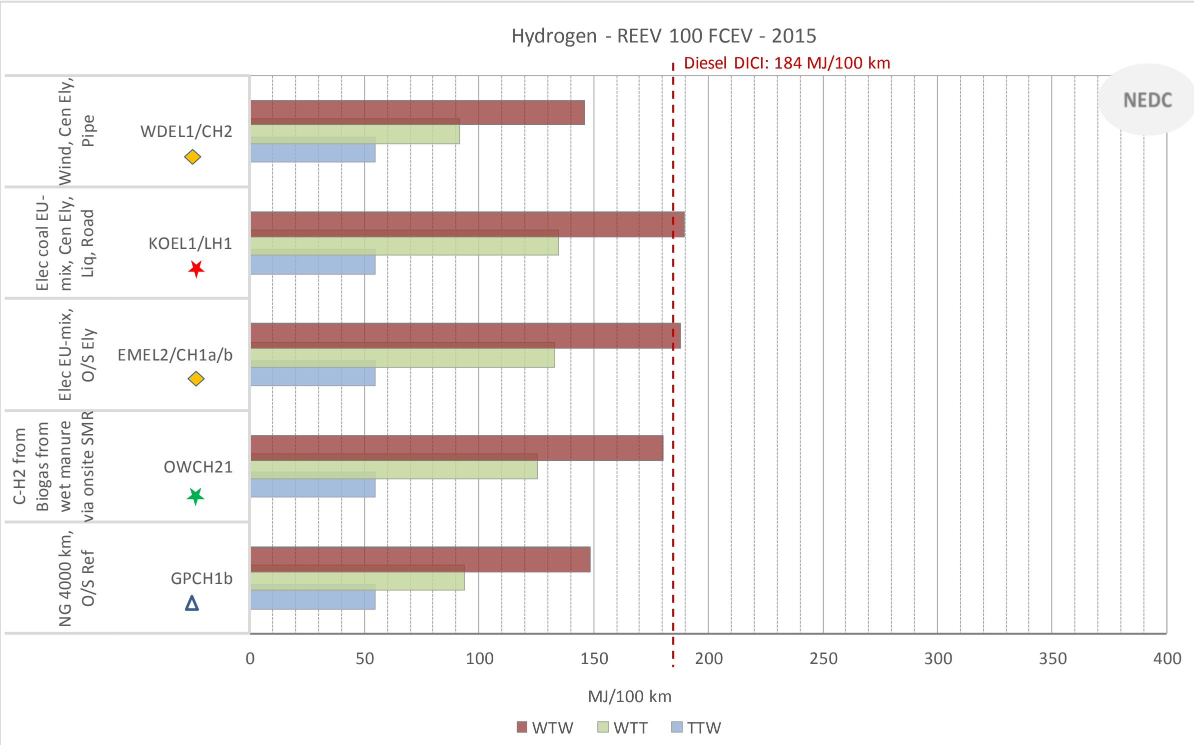
Compressed gaseous hydrogen generated via water electrolysis using wind power and via steam reforming from natural gas used in FCEV leads to lower energy use than conventional diesel in ICE engines. Cryo-compressed hydrogen from water electrolysis using coal electricity leads to the highest energy use of the selected pathways.

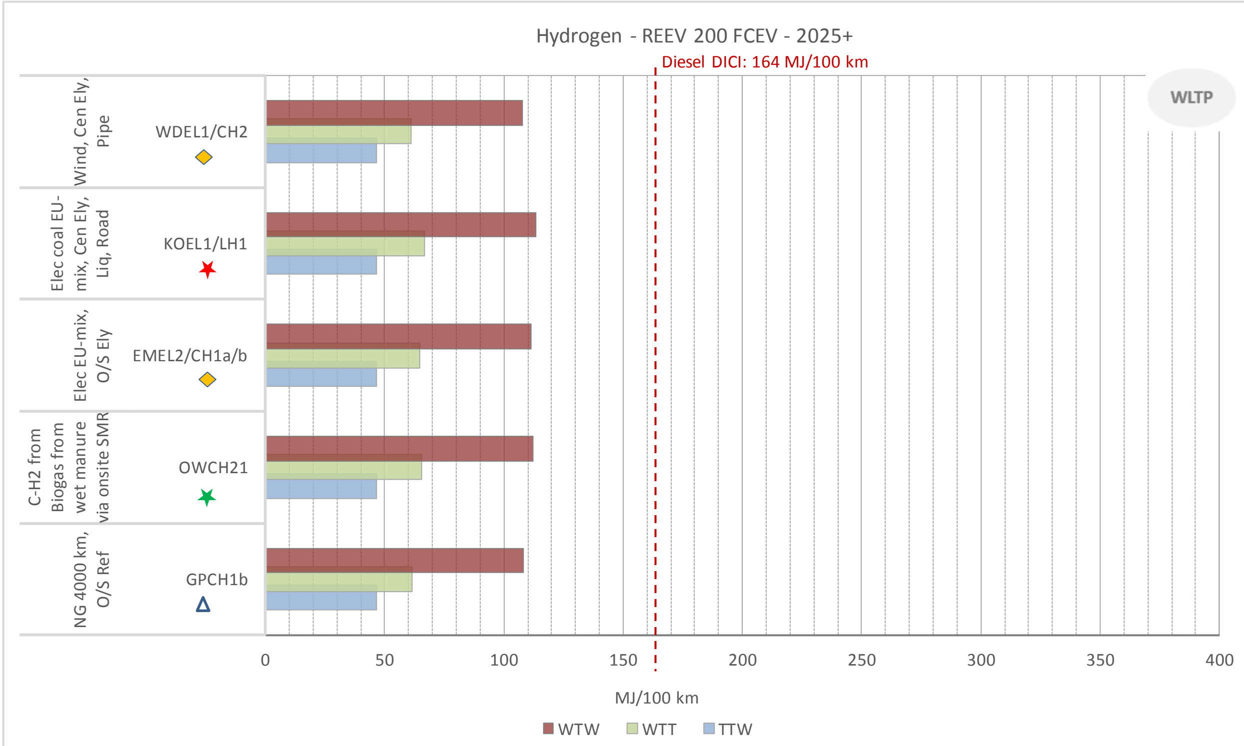
Figure 43. PHEV REEV FCEVs - Energy expended (MJ/100 km)





PHEV FCEV combined with the selected pathways leads to lower WTW energy use than conventional diesel used in ICE engines in 2025+.



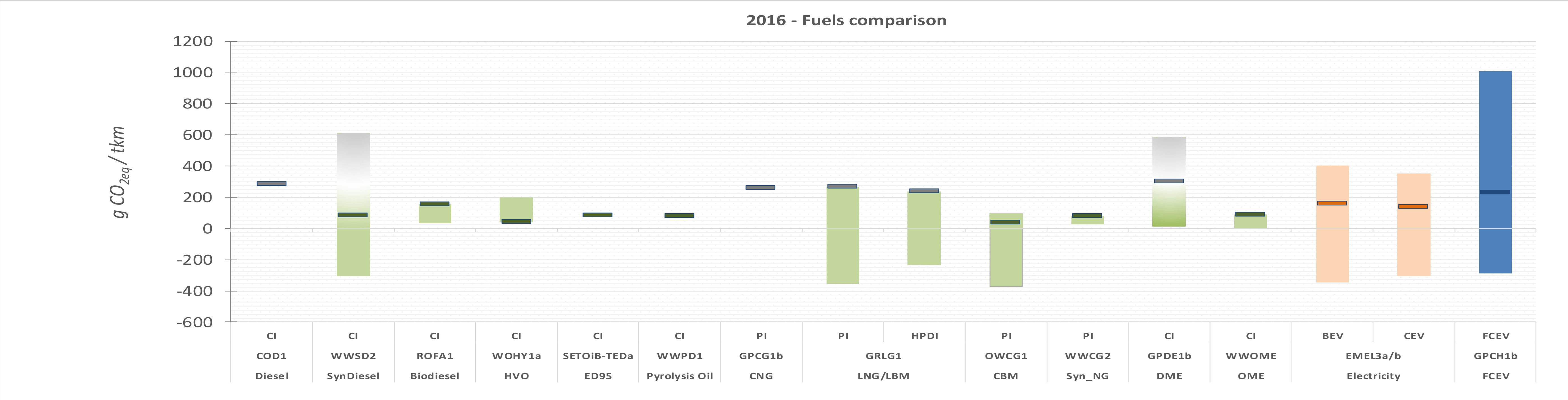


REEV FCEV combined with the selected pathways leads to lower WTW energy use than conventional diesel used in ICE engines in 2025+.

4 Heavy Duty – Type 4

4.1 WTW integration. Comparative Analysis

Figure 44. WTW fuel comparison - GHG emissions



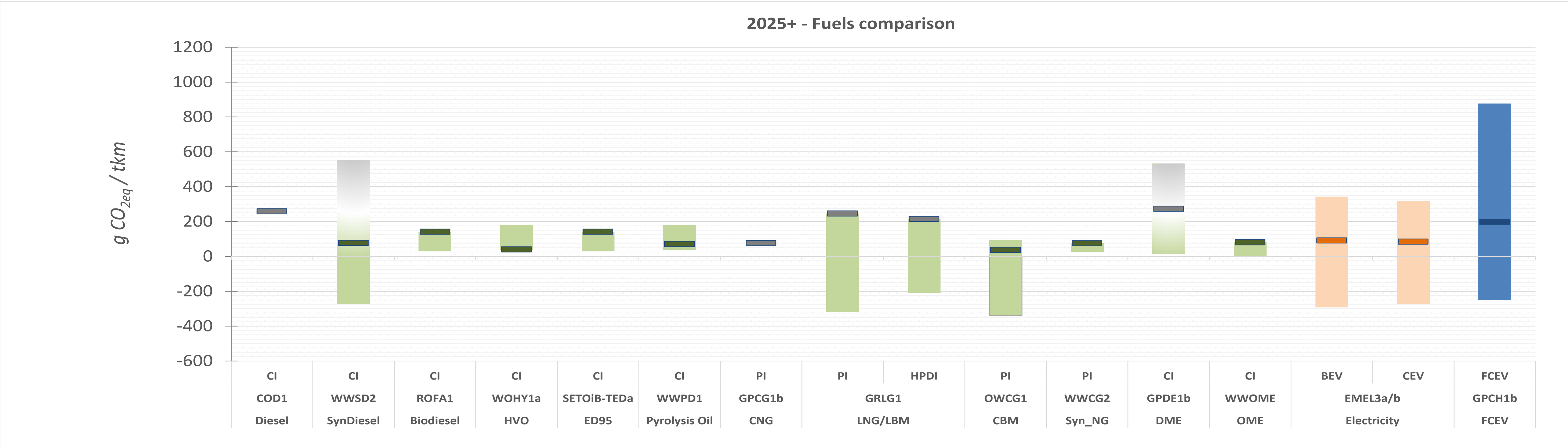
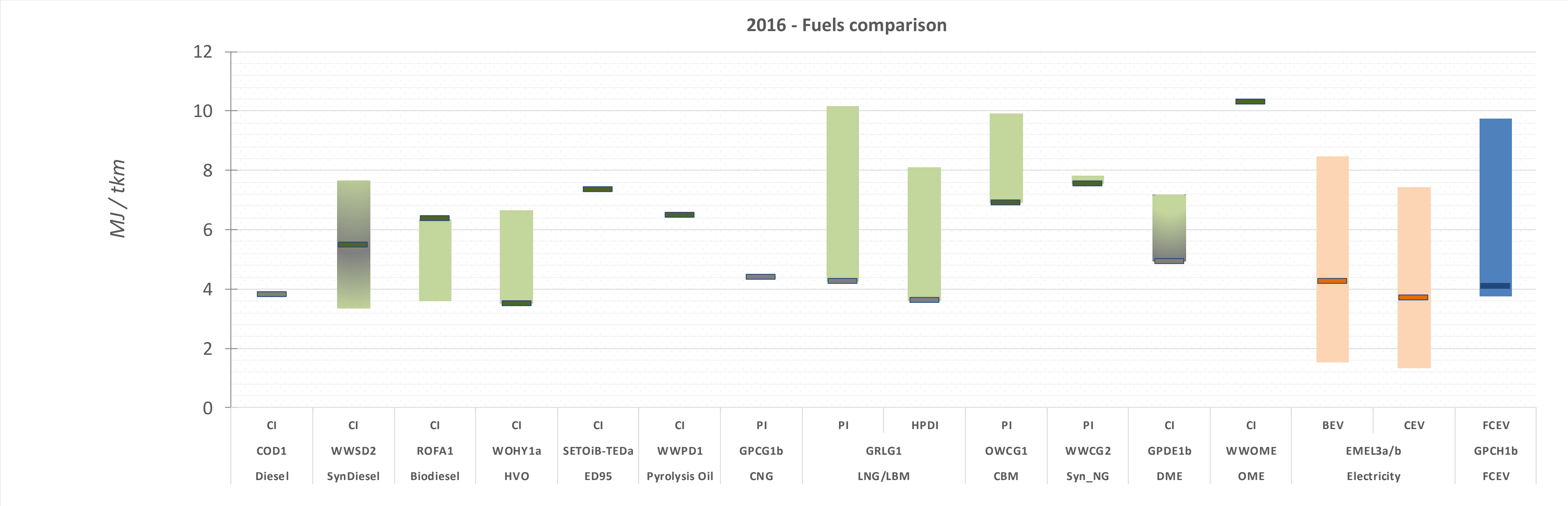
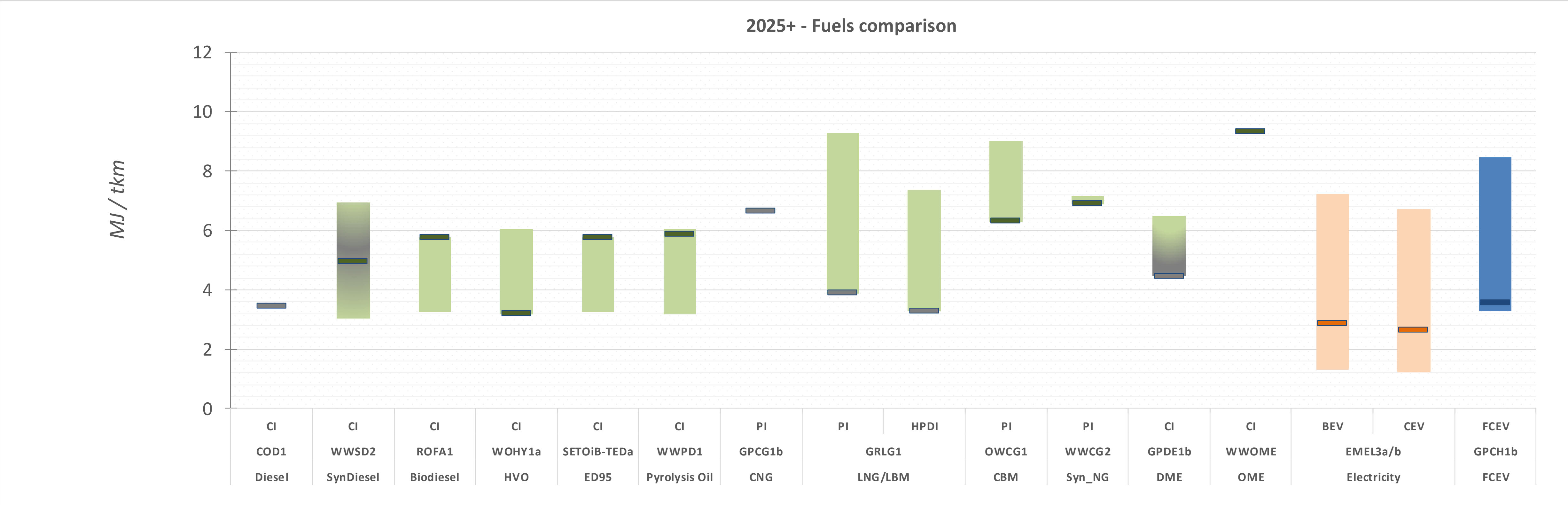


Figure 45. WTW fuel comparison – energy expended





Note. The charts above include selected pathways modelled for the JEC WTW v5 integration (not representing all possible WTW fuel and powertrain combinations following the criteria explained in section 2.5.2). Additional promising low-CO_2 intensive pathways, not available at commercial scale yet (Technology Readiness Level < 6), have not been included in this WTW comparison but all detailed data are available in the JEC WTT v5 report for the reader to conduct their own in-depth assessment.

Figure 46. WTW powertrain comparison - GHG emissions

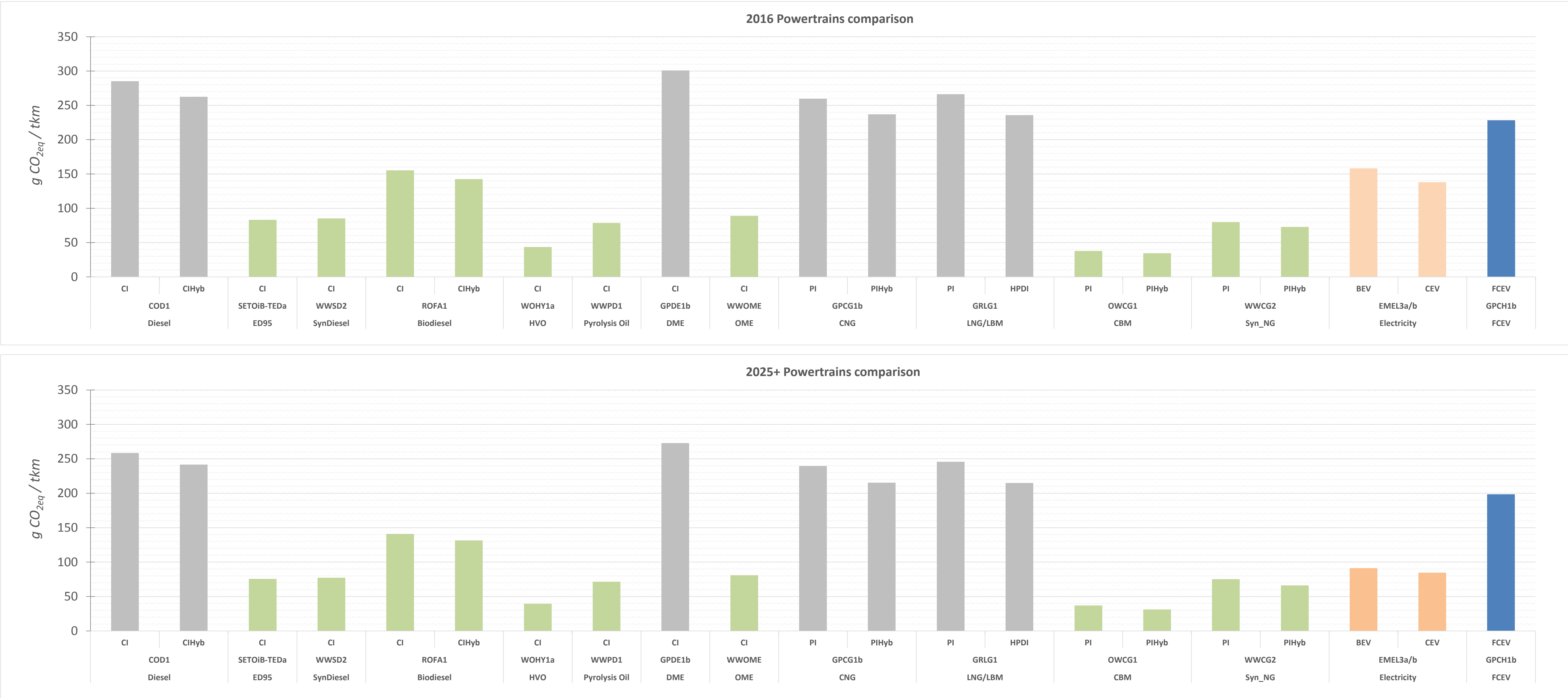
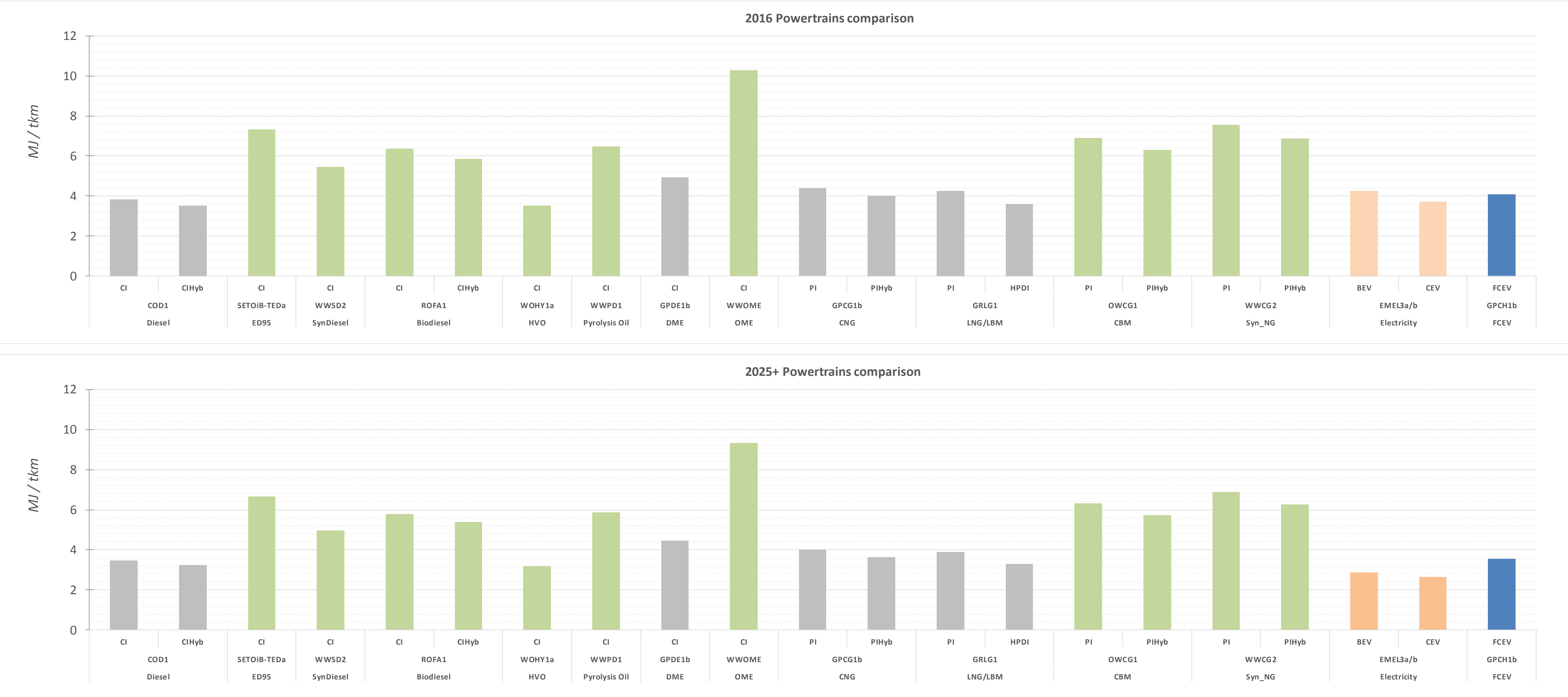


Figure 47. WTW powertrain comparison - energy expended



Conclusions:

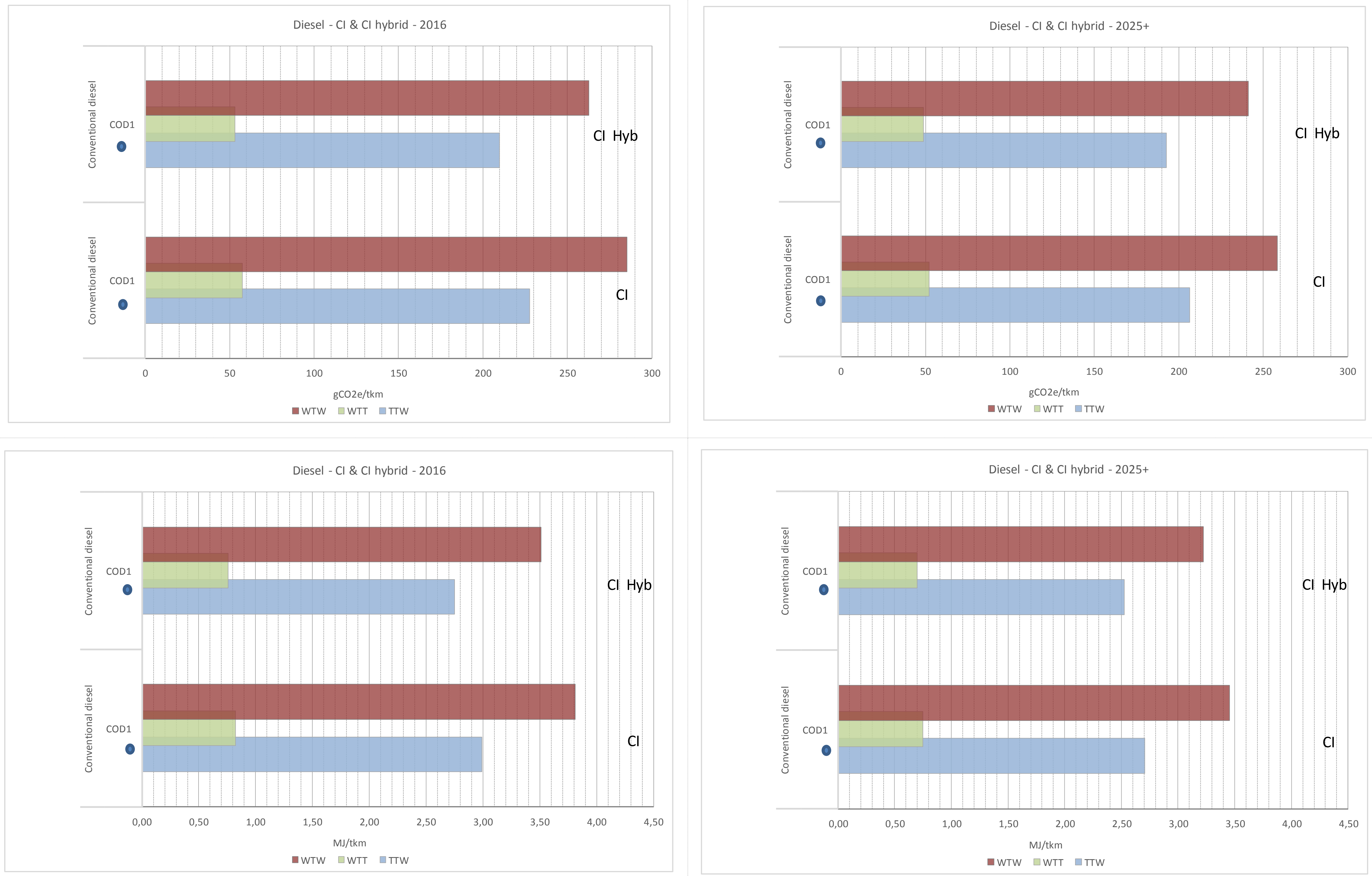
- Generally speaking, the hybridization of ICEs offers an effective option to reduce fuel consumption, up to ~8%
- Regarding diesel-like alternatives, the selected fuel pathways offer routes to lower the GHG emissions of conventional CI in 2016 from ~50% up to 85% (bio and synthetic diesel pathways).
- HPDI offers energy savings of about 20% compared to diesel CI engines leading to about up to 11% lower GHG emissions in 2016 and up to 13% lower GHG emissions in 2025+ compared to SI engines with the same fuel.
- The xEVs technology is expected to improve significantly towards 2025+. This effect, together with the decarbonisation of the electricity could trigger a relevant GHG reductions (when, as a proxy, the theoretical EU mix is used, reductions up to 40% versus the equivalent 2016 technology can be observed. However, as mentioned several times in this document, the real impact of the road electrification is country specific and out of the scope of the JEC analysis).
- From all combinations of fuel/energy carriers and powertrains explored in this WTW report, the HVO pathway with the CI technology (waste as feedstock) and the use of CBM in a PI hybrid represent the lowest GHG intensive routes.

4.2 WTW integration. Detailed results

4.2.1 Internal combustion engines (ICE) & Liquid fuels

4.2.1.1 Conventional Diesel

Figure 48. Conventional (fossil based) diesel - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm)



Conventional **diesel** (100% fossil) in CI technologies is expected to be subjected to improvements in term of efficiency.

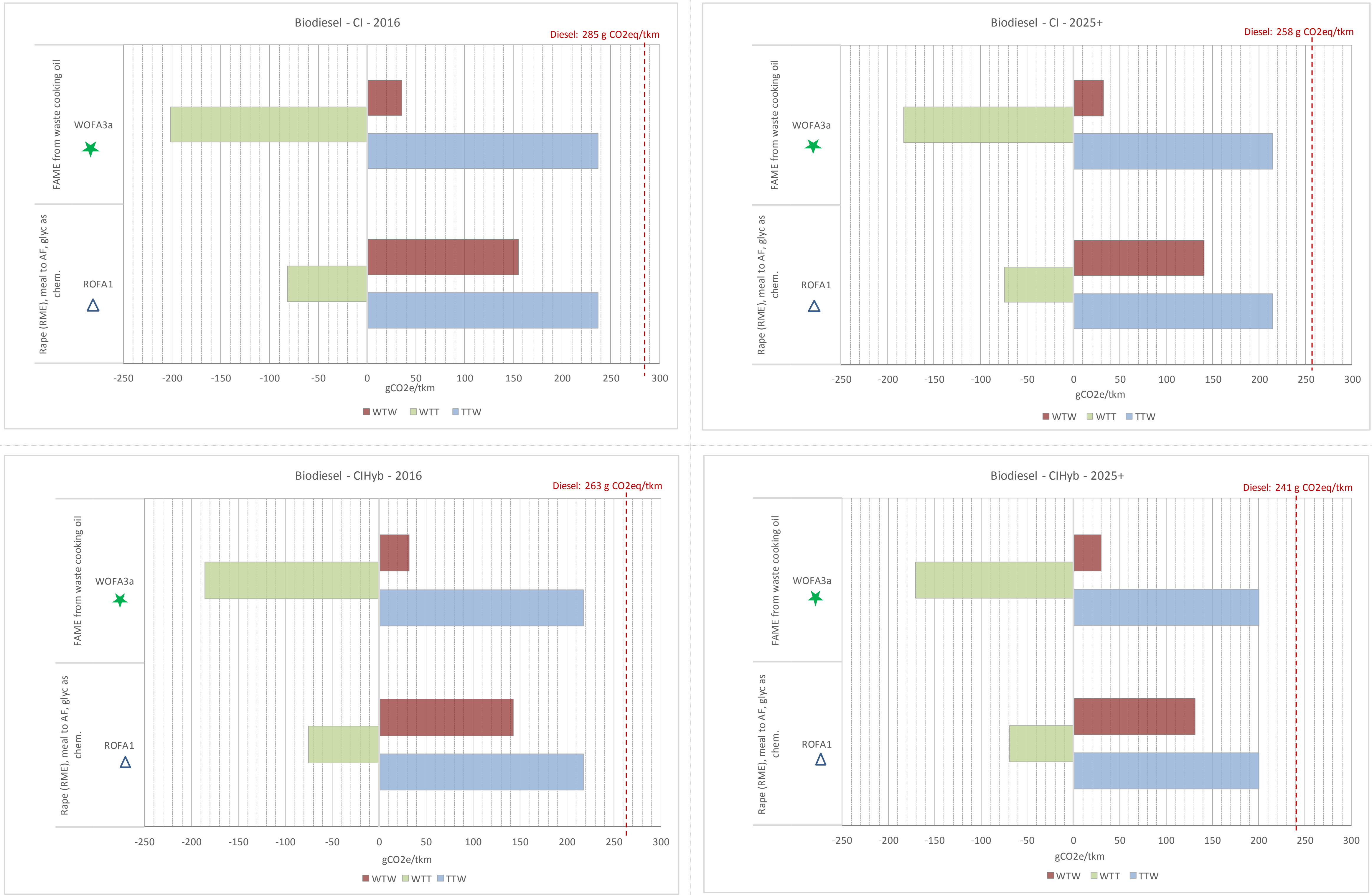
The consumption figures for 2025+ are lower than the 2016 ones, and further reductions are expected by hybridisation.

Compared to 2016 the WTW GHG emissions for non-hybridised CI engines decreases at about 9% in 2025+. Hybridisation leads to a decrease of GHG emissions of about 8% in 2016 and about 7% in 2025+ compared to the non-hybridised CI engine.

Compared to 2016 the WTW energy use for non-hybridised CI engines decreases at about 9% in 2025+. Hybridisation leads to a decrease of WTW energy use of about 8% in 2016 and about 7% in 2025+compared to the non-hybridised CI engine.

4.2.1.2 *Biodiesel*

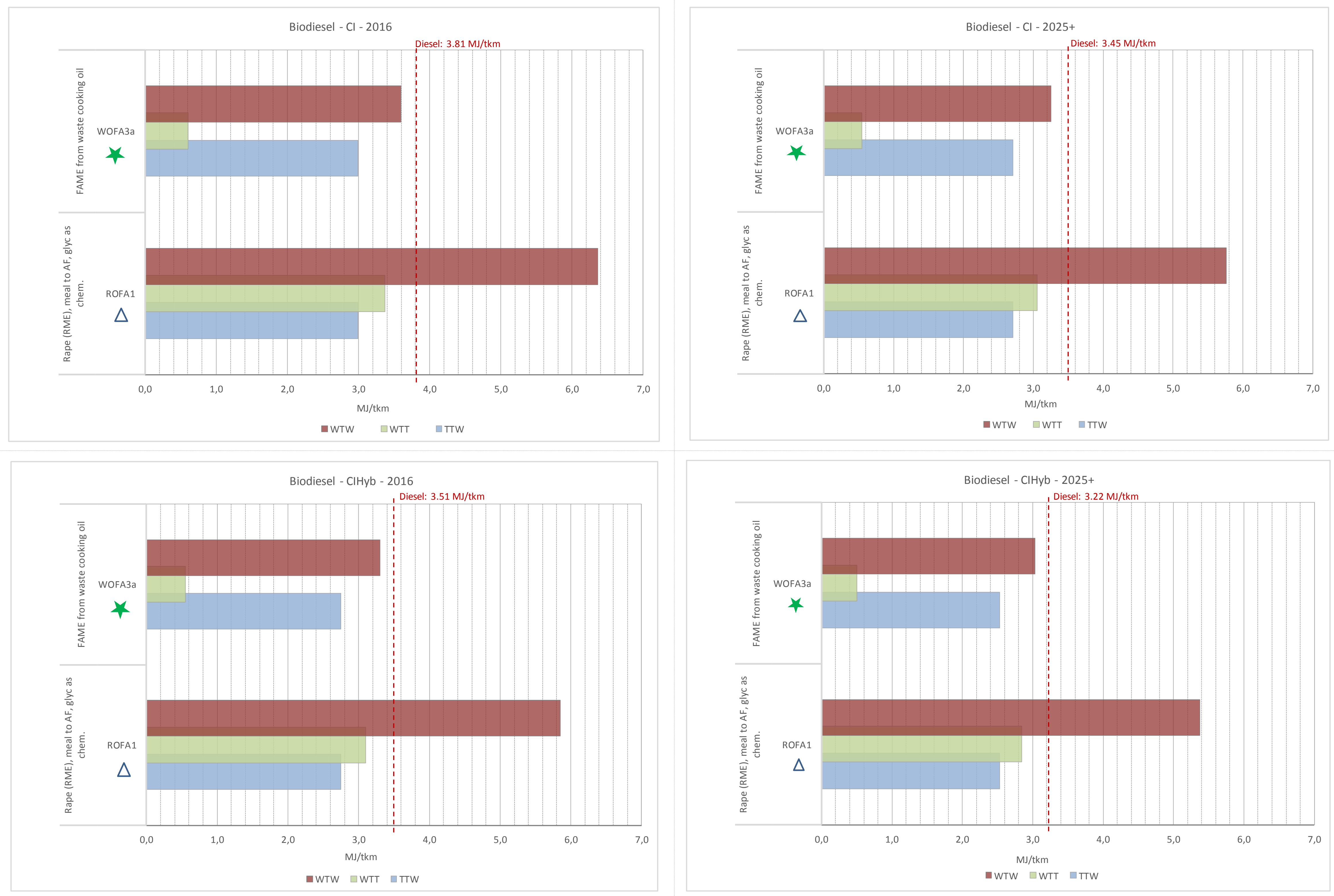
Figure 49. Biodiesel - GHG emissions (CO_{2eq}/t km)



Biodiesel is manly produced by lipid feedstock. The potential GHG saving offered by the use of biodiesel are strongly linked to the nature of the feedstock.

As for the ethanol case, interesting GHG savings can be achieved using residues and wastes, as waste cooking oil.

Figure 50. Biodiesel – Energy expended (MJ/tkm)



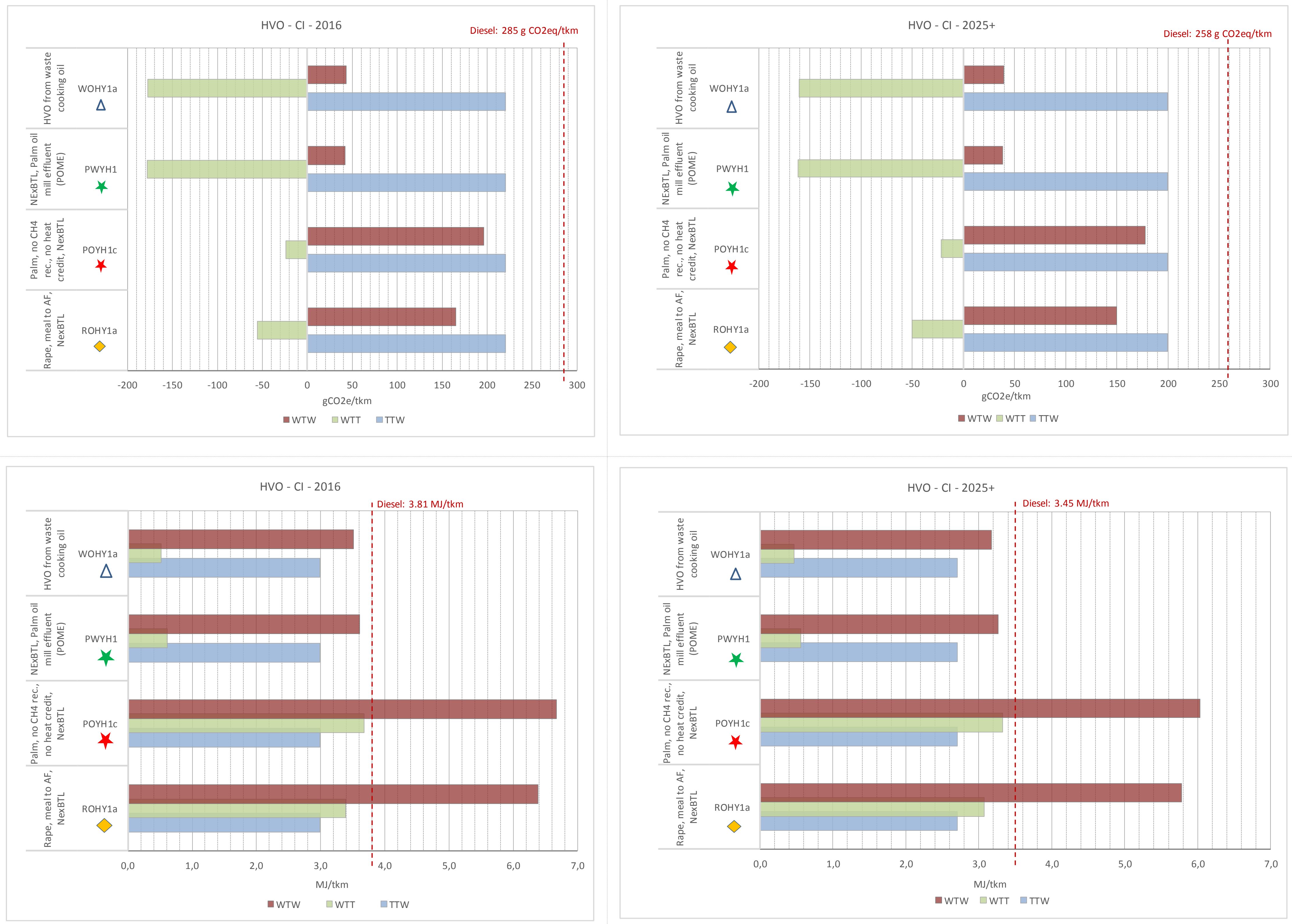
In case of biodiesel from waste cooking oil the WTW energy use is slightly lower than that for conventional diesel (100% fossil). For biodiesel from rapeseed the WTW energy use is higher.

However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

Hybridisation leads to a decrease of WTW energy use of about 7 to 8%.

4.2.1.3 HVO

Figure 51. HVO – GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm)



As the feedstock used for **HVO** production are mainly the same of the biodiesel, the potential GHG saving strongly linked to the nature of them.

High GHG savings can be achieved using residues and wastes, as waste cooking oil.

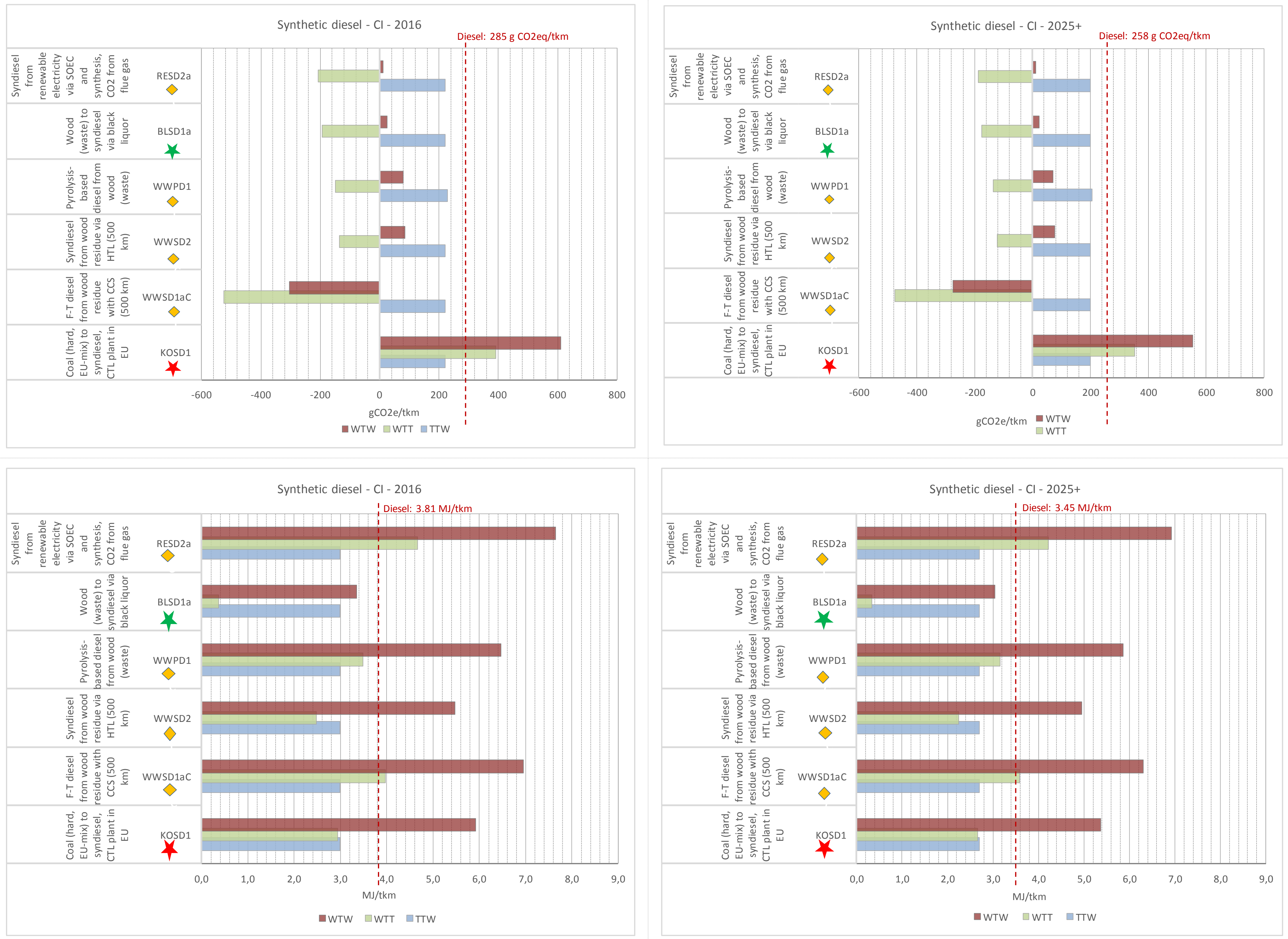
HVO from waste cooking oil (pathway WOHY1a) and residual oil from palm oil mill effluent (pathway PWYH1) leads to lower WTW energy used than conventional diesel used in CI engines.

For HVO from palm oil and rapeseed the energy use is higher than that for conventional diesel used in CI engines.

However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

4.2.1.4 *Synthetic Diesel*

Figure 52. Synthetic diesel - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm)



Being a mix of molecules, which results very similar to regular fossil derived product, **synthetic diesel** offers the advantage of being easily usable in standard infrastructures, and power trains.

GHG performances of synthetic diesel production and use are mainly determined by the primary source of energy used for its production.

When produced from coal, synthetic diesel does not offer any advantages, if compare d with regular fossil diesel

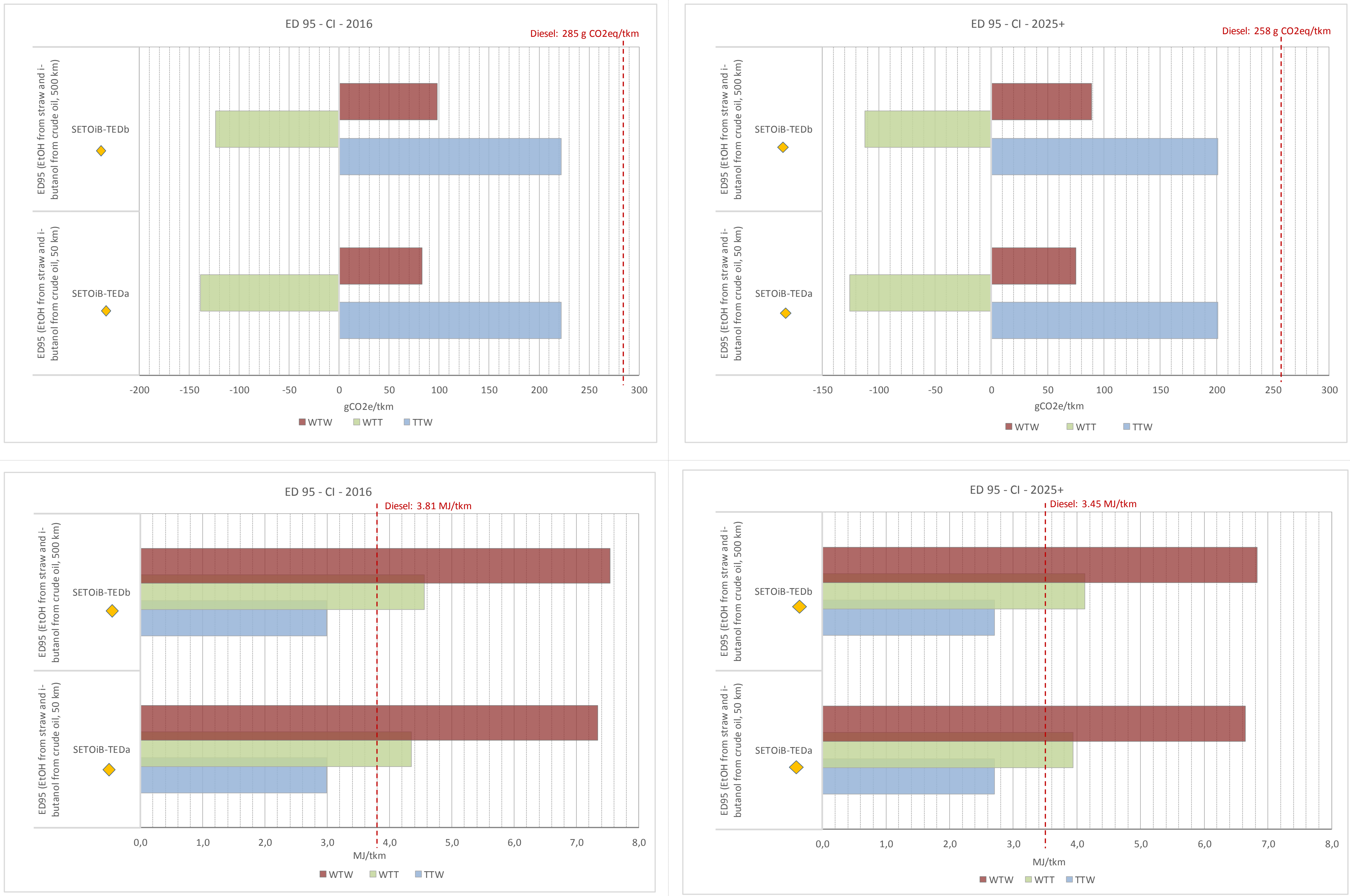
Benefits can be achieved through FT conversion process, using residual feedstock, such as waste wood, black liquor, pyrolysis oil derived from wood waste, or via power-to-liquid using renewable electricity. In these cases, the potential saving offered by using synthetic diesel can be remarkable.

Synthetic diesel from renewable energy sources except black liquor leads to higher WTW energy use than conventional diesel (100% fossil). However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

Synthetic diesel from coal also leads to higher WTW energy use (increase of about 56%) and simultaneously higher GHG emissions (more than two times higher) than conventional diesel due to the high carbon content of the coal.

4.2.1.5 ED95

Figure 53. ED95 - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm)



ED95 consists of a mixture of ethanol (95% by volume), polyethylene glycol (PEG), MTBE, iso-butanol, and lubricants.

Depending on the transport distance of the straw used for ethanol production the GHG emissions decrease with about 66 to 71% compared to conventional diesel (100% fossil).

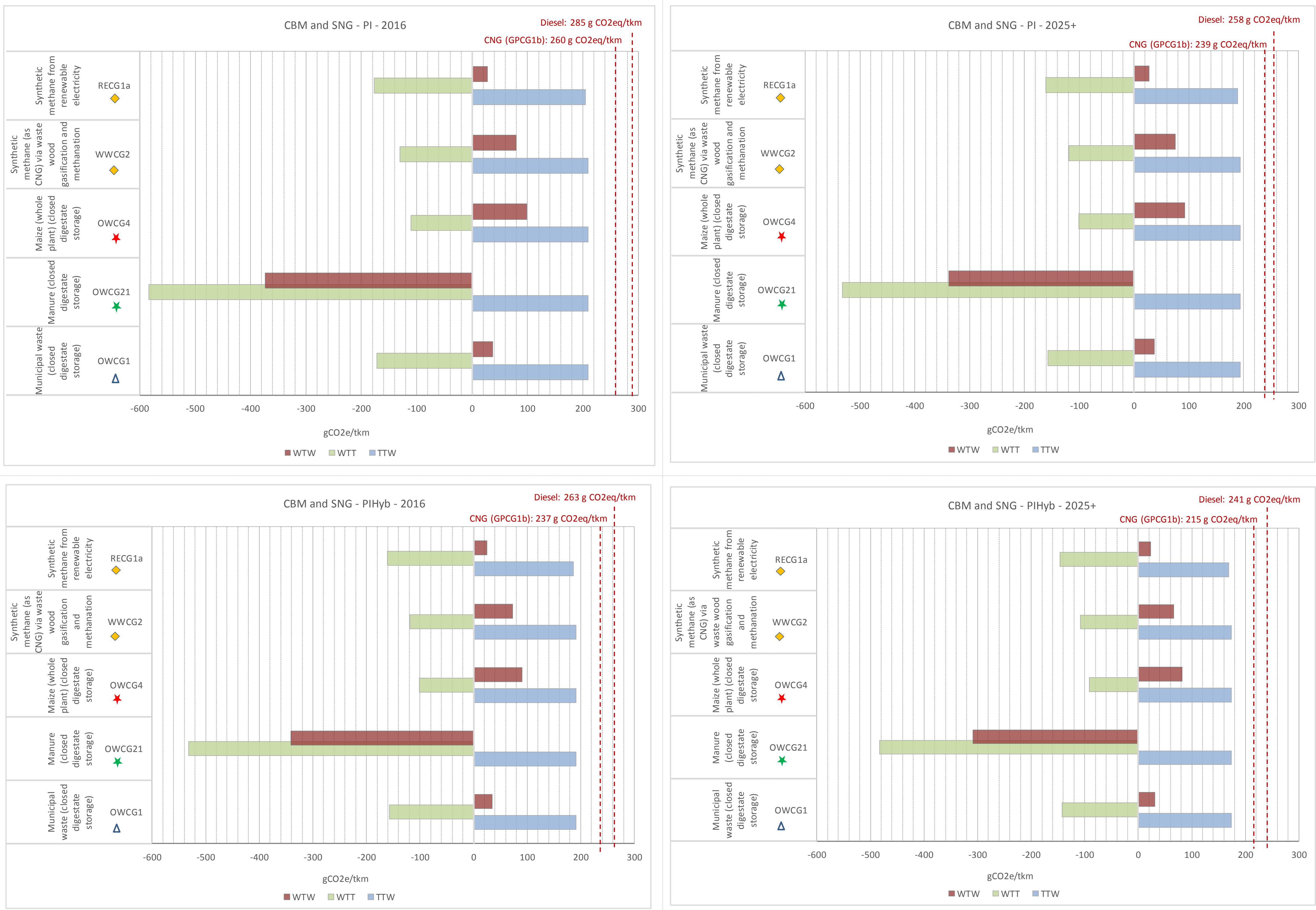
The WTW energy use of biomass derived fuels is generally higher than that for conventional diesel. The WTW energy use for ED95 combined with HDV with CI engines and from lignocellulosic ethanol from straw is about two times of that of conventional diesel used in CI engines.

However, since mainly carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

4.2.2 Internal combustion engines (ICE) & Gaseous fuels

4.2.2.1 Compressed biomethane (CBM) and synthetic natural gas (SNG)

Figure 54. CBM and SNG - GHG emissions (CO_{2eq}/t km)

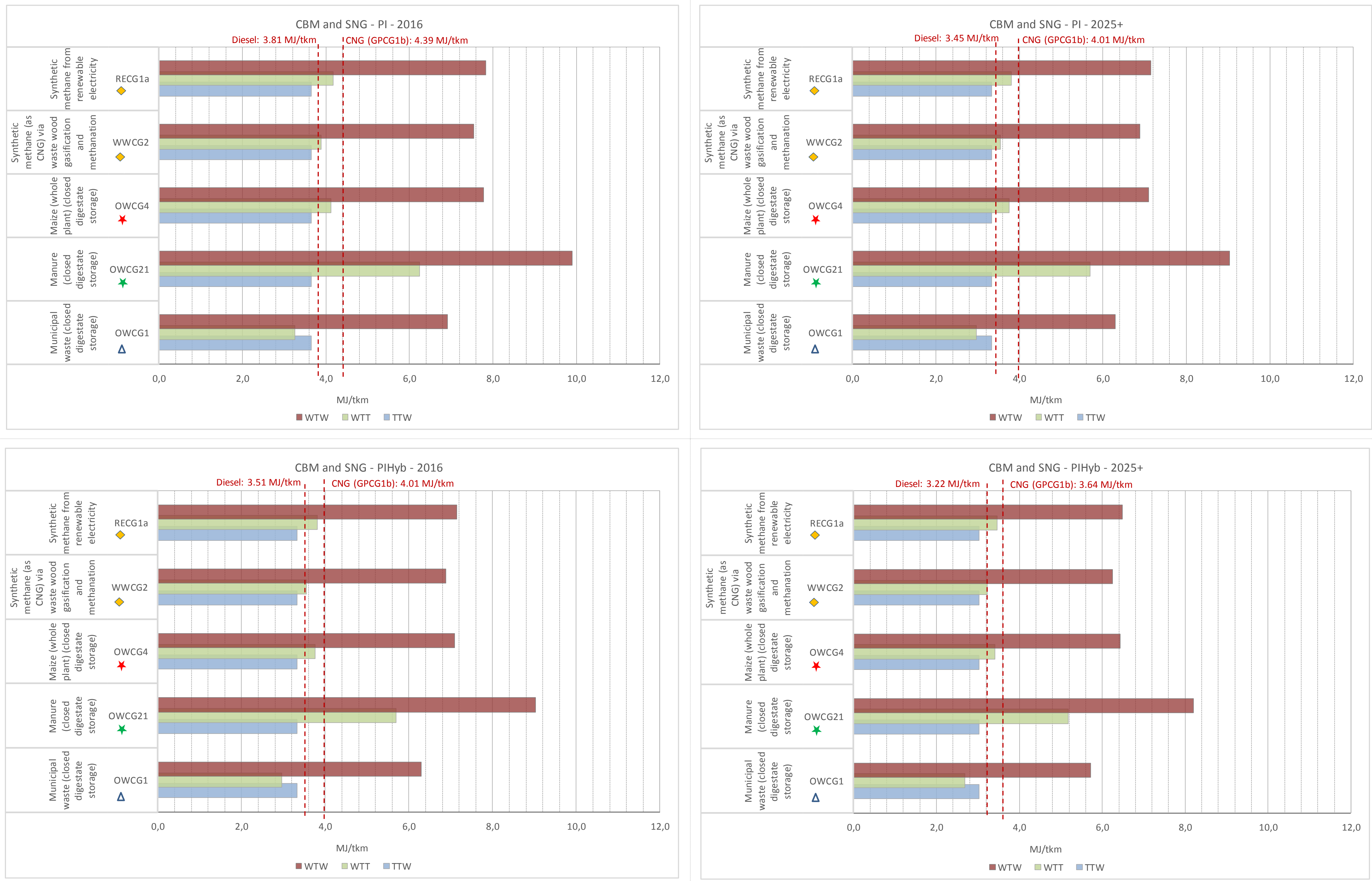


Considering the GHG saving potential, **gaseous fuels** offer significant advantages, with respect to fossil derived fuels.

The main advantages are related to the WTT part, as credit for the avoided CH_4 emissions from manure that allows for negative values due to the replacement of untreated manure storage.

It has to be noted that the negative GHG emissions for biomethane from manure only can be taken into account as long as there are farms where storage of untreated manure is applied.

Figure 55. CBM and SNG – Energy expended (MJ/tkm)

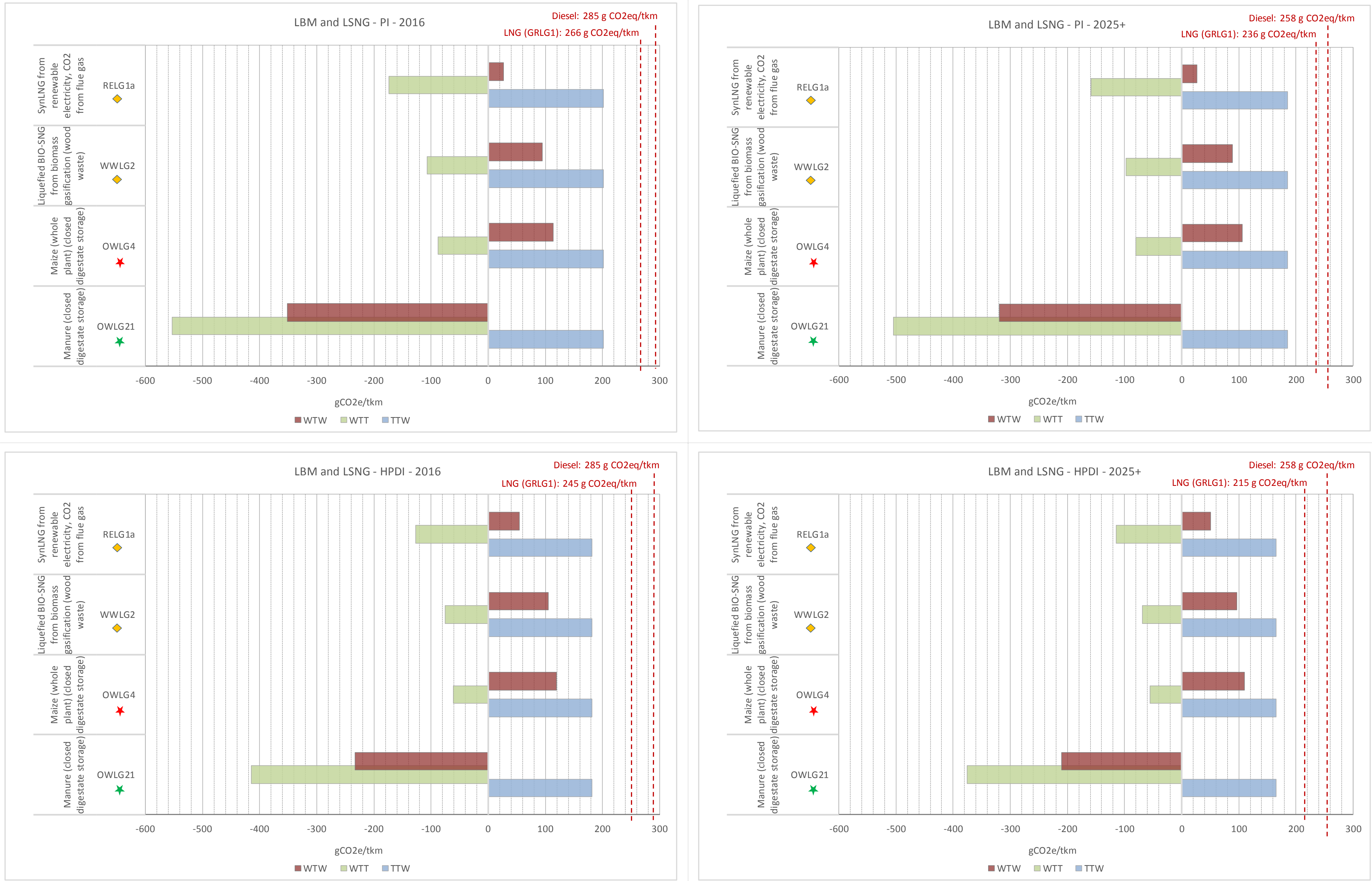


Generally, energy intensity is not a good measure for GHG emissions, as the latter depend on the carbon intensity of the specific feedstock. E.g. the conversion of renewable electricity to synthetic diesel via power-to-liquid and its use as transportation fuel leads to a high WTW energy use although the WTW GHG emissions are low.

Hybridisation of PI engines leads to a decrease of WTW energy ue of about 9% compared to non-hybridised PI engines.

4.2.2.2 *Liquefied biomethane (LBM) and liquefied synthetic natural gas (LSNG)*

Figure 56. LBM and LSNG - GHG emissions (CO_{2eq}/t km)

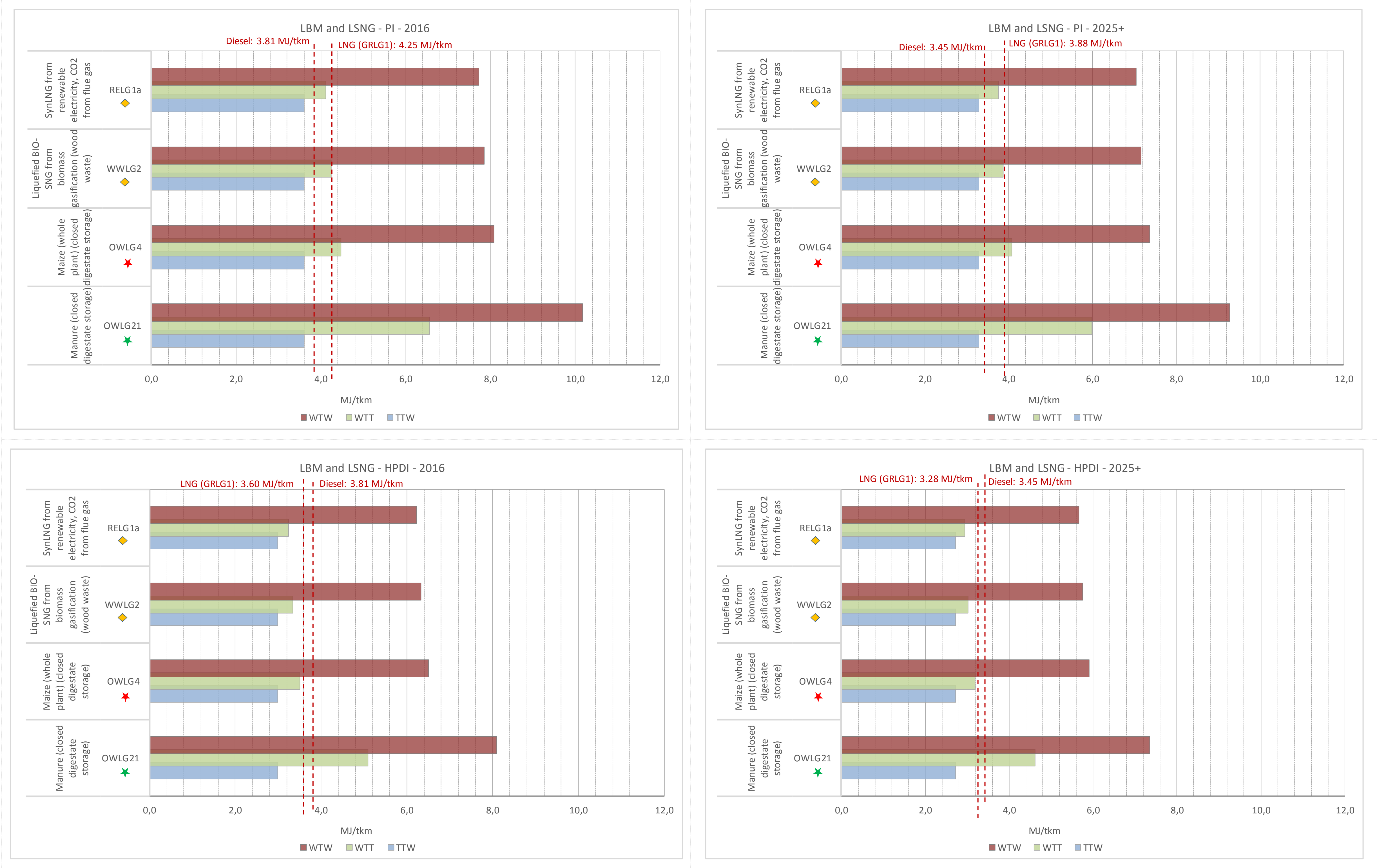


From a TTW perspective, the introduction of high-pressure direct injection (HPDI) engines is expected to lead to significant improvements.

From a WTW perspective, high pressure direct injection (HPDI) engines combined with liquefied biomethane (LBM) and liquefied synthetic natural gas (LSNG) may lead to a very minor advantage compared to traditional engines. The reason is the share of fossil diesel required for ignition.

From a TTW perspective the high-pressure direct injection (HPDI) engines lead to significant improvements (up to 20% reduction of GHG emissions compared to non - hybrid diesel engines). Compared to SI gas engines the GHG savings amount to about 11%. From a WTW perspective, HPDI engines operated with liquefied biomethane (LBM) or liquefied synthetic natural gas (LSNG) may lead to a minor advantage compared to traditional engines.

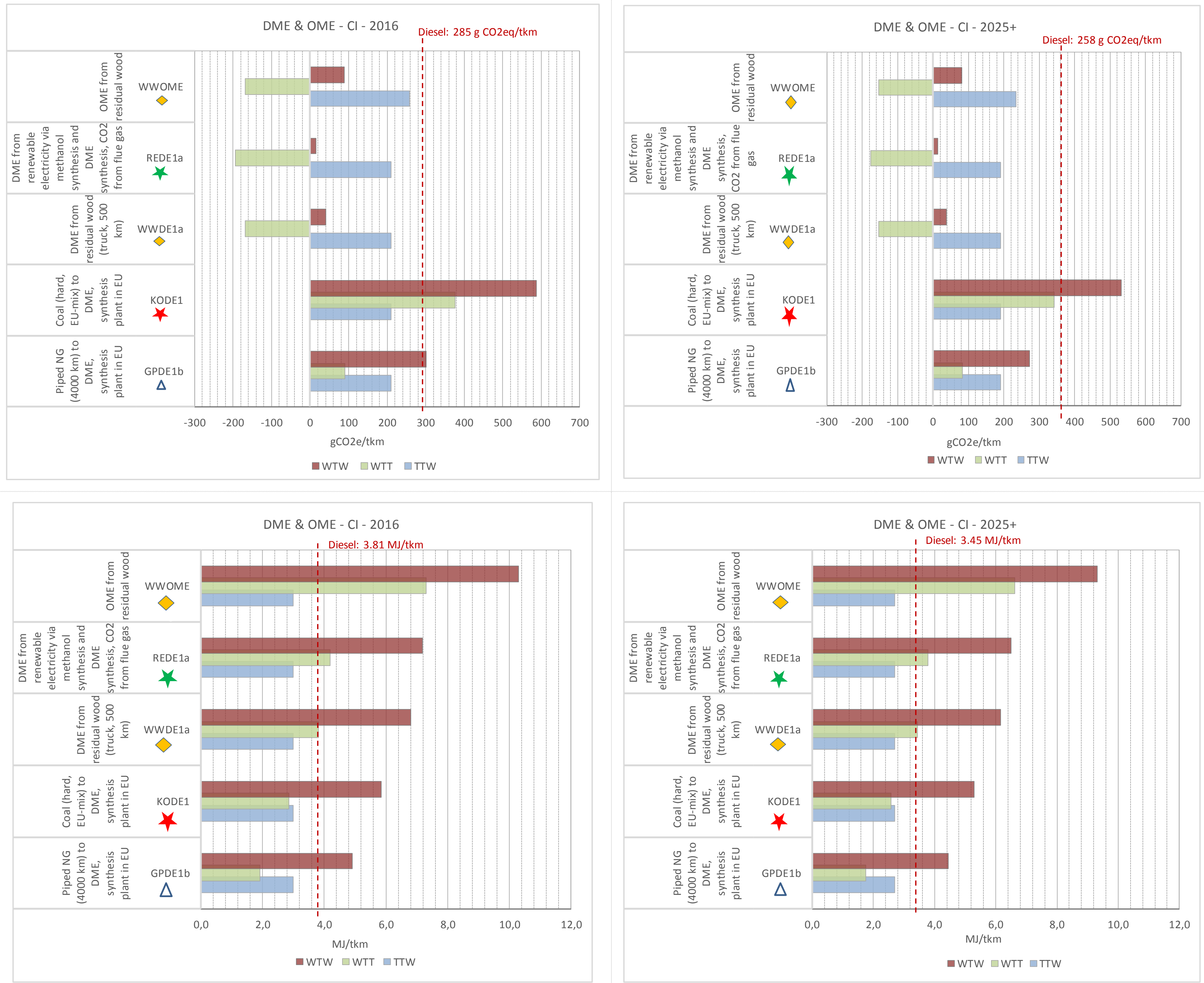
Figure 57. LBM and LSNG – Energy expended (MJ/tkm)



The introduction of HPDI engines lowers the WTW energy use compared to traditional engines (Energy consumption decreased at about 20% (See detailed comment in previous page)

4.2.2.3 DME and OME

Figure 58. DME and OME - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm)



GHG performances of DME and OME production and use are mainly determined by the primary source of energy used for its production.

When produced from coal, DME does not offer any advantages, if compare d with regular fossil diesel

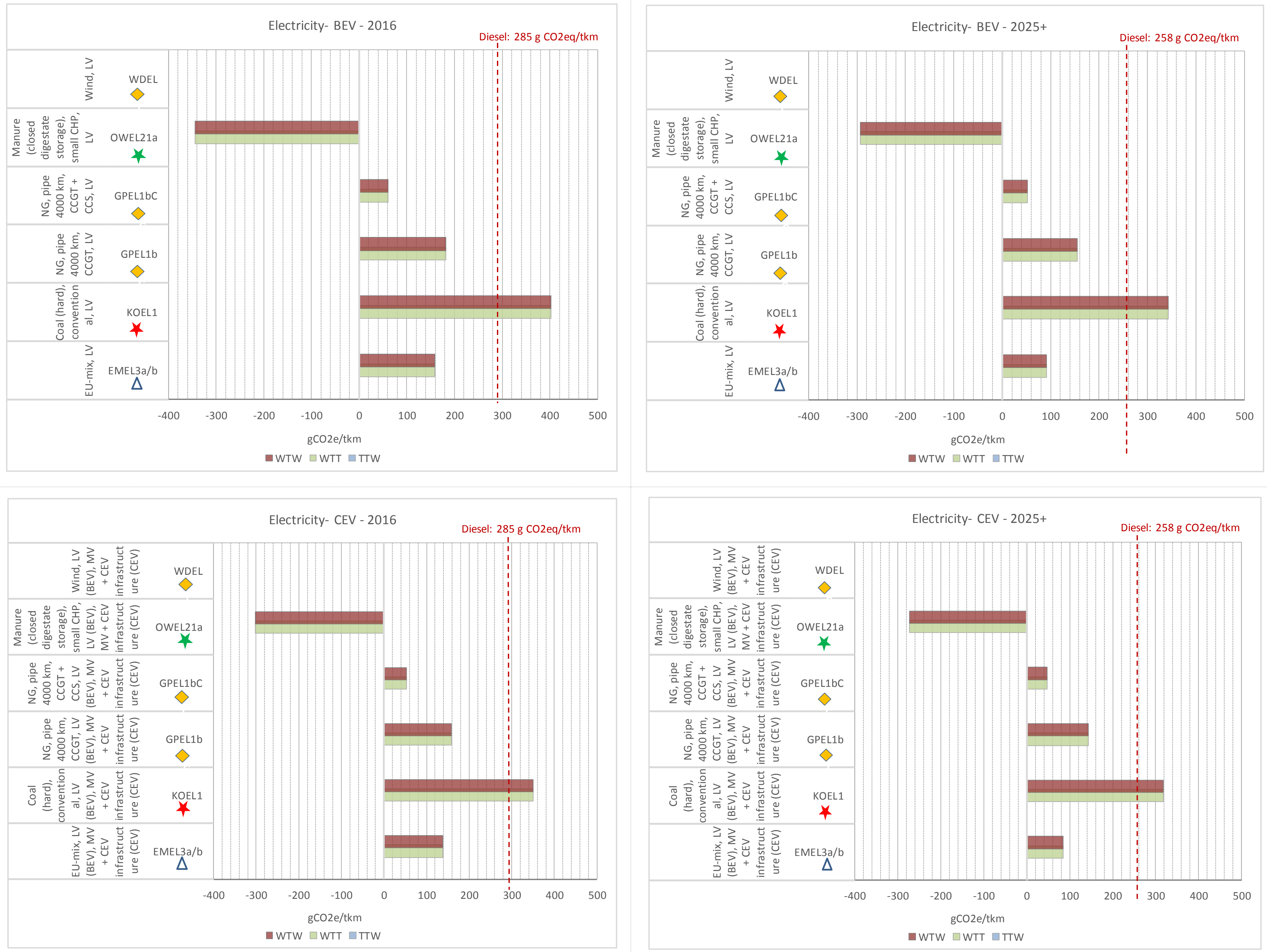
Benefits can be achieved using residual feedstock, such as: waste wood or via power-to-DME using renewable electricity. In these cases, the potential saving offered by using DME and OME can be remarkable. The GHG emissions from the supply of OME from waste wood are significantly higher than those for DME from waste wood due to the lower efficiency of OME production compared to DME production

The WTW energy use for OME from residual wood is 2.7 times higher than that for conventional diesel (100% fossil) and 1.5 times of that for DME from residual wood.

DME from coal leads to an increase of WTW energy use of about 54% compared to conventional diesel. DME from natural gas leads to an increase of WTW energy use of about 30% compared to conventional diesel.

4.2.3 Electricity driven powertrains – Battery Electric Vehicles (BEV) & Catenary Electric Vehicles (CEV)

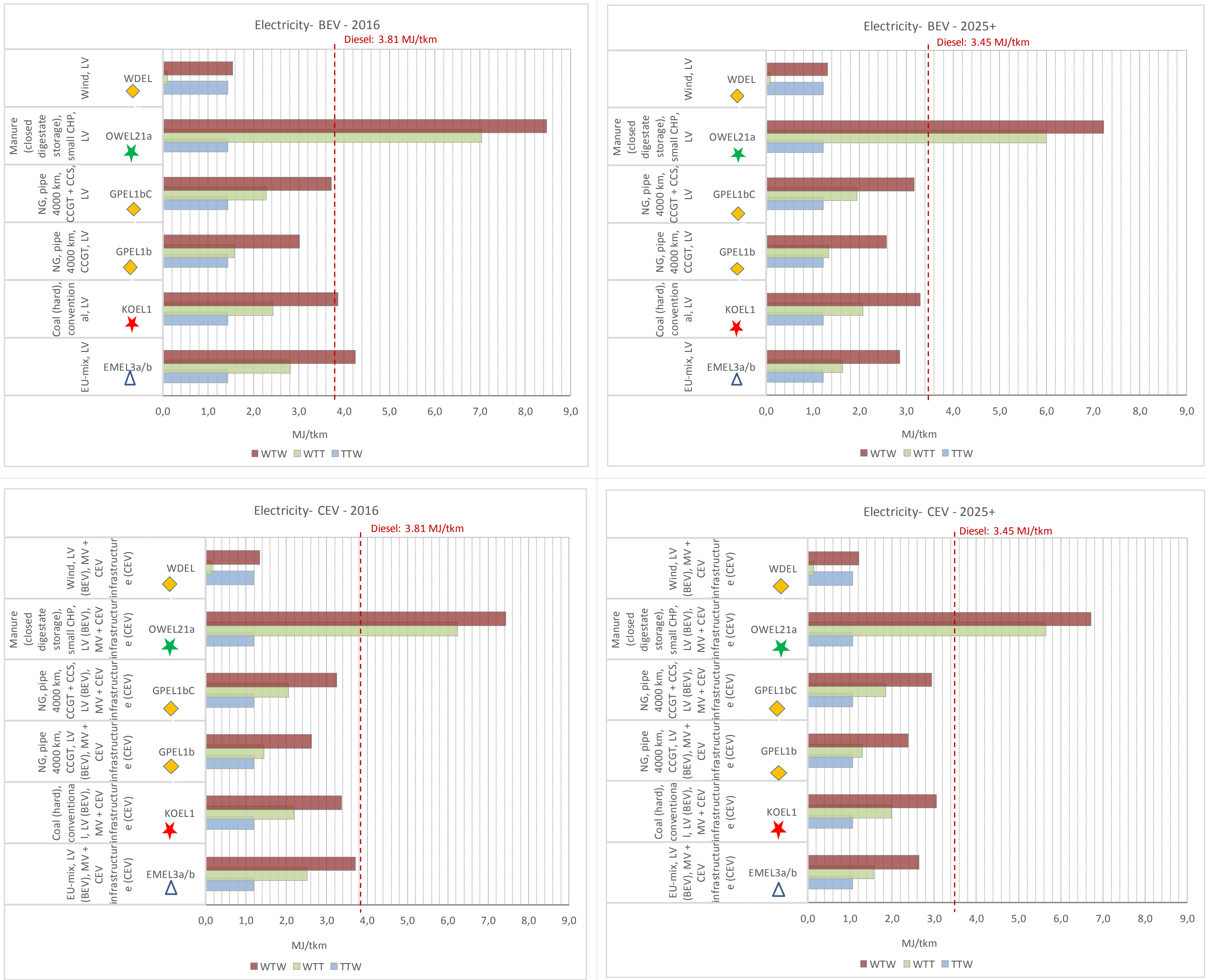
Figure 59. BEV & CEV - GHG emissions (CO2eq/t km)



Except in case of coal electricity, battery electric vehicles (BEV) and catenary electric vehicles (CEV) show lower GHG emissions for the selected electricity pathways than a similar HDV with CI engine fueled with conventional, crude oil-based diesel.

CEV are mainly operated at catenary mode and partly at battery (BEV) mode

Figure 60. BEV & CEV[19] - Energy expended (MJ/tkm)



For **2016** the WTW energy use for BEV combined with electricity from wind power and natural gas CCGT without CCS and with CCS is lower than that for conventional diesel used in CI engines.

For time horizon **2025+** the WTW energy use for BEV combined with the selected pathways except electricity from biogas from manure is lower than that for conventional diesel used in CI engines.

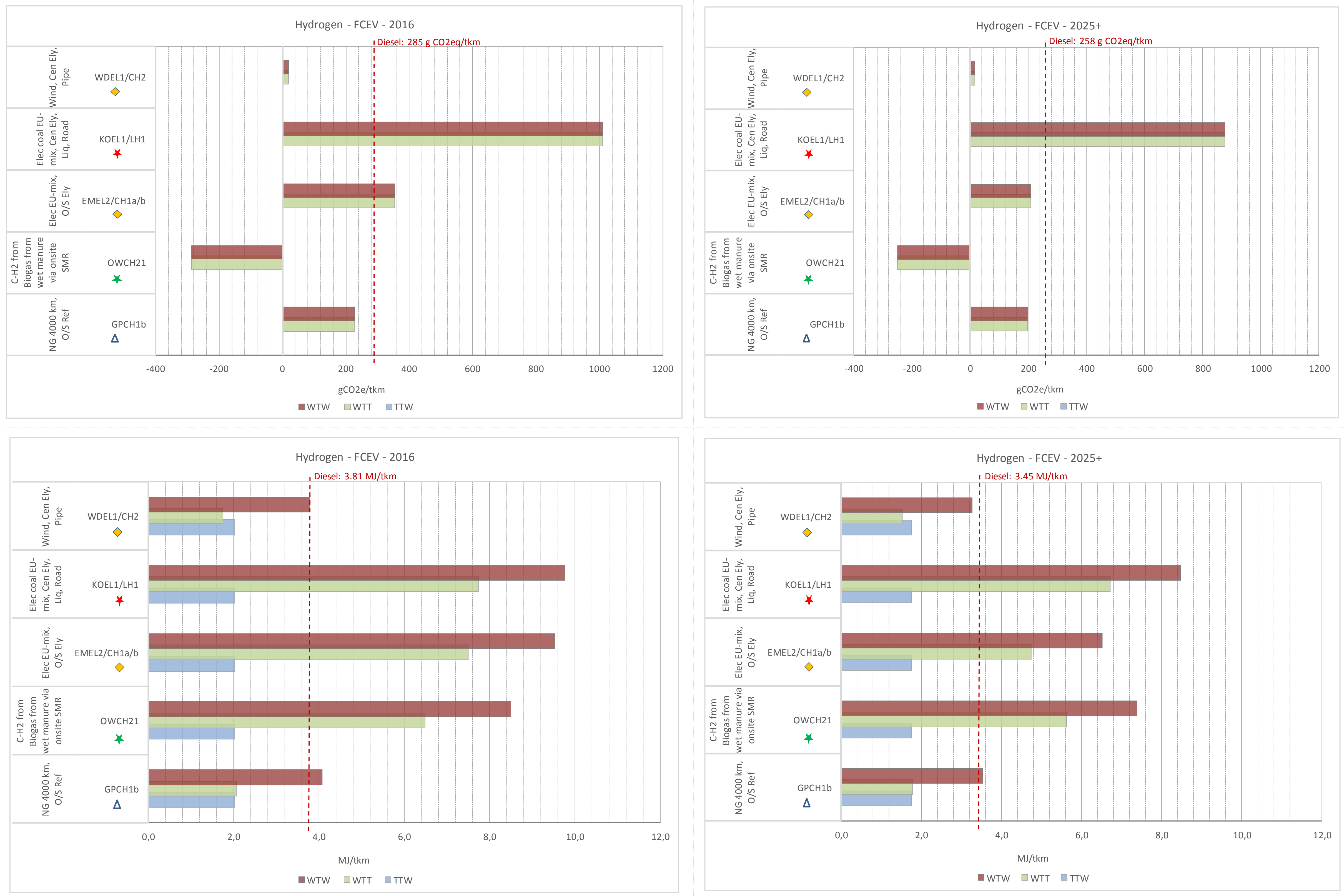
The reason for the high energy use is the low efficiency for the conversion of wet manure to biogas. In the fermenter about 46% of the dry matter LHV of the manure is recovered in the biogas. The auxiliary electricity for the fermenter is supplied by the downstream gas engine. The efficiency of the gas engine is 40%. As a result, the overall energy efficiency for the conversion of wet manure to electricity is about 18%.

For **2016** and for time horizon **2025+** the WTW energy use for CEV combined with the selected pathways, with the exception of electricity from biogas from manure, is lower than that for conventional diesel used in CI engines.

[19] Note that ~10% of additional losses in the overhead infrastructure would need to be considered (as a proxy). Currently not included in the JEC TTW v5 report.

4.2.4 Fuel Cell Hydrogen Vehicles (FCEV)

Figure 61. Hydrogen FCEV - GHG emissions (CO2eq/t km) and Energy expended (MJ/tkm)



In 2016 FCEV shows higher GHG emissions than conventional diesel ICE. This is because hydrogen is assumed to be produced from EU mix electricity, via electrolysis, and from coal-based electricity. In 2025+ FCEV shows lower GHG emissions than the conventional diesel ICE, according to the expected change in EU electricity mix.

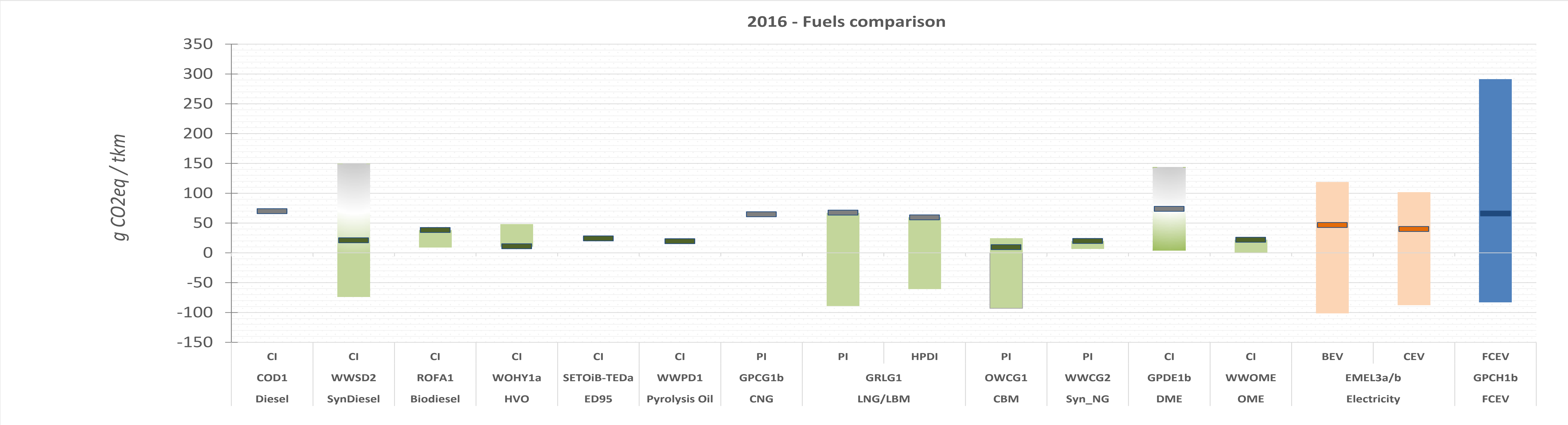
The WTW energy use for FCEV combined with the selected pathways is higher than that for conventional diesel used in CI engines.

If carbon neutral feedstocks are used (e.g. hydrogen from electricity from wind power and hydrogen from biogas steam reforming), the expended energy is not necessarily a good indicator for the environmental footprint of a fuel/drivetrain combination.

5 Heavy Duty – Type 5

5.1 WTW integration. Comparative Analysis

Figure 62. WTW fuel comparison - GHG emissions



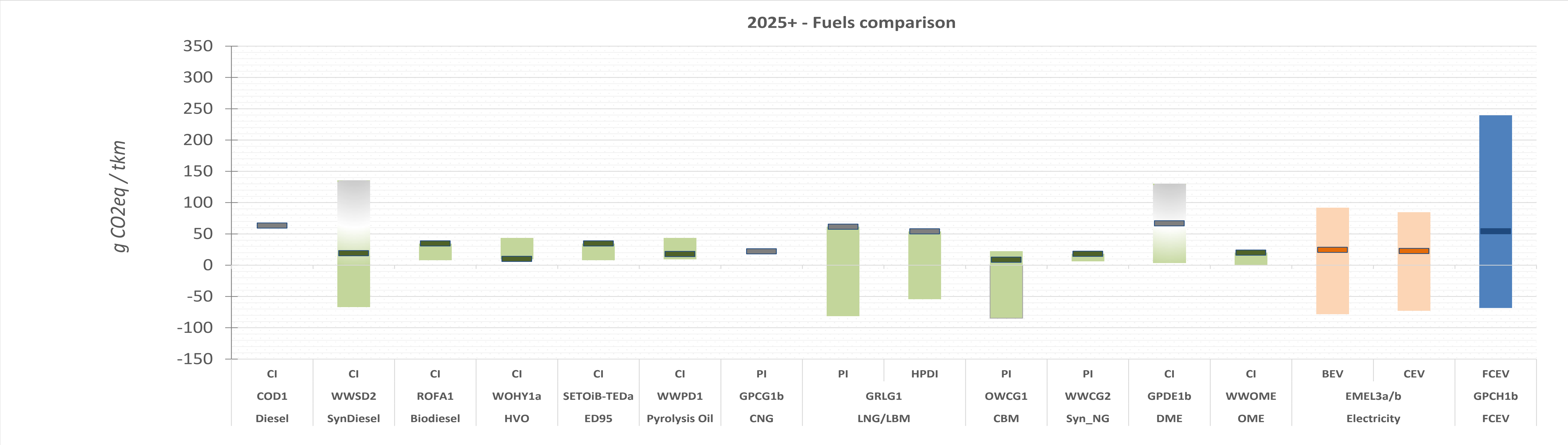
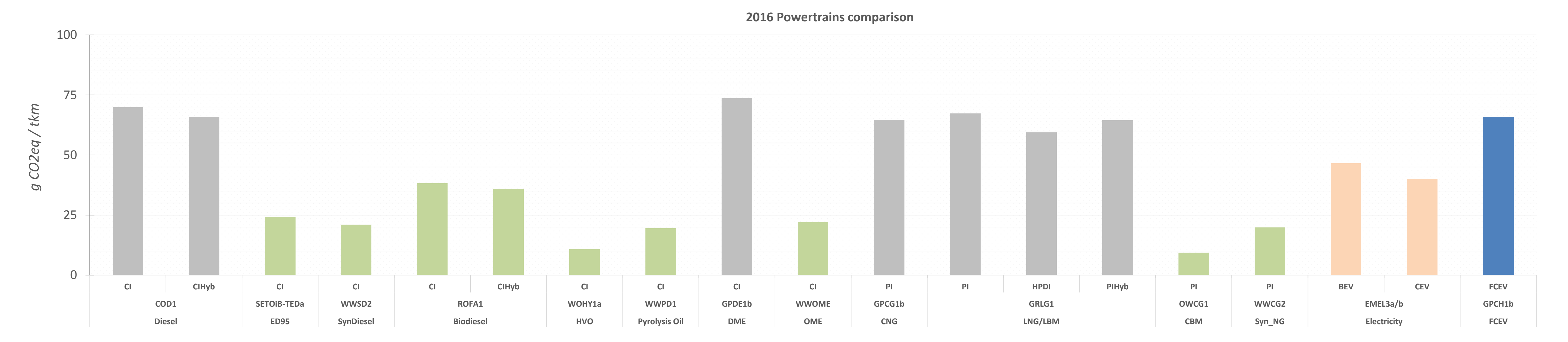


Figure 63. WTW fuel comparison - energy expended

Note. The charts above include selected pathways modelled for the JEC WTW v5 integration (not representing all possible WTW fuel and powertrain combinations following the criteria explained in section 2.5.2). Additional promising low-CO_2 intensive pathways, not available at commercial scale yet (Technology Readiness Level < 6), have not been included in this WTW comparison but all detailed data are available in the JEC WTT v5 report for the reader to conduct their own in-depth assessment.

Figure 64. WTW powertrain comparison – GHG emissions



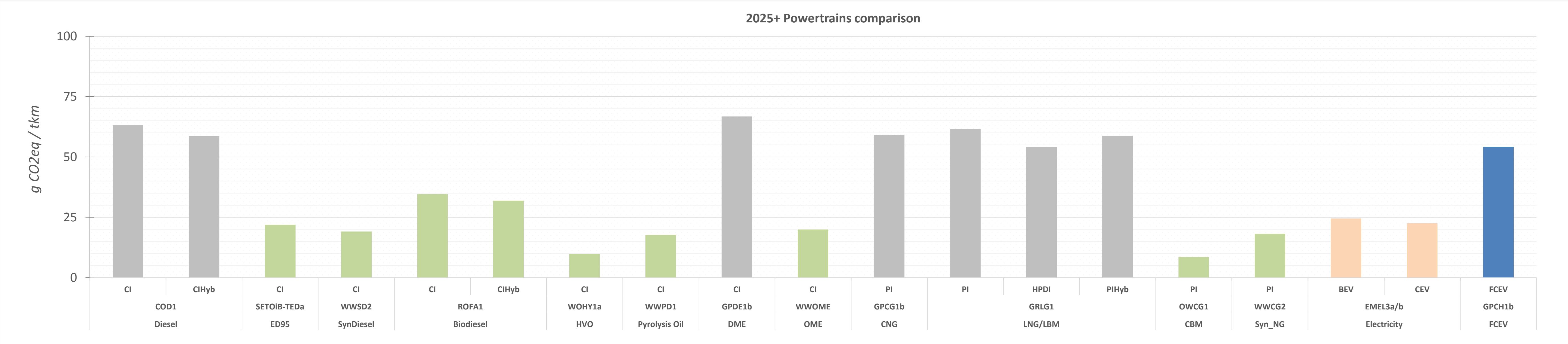
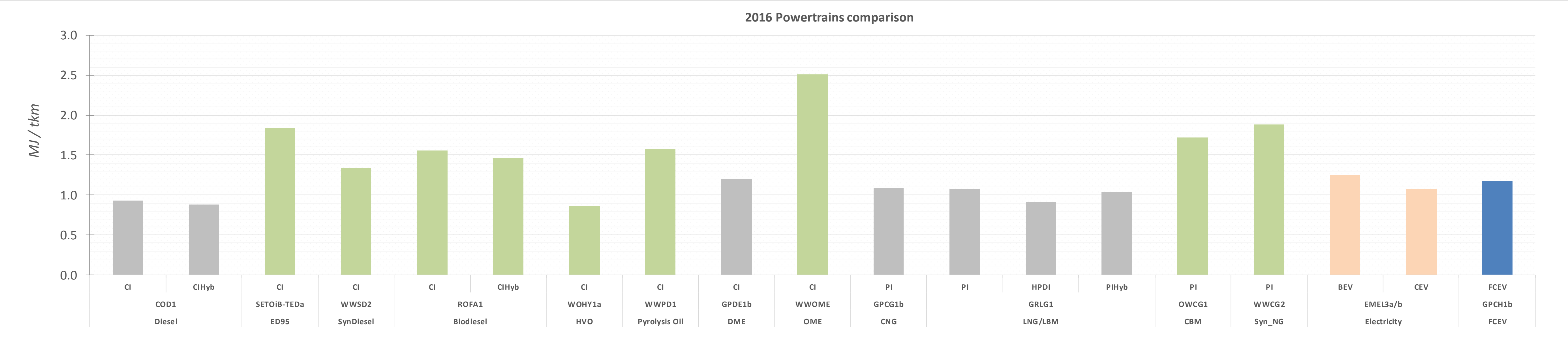
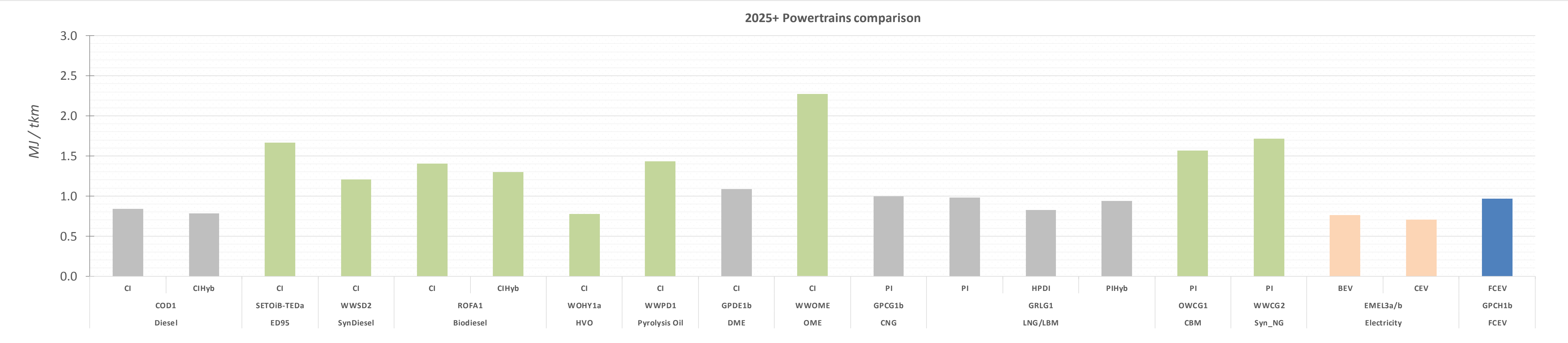


Figure 65. WTW powertrain comparison - energy expended





Conclusions:

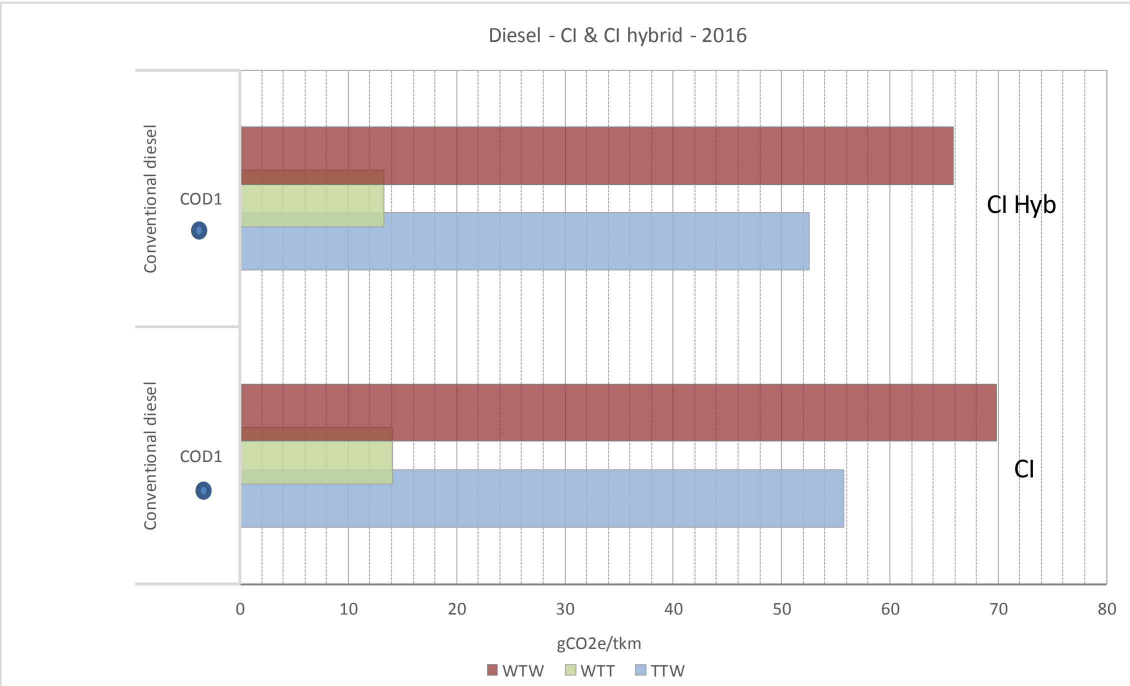
- Generally speaking, the hybridisation of ICEs offers an effective option to reduce fuel consumption, up to ~7%
- Regarding **diesel**-like alternatives, the selected fuel pathways offer routes to lower the GHG emissions of conventional CI in 2016 from ~50% up to 85% (bio and synthetic diesel pathways).
- HPDI offers energy savings of about 20% compared to SI engines leading to about up to 12% lower GHG emissions in 2016 and in 2025+ compared to SI engines with the same fuel.
- The xEVs technology is expected to improve significantly towards 2025+ and although the EU electricity mix is presented here as theoretical proxy, the real impact can only be analysed at country level (out of the scope of the JEC analysis).
- From all combinations of fuel/energy carriers and powertrains explored in this WTW report, the HVO pathway with the CI technology (waste as feedstock) and the use of CBM in a PI hybrid represent the lowest GHG intensive routes.

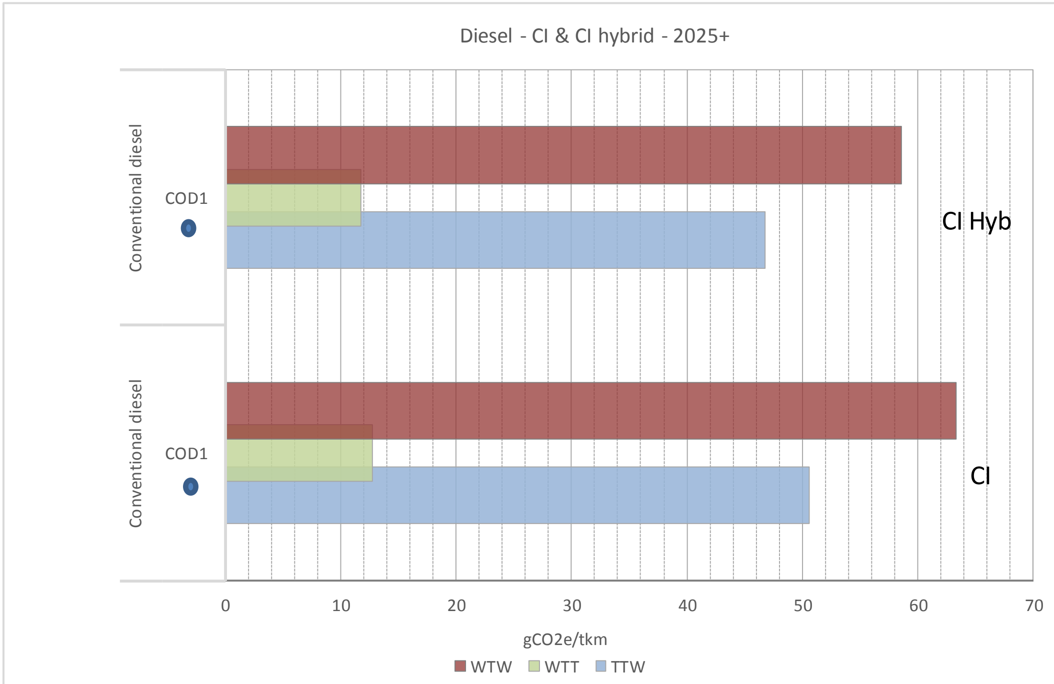
5.2 WTW integration. Detailed results

5.2.1 Internal combustion engines (ICE) & Liquid fuels

5.2.1.1 Conventional Diesel

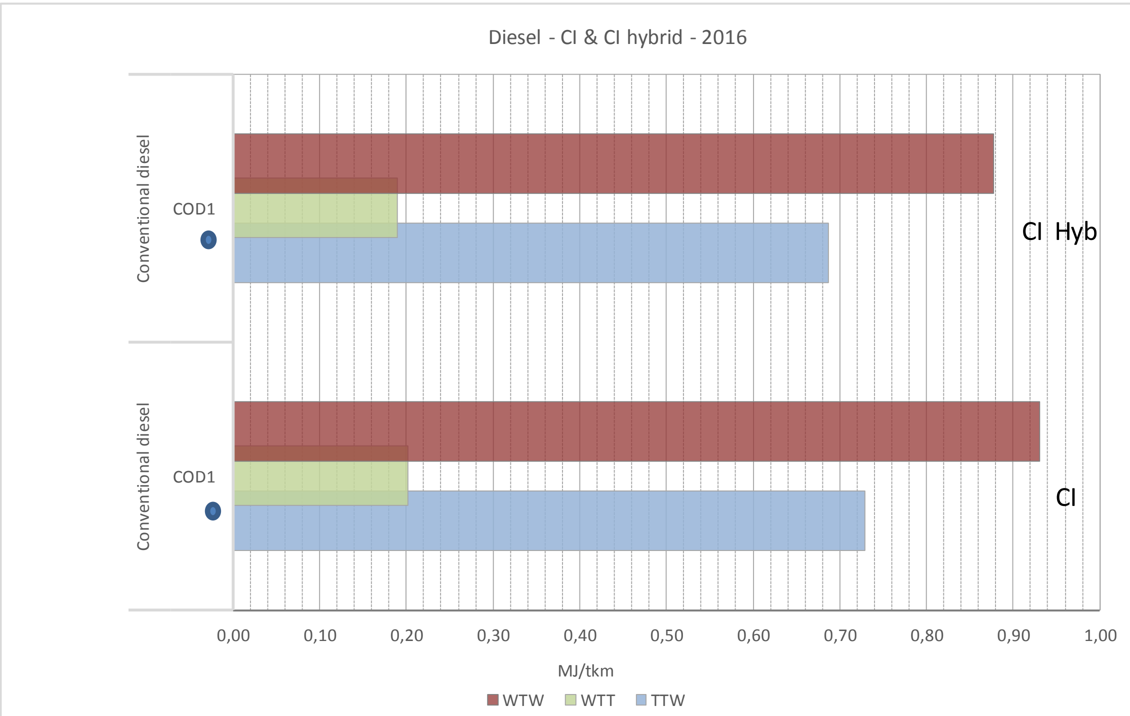
Figure 66. Conventional (fossil based) diesel - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm) – Type 5

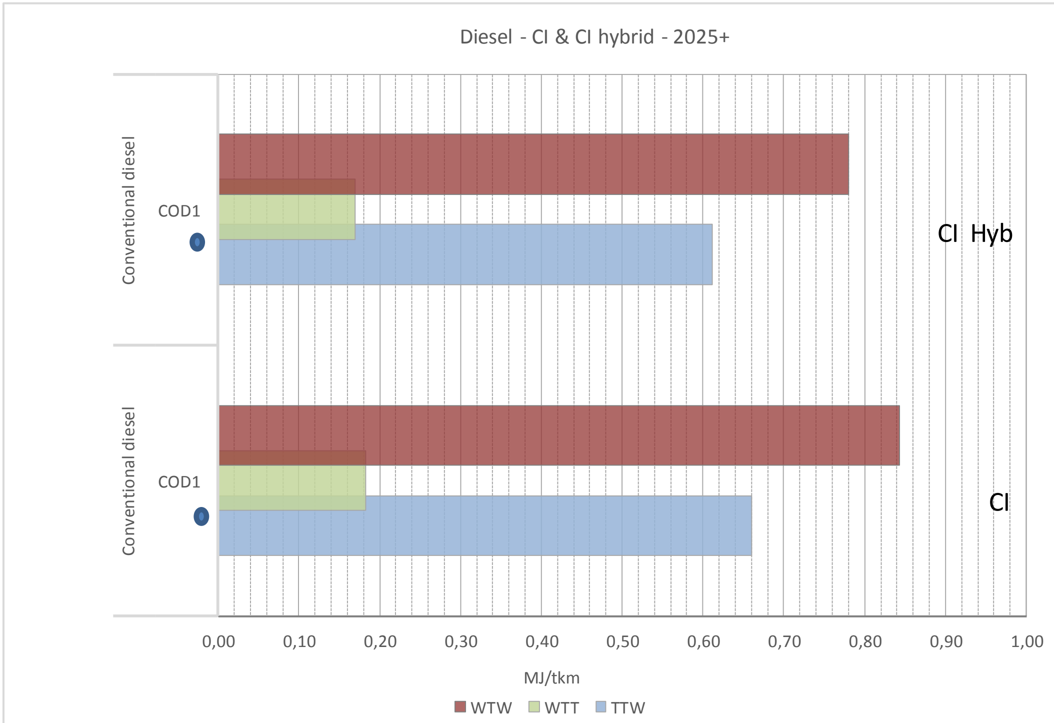




Conventional **diesel** (100% fossil) in CI technologies is expected to be subjected to improvements in term of efficiency.

The consumption figures for 2025+ are lower than 2016, and further reductions are expected by applied hybridisation. Compared to 2016 the WTW GHG emissions for non-hybridised CI engines decreases at about 9% in 2025+. Hybridisation leads to a decrease of GHG emissions of about 6% in 2016 and about 7% in 2025+ compared to the non-hybridised CI engine.

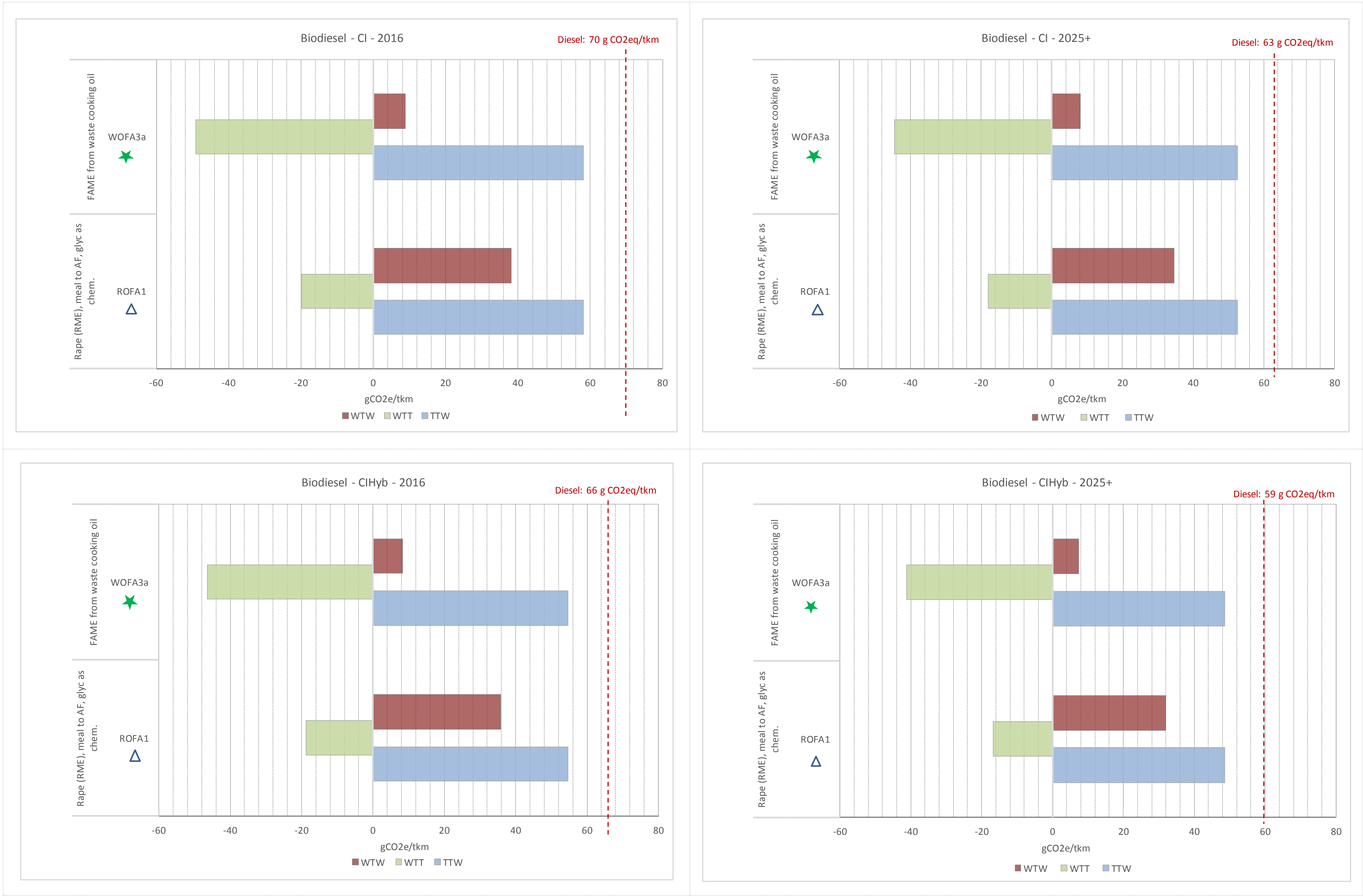




Compared to 2016 the WTW energy use for non-hybridised CI engines decreases at about 9% in 2025+. Hybridisation leads to a decrease of WTW energy use of about 6% in 2016 and about 7% in 2025+compared to the non-hybridised CI engine.

5.2.1.2 *Biodiesel*

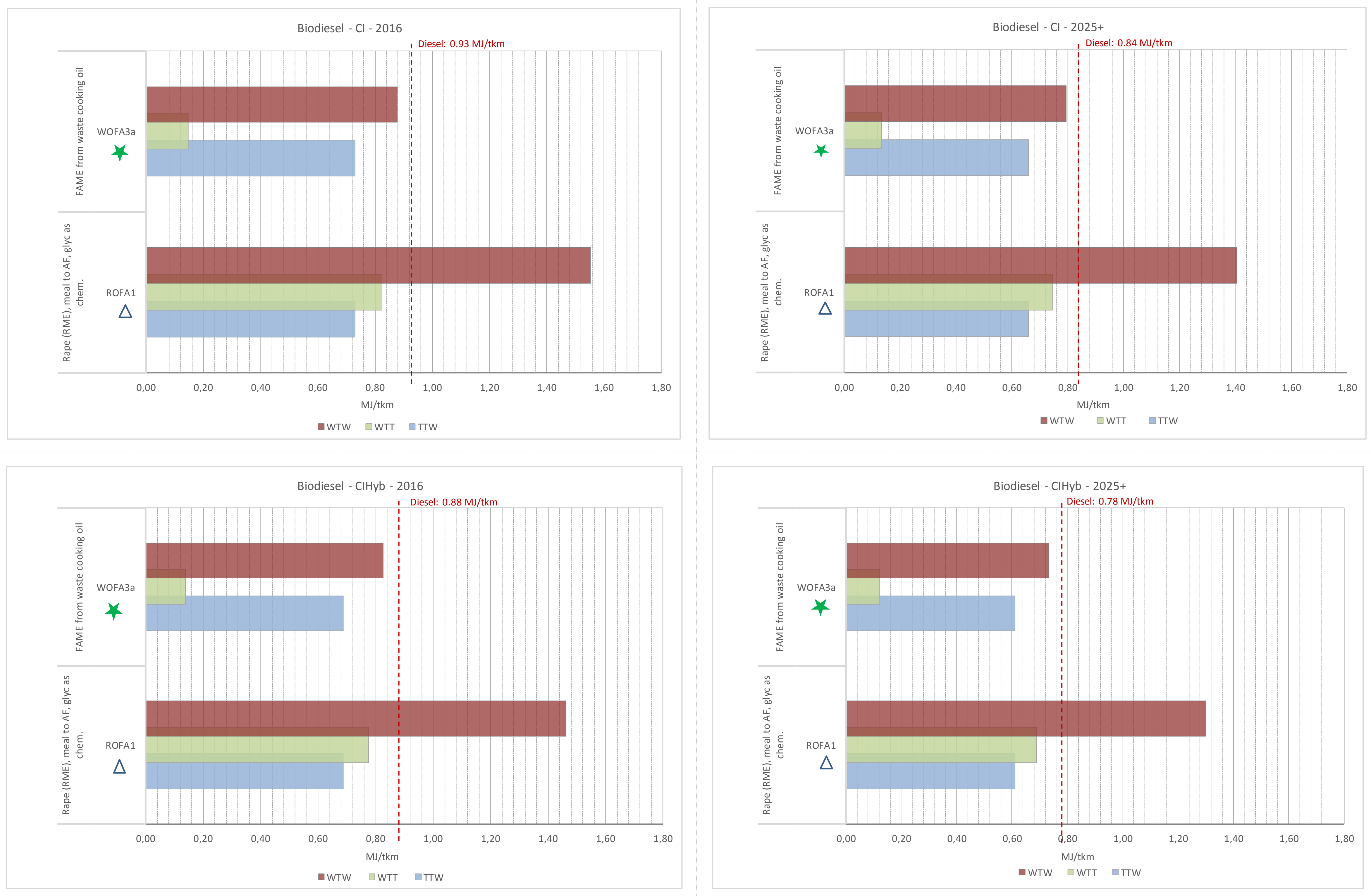
Figure 67. Biodiesel - GHG emissions (CO_{2eq}/t km) – Type 5



Biodiesel is manly produced by lipid feedstock. The potential GHG saving offered by the use of biodiesel are strongly linked to the nature of the feedstock.

As for the ethanol case, interesting GHG savings can be achieved using residues and wastes, as waste cooking oil.

Figure 68. Biodiesel – Energy expended (MJ/tkm) – Type 5



In case of biodiesel from waste cooking oil the WTW energy use is slightly lower than that for conventional diesel (100% fossil). For biodiesel from rapeseed the WTW energy use is higher.

However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

Hybridisation leads to a decrease of WTW energy use of about 6 to 8%.

5.2.1.3 HVO

Figure 69. HVO - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm) – Type 5

As the feedstock used for **HVO** production are mainly the same of the biodiesel, the potential GHG saving strongly linked to the nature of them.

High GHG savings can be achieved using residues and wastes, as waste cooking oil.

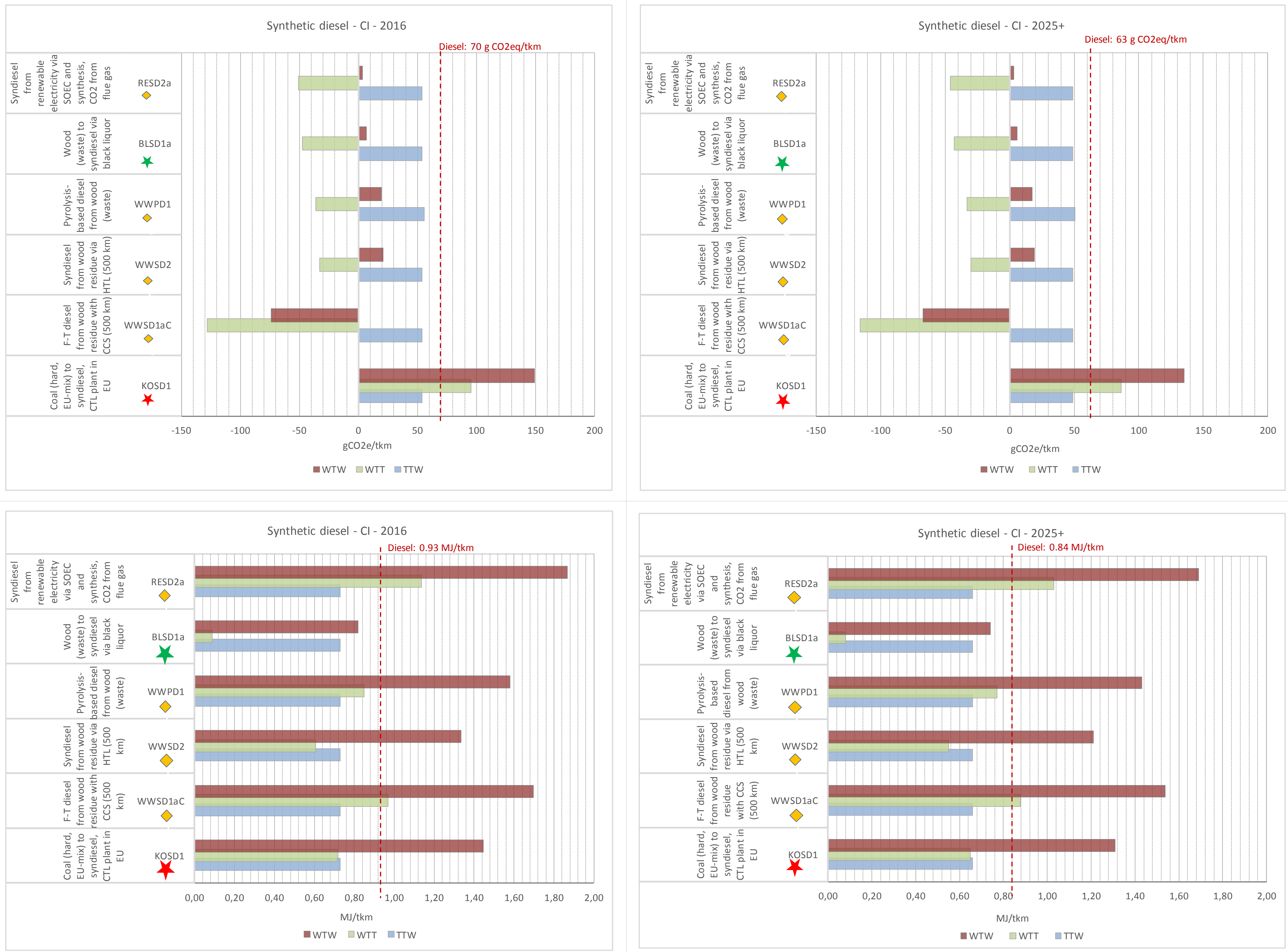
HVO from waste cooking oil (pathway WOHY1a) and residual oil from palm oil mill effluent (pathway PWYH1) leads to lower WTW energy used than conventional diesel used in CI engines.

For HVO from palm oil and rapeseed the energy use is higher than that for conventional diesel used in CI engines.

However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

5.2.1.4 *Synthetic Diesel*

Figure 70. Synthetic diesel - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm) – Type 5



Being a mix of molecules, which results very similar to regular fossil derived product, **synthetic diesel** offers the advantage of being easily usable in standard infrastructures, and power trains.

GHG performances of synthetic diesel production and use are mainly determined by the primary source of energy used for its production.

When produced from coal, synthetic diesel does not offer any advantages, if compare d with regular fossil diesel

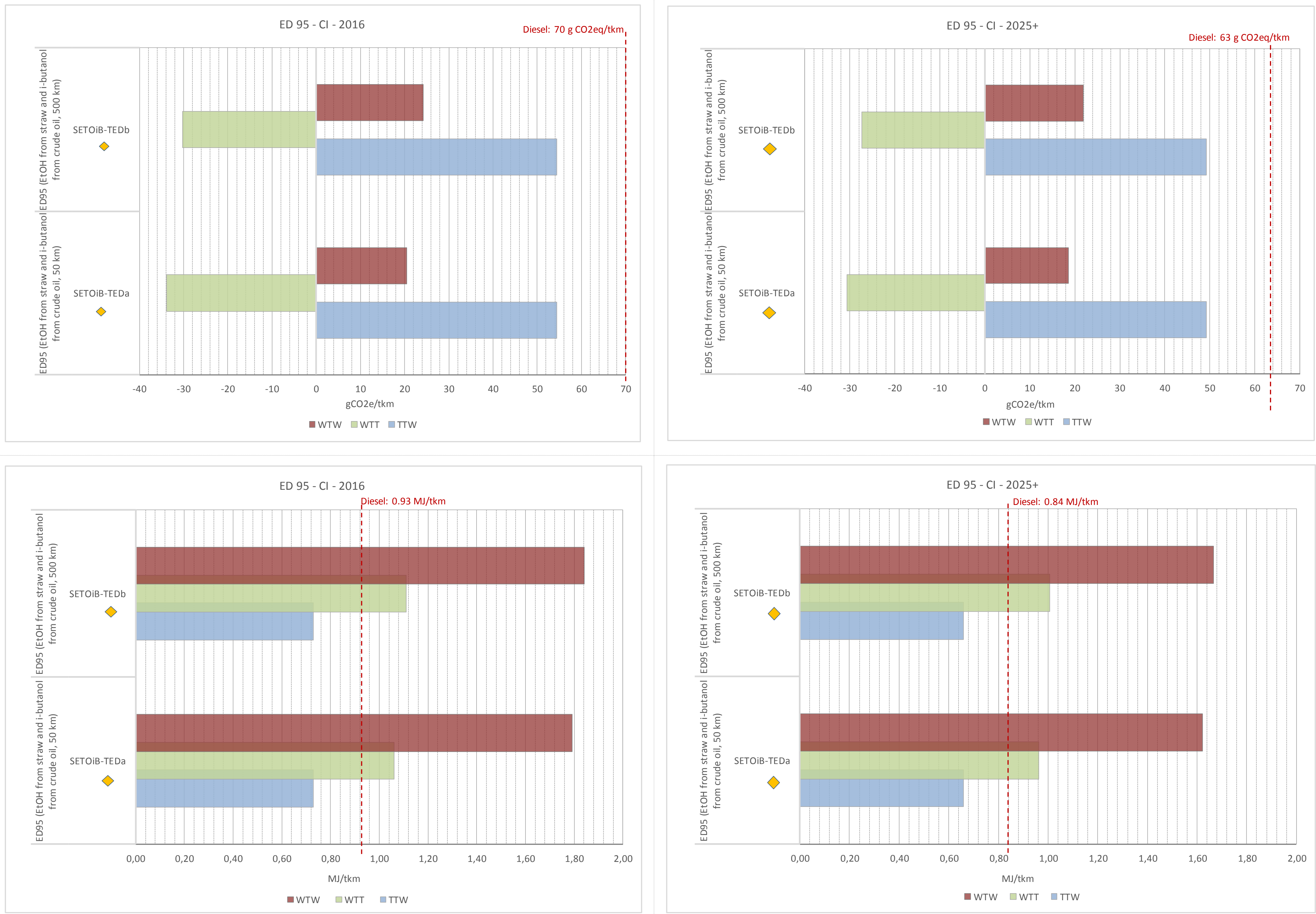
Benefits can be achieved through FT conversion process, using residual feedstock, such as: waste wood, black liquor, pyrolysis oil derived from wood waste, or via power-to-liquid using renewable electricity. In these cases, the potential savings offered by using synthetic diesel can be remarkable.

Synthetic diesel from renewable energy sources except black liquor leads to higher WTW energy use than conventional diesel. However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

Synthetic diesel from coal also leads to higher WTW energy use (increase at about 56%) and simultaneously higher GHG emissions (more than two times higher) than conventional diesel due to the high carbon content of the coal.

5.2.1.5 ED95

Figure 71. ED95 - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm) – Type 5



ED95 consists of a mixture of ethanol (95% by volume), polyethylene glycol (PEG), MTBE, iso-butanol, and lubricants.

Depending on the transport distance of the straw used for ethanol production the GHG emissions decreases at about 65 to 71% compared to conventional diesel.

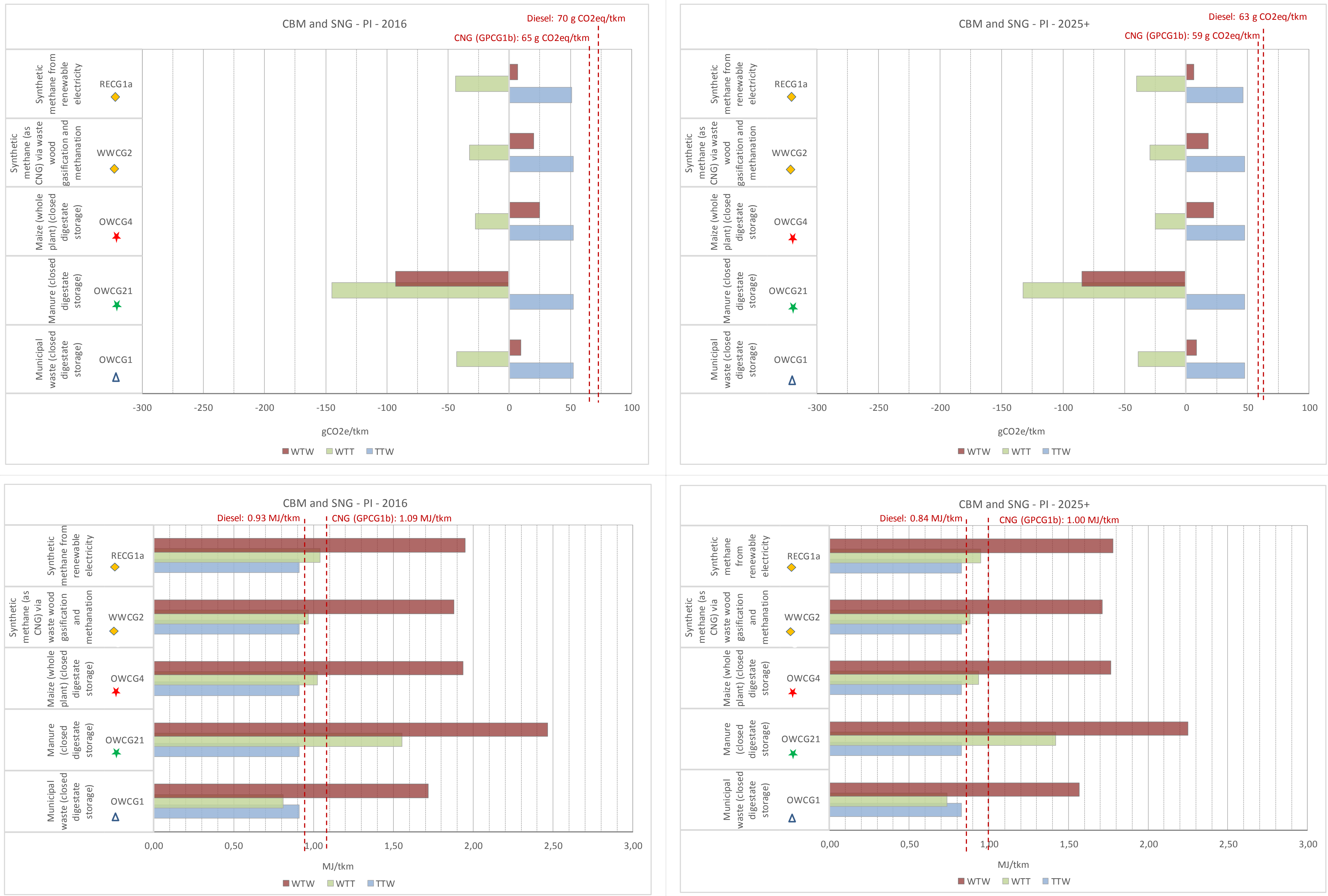
The WTW energy use of biomass derived fuels is generally higher than that for conventional diesel.

However, since carbon neutral feedstocks are used, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.

5.2.2 Internal combustion engines (ICE) & Gaseous fuels

5.2.2.1 Compressed biomethane (CBM) and synthetic natural gas (SNG)

Figure 72. CBM and SNG - GHG emissions (CO_{2eq}/t km) - Type 5



Considering the GHG saving potential, **gaseous fuels** offer significant advantages, with respect to fossil derived fuels.

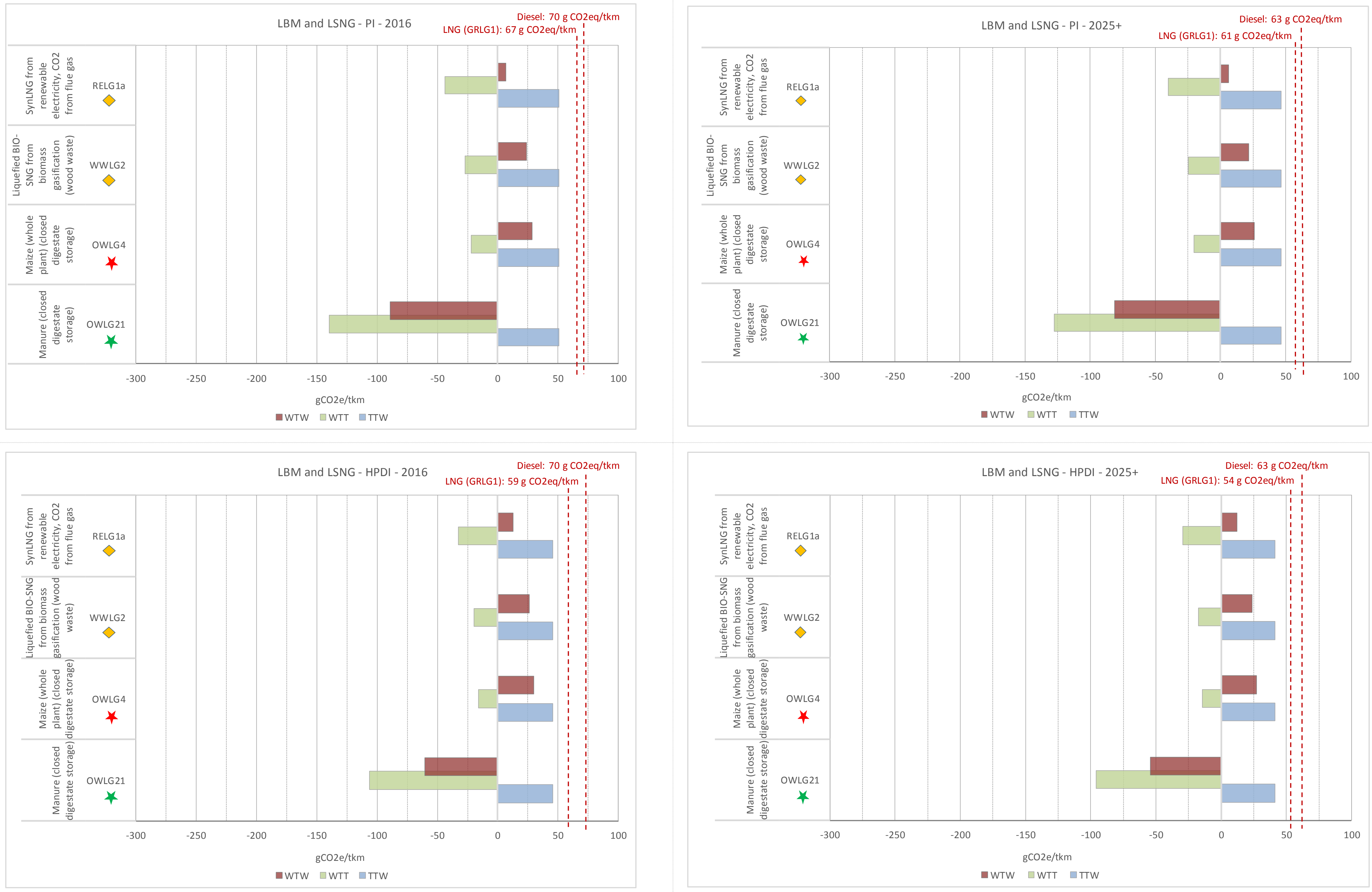
The main advantages are related to the WTT part, as credit for the avoid CH_4 emission from manure allows for negative values due to the replacement of untreated manure storage.

It has to be noted that the negative GHG emissions for biomethane from manure only can be taken into account as long as there are farms where storage of untreated manure is applied (see JEC WTT v5 report).

The WTW energy use does not correlate with GHG emissions if feedstock with a different carbon content or carbon neutral feedstocks are used. CBM from manure leads to the highest WTW energy use because the efficiency of the fermentation process is relatively low in case of manure.

5.2.2.2 *Liquefied biomethane (LBM) and liquefied synthetic natural gas (LSNG)*

Figure 73. LBM and LSNG – PI & HPDI & PI Hyb- GHG emissions (CO_{2eq}/t km) - Type 5



From a TTW perspective, the introduction of high-pressure direct injection (HPDI) engines is expected to lead to significant improvements.

From a WTW perspective, high pressure direct injection (HPDI) engines combined with liquefied biomethane (LBM) and liquefied synthetic natural gas (LSNG) may lead to a very minor advantage compared to spark ignition (SI) engines. The reason is the share of fossil diesel required for ignition.

From a WTW perspective, the introduction of HPDI engines is expected to lead to significant improvements compared to PI engines, even if combined with fossil LNG (see detailed explanation in section 4.2.2.1 "*Gaseous fuels (liquefied methane)*").

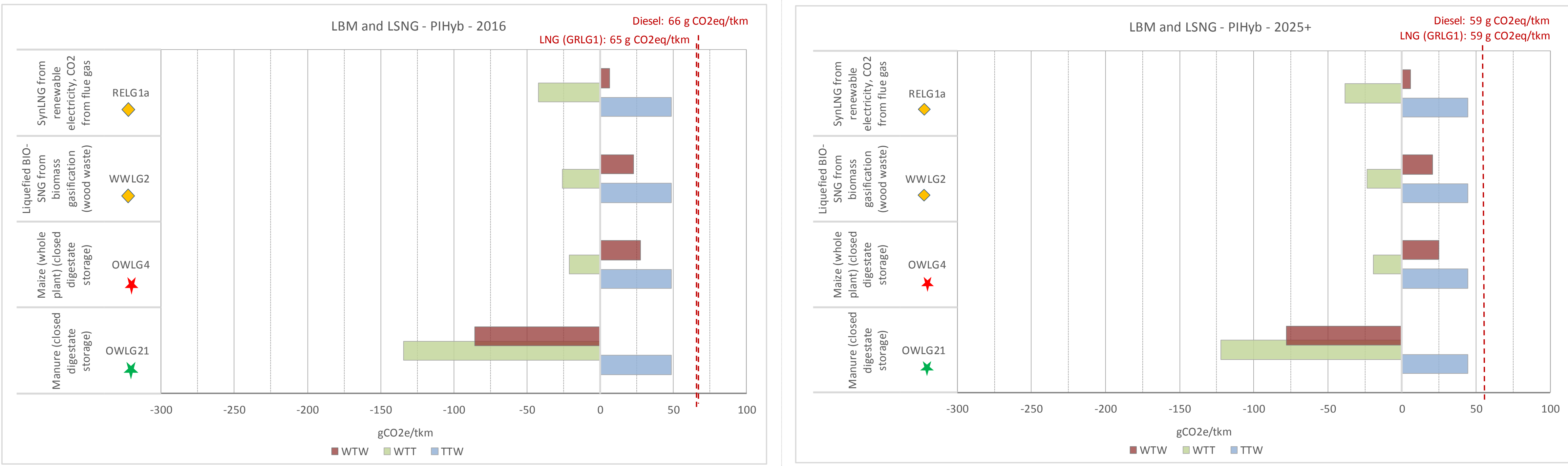
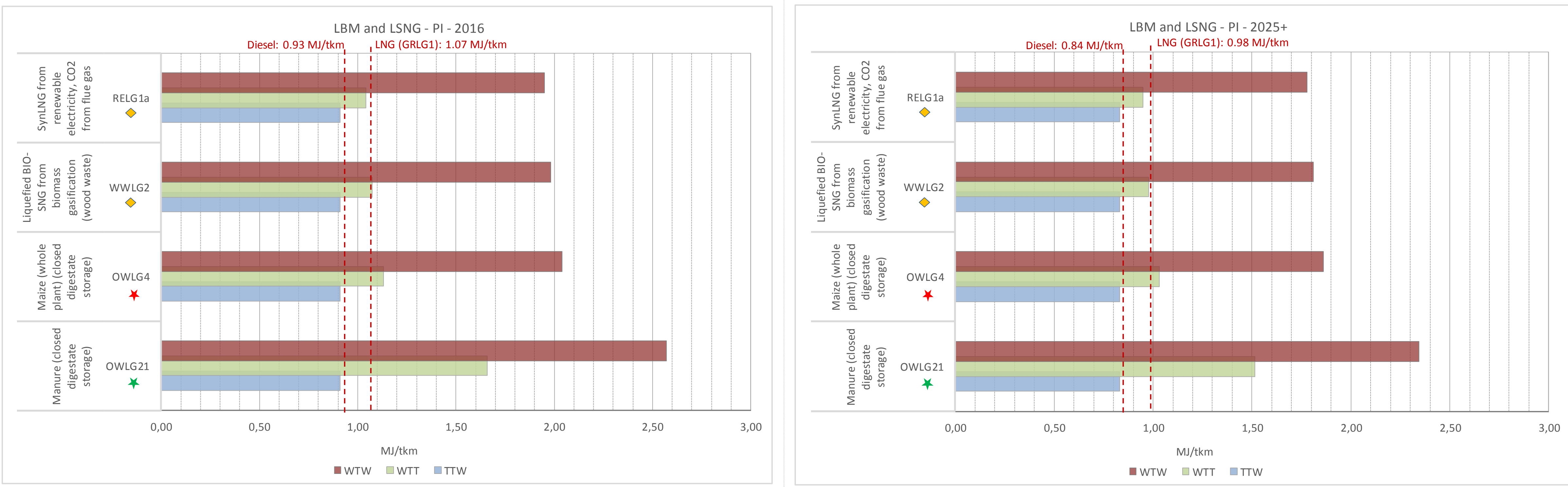
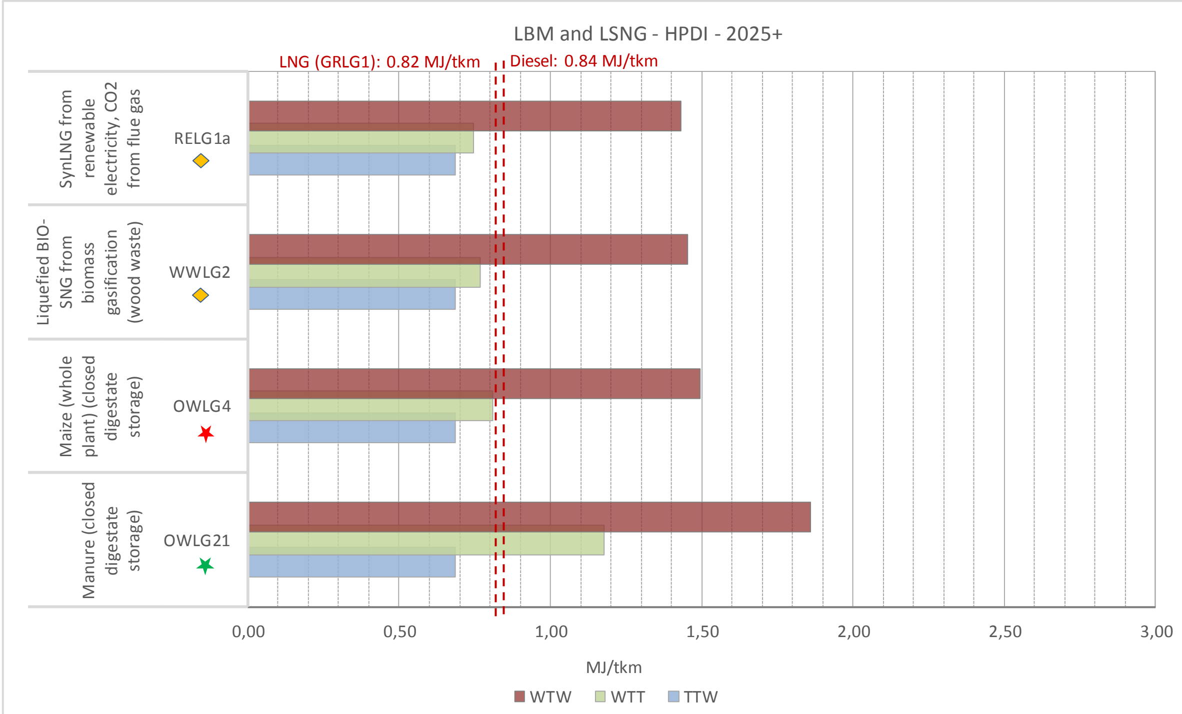


Figure 74. LBM and LSNG – PI & HPDI & PI Hyb - Energy expended (MJ/tkm) – Type 5

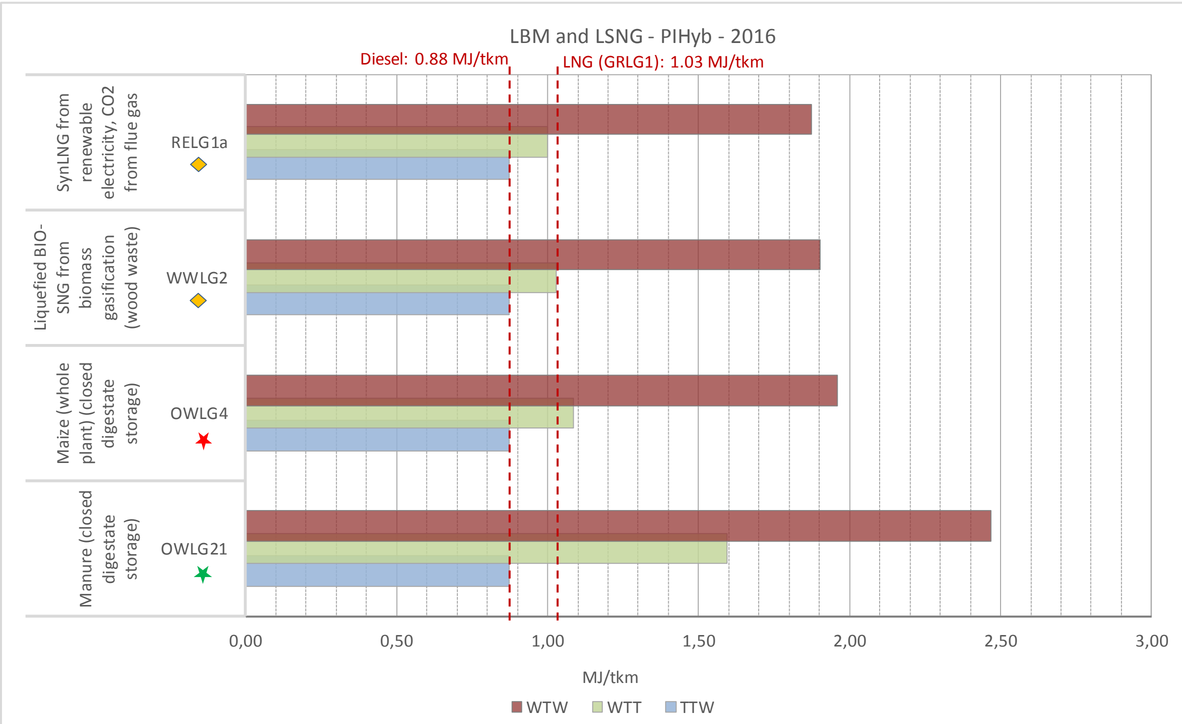


The WTW energy use for all renewable fuels is higher than that for conventional diesel (100% fossil) and for fossil LNG although the GHG emissions are significantly lower. The reason is that the carbon content of the feedstock is different or carbon neutral feedstocks are used.

Therefore, the expended energy is not necessarily an indicator for the environmental footprint of a fuel/drivetrain combination.



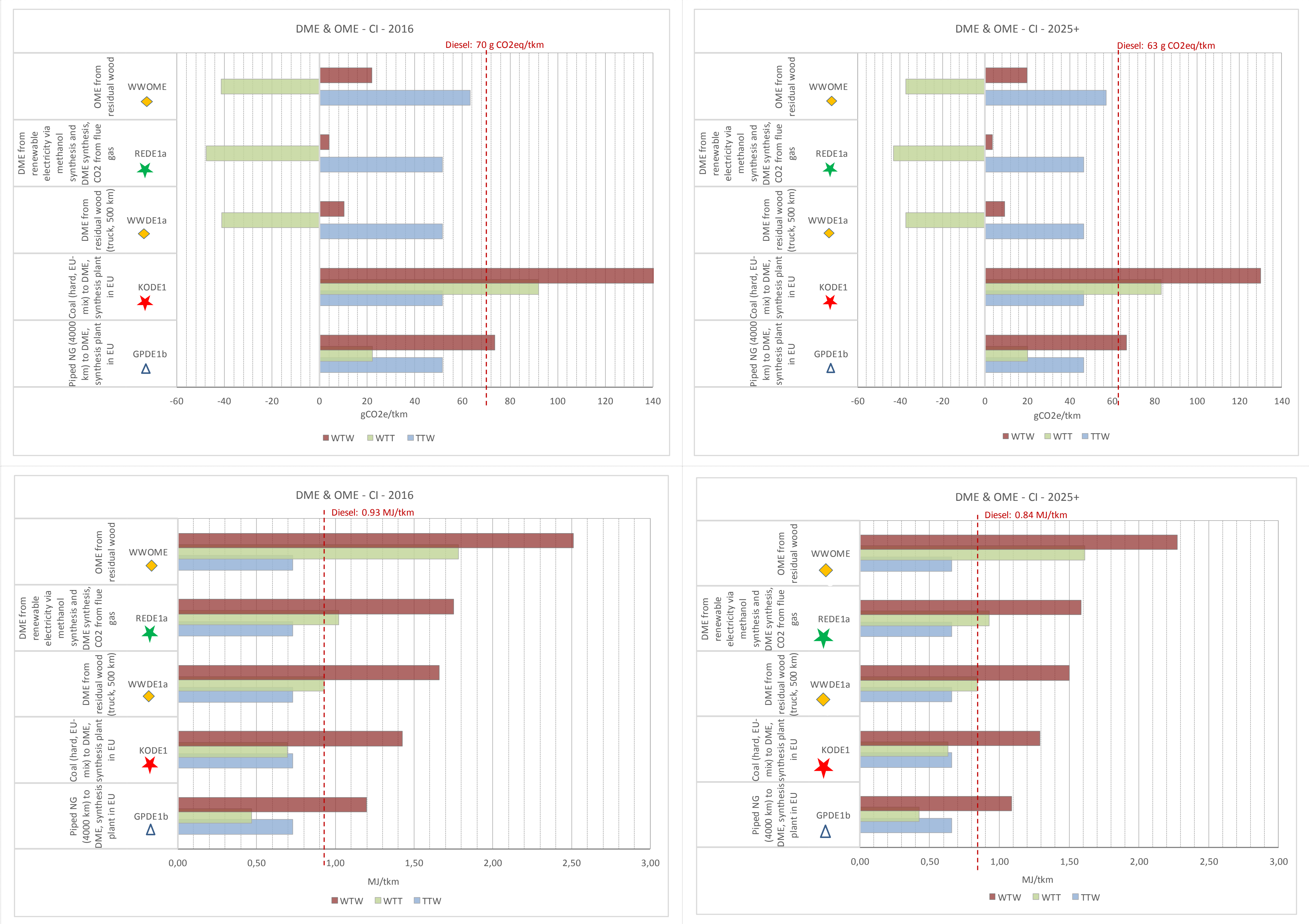
The introduction of HPDI engines lowers the WTW energy use compared to SI engines (energy consumption decreased at about 20% (see detailed explanation in section 4.4.2.2. "*Gaseous fuels (liquefied methane)" Type 4).*



Hybridisation of PI engines leads to a decrease of WTW energy use of about 4% compared to non-hybridised PI engines. However, HPDI engines without hybridization still have a lower WTW energy use (about 16% lower) than hybridised PI engines.

5.2.2.3 DME and OME

Figure 75. DME and OME - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm) – Type 5



GHG performances of DME and OME production and use are mainly determined by the primary source of energy used for its production.

When produced from coal, DME does not offer any advantages, if compare d with regular fossil diesel

Benefits can be achieved using residual feedstock, such as: waste wood or via power-to-DME using renewable electricity. In these cases, the potential saving offered by using DME and OME can be remarkable.

Both of them can be used in dedicated compression ignition engines.

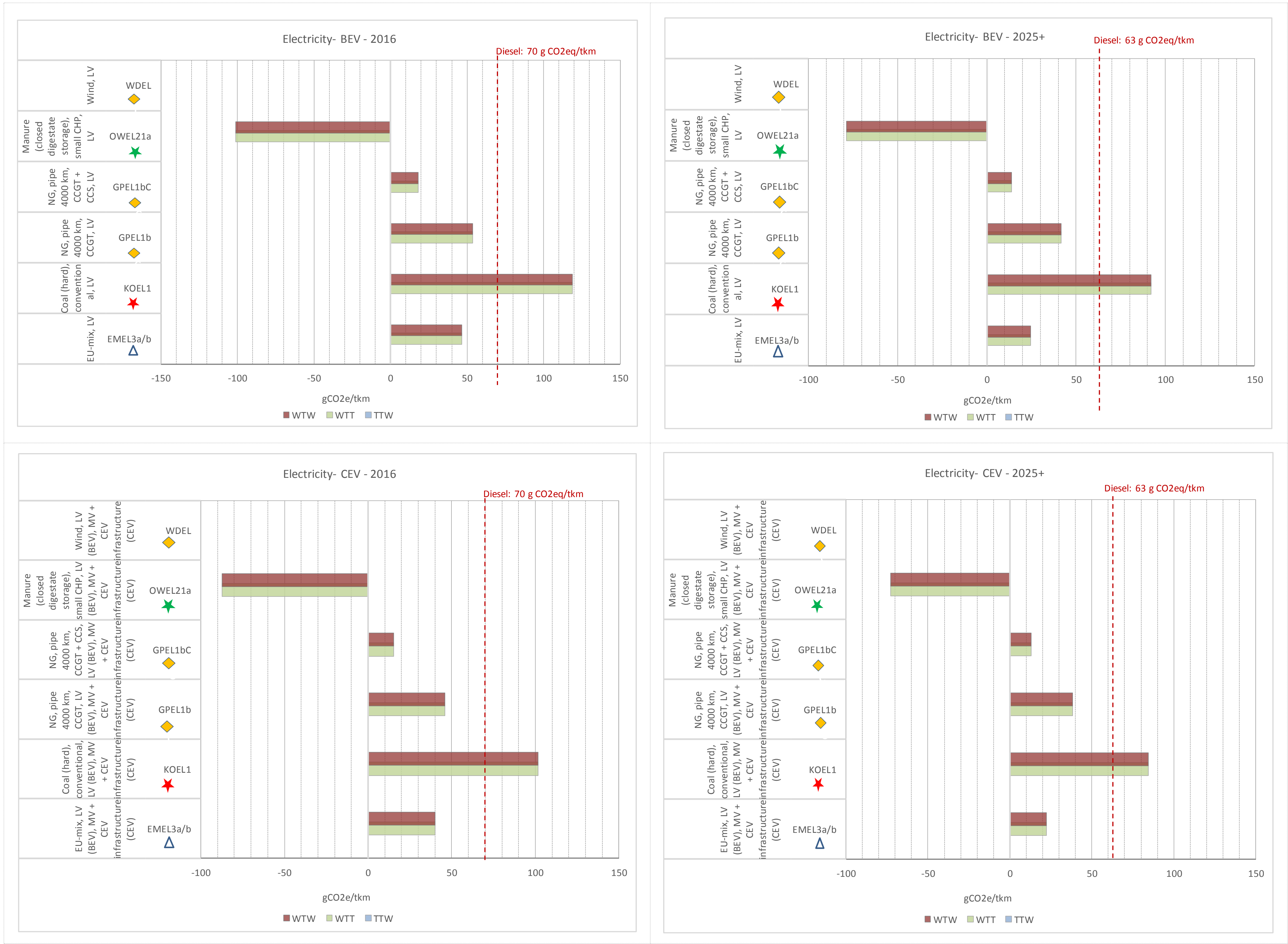
The GHG emissions from the supply of OME from waste wood are significantly higher than those for DME from waste wood due to the lower efficiency of OME production compared to DME production.

The WTW energy use for OME from residual wood is 2.7 times higher than that for conventional diesel and 1.5 times of that for DME from residual wood.

DME from coal leads to an increase of WTW energy use of about 54% compared to conventional diesel. DME from natural gas leads to an increase of WTW energy use of about 30% compared to conventional diesel.

5.2.3 Electricity driven powertrains – Battery Electric Vehicles (BEV) & Catenary Electric Vehicles (CEV)

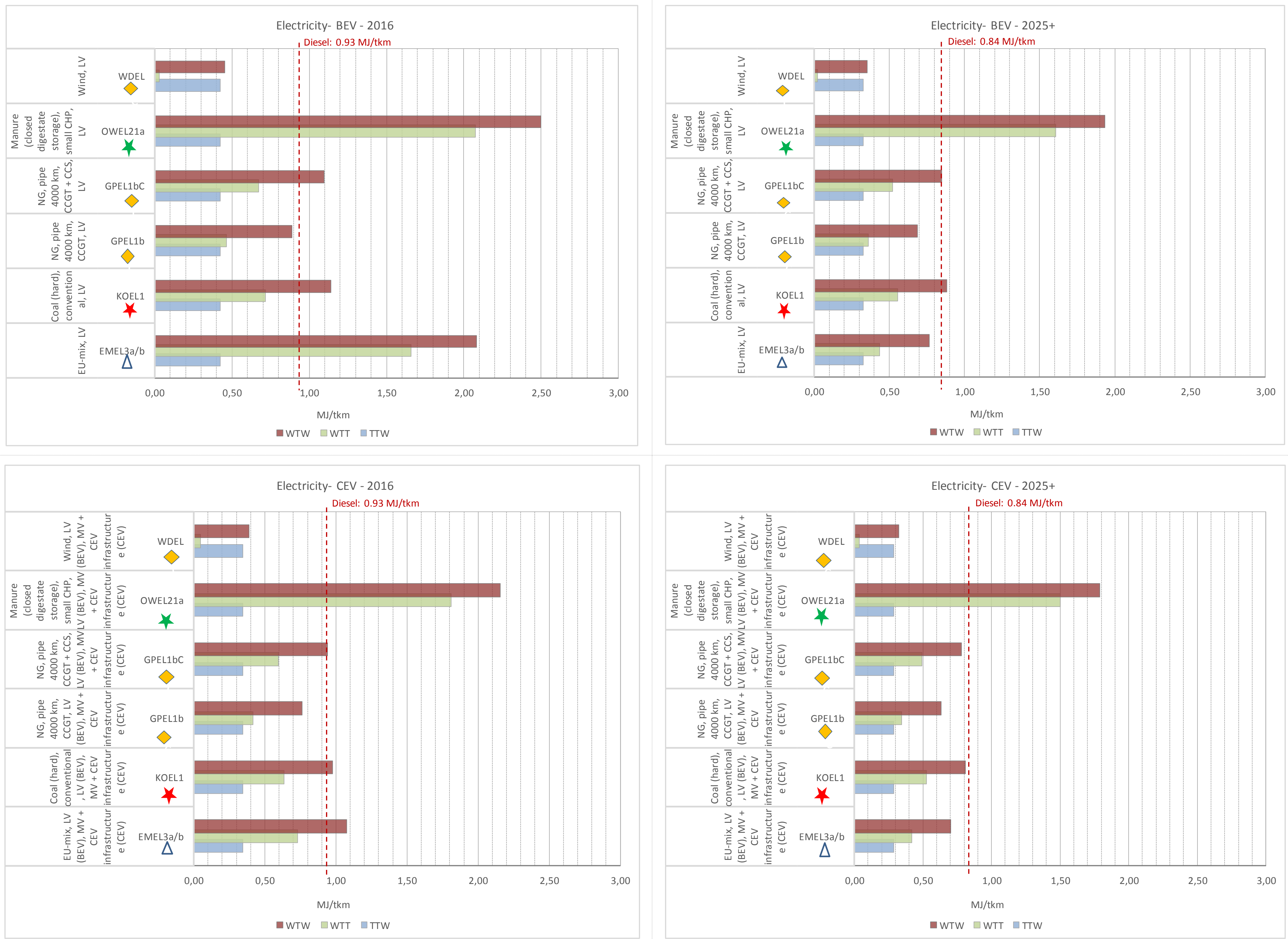
Figure 76. BEV & CEV - GHG emissions (CO_{2eq}/t km) – Type 5



Except in case of coal electricity, battery electric vehicles (BEV) and catenary electric vehicles (CEV) show lower GHG emissions for the selected electricity pathways than a similar HDV with CI engine fueled with conventional, crude oil-based diesel.

CEV are mainly operated at catenary mode and partly at battery (BEV) mode.

Figure 77. BEV & CEV[20] - Energy expended (MJ/tkm) – Type 5



For 2016 the WTW energy use for BEV combined with electricity, from wind power and natural gas CCGT without CCS, resulted in lower values than for conventional diesel in CI engines.

For time horizon 2025+ the WTW energy use for BEV combined with electricity from wind power, natural gas fueled CCGT without CCS and the EU electricity mix resulted lower than that for conventional diesel used in CI engines. For electricity from natural gas fueled CCGT with CCS combined with BEV the WTW energy use is approximately the same as for conventional diesel used in CI engines.

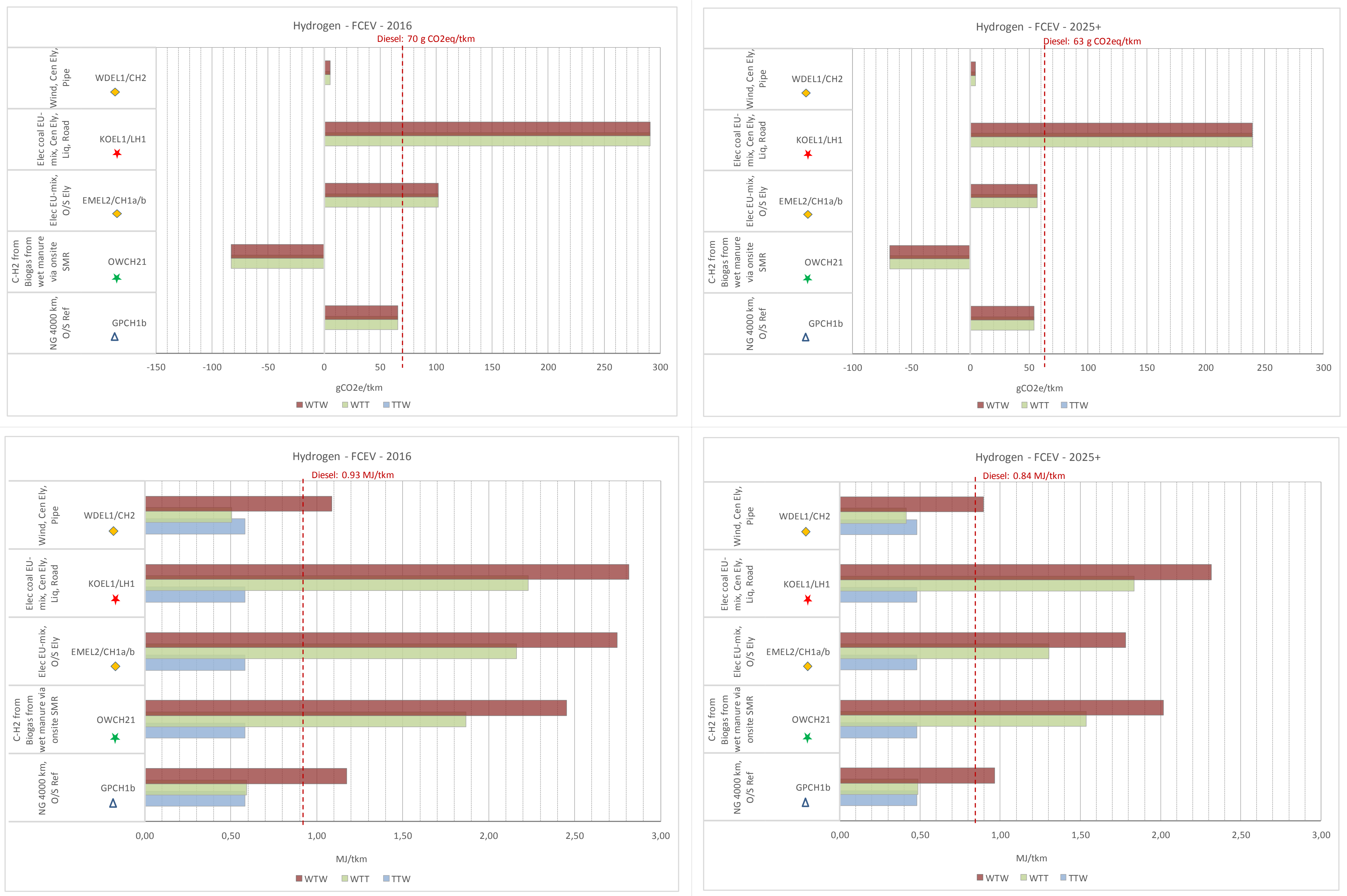
For 2016 the WTW energy use for CEV combined with electricity from wind power and natural gas CCGT without CCS is lower than that for conventional diesel used in CI engines. For electricity from natural gas fueled CCGT with CCS combined with BEV the WTW energy use is approximately the same as for conventional diesel used in DICI engines.

For time horizon 2025+ the WTW energy use for CEV combined with the selected pathways except electricity from biogas from manure is lower than that for conventional diesel used in CI engines.

[20] Note that ~10% of additional losses in the overhead infrastructure would need to be considered (as a proxy). Currently not included in the JEC TTW v5 report.

5.2.4 Fuel Cell Hydrogen Vehicles (FCEV)

Figure 78. Hydrogen FCEV - GHG emissions (CO_{2eq}/t km) & Energy expended (MJ/tkm) – Type 5



In 2016 FCEV shows higher GHG emissions than conventional diesel ICE. This is because hydrogen is assumed to be produced from EU mix electricity, via electrolysis, and from coal-based electricity. In 2025+ FCEV shows lower GHG emissions than the conventional diesel ICE, according to the expected change in EU electricity mix.

The WTW energy use for FCEV combined with the selected pathways is higher than that for conventional diesel used in CI engines.

If carbon neutral feedstocks are used (e.g. hydrogen from electricity from wind power and hydrogen from biogas steam reforming), the expended energy is not necessarily a good indicator for the environmental footprint of a fuel/drivetrain combination.

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Appendix 1. Summary of WTT selected pathways for the integration. Criteria applied.

As presented in section 2.5.2 and based on the criteria described, the following list of WTT pathways per individual fuels/energy carriers have been chosen for the JEC WTW v5 integration:

Table A1.1. Summary of WTT selected pathways based on criteria defined above

CONVENTIONAL FOSSIL LIQUID FUELS			VERSION 5		SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV CI	
COD1	Diesel	**18.9**	●	●	Current fossil fuel
COG1	Gasoline	**17.0**	●		Current fossil fuel
COGHOP1	Gasoline High Octane ($E10_{eq}$)	**15**	◆		Short-term interesting option for joint fuel and engine optimization (high compression ratio)
COGHOP3	Gasoline High Octane ($E10_{eq}$)	**13.1**	◆		Short-term interesting option for joint fuel and engine optimization (high compression ratio)

CNG			VERSION 5		SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV CI	
GPCG1B	Pipeline 4000 km	**15.1**	●	●	For the supply of marginal piped natural gas a transport distance of 4000 km has been assumed representing typical future South West Asian locations. For HEV, CNG considered as alternative to the fossil diesel, currently dominating the market.
GRCG1	LNG, vap, pipe	**17.4**	●		Representative pathway of the current LNG production route in Europe.
GRCG2	LNG, road, vap	**18.3**	★	★	Max GHG intensive pathway according to the described selection criteria.
SGCG1	Shale gas (EU)	**6.8**	★	★	Min GHG intensive pathway according to the described selection criteria.

COMPRESSED BIOMETHANE (CBM)		Version 5			Selection criteria
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV CI	
OWCG1	Municipal waste	**9.5**	△	△	High potential feedstock availability in 2030 supported by on-going initiatives in Europe.
OWCG21	Liquid manure (closed storage)	**-102.9**	★		Min GHG intensive pathway according to the described selection criteria.
OWCG4	Maize (whole plant)	**26.3**	★		Max GHG intensive pathway according to the described selection criteria.
WWCG2	Synthetic methane (as CNG) via waste wood gasification and methanation	**21.0**	◆	◆	Interesting pathway supplied by lignocellulosic/woody feedstocks.
RECG1A	Synthetic methane from renewable electricity, CO2 from flue gas	**2.4**	◆	◆	Power-to-X, supplied by RES, foreseen as an interesting asset for a highly decarbonized scenario.

LNG		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV **ICE PI (LNG), ICE CI (LNG HPDI)**	
GRLG1	LNG, road	**16.6**		△	Despite the fossil source, we consider this as an alternative to the current fuel (as in CNG).
		ORGANIC WASTE TO LBG			
OWLG21	Biogas from organic waste (wet manure, CS)	**-98.7**		★	Min GHG intensive pathway according to the described selection criteria.
OWLG4A	Biogas from maize whole plant as LNG (CS)	**30.5**		★	Max GHG intensive pathway according to the described selection criteria.
		SYNTHETIC LNG			
WWLG2	Liquefied BIO-SNG: biomass thermal gasification (wood waste)	**25.3**		◆	Interesting pathway supplied by lignocellulosic/woody feedstocks.
RELG1A	SynLNG: Renewable electricity, CO2 from flue gas	**6.7**		◆	Power-to-X, supplied by RES, foreseen as an interesting asset for a highly decarbonized scenario.

LPG			VERSION 5		SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	**HDV**	
LRLP1	LPG (remote)	**7.8**	△		Despite the fossil source, we consider LPG as an alternative to the current diesel / gasoline conventional fuels

ETHANOL			VERSION 5		SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	**HDV CI 2025+**	
			SUGAR BEET		
SBET1C	Sugar beet, pulp to fuel, slops to BG	**11.3**	★		Min GHG intensive pathway according to the described selection criteria.
			WHEAT		
WTET1A	Wheat, conv NG boiler, DDGs as AF	**64.5**	△ ★		High potential feedstock availability in 2030.
WTET5	Wheat, DDGS to biogas	**33.8**	◆		Interesting pathway to explore the impact of biogas route in reducing the maximum/representative pathway so far.
			WOOD BASED		
WWET1B	Waste residual wood (transport >500 km)	**29.0**	◆		Interesting pathway supplied by lignocellulosic/woody feedstocks to allow comparison with other residual feedstocks / processes and final fuels.
			STRAW		
STET1	Wheat straw (500 km)	**17.8**	◆		High potential feedstock availability in 2030 supported by on-going initiatives in Europe.

ED95		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	**HDV CI 2025+**	
SETOIB-TEDA	ED95 (EtOH from straw and i-butanol from crude oil, 50 km)	**17.6**		◆	One interesting example of an alternative fuel for the sector based on industrial current trends / availability of feedstock.

BIODIESEL (FAME 100)		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	**HDV CI 2025+**	
RAPE SEED OIL					
ROFA1	RME: Meal as AF, glycerine as chem,	**48.4**	△		Selected pathway on the base of most used feedstock for the current EU production.
WASTE COOKING OIL					
WOFA3A	FAME: waste cooking oil	**8.3**	★	★	Min GHG intensive pathway according to the described selection criteria.

HVO		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	**HDV CI 2025+**	
			RAPE SEED OIL		
ROHY1A	HVO RO (NExBTL), meal as AF	**51.9**	◆	◆	Interesting pathway for comparing HVO with current reference pathways used in biodiesel (FAME) and BTL (synthetic diesel)
			PALM OIL		
POHY1C	HVO PO (NExBTL), no CH4 rec, no heat credit	**62.4**	★	★	Max GHG intensive pathway according to the described selection criteria.
PWHY	NExBTL, Palm oil mill effluent (POME)	**10.8**	★	★	Min GHG intensive pathway according to the described selection criteria.
			WASTE COOKING OIL		
WOHY1A	HVO WO (NExBTL), waste cooking oil	11.1	△	△	Pathway representative of the industrial trend towards more sustainable/residual feedstocks.

SYNDIESEL			VERSION 5		SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV CI	
KOSD1	Syndiesel: CTL, diesel pool	**130.3**	★	★	Max GHG intensive pathway according to the described selection criteria.
RESD2A	Syndiesel: Renewable electricity via SOEC (FT route), CO_2 from flue gas	**0.7**	◆	◆	Power-to-X, supplied by RES, foreseen as an interesting asset for a highly decarbonized scenario.
WWSD1AC	F-T diesel from wood residue with CCS (500 km)	**-105.1**	◆	◆	Interesting pathway supplied by lignocellulosic/woody feedstocks to allow comparison with other residual feedstocks / processes and final fuels. It shows the potential for BECCS (negative emissions).
WWSD2	Syndiesel from wood residue via HTL (500 km)	**27.5**	◆ △	◆ △	Interesting thermochemical pathway supplied by lignocellulosic/woody feedstocks. Due to the wide range of the syndiesel pathways, selected as a “representative” pathway in the middle of the range.
BLSD1A	Syndiesel: W Wood via black liquor, diesel pool	**5.3**	★	★	Min GHG intensive pathway according to the described selection criteria.
WWPD1	Pyrolysis-based diesel: Wood (waste)	**23.0**	◆	◆	Interesting thermochemical pathway supplied by lignocellulosic/woody feedstocks.

MTBE / ETBE			VERSION 5		SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	**HDV CI 2025+**	
			MTBE		
GRMB1	MTBE: remote plant	**15.3**	△		Representative pathway of the current commercial route
			ETBE		
LREB1	ETBE: imported C4 and wheat ethanol	**28.4**	△		Representative pathway of the current commercial route
			BIO-ETBE		
SBBE1B	Bio-ETBE from sugar beet	**31.9**	◆		New alternative pathway from bio-derived feedstocks.

DME		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV CI	
GPDE1B	DME: NG 4000 km, EU prod., rail/road	**30.0**	△		Alternative fuel based on the reference natural gas pathway selected on the base of potential market availability.
KODE1	DME: Coal EU-mix, EU prod., rail/road	**125.7**	★		Max GHG intensive pathway according to the described selection criteria.
WWDE1A	DME: from residual wood (truck, 500 km)	**10.4**	◆		Interesting pathway supplied by lignocellulosic/woody feedstocks to allow comparison with other residual feedstocks / processes and final fuels.
REDE1A	eDME: Renewable electricity, CO2 from flue gas	**1.7**	★		Min GHG intensive pathway according to the described selection criteria.

OME		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC (DISI & DICI)	HDV CI	
WWOME	OME: Residual wood	**26.3**	◆	◆	Interesting pathway supplied by lignocellulosic /woody feedstocks allowing comparison versus DME route.

XEV		VERSION 5			SELECTION CRITERIA
		GHG (g CO2eq/MJfuel)	PC	**HDV**	
			EU-MIX		
EMEL3A	EU-mix low (Current mix) - LV	**110.1**	△	△	Electricity (energy vector) considered as an alternative "fuel" to enable comparison. Current and 2030 electricity mix
EMEL3B	EU-mix low (2030 mix) - LV	**74.5**	△	△	
			FOSSIL FUEL BASED ELECTRICITY		
KOEL1	EU-mix Coal conv.	**280.5**	★	★	Max GHG intensive pathway according to the described selection criteria.
GPEL1B	NG 4000 km, CCGT	**126.7**	◆	◆	Added to the comparison to analyze the impact of different primary energy sources.
GPEL1BC	NG 4000 km, CCGT+CCS	**42.6**	◆	◆	Added to the comparison to analyze the impact of different primary fossil energy sources coupled with CCS.
			ORGANIC WASTE TO ELECTRICITY		

OWEL21A	Biogas ex wet manure, local (closed storage)	**-239.3**	★	★	Min GHG intensive pathway according to the described selection criteria.
		LOW CARBON POWERPLANTS			
WDEL	Wind offshore	**0.0**	◆	◆	Added to the comparison to analyze the impact of different primary energy sources.

HYDROGEN VEHICLES			**VERSION 5**		**SELECTION CRITERIA**
		GHG (g CO2eq/MJfuel)	PC	**HDV**	
		COMPRESSED HYDROGEN (THERMAL)			
GPCH1B	C-H2: NG 4000 km, O/S Ref	**113.0**	△	△	Hydrogen (energy carrier) considered as an alternative "fuel" to enable comparison. Natural gas route chosen as a reference pathway for the current production in Europe.
OWCH21	C-H2: Biogas from wet manure via onsite SMR	**-142.4**	★	★	Min GHG intensive pathway according to the described selection criteria.
		COMPRESSED HYDROGEN (ELECTROLYSIS)			
EMEL2/CH1 A	C-H2: Elec EU-mix, O/S Ely	**175.2**	◆	◆	Electrolyzes with different electricity sources as interesting pathways for H2 production.
EMEL2/ ELCH1B	C-H2: Elec EU-mix (2030), onsite, IEA	**118.6**	◆	◆	
WDEL1/CH 2	C-H2: Wind, Cen Ely, Pipe	**9.5**	◆	◆	
		LIQUID/ CRYO-COMPRESSED HYDROGEN (ELECTROLYSIS)			
KOEL1/LH1	Cc-H2: Elec coal EU-mix, Cen Ely, Liq, Road	**499.6**	★	★	Max GHG intensive pathway according to the described selection criteria.

Appendix 2. GHG emissions for the EU biofuel mix: ethanol, biodiesel and HVO (2017 and 2025+).

A2.1. Current scenario (based on 2017)

The GHG emissions associated to biofuels consumed in the EU in **2017** have been estimated as weighted averages of two contributing factors:

1) the shares of the feedstocks used for the EU ethanol, biodiesel and HVO production estimated using data from ePure, 2018 and USDA, 2018;
2) the shares of the most representative WTT sub-pathways estimated on the basis of experts' judgment and coherently (to some extent) with the WTW integration.

Feedstocks for ethanol

The feedstocks used for ethanol consumed in EU and their relative shares in 2017 are shown in the table below. Imports of ethanol (mainly sugarcane) have been also taken into account in calculating those shares.

Table A2.1. Share of total EU ethanol consumption in 2017

Feedstocks	Share of total EU ethanol consumption in 2017
wheat	30%
maize	38%
sugars	21%
other cereals	7%
lignocellulosic material or other feedstocks listed in Annex IX-A RED	4%

Source: JRC elaborations based on ePure, 2018 and USDA, 2018 (for imports)

Feedstocks for biodiesel and HVO

The amounts of the different feedstocks used for biodiesel and HVO production in EU in 2017 derive from the aggregated figures available in USDA, 2018. Information from European biofuels producers (e.g. NESTE, etc.) suggest that, in 2017, 76% of the feedstocks used for HVO production consisted of 'waste fats and oils'. This broad definition encompasses used cooking oil (UCO), other residual oils and animal fats.

The initial values provided by USDA have been elaborated in order to produce two separated set of data for biodiesel and HVO. The assumptions here presented have been based on experts suggestions and data review. A differential in GHG performance of biodiesel and HVO resulted from the specific allocation of feedstocks mix. In particular, considering the results shown in table 10, A2.2 and A2.4. - although the authors do note that other data sources appear to consider that likely less UCO and animal fats are currently destined for HVO (Greenea, 2020) - for future mixes a larger demand deriving for aviation sector has been assumed for HVO/HEFA, resulting in an increased share of UCO in HVO/HEFA plant inputs. In particular:

a) For biodiesel:
   - we allocated a smaller share of UCO and animal fats to biodiesel, assuming that higher percentages are destined to HVO;
   - we increased the share of biodiesel produced by traditional oils – using rapeseed oil pathway for calculating the emission factor - to compensate the reduced shares of UCO and animal fat.
b) For HVO:
   - the relative shares of rapeseed/soybean/sunflower oils were made proportional according to their relative weights in biodiesel production;
   - the relative percentages were verified and modified to be coherent with the volumes of biodiesel and HVO provided by USDA, 2018.

Table A2.2. Share of total EU biodiesel and HVO consumption in 2017

	Share of total EU **biodiesel and HVO** production in 2017 (USDA, 2018)	Share of **biodiesel** production in 2017 (JRC elaboration)	Share of **HVO** production in 2017 (JRC elaboration)
rapeseed oil	45%	52%	18%
used cooking oil (UCO)	21%	17%	25%
palm oil	18%	20%	45%
animal fats	6%	5%	11%
soybean oil	5%	5%	2%
sunflower oil	1%	1%	0.4%
other oils	4%	-*	-*

* No other oils have been modelled in the JEC WTT v5. Therefore, as a simplification, UCO has been used as an approximation to describe these pathways.

Note. The % are recalculated based on the assumed volumes / split between HVO and biodiesel for each class of feedstock (leading to a different % in both cases).

Source: JRC elaboration based on USDA, 2018.

Pathways selection and average emissions

As mentioned above, pathways emissions have been also assigned to the WTT sub-pathways, identified as the most representative for the production of the various biofuels.

The following WTT sub-pathways were included with their respective weights.

Ethanol:

- Wheat ethanol: WTET1a (70%) and WTET2a (30%)
- Maize ethanol: CRET2a (100%)
- Sugar-based ethanol: SBET1a (63%), SBET1b (27%), SCET1 (10%)
- Other cereals ethanol: BRET2 (100%)
- Cellulosic ethanol: STET1 (100%)

Biodiesel:

- Rapeseed biodiesel: ROFA1 (50%) and ROFA2 (50%)
- Palm oil biodiesel: POFA3a (20%) and POFA3b (80%)
- UCO biodiesel: WOFA3a (100%)
- Animal fats biodiesel: TOFA3 (100%)
- Soybean biodiesel: SYFA3a (20%) and SYFA3b (80%)
- Sunflower biodiesel: SOFA3 (100%)

HVO:

- Rapeseed HVO: ROHYa (50%) and ROHYb (50%)
- Palm oil HVO: POHY3a (20%) and POHY3b (80%)
- UCO HVO: WOHY1a (100%)
- Animal fats HVO: TOHY1a (100%)
- Soybean HVO: SYHY1a (20%) and SYHY1b (80%)
- Sunflower HVO: SOHY1a (100%)

A2.2. 2025+ scenario

For the 2025+ scenario, the mix of feedstocks used for biofuels consumed in EU has been estimated taking also into account the provisions in Directive 2018/2001 (RED recast).

Final percentage and volumes have been cross-checked in light of the RED recast targets: an overall minimum target of 14% of renewable energy for the transport sector by 2025+, the sub-target of 3.5% for advanced biofuels from Annex IX-A, the 7% cap on food/feed feedstocks and the limit of 1.7% for feedstocks listed in Annex IX-B were taken into account to some extent to estimates the shares of the feedstocks.

For ethanol, we assumed that around 13% of the overall production will be obtained from lignocellulosic materials or other feedstocks listed in Annex IX-A of Directive 2018/2001 as a result of the 3.5% sub-target for advanced biofuels and the double-counting allowed for advanced biofuels feedstocks.

The shares of the other feedstocks have been estimated keeping the 2017 share for sugar-based ethanol that has the lowest amount of associated emissions and reducing accordingly wheat, maize and other cereals.

Table A2.3.Shares of ethanol in 2025+

	Share of total EU **ethanol** consumption in 2025+
wheat	26%
maize	34%
sugars	21%
other cereals	6%
lignocellulosic material or other feedstocks listed in Annex IX-A RED	13%

Source: JRC elaborations

For biodiesel, we kept constant the shares for UCO and animal fat considering the 1.7% cap in the RED recast and distributed some of conventional biodiesel production to the pathways, which exhibit better GHG performance assuming that more sustainable feedstocks will be possibly used for future production (e.g. Camelina). Only sustainable palm oil is considered in this scenario.

For HVO, we added a group of alternative feedstocks based on residual oils (to be still clearly identified), attributing the emission factor of UCO. Again, palm oil is assumed all sustainable in this scenario.

Table A2.4. Share of biodiesel and HVO in 2025+

	Share of **biodiesel** production in 2025+	Share of **HVO** production in 2025+
rapeseed oil	47%	16%
used cooking oil (UCO)	15%	25%
palm oil (all sustainable)	20%	42%
animal fats	5%	11%
soybean oil	5%	2%
sunflower oil	6%	0.4%
Other residual oils	2%	5%

Source: JRC elaborations

In terms of sub-pathways, for the 2030 scenario, more weight was assigned to the sub-pathways that are able to save more GHG emissions on the basis of the assumption that new investments will be made with the purpose of saving the greatest amount of GHG emissions.

This resulted in the following shares among ethanol sub-pathways:

- Wheat ethanol: WTET1a (0%), WTET2a (70%) and WTET4a (30%)
- Maize ethanol: CRET2a (100%)
- Sugar-based ethanol: SBET1a (27%), SBET1b (63%), SCET1 (10%)
- Other cereals ethanol: BRET2 (100%)
- Cellulosic ethanol: STET1 (100%)

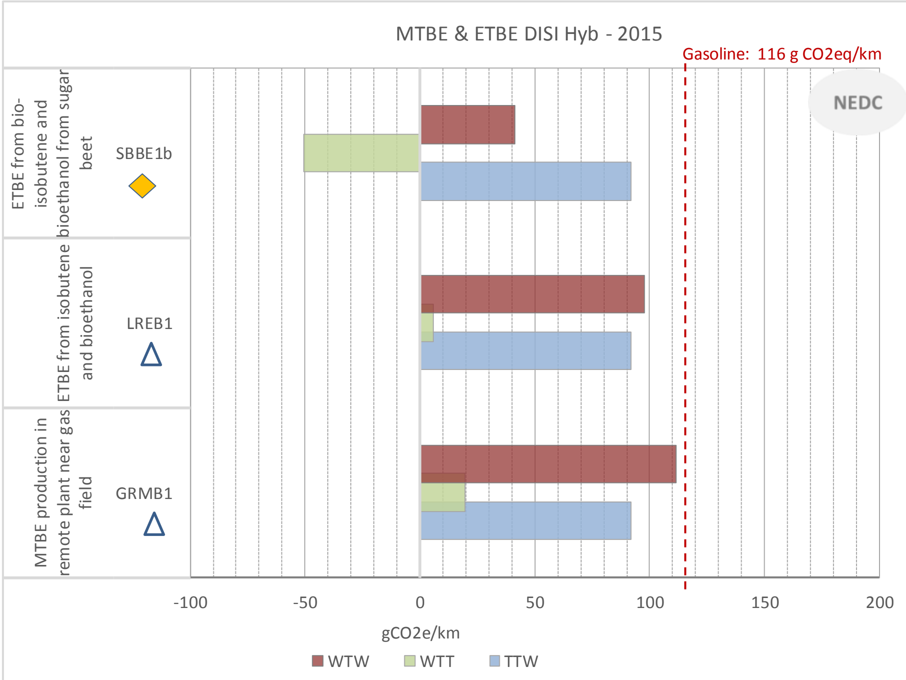
While, for biodiesel, the following weights for the selected sub-pathways have been assumed:

- Rapeseed biodiesel: ROFA1 (40%); ROFA2 (50%); ROFA3 (10%)
- Palm oil biodiesel: POFA3b (100%)
- UCO biodiesel: WOFA3a (100%)
- Animal fats biodiesel: TOFA3 (100%)
- Soybean biodiesel: SYFA3a (10%) and SYFA3b (90%)
- Sunflower biodiesel: SOFA3 (100%)

For HVO, the following sub-pathways (and weights) were considered:

- Rapeseed HVO: ROHYa (50%) and ROHYb (50%)
- Palm oil HVO: POHY3b (100%)
- UCO and other residual oils HVO: WOHY1a (100%)
- Animal fats HVO: TOHY1a (100%)
- Soybean HVO: SYHY1a (10%) and SYHY1b (90%)
- Sunflower HVO: SOHY1a (100%)

Appendix 3. WTW results. MTBE and ETBE (100%). GHG emissions and Energy expended.

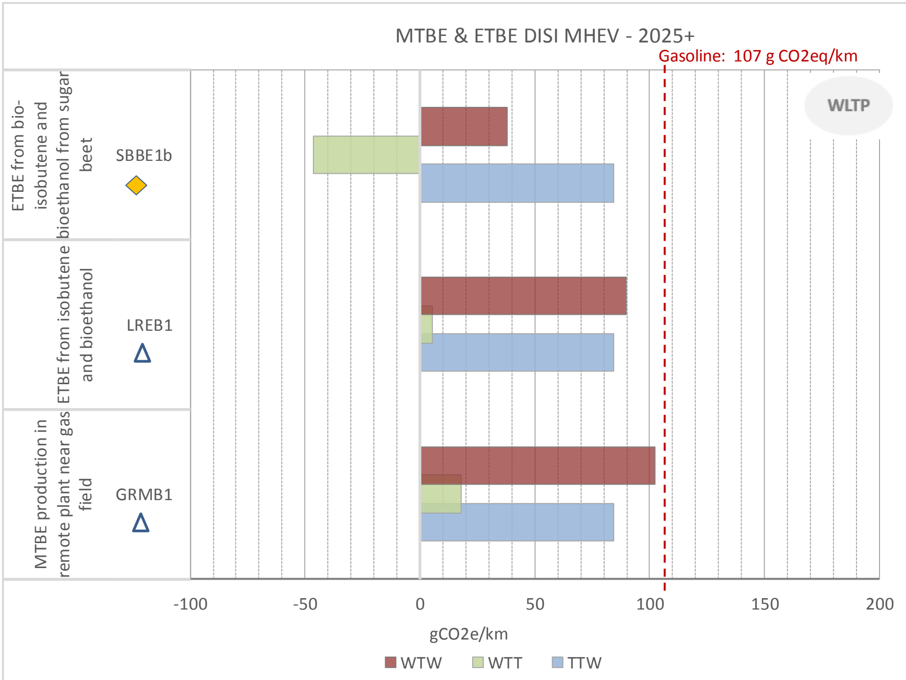


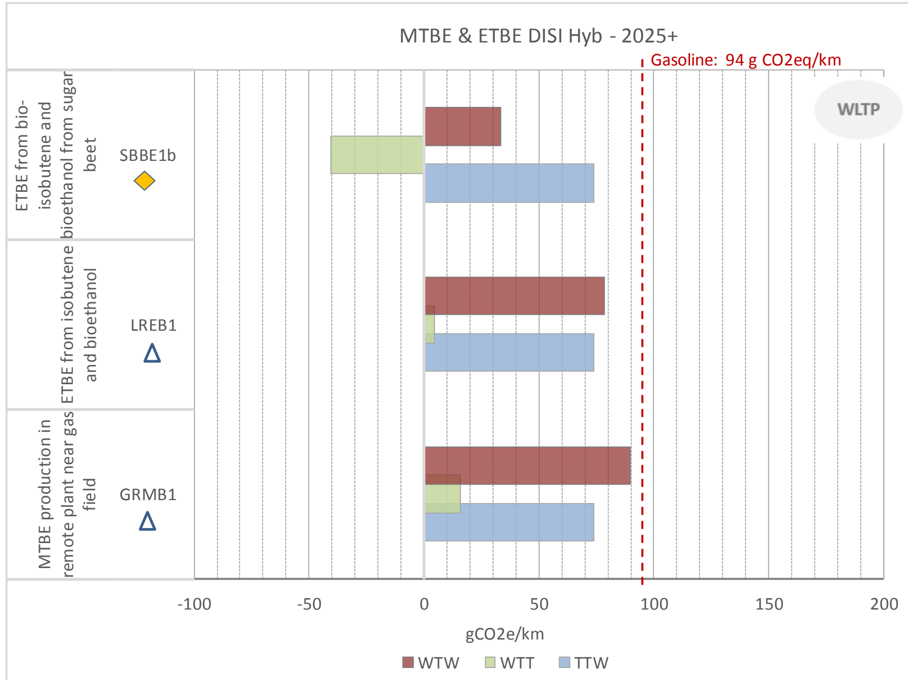
MTBE and ETBE are only used as blending agent for gasoline. However, for the calculation of the GHG emissions MTBE and ETBE have been treated as neat fuels for comparison with conventional crude oil-based gasoline.

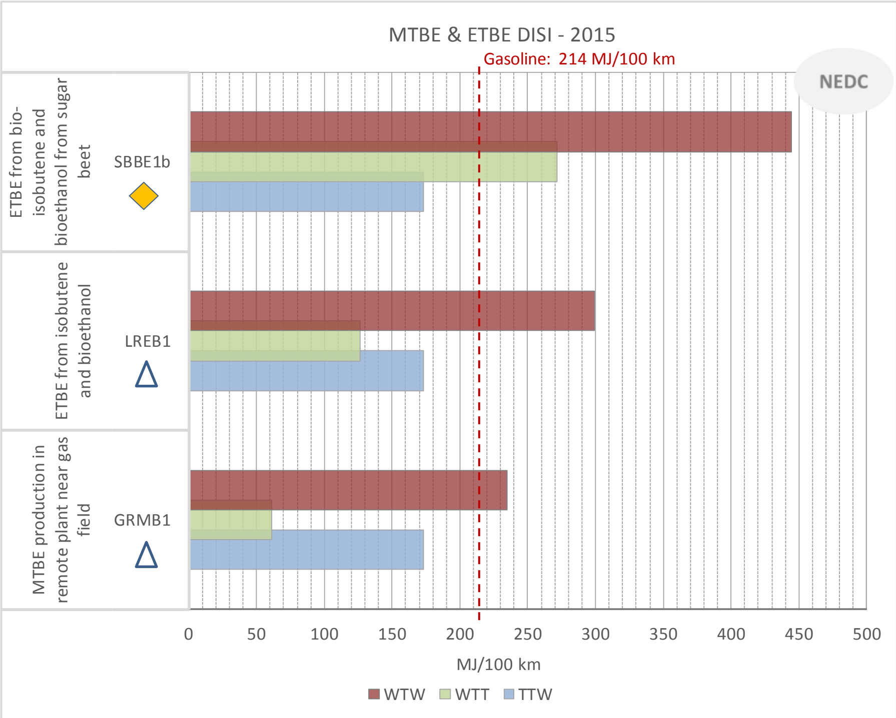
The methanol for MTBE production is derived from natural gas, the isobutene from natural gas processing, isomerization of butane and downstream conversion to isobutene. The GHG emission savings amounts to about 4% mainly due to the lower carbon content of natural gas and butane compared to crude oil.

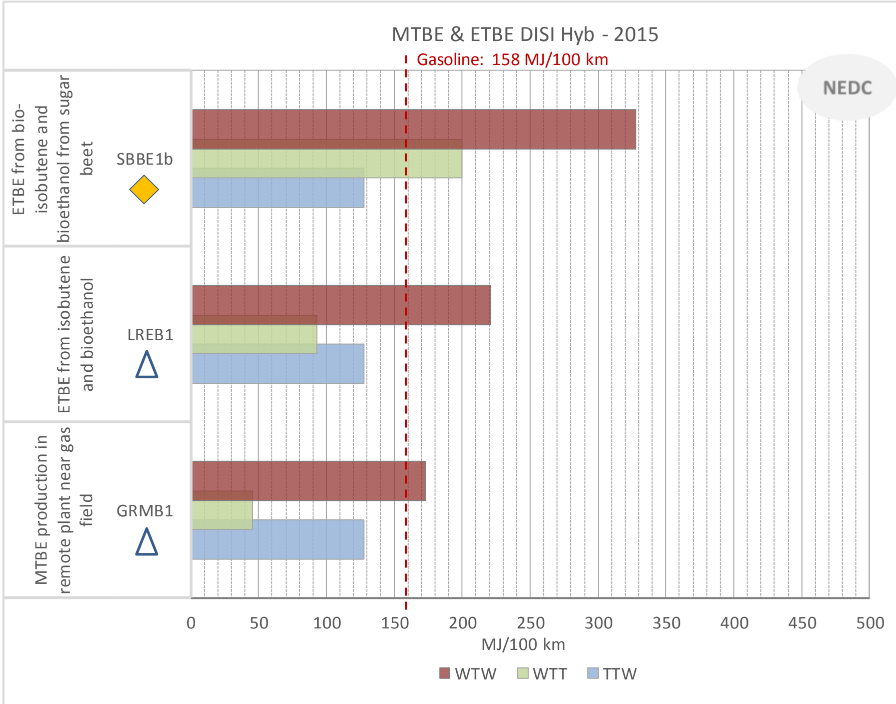
The GHG emissions savings for ETBE using fossil isobutene and ethanol from wheat amount to about 15%.

If both ethanol and isobutene are derived from sugar beet, significant GHG savings of about 75% can be achieved.

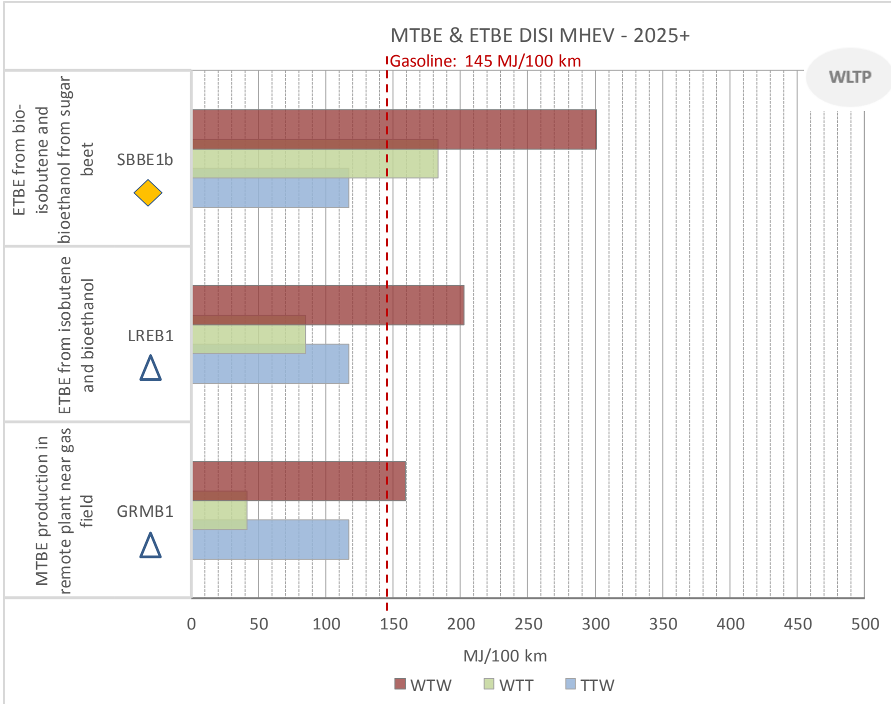


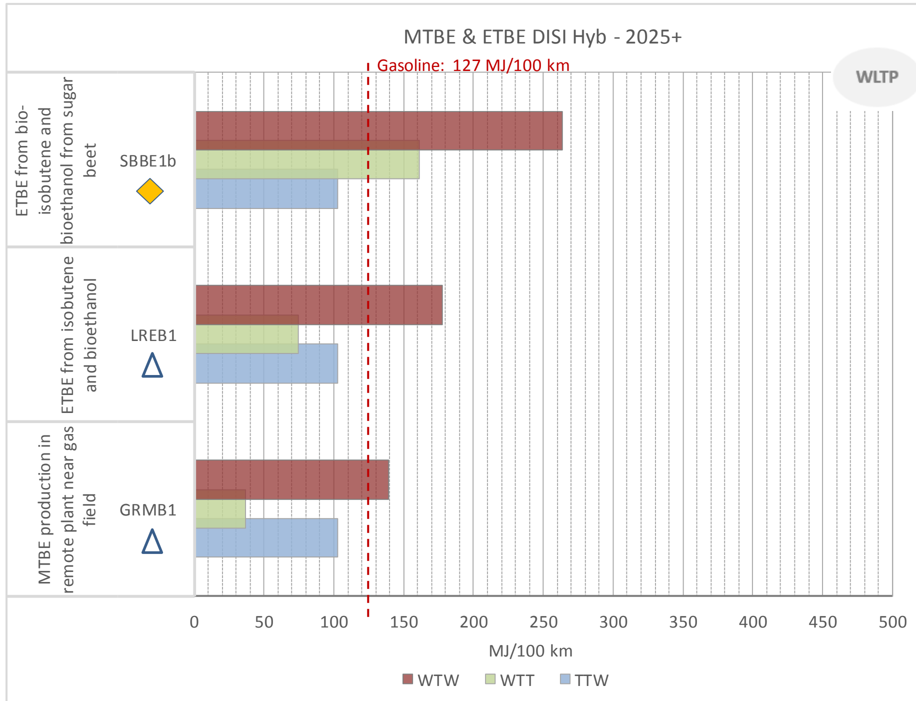



MTBE & ETBE DISI - 2015
Gasoline: 214 MJ/100 km
NEDC
ETBE from bio-isobutene and bioethanol from sugar beet
SBBE1b
ETBE from isobutene and bioethanol
LREB1
MTBE production in remote plant near gas field
GRMB1
0 50 100 150 200 250 300 350 400 450 500
MJ/100 km
WTW WTT TTW


MTBE & ETBE DISI Hyb - 2015
Gasoline: 158 MJ/100 km
NEDC
ETBE from bio-isobutene and bioethanol from sugar beet
SBBE1b
ETBE from isobutene and bioethanol
LREB1
MTBE production in remote plant near gas field
GRMB1
0 50 100 150 200 250 300 350 400 450 500
MJ/100 km
WTW WTT TTW


MTBE & ETBE DISI - 2025+
Gasoline: 174 MJ/100 km
WLTP
ETBE from bio-isobutene and bioethanol from sugar beet
SBBE1b
ETBE from isobutene and bioethanol
LREB1
MTBE production in remote plant near gas field
GRMB1
0 50 100 150 200 250 300 350 400 450 500
MJ/100 km
WTW WTT TTW


MTBE & ETBE DISI MHEV - 2025+
Gasoline: 145 MJ/100 km
WLTP
ETBE from bio-isobutene and bioethanol from sugar beet
SBBE1b
ETBE from isobutene and bioethanol
LREB1
MTBE production in remote plant near gas field
GRMB1
0 50 100 150 200 250 300 350 400 450 500
MJ/100 km
WTW WTT TTW


MTBE & ETBE DISI Hyb - 2025+
Gasoline: 127 MJ/100 km
WLTP
ETBE from bio-isobutene and bioethanol from sugar beet
SBBE1b
ETBE from isobutene and bioethanol
LREB1
MTBE production in remote plant near gas field
GRMB1
0 50 100 150 200 250 300 350 400 450 500
MJ/100 km
WTW WTT TTW

List of abbreviations and definition

BEV	Battery Electric Vehicles
BECCS	Bioenergy with CO_2 Capture and Storage
BTL	Biomass-To-Liquids: denotes processes to convert biomass to synthetic liquid fuels, primarily diesel fuel
CAP	Common Agricultural Policy (of the European Union)
CAPEX	Capital Costs
CBM	Compressed Bio-Methane
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture & Storage
CCU	Carbon Capture and Utilisation
CEV	Catenary Electric Vehicle
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2eq}	CO_2 equivalent
Concawe	the scientific body of the European Refiners' Association for environment, health and safety in refining and distribution
CRL	Commercial Readiness Levels
CTL	Coal-To-Liquids
DDGS	Distiller's Dried Grain with Solubles: the residue left after production of ethanol from wheat grain
DICI	Direct Injection Compression Ignition
DISI	Direct Injection Spark Ignition
DLUC	Direct Land Use Change
DME	Di-Methyl-Ether
e-DME	e-Dimethyl Ether
ED95	Ethanol based fuel for diesel engines
EEA	European Environment Agency
e-OME	e-Oxymethyl Ether
ETBE	Ethyl-Tertiary-Butyl Ether
ETS	Emissions Trading Scheme
EU	European Union
EUCAR	the European council for Automotive Research and development
EU-mix	European average composition of a certain resource or fuel, typically used to describe natural gas, coal and electricity
EV	Electric Vehicles
FAEE	Fatty Acid Ethyl Ester
FAME	Fatty Acid Methyl Ester

FCEV	Fuel Cell driven Electric Vehicle
FCEV	Fuel Cell Hydrogen Electric Vehicle
FT	Fischer-Tropsch: process that converts syngas to linear hydrocarbons
GHG	Greenhouse Gas
GTL	Gas-To-Liquids
HDV	Heavy Duty Vehicles
HEV	Hybrid Electric Vehicle
HFO	Heavy Fuel Oil
HOP	High Octane gasoline
HTL	Hydrothermal Liquefaction
HVO	Hydrotreated Vegetable Oils
ICE	Internal Combustion Engines
IEA	International Energy Agency
ILUC	Indirect Land Use Change
JEC	JRC, EUCAR, and Concawe
JRC	Joint Research Centre (of the European Commission)
LBM	Liquefied Bio-Methane
LBST	Ludwig-Bölkow-Systemtechnik GmbH
LCA	Life-Cycle Assessment
LH_2	Liquid (or Liquefied) Hydrogen
LHV	Lower Heating Value ('Lower" indicates that the heat of condensation of water is not included)
LNG	Liquefied Natural Gas
LSNG	Liquefied Synthetic Natural Gas
LPG	Liquefied Petroleum Gas
LV	Low Voltage
MIT	Massachusetts Institute of Technology
MHEV	Mild Hybrid Electric Vehicle (48v)
MTBE	Methyl-Tertiary-Butyl Ether
N	Nitrogen
NEDC	New European Driving Cycle
N_2O	Nitrous Oxide
NExBTL®	Neste Renewable Diesel, Proprietary technology for producing renewable diesel (Neste Oil)
NG	Natural Gas
NO_x	Nitrogen Oxides emitted from vehicles and combustion sources
OME	Oxymethylene dimethyl Ether
OPEX	Operational Costs
PC	Passenger Cars
PEG	Polyethylene Glycol

PHEV	Plug In Hybrid Electric Vehicle
PI	Positive Ignition
PO	Palm Oil
POME	Palm Oil Methyl Ester
RED	Renewable Energy Directive
REE	Rapeseed Ethyl Ester
REEV	Range Extender Electric Vehicle
RESx	Renewable Electricity
RME	Rapeseed Methyl Ester: biodiesel derived from rapeseed oil (colza)
SLNG	Synthetic Liquefied Natural Gas
SNG	Synthetic Natural Gas
SOEC	Solid Oxide Electrolysis Cells
TRL	Technology Readiness Levels
TTW	Tank-to-Wheels
VECTO	Vehicle Energy Consumption Calculation Tool
WLTP	Worldwide harmonized Light vehicles Test Procedure
WTT	Well-To-Tank: the cascade of steps required to produce and distribute a fuel (starting from the primary energy resource), including vehicle refuelling
WTW	Well-To-Wheels: the integration of all steps required to produce and distribute a fuel (starting from the primary energy resource) and use it in a vehicle
xEVs	Electricity driven powertrains (xEVs)

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