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Research Paper

Energy use and greenhouse gas emissions of traction alternatives for regional railways

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ABSTRACT

This paper presents a method for estimating Well-to-Wheel (WTW) energy use and greenhouse gas (GHG) emissions attributed to the advanced railway propulsion systems implemented in conjunction with different energy carriers and their production pathways. The analysis encompasses diesel-electric multiple unit vehicles converted to their hybrid-electric, plug-in hybrid-electric, fuel cell hybrid-electric or battery-electric counterparts, combined with biodiesel or hydrotreated vegetable oil (HVO) as the first and second generation biofuels, liquefied natural gas (LNG), hydrogen and/or electricity. The method is demonstrated using non-electrified regional railway network with heterogeneous vehicle fleet in the Netherlands as a case. Battery-electric system utilizing green electricity is identified as the only configuration leading to emission-free transport while offering the highest energy use reduction by 65–71% compared to the current diesel-powered hybrid-electric system. When using grey electricity based on the EU2030 production mix, these savings are reduced to about 27–39% in WTW energy use and around 68–73% in WTW GHG emissions. Significant reductions in overall energy use and emissions are obtained for the plug-in hybrid-electric concept when combining diesel, LNG, or waste cooking oil-based HVO with electricity. The remaining configurations that reduce energy use and GHG emissions are hybrid-electric systems running on LNG or HVO from waste cooking oil. The latter led to approximately 88% lower WTW emissions than the baseline for each vehicle type. When produced from natural gas or EU2030-mix-based electrolysis, hydrogen negatively affected both aspects, irrespective of the prime mover technology. However, when produced via green electricity, it offers a GHG reduction of approximately 90% for hybrid-electric and fuel cell hybrid-electric configurations, with a further reduction of up to 92–93% if combined with green electricity in plug-in hybrid-electric systems. The results indicate that HVO from waste cooking oil could be an effective and instantly implementable transition solution towards carbon–neutral regional trains, allowing for a smooth transition and development of supporting infrastructure required for more energy-efficient and environment-friendly technologies.

1. Introduction

Approximately one-quarter of the total greenhouse gas (GHG) emissions emitted in the European Union (EU) are attributed to transport, with climate neutrality for this sector requiring a 90% reduction of its emissions by 2050 [1]. A modal shift from road and aviation to rail is one of the main instruments in achieving this goal, with further synergetic electrification of railways and electricity production from renewables [2]. The national railway network in the Netherlands features one of the highest electrification rates in the EU, with over 75% electrified lines [3] and traction electricity claimed to be completely produced from wind power [4]. In 2018, electricity accounted for 85% of the total energy demand in the Dutch railway sector [5]. The remaining 15% is attributed mainly to diesel trains operating on non-electrified regional lines, for which passenger transport accounted for an estimated 55–60% of total diesel consumption [6]. Considering the scale and high utilization of the Dutch railway network, even when the share of diesel traction is relatively low, the resulting GHG emissions are in the order of millions of kilograms per year. New railway technologies allow the reduction of these emissions; however, finding the most suitable solution imposes a

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significant challenge to railway undertakings (RUs) and policy makers. The fair evaluation of solutions requires assessment methods that capture the complexities of railway systems, including the dynamic interlinks between infrastructure and operations, context-specific information in the decision making process, and involvement of multiple stakeholders.

Due to the relatively low utilization of regional lines, complete electrification is often not economically viable. In addition, the planning and construction phases can take several years or even decades [7]. Therefore, solutions for improving energy efficiency and reducing GHG emissions are being sought in advanced catenary-free propulsion systems and alternative low-carbon fuels. The former primarily relates to vehicle hybridization with intelligent energy storage systems (ESSs) that allow the utilization of braking energy by traction and auxiliary systems, which results in reduced energy use and produced emissions [8]. Similar to the automotive sector's long-term strategy to completely phase-out internal combustion engines (ICEs), several established manufacturers rolled-out fuel-cell multiple unit (FCMU) and battery-electric multiple unit (BEMU) vehicles into the rail market [9]. Although these vehicles allow for (locally) emission-free train operation, their readiness to operate on existing networks is subjected to local requirements and constraints [10].

In addition to the advanced energy-efficient powertrains, the use of alternative fuels aims to reduce emissions from direct combustion and those related to their production and supply. A number of alternatives to fossil diesel have emerged in the transport sector, including first and second-generation biofuels, hydrogen, and synthetic or e-fuels [11]. Despite the variety of novel propulsion systems and energy carriers, more studies are needed on energy use and environmental impacts from their synergetic implementations in the railway sector. In the railway literature, different methods have been proposed, including *meta*-analyses [12], top-down approaches [13], and the application of high-level models [14]. However, to the best of our knowledge, a method that also includes both the complexity of the advanced propulsion systems and the local conditions that pertain to the particular geographical scope or use case is not yet available. Relaxing conservative assumptions such as uniform conditions or including the analysis of potentially influential factors such as infrastructure characteristics and ambient conditions are needed to avoid biased conclusions.

This paper focuses on the Northern lines in the Netherlands (in Dutch, *Noordelijke lijnen*), a common name for the seven non-electrified railway lines that constitute the regional rail network in the provinces of Friesland and Groningen. Arriva, Dutch largest regional RU, operates passenger trains on the network. As part of the new 15-year concession that started in December 2020, the RU committed to significantly reduce the overall GHG emissions on the network [15]. Near-term solutions include gradual retrofitting and hybridization of existing diesel-electric multiple units (DEMUs) [16] and the introduction of new bi-mode hybrid vehicles with ICEs compatible with hydrotreated vegetable oil (HVO) [17]. Given the range of available propulsion system technologies, energy carriers, and their production pathways, it is essential to understand the overall energy demand and GHG emissions attributed to each alternative. This information would enable a consistent and credible comparative analysis, which is crucial in policy decision-making and long-term planning of energy efficient and low- or zero-emission regional railway transport.

2. Literature review

Various approaches are used in assessing energy use and GHG emissions from transport, differing in scope, background methods, and assumptions. In this section, a review of the literature on different approaches is provided, focusing primarily on railway transport.

Life Cycle Assessment (LCA), as the most thorough method, encompasses the entire life cycle of a product, process, or activity, typically starting with the raw materials extraction and treatment, followed by construction/manufacture, operation, maintenance, down to end-of-life processes [18]. Traditionally product-oriented, LCA can provide a set of environmental impact indicators such as global warming potential, ozone depletion, human toxicity, and acidification [19]. With local specifications typically not considered and assumed uniform conditions, assessing GHG emissions in such analysis could lead to biased conclusions, as they highly depend on the context and the case-specific energy sources [20].

While in some cases, the construction-related processes of railway infrastructure led to considerable environmental impacts [21,22], several LCA studies showed that GHG emissions that result from train production, maintenance, recycling and/or disposal usually have minor contribution when compared to the train operation stage [23–26]. This is mainly due to the relatively long service life of railway vehicles, which typically spans thirty or more years, and the required infrastructure considered as already in place. However, the emergence of advanced powertrains in the transport sector and new technologies such as Lithium-ion batteries and hydrogen fuel cells stipulate the need for further investigation of the environmental implications of their production and deployment. The knowledge of the life cycle impacts of these emerging technologies in heavy-duty transport, especially in the railway sector, is still very limited. While the literature presented diverse results for the automotive sector [27], studies on heavy-duty transport report that the emerging powertrains lead to lower life cycle emissions than the conventional diesel ones, with the relative contribution of each life cycle stage depending on the particular use case.

Regarding hybridized regional DEMU vehicles, which are the main subject in this paper, an LCA study by Meynerts et al. [28] on hybridized diesel vehicle with and without additional recharging stations showed that the operation phase accounts for the largest portion of emissions released over the life cycle of vehicles. They reported a negligible impact from the production phase, mainly attributed to the battery production. The authors suggest that further progress could be made by increasing the efficiency in braking energy utilization and using green electricity for battery recharging. Kapetanović et al. [29] estimated and compared life cycle GHG emissions of different powertrain technologies in regional two-coach multiple unit vehicles employed on a selected railway line. Using a standard vehicle powered by the two 390 kW diesel ICEs as a benchmark, fuel cell hybrid-electric vehicle equipped with a 420 kW fuel cell system and a 196 kWh Lithium-ion battery pack provided the reduction of overall emissions by 9.7% and 96.8%, for hydrogen obtained from natural gas and green electricity-based electrolysis, respectively. The emissions attributed to the production of fuel cells and batteries contributed to less than 1% and 23.9% in the first and second scenarios, respectively. The battery-electric vehicle powered by a 619 kWh battery pack provided 77.1% lower emissions when utilizing grey electricity, with electrification and battery production contributing 17.8% of overall emissions. When running on green electricity, this system provides a 95.9% cut in emissions. Regarding other heavy-duty applications, Booto et al. [30] performed an LCA of a conventional diesel, hydrogen fuel cell, and battery-electric heavy-duty road vehicle in Norway. The study indicated the best environmental performance for the battery-electric truck (0.286 $kgCO_2e/km$), followed by the fuel cell truck (0.477 $kgCO_2e/km$), and the conventional truck exhibiting the highest global warming potential (GWP) score (0.907 $kgCO_2e/km$). For conventional vehicles, the fuel production and distribution phase contributed 23.97%, and the fuel use phase contributed 65.32% of the overall emissions. For fuel cell vehicles, the fuel production and distribution contribution was 65.95% and 16.77% of the assembly-production phase. Due to the use of green electricity, the dominant life cycle stages for battery-electric vehicles are assembly production (26.81%) and battery pack production (58.68%). Trillos et al. [31] estimated that using hydrogen derived from wind energy in a hybrid fuel cell system for a RoPax ferry reduced life cycle GHG emissions by up to 89% compared with a conventional diesel ferry. While the relative contribution of novel technology production and end-of-life processes varies between different heavy-duty applications, it can be noted that the overall emissions mainly depend on the production and direct use of fuel or electricity, namely to the vehicle operation stage.

A Well-to-Wheel (WTW) approach is a sub-class of the LCA, focusing on the vehicle operation phase and the life cycle of an energy carrier (e.g., diesel, electricity), commonly referred to as the fuel cycle. A WTW analysis is subdivided into the Well-to-Tank (WTT) phase, related to the production and distribution pathway of an energy carrier, and the Tank-to-Wheel (TTW) phase, linked to the energy expended and tailpipe emissions released directly by the vehicle over its drive cycle. Therefore, a clear distinction is made between the energy use and GHG emissions attributed to the primary energy source and the vehicle powertrain efficiency [20]. In contrast to the LCA approach, in which vehicle upstream and end-of-life stages are influenced by the processes of external parties, e.g., vehicle manufacturers, the WTW system boundary reflects the sphere of influence of transport operators where they can actively influence energy use and GHG emissions, for instance by employing novel propulsion systems and/or alternative transport fuels [32]. Moreover, European and global standards such as EN16258 [33] and ISO 14083 [34] stipulate the WTW system boundary in calculating and declaring energy use and GHG emissions from transport while excluding other vehicle life cycle stages. Therefore, this study limits its analysis to the WTW system boundary.

Extensive research on WTW energy use and GHG emissions linked to alternative powertrain configurations and transport fuels has been carried out for cars [35–37], buses [32,38–40] and heavy-duty road transport [41–43]. However, only a few studies have considered the railway sector.

Hoffrichter et al. [12] evaluated WTW energy efficiency and CO_2 emissions linked to the electricity-, diesel- and hydrogen-powered trains using existing estimations in the literature and *meta*-analysis for each energy pathway component. They found that a fuel cell system running on hydrogen as a compressed gas obtained by steam methane reforming (SMR) features a WTW efficiency of 25%, comparable to diesel and electric scenarios in the UK and US. They suggest that the mentioned hydrogen fuel cell alternative could contribute to a CO_2 emissions reduction of approximately 19% compared to the diesel scenario and about 3% compared to US electricity. The case of diesel-based propulsion demonstrated that alternatives featured by a high WTW efficiency do not necessarily account for low emissions.

Esters and Marinov [44] analyzed different resistance-based methods for calculating emissions for various train types in the UK (conventional, high-speed, and freight) and propulsion systems (diesel, electric, and bi-mode). The results for a trip on a hypothetical flat and straight track indicated that diesel trains feature lower emissions compared to their electric counterparts as a consequence of the high carbon intensity of the electricity in the UK. Despite time efficiency, high-speed trains release more emissions due to the energy use being proportional to the square of speed. The authors also predict redundancy of bi-mode trains in the future, keeping in mind the electrification trends, and recommend biodiesel (blends) as an alternative to diesel fuel.

Gangwar and Sharma [13] quantified the WTW emissions for diesel- and electricity-powered locomotives in India. Their study identified higher accumulated emissions for electric locomotives due to predominantly coal-based electricity production. The authors highlight the requirement of a well-balanced mix of both traction alternatives by considering different aspects such as environmental efficiency, economic sustainability, and equity.

Washing and Pulugurtha [45] estimated WTW efficiencies of electric and hydrogen light rail in Charlotte, North Carolina (US). A fuel cell vehicle running on SMR-produced hydrogen showed WTW efficiency of 16.6–19.6%, while electric trains featured WTW efficiency of 25.3%. The authors attribute this difference to the inefficiencies of the fuel cell system and hydrogen production process and the significantly lower feedstock energy required by the electric trains. The study also confirmed the substantial influence of the main electricity production source on the efficiency of the electric train by observing other regions, i.e., 24.6% in Cleveland, Ohio (predominantly coal-based) and 50.3% in Portland, Oregon (predominantly hydroelectric power).

Zhang et al. [46] presented a techno-economic study of ammonia-powered fuel cell freight train as an alternative to the current diesel engine-based system and emerging hydrogen fuel cell system. Results for a train running on a freight line in the UK showed that ammonia has a feasible potential as fuel for freight rail, with the ammonia fuel storage requiring 61.5–75% less space compared to the hydrogen storage. The solid oxide fuel cells (SOFCs) powertrain demonstrated the highest electricity generation efficiency reaching 56%, however, the overall cost requires a major reduction by 70% before it could be considered as an economically viable solution. The authors indicate that brown ammonia-fueled trains could reduce WTW carbon emissions by 66% compared to the diesel baseline.

Several studies analyzed the environmental impacts of alternative traction options for diesel trains while limiting their scope to the TTW stage. Carvalhaes et al. [47] presented a method to measure freight locomotives' eco-efficiency by evaluating energy use, emissions and costs, using one of the Brazilian rail corridors as a case study. The comparative analysis is based on historical measurement data by considering different combinations of biodiesel blends (B5 and B25) and liquefied natural gas (LNG). Optimal results were obtained for the scenario that mixes the use of both biodiesel B25 and LNG with CO_2 savings of 32% compared to the B5 benchmark. However, the study considers only direct emissions (TTW), neglecting the emissions generated during production of the fuel.

Luque et al. [48] proposed a predictive model to estimate the emissions impact of LNG use as alternative to diesel on different rail routes or networks. The model was fitted with real data obtained from pilot tests using a train with two engines, one diesel and the other LNG. The methodology was applied to evaluate the impact on consumption and direct (TTW) emissions of the two fuels on a narrow-gauge commuter line in Spain. The study concluded that LNG engine produces lower direct CO_2 emissions, higher CO emissions, and lower emissions of other pollutants (nitrogen oxide and particles) by several orders of magnitude compared to the diesel counterpart.

Aredah et al. [49] presented a simulation-based assessment of TTW energy efficiency and CO_2 emissions of six powertrain technologies in the US freight rail network, including conventional diesel, biodiesel, diesel-hybrid, biodiesel-hybrid, hydrogen fuel cell, and electric. The study identified electric powertrains as the most energy efficient, reducing TTW energy consumption by 56% compared to traditional diesel, with the potential for zero CO_2 emissions when powered by green energy sources. Biodiesel and biodiesel-hybrid also outperformed conventional diesel, reducing direct CO_2 emissions by 6% and 21%, respectively. Diesel-hybrid and hydrogen fuel cells demonstrated the reduction in TTW energy consumption of 16% and 15%, respectively, with latter also providing zero direct emissions. The authors conclude that implementing these advanced technologies requires considerable infrastructure investment and adaptation, while stipulating the need for further investigation of the financial and environmental implications from the WTW perspective.

The review of prior research revealed several research gaps regarding the assessment of WTW energy use and produced emission in the railway sector. While significant fuel savings from hybridization of diesel trains have been demonstrated in various European projects [50–53] and studies [54–56], environmental aspects of advanced hybrid solutions are limited to the direct impacts from the operation (TTW) stage. Railway-related WTW studies have considered mainly conventional (non-hybrid) powertrain topologies, with considered energy carriers typically limited to biodiesel and/or hydrogen as the only alternatives to diesel fuel. Despite the range of alternative fuels and their production pathways that emerged in the transport sector [57,58], no scientific study on the comparative assessment of WTW energy use and

GHG emissions from the synergetic implementation of advanced (hybrid) propulsion systems and a wider set of alternative energy carriers is available in the railway literature. In assessing the energy consumption, which directly influences the produced emissions, literature has contributed with simulation models such as ARTEMIS [59], EcoTransit [14] and EcoPassenger [60]. However, these models do not include hybrid configurations, featuring multiple power sources, their interaction, and simultaneous operation. Moreover, prior analyses are often conducted for a hypothetical use case or a single existing railway line and vehicle, hindering the applicability of obtained conclusions in wider contexts. Analysis of real-world cases requires consideration of numerous local factors that influence vehicle performance, such as track geometry, scheduled running times, passenger load, ambient conditions, and others, while explicitly accounting for the degree of variability in corresponding parameters.

This paper aims to fill the identified research gaps while considering the present geographical and use case context and provides the following contributions to the scientific literature and practice:

(i) A comparative analysis of implementations of various advanced (hybrid) propulsion systems combined with prominent low-emission energy carriers while including commercially mature and novel technologies and energy carrier production pathways.
(ii) The analysis and developed framework adopts a bottom-up approach, with direct fuel and/or electricity consumption estimated via a high-fidelity simulation model that captures relevant factors influencing direct energy use and, thus, the resulting overall energy demand and emissions.
(iii) The proposed method is applied to the real-world case of regional rail passenger transport in the Netherlands, including a heterogenous vehicle fleet and an entire railway network. Energy carriers pathways and emission factors relevant to European and Dutch contexts are used, providing the RU and policy-makers with new essential information for planning future rolling stock and infrastructure investments.
(iv) Lastly, new estimates of primary energy use and GHG emissions are obtained, which can benefit future research, especially in comparable cases when detailed vehicle, infrastructure and/or operational parameters are unavailable.

3. Materials and methods

This paper proposes a comparative assessment of energy demand and produced GHG emissions from implementing advanced propulsion systems combined with various alternative energy carriers in the regional railway transport. The following subsections provide a description of the general framework developed for assessing energy use and GHG emissions, the considered alternative propulsion systems including their modelling and control, the considered energy carriers and their production pathways, and external factors that influence the vehicle performance.

3.1. *Framework for the assessment of overall energy use and greenhouse gas emissions*

For assessing the overall energy use and produced GHG emissions, a WTW analysis is applied, allowing for a fair comparison between different scenarios by accounting for the energy use and emissions linked to both stages of WTT (energy carrier producing and distributing, e.g., from the feedstock extraction/harvesting to the fuelling station and/or pantograph) and TTW (energy use in the train during operation, e.g., from the onboard fuel storage system, pantograph and/or battery system to the motion power at the wheel). A WTW analysis is an effective tool for assessing the magnitude of the impact of measures instituted by decision-makers in a regional railway transport system (e.g., RUs), particularly for the estimation of energy use and GHG emissions reduction.

The WTW analysis in this paper adopts a consumption-based approach [33,61,62]. In this approach, the energy demand and GHG emissions are calculated from the fuel or electricity consumed in a vehicle operation, i.e., by multiplying the given amount with the corresponding energy and emission factors, respectively. To compare different energy carriers, the quantity of the energy used is expressed in a common unit of megajoule (MJ), while the quantity of GHG emissions is expressed in kilograms of CO_2 equivalents ($kgCO_2e$), accounting for the impact of all the main GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [63]. With the measured or estimated fuel and/or electricity consumption, energy use and GHG emissions can be computed using the following relationships:

$$E_s = \sum_{i=1}^{n} C_i \cdot e_{s,i} \tag{1}$$

$$GHG_s = \sum_{i=1}^{n} C_i \cdot g_{s,i} \tag{2}$$

where

E_s is the energy demand related to a particular scope $s \in \{\text{WTT}, \text{TTW}, \text{WTW}\}$, expressed in MJ, where $E_{\text{WTW}} = E_{\text{WTT}} + E_{\text{TTW}}$;
C_i is the estimated powertrain consumption of energy carrier i during a trip, expressed in liters (l) for liquid fuels, kilograms (kg) for gaseous fuels, and kilowatt hours (kWh) for electricity;
$e_{s,i}$ is the energy factor related to a scope s and energy carrier i, expressed in MJ/l, MJ/kg and MJ/kWh for liquid fuels, gaseous fuels, and electricity, respectively, and where $e_{\text{WTW},i} = e_{\text{WTT},i} + e_{\text{TTW},i}$;
GHG_s is the produced GHG emissions related to a scope s, expressed in $kgCO_2e$, where $GHG_{\text{WTW}} = GHG_{\text{WTT}} + GHG_{\text{TTW}}$;
$g_{s,i}$ is the GHG emissions factor related to a scope s and energy carrier i, expressed in $kgCO_2e$/l, $kgCO_2e$/kg and $kgCO_2e$/kWh for liquid fuels, gaseous fuels, and electricity, respectively, where $g_{\text{WTW},i} = g_{\text{WTT},i} + g_{\text{TTW},i}$;
n is the total number of energy carriers used for train propulsion (maximum 2 in this study).

While the consumption-based approach is straightforward in ex-post evaluations for the transport that took place already with fuel consumption known, assessment of energy demand and emissions for potential future solutions requires the application of reliable forecasting models. This process is especially challenging for hybrid propulsion systems due to the simultaneous operation of multiple power sources. Therefore, this study proposes implementing a comprehensive simulation model for assessing the direct fuel and/or electricity consumption from train operation (TTW stage), which is then used to calculate primary (WTW) energy use and GHG emissions.

The methodological framework for estimating WTW energy use and GHG emissions is provided in Fig. 1, with arrows indicating the information flow and/or computation sequence. The simulation model captures the main factors that affect vehicle dynamics and provides cumulative fuel and/or electricity consumption during the trip as the main output. The required inputs include rolling stock data (technical specifications of the vehicle and system components, implemented onboard energy management strategy), infrastructure characteristics (speed limits, track geometry, electrification status), train operation attributes (timetable and vehicle circulation plan), and external factors (vehicle occupancy and ambient conditions). The obtained direct fuel and/or electricity consumption is then coupled with corresponding energy use and GHG emissions factors using (1)-(2) to compute the energy use and GHG emissions linked to each TTW and WTT stage. Finally, the overall WTW energy use and produced GHG emissions are given as the

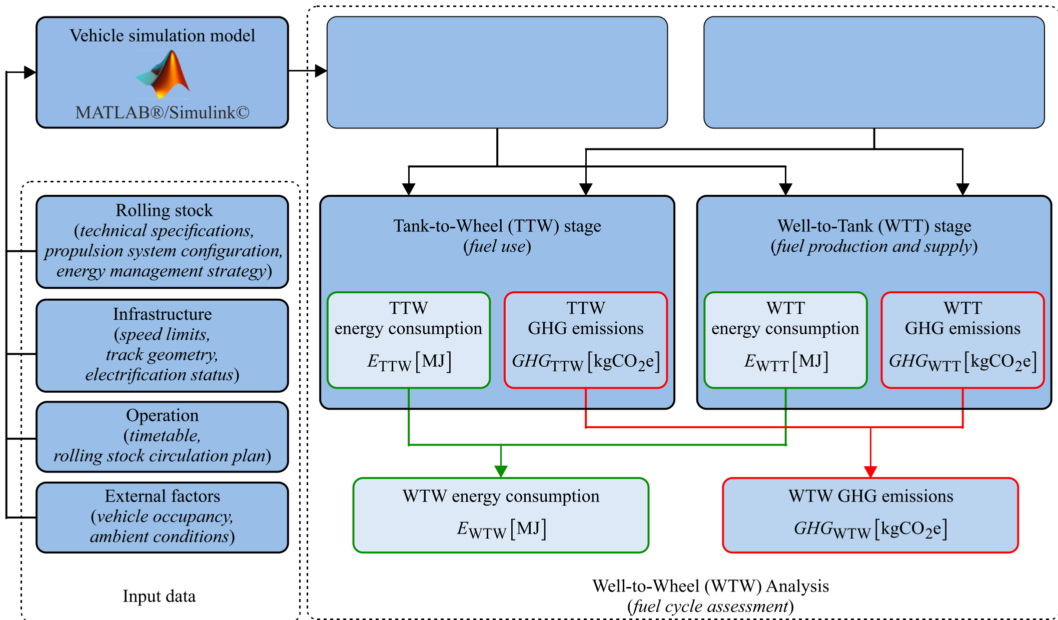

Fig. 1. Methodological framework for the assessment of Well-to-Wheel energy use and greenhouse gas emissions of regional trains.

sum of the TTW and WTT estimates.

3.2. *Alternative propulsion systems*

In general, a propulsion system represents a set of different components that, through their interaction, provide motion power to the wheels [64]. This study focuses on diesel-electric multiple unit vehicles as the baseline, featuring a serial topology and electric transmission system in place. The presence of a DC link between the prime mover (i.e., engine-generator unit, EGU) and the electric motor allows for relatively simple hybridization and/or customization of the propulsion system configuration by adding and/or removing the power sources. Table 1 provides an overview of analyzed alternative systems, with indicated corresponding power sources. Considered alternatives to a conventional diesel-electric system are hybrid-electric, plug-in hybrid-electric, fuel cell hybrid-electric, and battery-electric. Fig. 2 shows the simplified schematic layouts of the five configurations considered in this paper.

In a *conventional (diesel-electric)* system used as a baseline (Fig. 2a), the EGU (ICE coupled with an AC electric generator) supplies an AC electric traction motor via a rectifier and an inverter, as well as the auxiliary onboard consumers such as heating, ventilation and air conditioning (HVAC) systems, lighting, compressors, etc. The gearbox located at the drive shaft transmits the output mechanical power of the motor to the wheels at a constant transmission ratio. In this system, regenerated braking energy provided by the motor is completely dissipated at the braking resistors, typically mounted on the roof of the vehicle.

Conversion to its *hybrid-electric* counterpart (Fig. 2b) can be achieved by connecting an energy storage system (ESS) to the DC link via a bi-directional DC/DC converter. The ESS enables the recuperation of regenerative braking energy, which can support the ICE in supplying the traction and/or auxiliary consumers, eventually leading to an improved fuel economy compared to conventional (diesel-electric) vehicles. Various ESS technologies, such as batteries, supercapacitors, and flywheels, have emerged in the transport sector, featuring different benefits, limitations, and main applications [65]. Lithium-ion batteries are considered ESS technology in this study due to their rapid technology advancements, market availability, and ongoing implementation in the current Dutch fleet.

A *plug-in hybrid-electric* system (Fig. 2c) requires the installation of a pantograph and accompanying power converter that complies with the electricity type (AC or DC) and voltage of the external grid, and adjusts the input voltage to the DC link. The system expands the functionalities of the aforementioned hybrid-electric system and the benefits of the ESS by providing additional charging directly from the external electric power grid during stabling periods [28]. This potentially contributes to a further improvement of ICE fuel economy and the overall energy use and environmental performance.

A *fuel cell hybrid-electric* system (Fig. 2d) can be obtained by replacing the prime mover in the hybrid-electric system, i.e., EGU and the corresponding AC/DC converter, with the hydrogen fuel cell stack and unidirectional DC/DC converter. Featuring a slow response and low dynamics, fuel cells require the implementation of an ESS that would cover high fluctuations in demanded power for traction and auxiliaries. Since fuel cells cannot absorb energy as ESSs, unidirectional converters protect the fuel cells from the high voltage at the DC link during braking phases by switching off. Hydrogen fuel cells offer various benefits

Table 1
Overview of alternative propulsion systems with corresponding power sources.

Propulsion system	Power source			
	Internal combustion engine	Pantograph (external grid)	Fuel cell system	Energy storage system
Diesel-electric	✓			
Hybrid-electric	✓			✓
Plug-in hybrid-electric	✓	✓		✓
Fuel cell hybrid-electric			✓	✓
Battery-electric		✓		✓

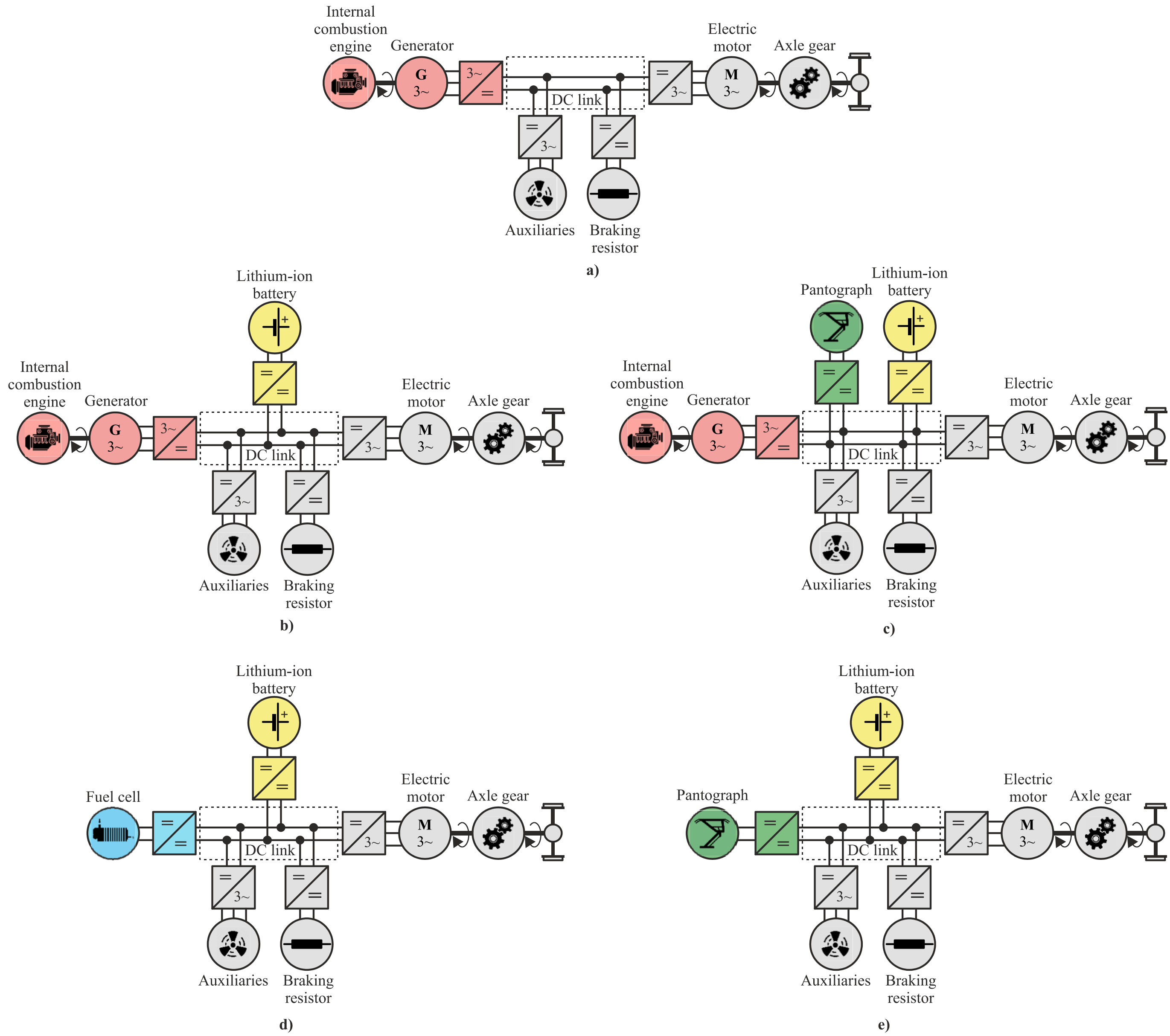

Fig. 2. Schematics for alternative propulsion systems: (a) conventional (diesel-electric), (b) hybrid-electric, (c) plug-in hybrid-electric, (d) fuel cell hybrid-electric, and (e) battery-electric.

compared to the ICE technology, reflected in higher efficiency, reduced noise and eliminated tailpipe emissions (both GHGs and local pollutants) [66].

In a *battery-electric* system (Fig. 2e), the required power is provided either from the external grid via a pantograph, where available, or from the large battery ESS when the train runs on non-electrified track sections. The ESS is recharged from both the external grid and from the regenerative braking energy [9]. Powertrain energy losses are fully attributed to inefficiencies of the electrical components, namely of the ESS, electric motors and power converters, which generally feature higher efficiencies than ICEs and fuel cell systems [7].

Other propulsion system configurations and operation modes, such as bi-mode or three-mode, are not considered, as they are derived from the five scenarios above, with expected estimations yielding within the intervals of the original systems. Furthermore, they would add a new dimension and increase the complexity of the present analysis. For instance, the performance of a bi-mode train (pure diesel vs. pure electric) highly depends on the length of the electrified track sections.

Note that in addition to the main powertrain components, vehicles might also differ in their fuel storage systems, depending on the energy carrier in use. While for liquid fuels such as biofuels, the same fuel tanks as for diesel can be used, gaseous and cryo-compressed fuels require the replacement of conventional fuel tanks with cylinders that comply with the requirements for their storage. The difference in vehicle weight between alternatives due to added and/or replaced components should be explicitly considered in the analysis, as it potentially influences the vehicle dynamics and overall performance.

3.2.1. *Modelling propulsion systems*

A crucial step in assessing the WTW energy demand and GHG emissions is estimating the fuel and/or electricity consumption from train operation, requiring reliable simulation models (c.f., [67–69]). This paper uses a comprehensive simulation model built on a backward-looking quasi-static simulation approach [70]. The model is developed in MATLAB®/Simulink© [71] using the OPEUS Simulink library and simulation tool [72] – an outcome of the knowledge accrued in

European projects MERLIN [73], Cleaner-D [74] and OPEUS [75]. Compared to commercial simulation software such as LMS Imagine.Lab Amesim from Siemens [76], its modular structure and programming environment allowed for relatively easy development or customization of railway vehicle's propulsion system configurations and onboard power management implementation [77]. The model was validated in a number of studies, c.f., Kapetanović et al. [78–80], Leska et al. [81], Meinert et al. [55,56], Prohl and Aschemann [82].

Fig. 3 shows the structure of the backward-looking simulation model, with indicated low-order models of individual components, and the sequence of their evaluation opposed to the direction of the physical power flow. The alternative propulsion systems are simulated by disconnecting power sources not included in the respective system. The model captures technical characteristics and efficiencies of the system components, infrastructure and operation (timetable) attributes, and provides cumulative fuel and/or electricity consumption during the trip as the main output. As one of the main input signals, the energy-optimized velocity profile is pre-calculated using the bi-section algorithm [83]. The algorithm considers optimal transitions between the acceleration, cruising, coasting and braking phases, while complying with the scheduled running times, track geometry and speed limitations, vehicle weight, and maximum tractive/braking effort characteristics. According to the energy management and control strategy (EMCS), the control unit distributes the requested power for traction and auxiliaries between the power sources in place (see Section 3.2.2). For a detailed description of low-order models and implemented dynamic equations, readers are referred to the work of Kapetanović et al. [78–80].

3.2.2. Energy management and control strategy

While estimating system dynamics for conventional (diesel-electric) and battery-electric vehicles is straightforward, the main driver of fuel economy in hybrid vehicles is the implemented EMCS, i.e., how the requested power for traction and auxiliary consumers is distributed between the multiple power sources which operate simultaneously (c.f., [84–87]). To allow for realistic and achievable estimates, the real-time EMCS based on a finite state machine control (FSMC) for hybrid-electric, plug-in hybrid-electric and fuel-cell hybrid-electric vehicles is adopted from Kapetanović et al. [78,80]. FSMCs offer relatively easy programmability of microcontrollers [88], making them especially suited for the control of complex systems such as hybrid vehicle powertrains [89,90].

Adopted FSMC allows the ESS to support the prime mover (EGU or fuel cell system) during high power demand (boost mode), e.g., during acceleration, while avoiding low load operation during coasting phases (load level increase mode), thus improving the overall efficiency of the prime mover. For hybrid-electric trains, it explicitly considers the emission-free and noise-free operation requirement in terminal stops with longer stabling periods by switching off the EGU and supplying the auxiliary systems solely from the ESS during the layover.

To assess the impact of the EMCS on energy performance, an alternative zero-emission station control (ZESC) is introduced. This control is a simplified FSMC and reflects the strategy implemented in the current fleet. It also assumes ESS utilization in supplying the auxiliary systems in terminal stations with the ICE switched off. If needed, the ESS is charged primarily from regenerative braking energy, with additional energy provided from the EGU in the last track sections (load level increase mode). According to this strategy, the ESS provides no active support to the EGU (boost mode) during the vehicle trip. It should be noted that plug-in hybrid-electric, fuel cell hybrid-electric and battery-electric systems, by default, provide emission-free and noise-free trains operation at terminal stops.

3.3. Energy carriers

A range of energy carriers has emerged over the last decade(s) as alternatives to fossil diesel. For the present WTW analysis, the most prominent energy carriers are selected, considering their applicability to the railway sector and with respect to the 15-year analysis perspective. Considered energy carriers include biodiesel, commonly referred to as fatty acid methyl esters (FAME), as the first-generation biofuel; hydrotreated vegetable oil (HVO) as the second-generation biofuel; liquefied natural gas (LNG); hydrogen; and electricity. Although synthetic or e-fuels offer numerous benefits reflected in low emissions, compatibility with current ICE technologies, and no significant infrastructure requirements, they are expected to remain prohibitively expensive until 2050 [91]. Thus, they are omitted in this study.

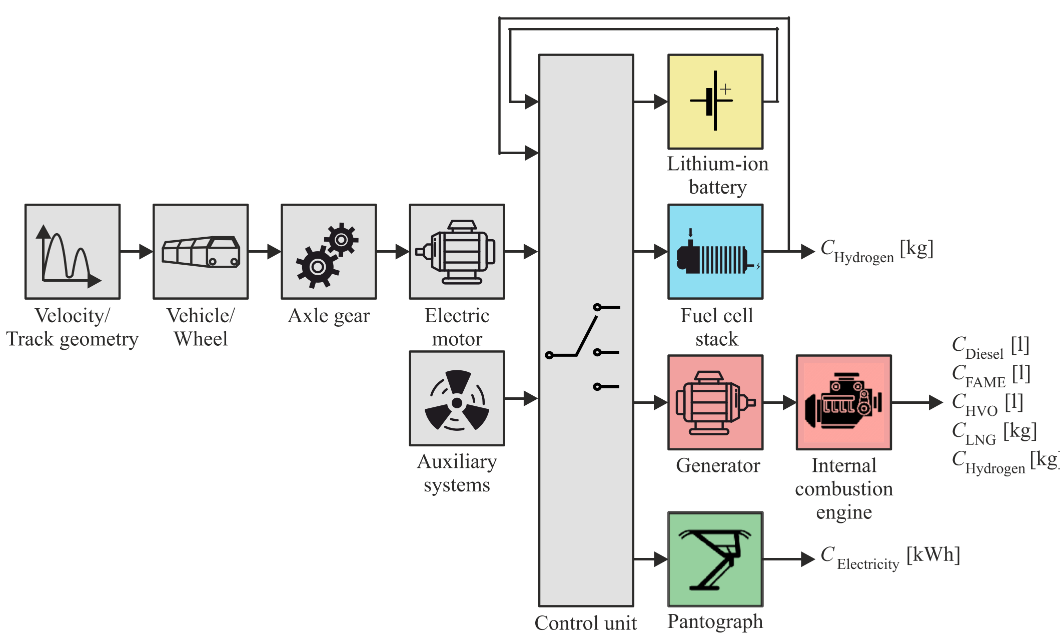

Fig. 3. Structure of the backward-looking quasi-static simulation model for estimating cumulative fuel and/or electricity consumption of alternative propulsion systems.

For deriving the energy use and GHG emission factors for selected energy carriers and corresponding production paths, this study reference the JEC's well-to-wheel report [92,93], as the latest and the most comprehensive source disposable. JEC is a product of collaboration between the European Commission's Joint Research Centre (JRC), European Council for Automotive R&D (EUCAR) and Conservation of Clean Air and Water in Europe (CONCAWE). In contrast to other widely used databases such as the North American GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) [94] and GHGenius [95], or UK's Defra [96], JEC's report encompasses data reflecting energy production pathways in Europe, which are pertinent to our research. Derived energy use and GHG emissions factors for the considered energy carriers are given in Table 2, with indicated primary sources and corresponding production and distribution paths. For comparing the impact of upstream processes for different energy carriers, Fig. 4 shows (a) the WTT energy use per unit of energy content of a final fuel/electricity consumed in the TTW stage, e.g., energy used for the raw material extraction and processing, final fuel production and distribution, and energy losses due to electricity transmission, and (b) GHGs emitted from the use of fossil energy in these processes.

Considered diesel fuel is produced from crude oil from typical EU supply (mainly North Sea, North and West Africa), transported mainly by sea, refined in EU (marginal production), and with typical EU distribution (road tanker, pipeline, train or barge) and retail. Production and conditioning of crude oil at source contributes to about 50% of the overall WTT energy use and produced GHG emissions, followed by the refining processes (about 40%) [93].

Compared to fossil fuels, biofuels are produced from renewable sources such as biomass, significantly reducing overall GHG emissions due to the CO_2 captured by plants during their growth. FAME produced from rapeseed (Rapeseed Methylester) as the main feedstock for biofuels in the EU, with meal export as animal feed, is considered. Rapeseed production, particularly rape cultivation, is a dominant contributor to the WTT GHG emissions, mostly through N_2O emissions associated with nitrogen fertilizer [93].

Although HVO can be produced by deep-hydrotreating oils using the same feedstock as FAME, the use of HVO avoids the detrimental effects of ester-type biofuels [97]. In addition to the rapeseed-based HVO, the alternative production pathway based on processing waste cooking oil is included, which features significantly lower WTT energy demand and GHG emissions (see Fig. 4). HVO produced from waste cooking oil also helps in addressing the land use issues, and is becoming an increasingly used alternative to fossil diesel by public transport companies [98].

Natural gas is the fossil fuel with the lowest GHG emissions, used either as compressed natural gas (CNG) or LNG. We limit our analysis to LNG as a preferred alternative for railway applications due to its advantages related to range, costs, volumetric space and refueling requirements [57,58,99]. LNG produced from remote natural gas liquefied at source (mainly the Arabian Gulf), LNG transported by sea and distributed by road is considered.

Although hydrogen and electricity eliminate tailpipe GHG emissions, their production pathways can significantly reduce the potential benefits of their implementation (see Fig. 4). Hydrogen can be used in both, ICEs [100,101] and fuel cells [66], with steam methane reforming (SMR) and electrolysis of water being the main production alternatives. For the SMR scenario, EU-mix piped natural gas transported by a 1900 km pipeline to the EU and 500 km inside the EU, distributed through high-pressure trunk lines and low-pressure grid, and reformed at the retail site using a small-scale reformer is considered. For the electrolysis scenarios, either medium voltage electricity based on EU production mix for 2030 with retail site electrolysis, or electricity from wind energy with central electrolysis and pipeline transport are analyzed. Finally, hydrogen compression to 88 MPa is considered in all scenarios.

Same as for hydrogen production, medium-voltage grey electricity with a predicted EU production mix for 2030 and green electricity produced from wind power are considered. As shown in Fig. 4, wind power-based electricity is the only energy carrier that features net-zero GHG emissions while offering the lowest WTT energy use, resulting mainly from the distribution losses in the grid.

4. Case study of the Dutch Northern lines

This section presents the application of the proposed method to a case study of the regional non-electrified railway network and multiple unit vehicles in the Netherlands. First, the input parameters are provided for the rolling stock, railway lines and passenger transport services, followed by a comparative assessment of different scenarios.

Table 2
Energy use and greenhouse gas (GHG) emissions factors for the considered energy carriers.

Energy carrier	Energy use				GHG emissions			
	Unit	e_{WTT}	e_{TTW} [g)]	e_{WTW}	Unit	g_{WTT}	g_{TTW}	g_{WTW}
Diesel [a)]	MJ/l	9.323	35.859	45.182	kgCO_2e/l	0.678	2.625	3.303
FAME [b)]		36.750	33.108	69.858		1.602	0.000	1.602
HVO [c)] (rapeseed)		38.438	34.320	72.758		1.781	0.000	1.781
HVO (waste cooking oil)		5.491	34.320	39.811		0.381	0.000	0.381
LNG [d)]	MJ/kg	8.838	49.100	57.938	kgCO_2e/kg	0.815	2.769	3.584
Hydrogen [e)] (SMR)		112.800	120.000	232.800		13.128	0.000	13.128
Hydrogen (elec. EU2030-mix)		326.400	120.000	446.400		14.232	0.000	14.232
Hydrogen (elec. wind)		104.400	120.000	224.400		1.140	0.000	1.140
Electricity [f)] (EU2030-mix)	MJ/kWh	4.536	3.600	8.136	kgCO_2e/kWh	0.259	0.000	0.259
Electricity (wind)		0.252	3.600	3.852		0.000	0.000	0.000

Source: Energy use and GHG emissions factors adopted/derived from [93]:
a) Produced from crude oil from typical EU supply, transported by sea, refined in the EU (marginal production), and with typical EU distribution and retail. Diesel final fuel density is 0.832 kg/l.
b) Produced from rapeseed (Rapeseed Methylester) as the main feedstock for biofuels in the EU, with meal export as animal feed. FAME fuel density is 0.890 kg/l.
c) Produced from either rapeseed with meal export as animal feed, or from waste cooking oil. HVO fuel density is 0.780 kg/l.
d) Produced from remote natural gas liquefied at the source, LNG is transported by sea and distributed by road, used as LNG in the vehicle.
e) Produced from either SMR or electrolysis of water. For the SMR scenario, assumed EU-mix piped natural gas supply, transport to EU by pipeline (1900 km), transport inside EU (500 km), distribution through high-pressure trunk lines and low-pressure grid, small scale reformer at retail site, hydrogen compression to 88 MPa. For the electrolysis scenarios, production using either medium voltage electricity based on EU2030-mix with retail site electrolysis, or electricity from wind energy with central electrolysis and pipeline transport and hydrogen compression to 88 MPa in both scenarios.
f) Medium voltage electricity based on EU2030-mix, or produced from wind energy.
g) Represents low heating value (LHV) of a fuel.

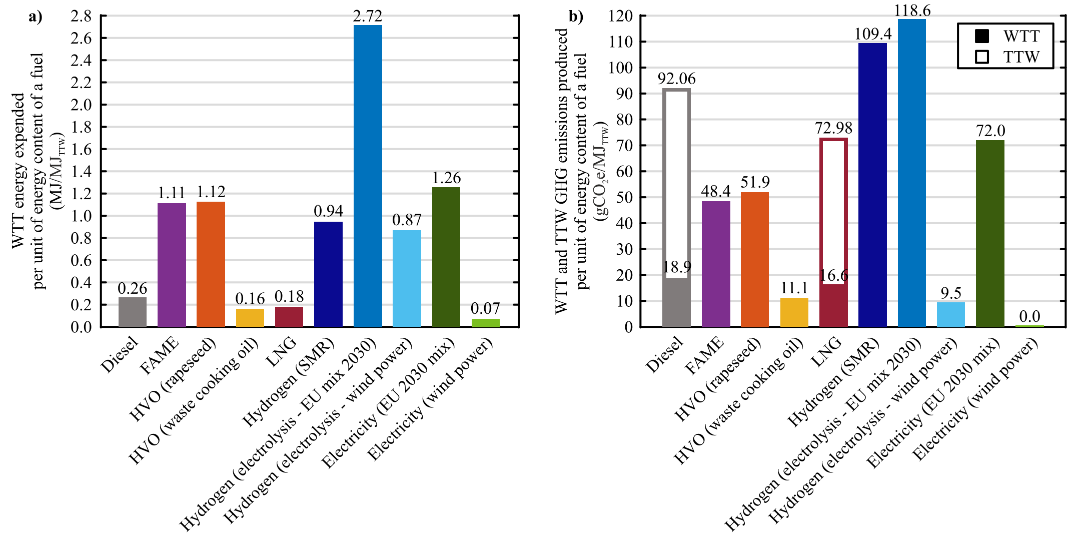

Fig. 4. Well-to-Tank (WTT) (a) energy expended and (b) GHG emissions per unit of energy content of a fuel consumed in Tank-to-Wheel (TTW) stage.

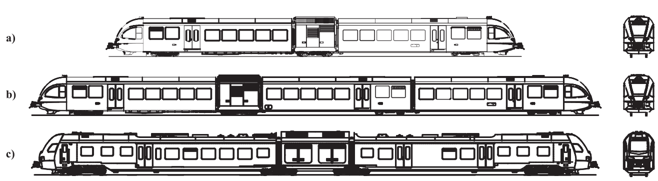

Fig. 5. Graphical representation of Stadler's multiple unit vehicles employed on the Northern lines: (a) GTW 2/6, (b) GTW 2/8, and (c) WINK [17,102].

4.1. Rolling stock fleet

The rolling stock fleet of the Northern lines consists of three types of multiple units from the Swiss manufacturer Stadler (Fig. 5). GTW (abb. for *Gelenktriebwagen*, in English, *articulated multiple-unit train*) DEMUs include two-coach GTW2/6 and three-coach GTW2/8 configurations [102]. Currently at their mid-life stage, with the foreseen operation until 2035, these vehicles are being retrofitted and hybridized with a Lithium-ion battery ESS [16]. As of 2021, the fleet is being extended with bi-mode hybrid-electric DEMUs, based on the newly developed two-coach platform WINK (abb. for *Wandelbarer Innovativer Nahverkehrs-Kurzzug*, in English, *convertible innovative commuter short train*) [17]. These vehicles are already equipped with a pantograph, allowing for a bi-mode operation, and a Lithium-ion battery ESS. The main characteristics of the rolling stock are given in Table 3.

The approach described in Section 3.2 is followed in further conceptual vehicles retrofitting to assess potential future powertrain solutions. Commercially available technologies with proven applications in the railway sector are selected while maintaining the vehicle weight limits to the current fleet to prevent exceeding the maximum axle load.

Table 3
Main characteristics of multiple unit vehicles on the Northern lines.

Characteristic	Vehicle		
	GTW2/6	GTW2/8	WINK
Number of vehicles	14	37	18
Maximum speed (km/h)	140	140	140
Length (m)	40.890	55.937	55.550
Width (m)	2.950	2.950	2.820
Height (m)	4.035	4.035	4.120
Seating capacity	106	165	153
Maximum capacity (seating and standing)	196	295	273

Source: Stadler [17,102]; Personal communication with Arriva.

We assume to maintain the number and attributes in terms of weight and rated power of ICEs and electric motors to those found in the current fleet in all considered scenarios. The efficiency maps of electric motors and generators are reconstructed using normalized efficiency maps provided by Paukert [103] and Pröhl [72]. Similarly sized diesel ICEs from the same sources are scaled to those found in GTWs and WINK vehicles by employing Willan's lines technique [104], with the specific consumption maps for alternative fuels further linearly scaled according to the low heating value of the fuel [78].

The current fleet is equipped with two battery packs based on SCiB™ technology from Toshiba [105]. The present ESS configuration (size) is considered for hybrid-electric and plug-in hybrid-electric scenarios. Identical additional battery packs are considered for further vehicles conversion to their fuel-cell hybrid-electric and battery-electric counterparts. Fuel cell modules FCmove™-HD from Ballard [106] are considered as the replacement technology for EGUs, with their number defined to satisfy gradeability power [107], i.e., the power load at the DC link at the maximum constant speed (140 km/h). The maximum number of battery packs is then derived according to the remaining power and energy demand and overall weight limits. The maximum weight criteria is also adopted for determining the number of battery packs in battery-electric configurations.

Current fuel tanks are kept for the FAME and HVO scenarios, with their overall weight used as a benchmark for the LNG and hydrogen storage systems. Fuel tanks with 383 kg capacity from Enric [108] are considered as LNG storage system, and Luxfer G-Stor™ H2, model W322H35 cylinders with 7.8 kg capacity, as the storage system for compressed hydrogen [109,110].

Finally, to assess the effects of the ongoing refurbishment and hybridization of GTW DEMUs, the analysis also includes the pre-refurbishment standard (diesel-electric) vehicles configurations. The list of vehicle parameters, number and characteristics of individual components used in the simulations are provided in Appendix A (Tab "Rolling Stock - Input Data"; Table A1 and Figs. A1-A5). Due to the existence of a non-disclosure agreement with Stadler, some data are treated as confidential and marked as such.

4.2. Regional railway network and passenger services

The Northern lines encompass a seven-branches rail network in the Dutch provinces Friesland and Groningen, providing sixteen passenger transport services, as shown in Fig. 6. As can be noted, some services share the same route and terminal stations, yet differ in stopping patterns, e.g., at the Leeuwarden – Groningen line. This situation results in

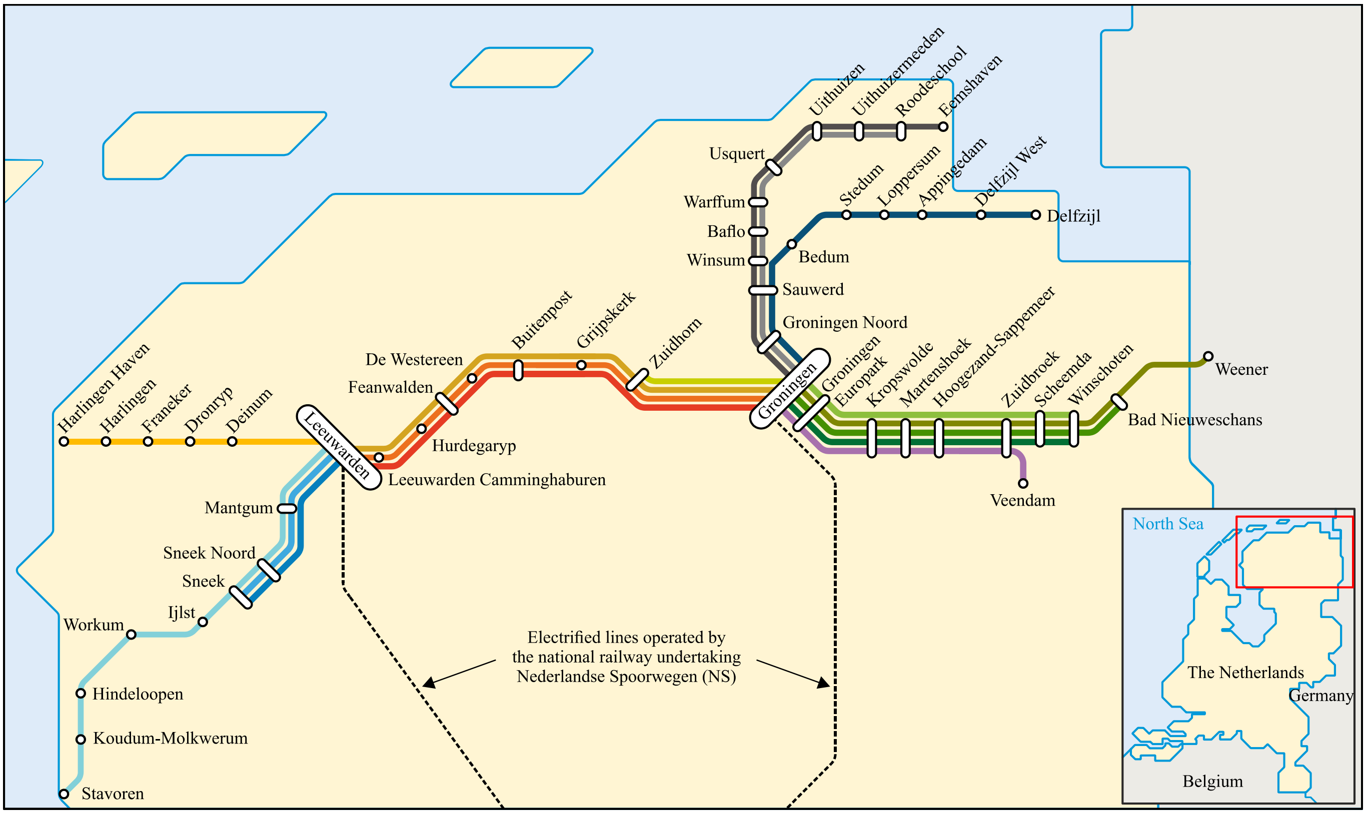

Fig. 6. Regional railway network and passenger transport services in the Northern Netherlands.

different duty cycles, corresponding power demand and energy consumption, linked to the same vehicle and route. Therefore, it is necessary to include all the services in the analysis to obtain overall performance. Furthermore, the simulations are carried out for both directions to account for the difference in track geometry, speed limits, running times, and layover times in terminal stops. The distance between stops and scheduled running times according to the current timetable provided by Arriva are given in Appendix A (Tab “Railway Timetable - Input Data”, Tables A2–A33).

For the plug-in hybrid-electric system scenarios, the installation of charging facilities in all twelve terminal stations is assumed (see Fig. 6). For the battery-electric system scenarios, the continuous partial tracks electrification is considered, starting from stations Leeuwarden and Groningen, as the only two stations connected to the rest of the electrified national railway network. Using the simulation model, the length of the electrified tracks is derived from the minimum number of electrified track sections required to maintain the ESS state-of-charge above the lower threshold for each vehicle series separately, as shown in Fig. 7. To comply with the national traction power supply, a 1.5 kV DC system with 2 kA traction current [111] is considered for both charging facilities and partial tracks electrification.

4.3. Overview of scenarios and external factors

A schematic overview of the analyzed scenarios is provided in Fig. 8, indicating the pathways from the main energy sources through production processes into energy carriers (WTT), and their use with the respective propulsion systems and multiple unit vehicles (TTW). Within the WTT phase, different line colors are used to distinguish the considered energy carriers and corresponding alternative production pathways, presented in Section 3.3. For instance, different shades of blue denote the three hydrogen production scenarios, while different shades of green distinguish between the gray electricity based on the EU 2030 production mix for the EU and the green electricity produced from wind power. As depicted in the TTW stage, all six propulsion system configurations are evaluated for both GTW vehicle series, while the standard diesel-electric system is omitted for the new WINK vehicles, as these are manufactured as hybrids.

In addition to fixed factors such as track topology, external factors (for instance, ambient temperature and passengers load) have a degree of variability that can potentially have a great impact on the train’s energy consumption [112]. The ambient conditions are taken into account via the auxiliary systems consumption (e.g., HVAC), provided by the vehicle manufacturer, where each vehicle trip is simulated separately for the summer and winter season operation. Furthermore, to assess the influence of the passengers load on vehicle’s performance, each scenario is simulated separately for the case of an empty and fully loaded vehicle, with the weight of the vehicle kept constant during the trip.

4.4. Comparative assessment results

This section presents the comparative assessment of alternative traction options for the analyzed Dutch case study. Following the method presented in Section 3, the consumption of fuel and/or electricity for each vehicle, propulsion system, energy carrier, passenger load and ambient conditions scenario is computed for each individual trip using the simulation model (Appendix A: Tab “Fuel, Electricity Consumption”, Table A34), and corresponding WTT, TTW and WTW energy use and GHG emissions are calculated using (1)-(2) (Appendix A: Tabs “WTT, TTW, WTW Energy Use” and “WTT, TTW, WTW GHG Emissions”, Tables A35–A40). Appendix B provides the summary of the estimated average fuel and/or electricity consumption per distance traveled from simulated trips in the Northern lines. In the following subsections, distance (km) and seat-distance (skm) travelled are used as functional units, and commonly used indicators of energy use and GHG

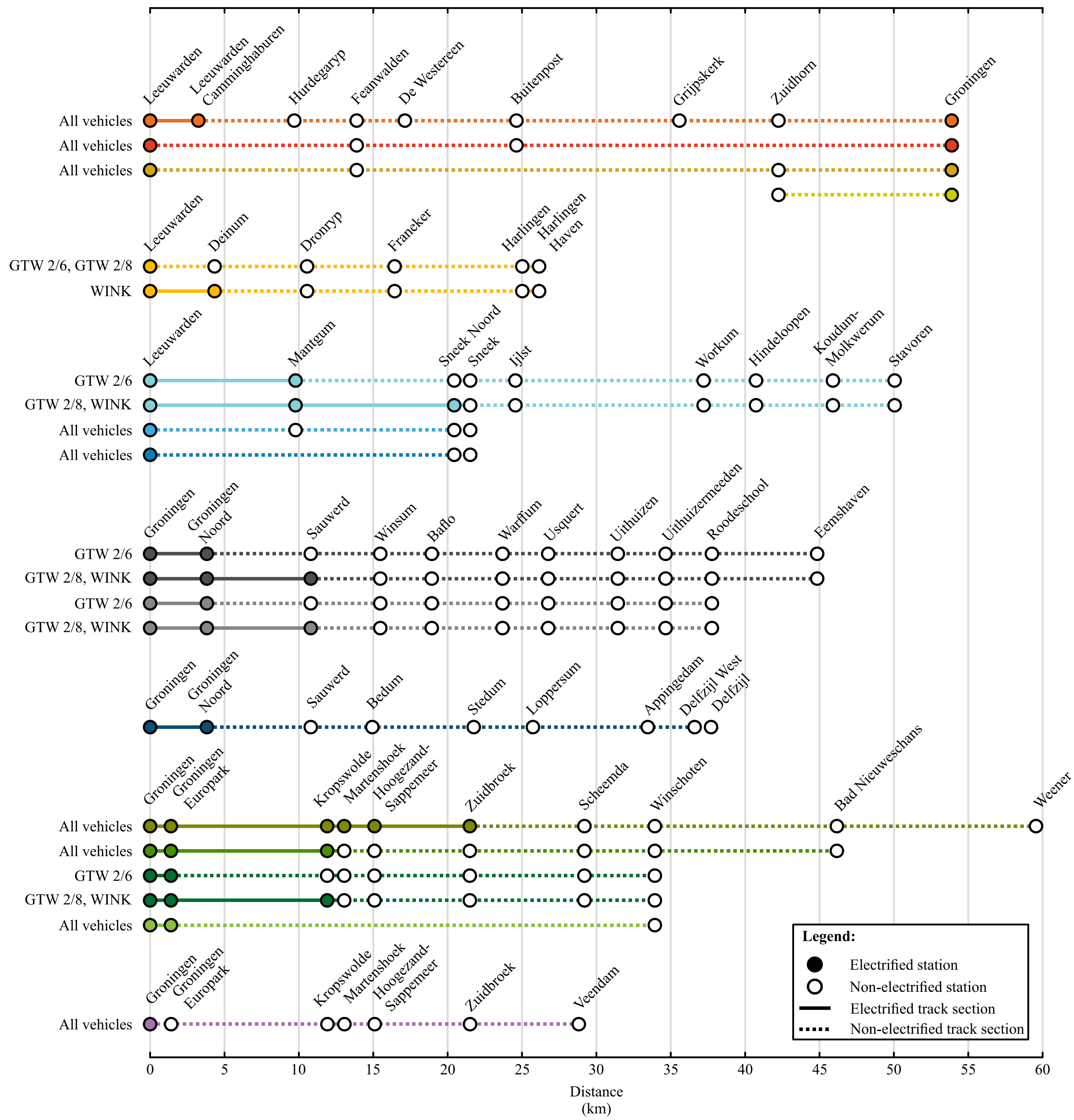

Fig. 7. Required electrification for the operation of battery-electric regional trains for each vehicle series and transport service in the network.

emissions per distance (in MJ/km and kgCO_2e/km) and seat-distance (in kJ/skm and gCO_2e/skm) are derived to allow for the overall comparison between different scenarios.

4.4.1. Tank-to-wheel stage

The overall (WTW) energy use and GHG emissions are directly proportional to the energy use in the TTW stage, with the efficiency of the individual components in the powertrain and the EMCS being the main drivers of the fuel economy. Appendix C provides the overall estimates of TTW energy use per distance and seat-distance for each considered scenario. To compare the TTW energy use associated with the alternative propulsion systems, the overall mean values are further aggregated over alternative energy carriers (Fig. 9). The relative difference compared to the current hybrid-electric system with ZESC as a benchmark is derived (Fig. 10).

The retrofit of conventional (diesel-electric) powertrains to their diesel-powered hybrid-electric counterpart with ZESC demonstrated positive effects on fuel economy, with estimated average direct energy use per distance and seat-distance reduced by 8.5% (from 35.5 MJ/km to 32.4 MJ/km, and 334.6 kJ/skm to 306.0 kJ/skm) for GTW 2/6 and 6.5% (from 38.1 MJ/km to 35.7 MJ/km, and 231.1 kJ/skm to 216.2 kJ/skm) for GTW 2/8 vehicles (see Appendix C). Thus, significant economic benefits are obtained in addition to the emission-free and noise-free operation at terminal stops by switching-off ICEs and supplying auxiliary systems from the ESS, despite the increased overall vehicle weight.

As one of the potential future solutions, the implementation of FSMC instead of ZESC in hybrid-electric vehicles is associated with diverse impacts on fuel economy, depending on the vehicle series and energy carrier scenarios. While it resulted in the average energy savings of 0.54% for GTW 2/6 and 0.09% for GTW 2/8 vehicles, an increase of 3.38% is obtained for WINK vehicles (see Fig. 10). The latter implies high energy demand for auxiliary systems during layovers, with the additional energy required from the ICEs for charging the ESS exceeding the benefits obtained from the enabled boost mode in this case, i.e.,

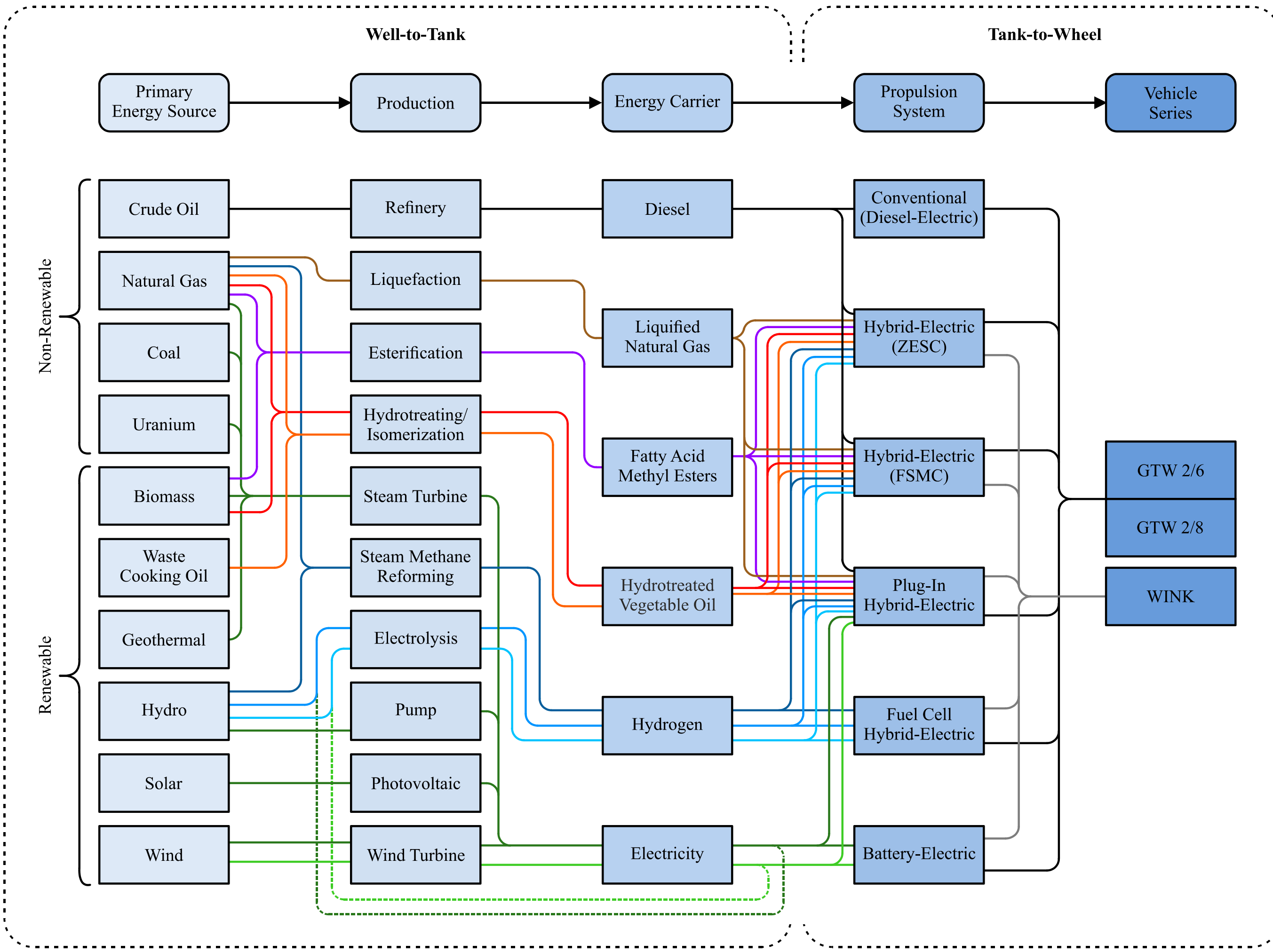

Fig. 8. Overview of the analyzed scenarios: primary energy sources, production processes and relevant energy carriers used in the propulsion of different powertrain configurations.

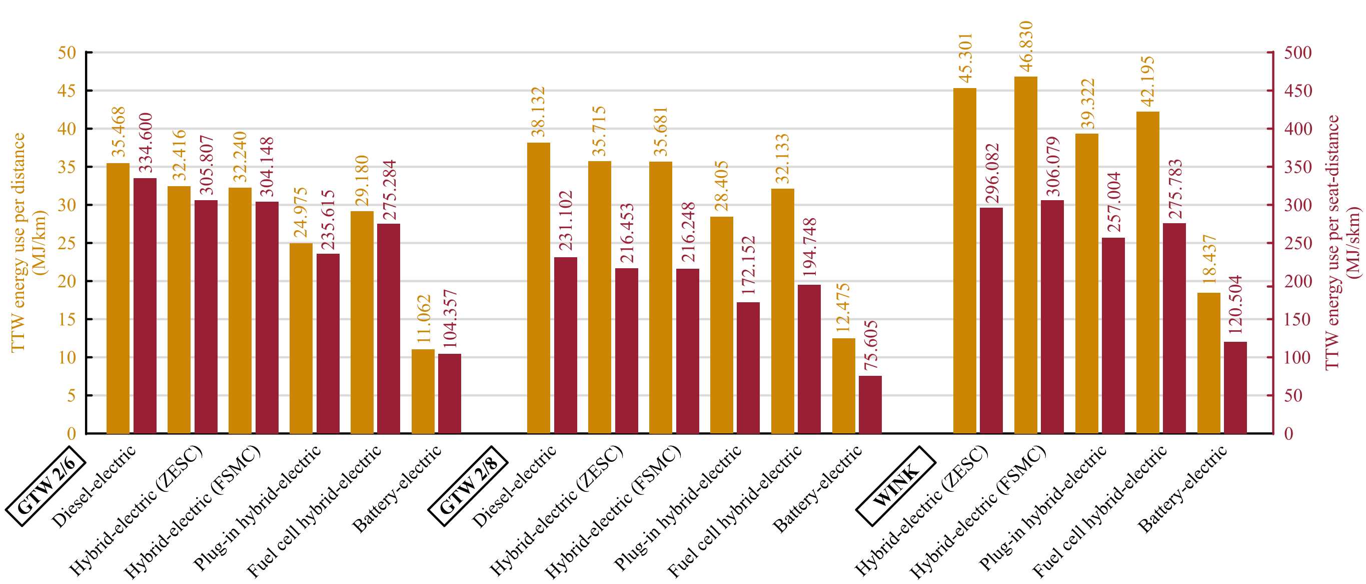

Fig. 9. Tank-to-Wheel (TTW) energy use per distance and seat-distance for the multiple unit vehicles and corresponding propulsion systems, based on the overall mean values aggregated over alternative energy carriers.

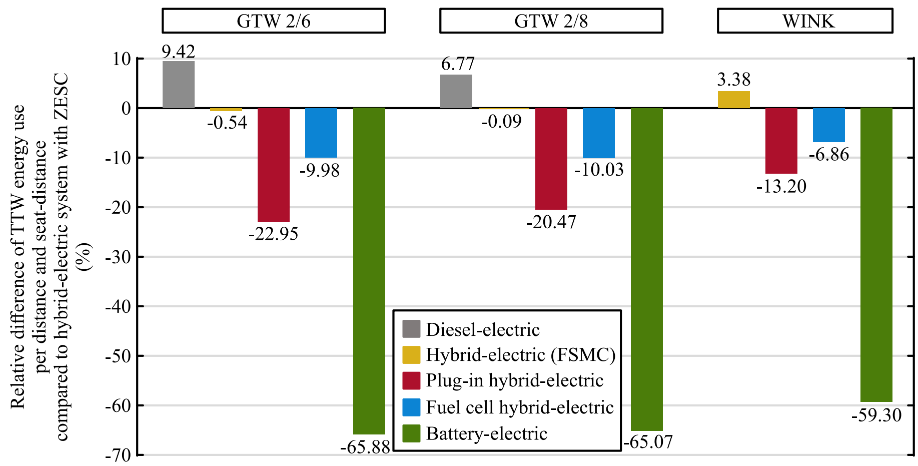

Fig. 10. Comparison of Tank-to-Wheel (TTW) energy use between alternative propulsion systems, based on hybrid-electric system with ZESC as a benchmark, and the overall mean values aggregated over alternative energy carriers.

supporting the ICEs during acceleration phases by using stored regenerative braking energy.

The significant impact of train operation during layovers is most evident in the case of the plug-in hybrid-electric concept, where the external power grid is used for both supplying the auxiliaries and charging the ESS, thus providing additional energy to support the prime mover during trips. Compared to the baseline, the implementation of this system led to the average reduction of TTW energy use per distance and seat-distance of approximately 23%, 20%, and 13% for GTW 2/6, GTW 2/8 and WINK vehicles, respectively.

Despite the limitation of fuel cells reflected in slow dynamics, the fuel cell hybrid-electric system demonstrated a reduction of TTW energy use of approximately 10% for both GTW vehicles and 7% for WINK vehicles, mainly due to the higher energy efficiency of a fuel cell system compared to the ICEs. Lastly, the battery-electric system offered the highest reduction of direct energy use by approximately 66% for GTW 2/6, 65% for GTW 2/8, and 59% for WINK vehicles, with eliminated energy losses linked to inefficiencies of both ICE and fuel cell technologies.

The selection of performance indicators is of high importance in calculating and reporting energy use and environmental impacts from trains operation, especially in the case of heterogeneous fleets. Fig. 11 shows the relative difference in TTW energy use per distance and seat-distance traveled between different vehicle series, using GTW 2/6 as a benchmark. The two-coach GTW 2/6 multiple units showed the lowest energy use and GHG emissions in each scenario when estimates per vehicle-distance were used. With an identical propulsion system to that of GTW 2/6, the three-coach GTW 2/8 vehicles feature both higher weight and capacity, leading to higher energy use per vehicle-distance, but at the same time to the lowest estimates per seat-distance traveled among all three vehicle series. The new WINK vehicles feature the highest overall weight, power demand for traction and auxiliaries compared to GTW configurations, resulting in the overall highest average energy use per vehicle-distance, and diverse results if performance per seat-distance is considered.

4.4.2. Well-to-tank stage

The estimations of overall (WTW) energy use and GHG emissions per vehicle-distance and seat-distance for each vehicle series, propulsion system and energy carrier scenario are shown in Fig. 12–17, with distinguished WTT and TTW stages. In contrast to the TTW stage, the contribution of the WTT stage to the WTW energy use and GHG emissions depends on the energy carriers' primary source(s) and their production pathways (see Table 2 and Fig. 4).

Regarding fossil fuels, the WTT stage has a minor contribution to both WTW energy use (diesel: 20.6%, LNG: 15.3%) and GHG emissions

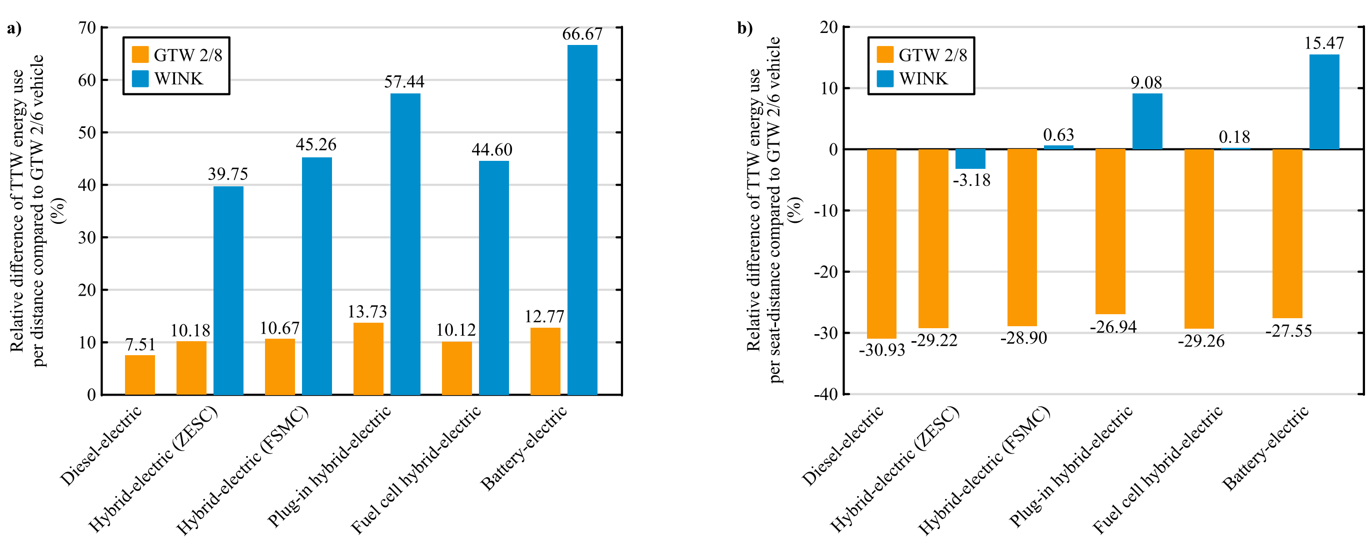

Fig. 11. Comparison of Tank-to-Wheel (TTW) energy use between different vehicle series for the alternative propulsion systems per (a) distance and (b) seat-distance, based on the overall mean values and GTW 2/6 as a benchmark.

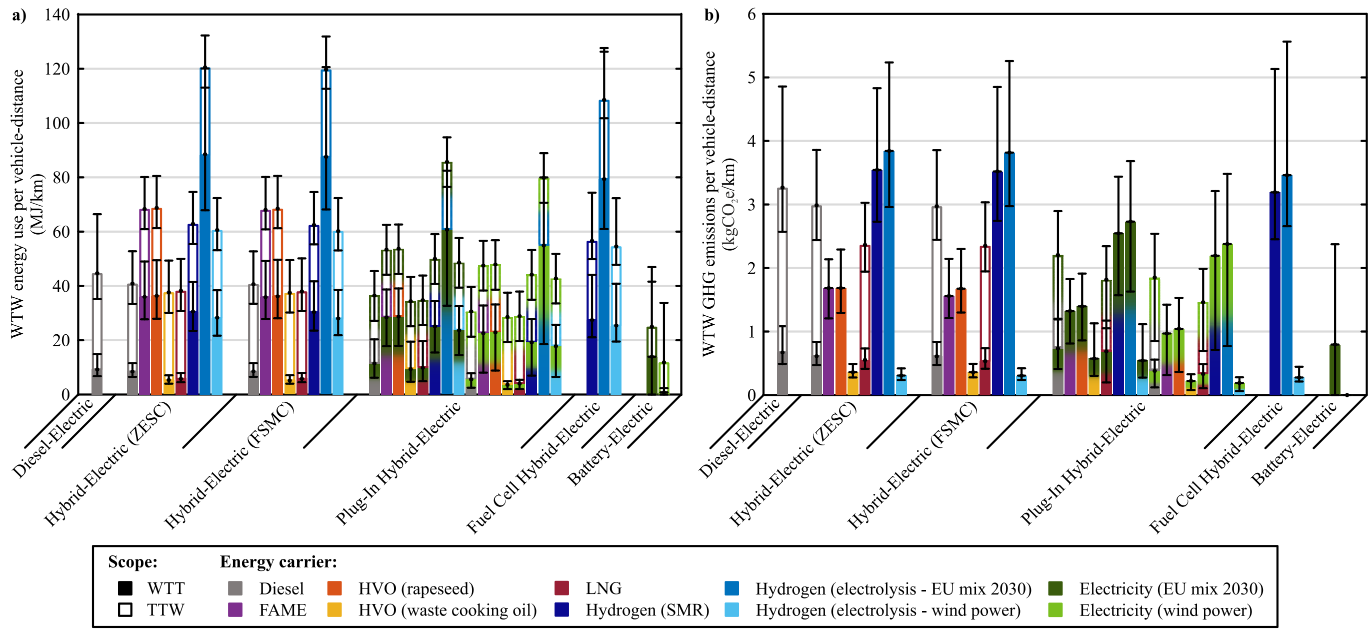

Fig. 12. Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) estimations of (a) energy use and (b) greenhouse gas (GHG) emissions per vehicle-distance for GTW 2/6 multiple unit vehicle.

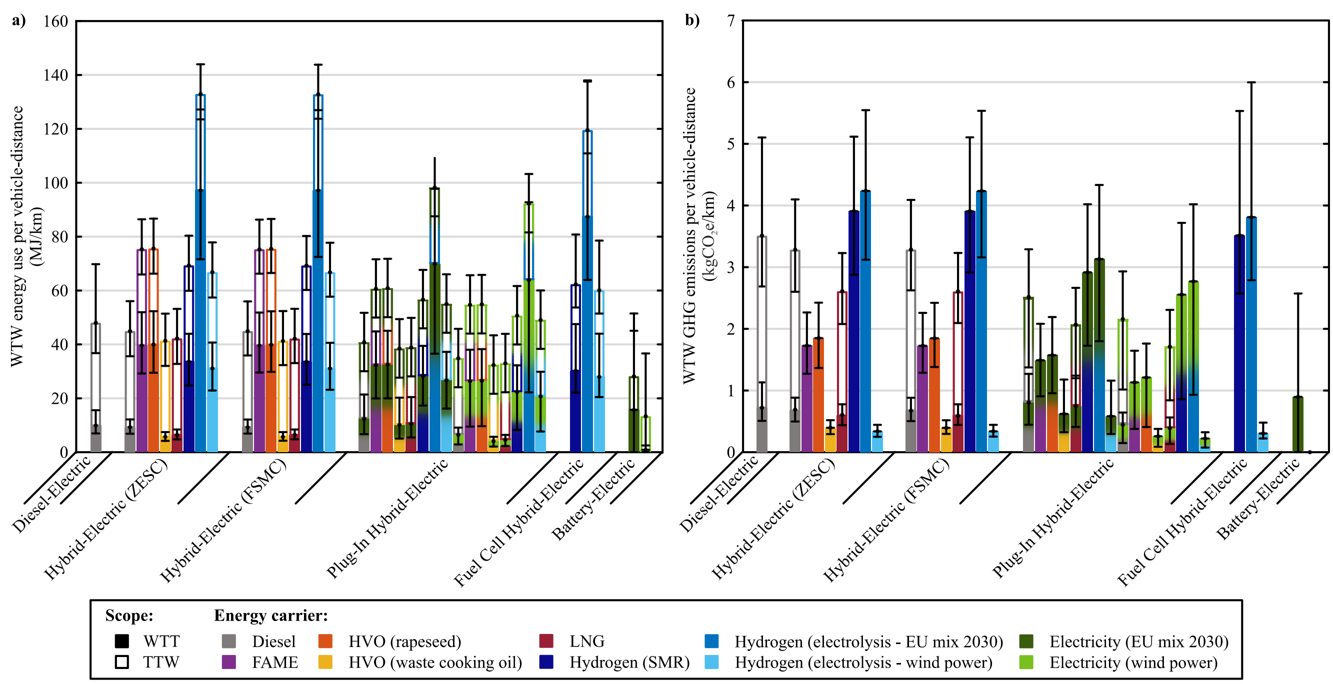

Fig. 13. Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) estimations of (a) energy use and (b) greenhouse gas (GHG) emissions per vehicle-distance for GTW 2/8 multiple unit vehicle.

(diesel: 20.5%, LNG: 22.7%) when used in conventional and hybrid-electric vehicles. The influence of the primary energy source and production pathway is notable in the case of non-fossil fuels, for which WTT accounts for the overall GHG emissions. For instance, for hybrid-electric vehicles, the WTT stage contributes to 52.9% of HVO's WTW energy use if produced from rapeseed (similar to FAME: 52.6%), compared to 13.8% if HVO produced from waste cooking oil is used, which at the same time leads to 78.6% lower GHG emissions. Although both FAME and HVO from rapeseed have higher WTW energy use than considered fossil fuels, they significantly reduced overall GHG emissions in all scenarios.

The impact of the WTT stage on the overall estimates is most evident in the case of hydrogen, contributing to 48.5% (SMR), 73.1% (electrolysis using EU2030-mix electricity) and 46.5% (electrolysis using green electricity from wind power) of WTW energy use for hybrid-electric and fuel cell hybrid-electric scenarios. Hydrogen usage is associated with the increased WTW energy use in all scenarios compared to the baseline, with EU2030-mix-based electrolysis having the overall highest energy use. This production pathway and SMR also have the highest WTW GHG emissions in all scenarios, with only wind power electrolysis-based hydrogen leading to significantly reduced GHG emissions.

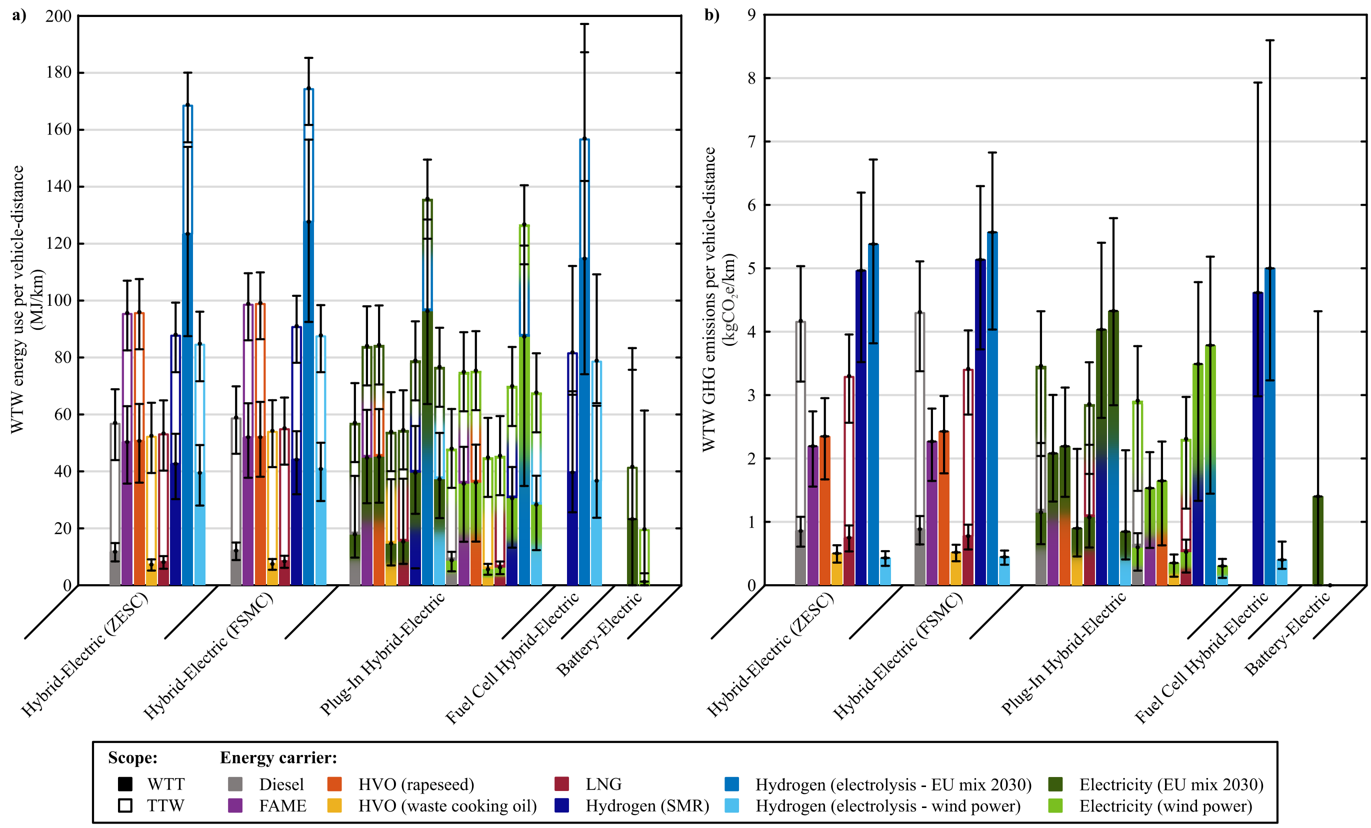

Fig. 14. Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) estimations of (a) energy use and (b) greenhouse gas (GHG) emissions per vehicle-distance for WINK multiple unit vehicle.

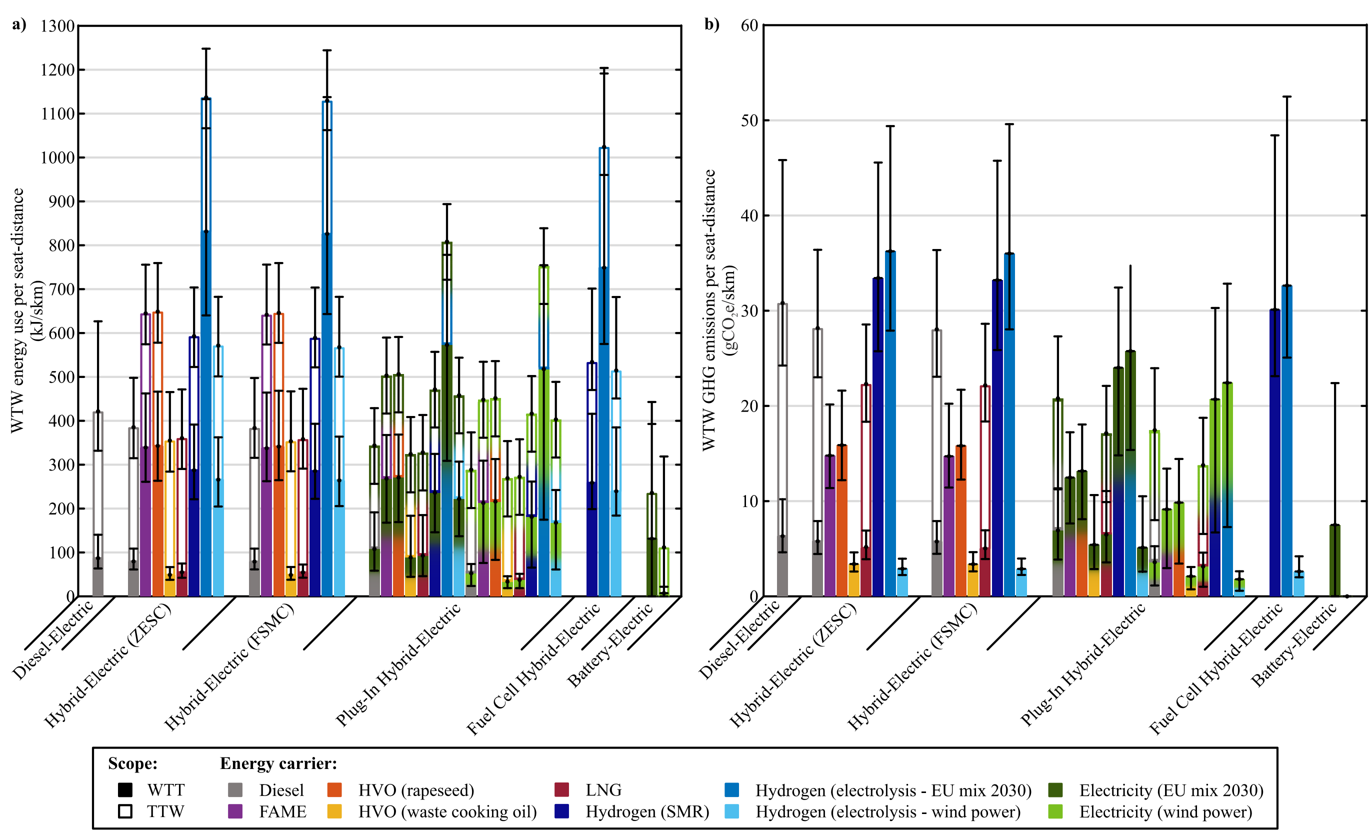

Fig. 15. Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) estimations of (a) energy use and (b) greenhouse gas (GHG) emissions per seat-distance for GTW 2/6 multiple unit vehicle.

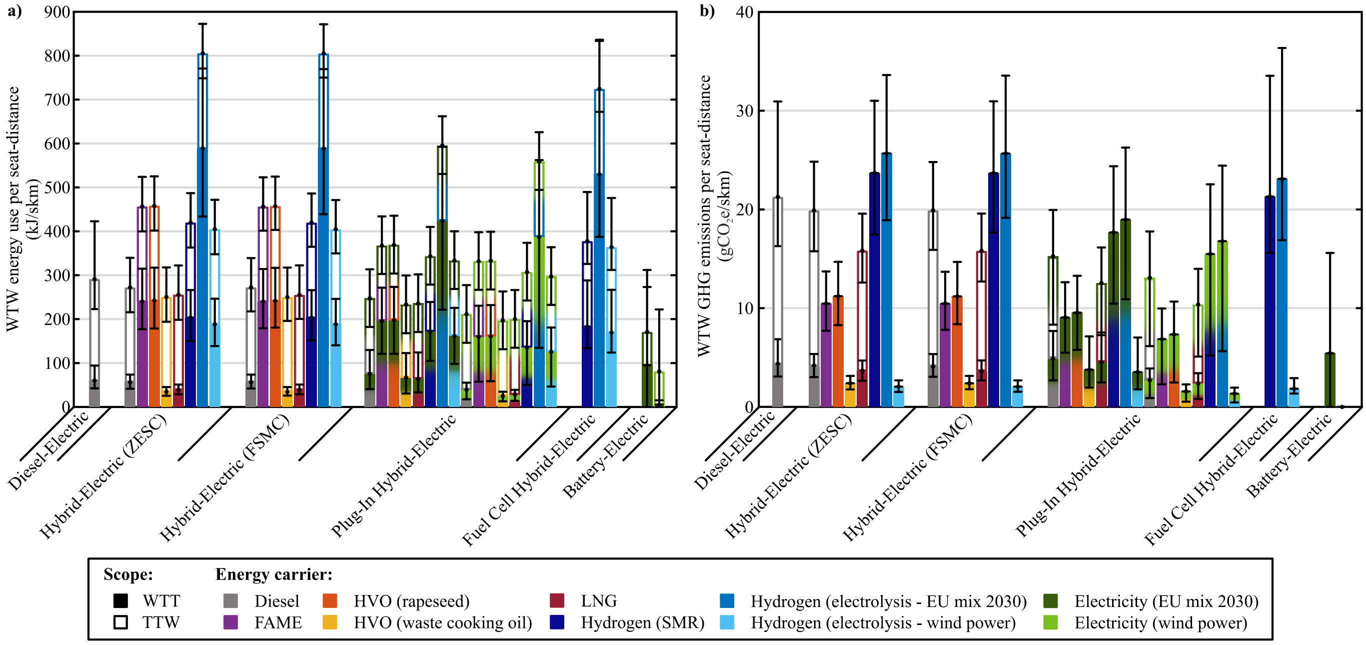

Fig. 16. Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) estimations of (a) energy use and (b) greenhouse gas (GHG) emissions per seat-distance for GTW 2/8 multiple unit vehicle.

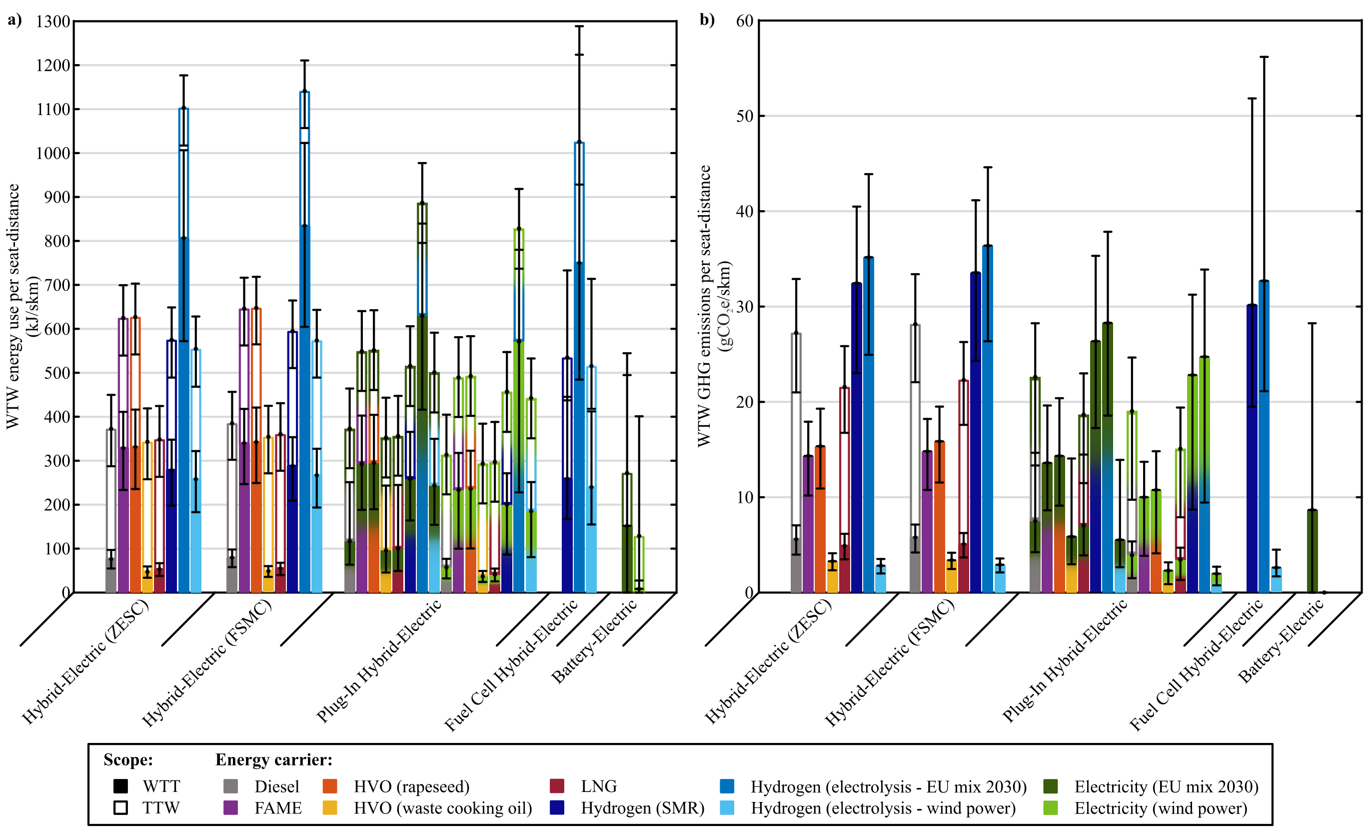

Fig. 17. Well-to-Tank (WTT), Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) estimations of (a) energy use and (b) greenhouse gas (GHG) emissions per seat-distance for WINK multiple unit vehicle.

Regarding electricity used in battery-electric systems, the WTT stage contributes to 55.8% of overall energy use for EU2030-mix scenario, and only 6.5% for wind power-based production. Lastly, the contribution of the WTT stage in the case of plug-in hybrid-electric vehicles depends on the combination of fuel used with electricity and the associated production path.

4.4.3. Relative change of well-to-wheel energy use and greenhouse gas emissions

Using the present diesel-powered hybrid-electric system with ZESC

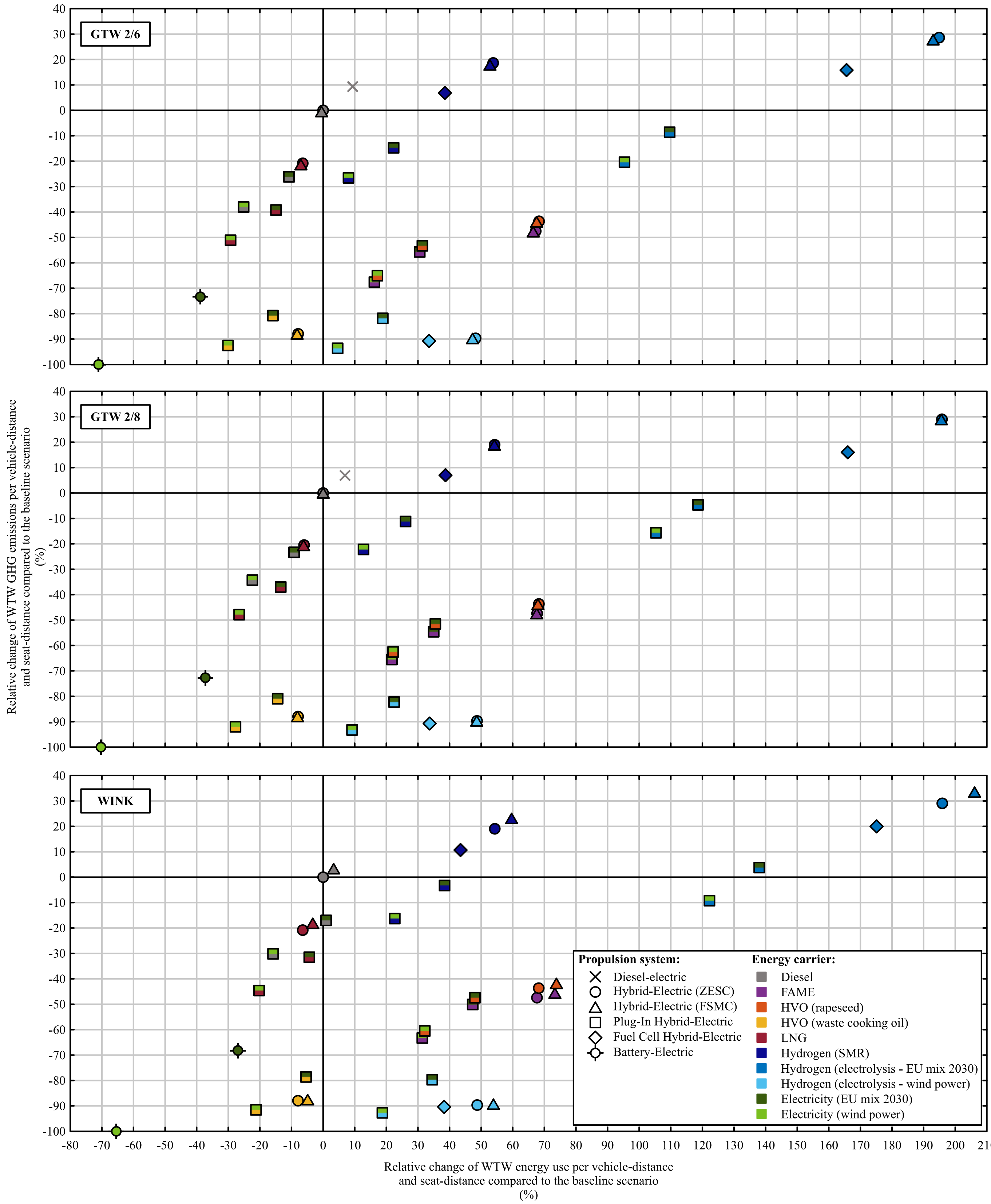

Fig. 18. Estimated relative change in Well-to-Wheel (WTW) energy use and greenhouse gas (GHG) emissions per vehicle-distance and seat-distance compared to the baseline scenario (hybrid-electric vehicle with Zero-Emission Station Control (ZESC) and diesel as a fuel) for different multiple unit vehicles in the Northern lines.

as a benchmark, the relative change in WTW energy use and GHG emissions is derived using the overall mean estimates for each vehicle series, as shown in Fig. 18 and Table A41 (Appendix A: Tab "Relative Change").

When using wind power-based electricity, the battery-electric system is the only configuration leading to zero-emission train operation from the WTW perspective while at the same time offering the highest reduction of overall energy use by about 65–71%, depending on the vehicle series. When using electricity based on the EU2030 production mix, these savings are reduced to about 27–39% in WTW energy use and around 68–73% in WTW GHG emissions.

The plug-in hybrid-electric concept significantly reduced overall energy use and emissions when combining diesel, LNG or waste cooking oil-based HVO with electricity. The remaining configurations that reduce energy use and GHG emissions are hybrid-electric systems running on LNG or HVO from waste cooking oil. The latter leads to approximately 88% lower WTW emissions than the baseline for each vehicle type.

When produced from SMR or EU2030-mix-based electrolysis, hydrogen demonstrated negative effects in both aspects, irrespective of the prime mover technology, i.e., in both ICEs (hybrid-electric) or fuel cell systems. However, when produced via green electricity, it offers a GHG reduction of approximately 90% for hybrid-electric and fuel cell hybrid-electric configurations, with further reduction of up to 92–93% if combined with green electricity in plug-in hybrid-electric systems.

5. Discussion

The results presented in Section 4 provided various valuable insights for policy-makers and railway undertakings regarding potential measures to reduce WTW energy use and GHG emissions. Due to eliminated energy losses linked to the inefficiencies of ICE and fuel cell technologies, the battery-electric system demonstrated the highest reduction of WTW energy use while offering zero-carbon trains operation if green electricity is used. Often regarded as another long-term solution for non-electrified railway networks, fuel cell hybrid-electric configurations demonstrated higher energy savings than hybrid-electric systems due to improved powertrain efficiency while eliminating local pollutants and noise emissions. However, hydrogen adoption can be justified only if green hydrogen obtained from renewable sources is used. The plug-in hybrid-electric concept offers exploitation of external charging facilities in terminal stops, providing additional energy to support the ICEs during trips and thus improving overall efficiency. When utilizing green electricity, it also demonstrated better performance than the current hybrid-electric system in terms of the produced emissions in all scenarios.

Overall, the production pathway of the energy carrier is identified as the most significant contributor to the WTW energy use and produced emissions, followed by the efficiency of the powertrain. In the short term, focusing on the WTT stage would be an effective approach in achieving significant improvement of the environmental performance of regional trains. In this regard, low-carbon fuels such as HVO from waste cooking oil could be considered an instantly implementable cost-effective transition solution toward carbon–neutral regional railways. Focusing on such ICE-based propulsion systems with infrastructure already in place would allow for significant positive effects in the short term while allowing for a smooth transition and development of supporting infrastructure required for more energy-efficient and environment-friendly technologies. In addition to the vehicles retrofit in the transition to more advanced powertrains, required supporting infrastructure includes stationary charging facilities for plug-in hybrid-electric system, partial track electrification for battery-electric vehicles, and hydrogen refueling facilities for hydrogen-based systems.

As discussed in Section 2, emissions from train operation not only arise due to the fuel or electricity consumption, but are also emitted from a number of direct and indirect sources, including the production of vehicle components, development of supporting infrastructure, and associated end-of-life processes. Although this study limits the system boundary to the WTW perspective, the contribution of other life cycle stages associated with the new technology are roughly estimated for the main components. For this, obtained average estimates of WTW GHG emissions (Appendix A) are combined with historical data on transport activity, general technology features of fuel cell hybrid-electric and battery-electric vehicles, and emission factors retrieved from the literature, while considering a time horizon of fifteen-years. Eight million vehicle-kilometers achieved in 2021 in the Northern lines are assumed to remain constant over the observed period, and equally divided among the 69 vehicles in the fleet. In addition to the initial retrofit, fuel cell systems, and Lithium-ion batteries are assumed to be replaced twice during the observed fifteen-year period due to the limited service life of these technologies. Following GHG emission factors are adopted to assess the impact of production and end-of-life stage for the analyzed

Table 4
Overall estimates of life cycle emissions for different propulsion system/energy carrier combinations.

Vehicle / Propulsion system		GHG emissions per vehicle-kilometer (kgCO2e/km)				
		WTW	Battery	Fuel cell	Electrification	Total
GTW 2/6						
	HE with ZESC (diesel)	2.988 (99.8%)	0.007 (0.2%)	–	–	2.995
	FCHE (SMR)	3.192 (98.2%)	0.022 (0.7%)	0.036 (1.1%)	–	3.250
	FCHE (elec. EU2030-mix)	3.461 (98.4%)	0.022 (0.6%)	0.036 (1.0%)	–	3.519
	FCHE (elec. wind)	0.277 (82.7%)	0.022 (6.6%)	0.036 (10.7%)	–	0.335
	BE (EU2030-mix)	0.796 (50.1%)	0.044 (2.8%)	–	0.749 (47.1%)	1.589
	BE (wind)	0.000 (0.0%)	0.044 (5.5%)	–	0.749 (94.5%)	0.793
GTW 2/8						
	HE with ZESC (diesel)	3.285 (99.8%)	0.007 (0.2%)	–	–	3.292
	FCHE (SMR)	3.515 (98.4%)	0.022 (0.6%)	0.036 (1.0%)	–	3.573
	FCHE (elec. EU2030-mix)	3.811 (98.5%)	0.022 (0.6%)	0.036 (0.9%)	–	3.869
	FCHE (elec. wind)	0.305 (84.0%)	0.022 (6.1%)	0.036 (9.9%)	–	0.363
	BE (EU2030-mix)	0.897 (53.1%)	0.044 (2.6%)	–	0.749 (44.3%)	1.690
	BE (wind)	0.000 (0.0%)	0.044 (5.5%)	–	0.749 (94.5%)	0.793
WINK						
	HE with ZESC (diesel)	4.171 (99.8%)	0.009 (0.2%)	–	–	4.180
	FCHE (SMR)	4.616 (98.4%)	0.031 (0.7%)	0.042 (0.9%)	–	4.689
	FCHE (elec. EU2030-mix)	5.004 (98.6%)	0.031 (0.6%)	0.042 (0.8%)	–	5.077
	FCHE (elec. wind)	0.401 (84.6%)	0.031 (6.5%)	0.042 (8.9%)	–	0.474
	BE (EU2030-mix)	1.326 (62.1%)	0.062 (2.9%)	–	0.749 (35.0%)	2.137
	BE (wind)	0.000 (0.0%)	0.062 (7.6%)	–	0.749 (92.4%)	0.811

Legend: HE = Hybrid-electric, ZESC = Zero-emission station control, FCHE = Fuel cell hybrid-electric, BE = Battery-electric.

components: 43 $kgCO_2e/kW$ of the rated power of a fuel cell system [113], 83.5 $kgCO_2e/kWh$ of the energy content of a Lithium-ion battery [11], and 1750 $kgCO_2e/km/year$ for the track electrification [114]. Overall estimations are presented in Table 4.

While the production of batteries and fuel cells and corresponding end-of-life stages feature minor contributions to the overall emissions, with fuel cells causing slightly higher emissions, partial track electrification required for battery-electric systems shows a significantly higher impact on produced GHG emissions. Including these emissions resulted in the change of the relative rating of alternative solutions, with fuel cell hybrid-electric systems running on wind power-based hydrogen featuring the lowest life cycle emissions among considered solutions. It is important to note that the obtained results represent a rough estimation based on various assumptions and emission factors pertinent to other use contexts. Therefore, the need for further investigation in terms of detailed LCA is stipulated to accurately assess the overall environmental impact of a particular solution. In this regard, estimates of WTW energy use and GHG emissions provided by this study can serve as a profound basis in a wider-scope LCA framework according to the ISO 14040/44 standards [115,116] while tackling challenges of detailed data availability and involvement of external stakeholders such as vehicle and equipment suppliers.

Similar to the GHG emissions, next to the operational (fuel/electricity) costs, other investment costs will occur when rolling out a new propulsion system concept. These monetary costs are related to a particular technology and its lifetime, and include initial, maintenance, and replacement costs both for the onboard equipment and stationary supporting infrastructure. To identify the overall costs and benefits in this investment decision process, a comprehensive life cycle costs (LCC) analysis [117] is required.

In addition to the technology solutions analyzed in this paper, operational measures can further improve the environmental performance of regional railways. Depending on the performance indicator adopted, i.e., energy use and/or GHG emissions per vehicle-distance or per seat-distance, the estimations obtained in this study can serve as an input in planning the optimal deployment of heterogenous rolling stock on the network [118,119], leading to improved overall energy efficiency and/or reduced carbon footprint.

6. Conclusions

Non-electrified regional railways are witnessing increased penetration of advanced powertrains and alternative fuels aimed at replacing traditional diesel traction. This study presented a comprehensive comparative assessment of WTW energy use and GHG emissions linked to the implementation of various powertrain technologies for regional trains in the Netherlands, in conjunction with a range of energy carriers and their production pathways. As a critical step in ex-ante evaluations, direct fuel and/or electricity consumption is assessed in the vehicle operation (TTW) stage by employing a detailed backward-looking quasi-static simulation model. The model is able to tackle the high complexity of novel hybrid systems, and to capture the degree of variability in obtained estimates reflecting heterogenous fleet, differences in track topology over entire network, ambient conditions, passengers load, etc. The obtained estimations are then combined with various energy carriers' production pathways in the Dutch and European contexts in the WTT stage to conduct the overall comparative assessment.

The results show positive effects from conducted hybridization of GTW vehicles, with non-hybrid configurations featuring higher energy use and produced GHG emissions by more than 9% and about 7% for GTW 2/6 and GTW 2/8 vehicle, respectively. Transition from diesel to HVO produced from waste cooking oil is identified as the most effective instantly implementable solution towards carbon–neutral regional trains, offering the reduction of WTW energy use by 8% and GHG emissions by 88% for the current hybrid-electric configurations. When combined with green electricity in plug-in hybrid-electric systems, energy use and GHG emissions savings are further increased to 21–30% and 92–93%, respectively. Due to the high energy intensity of hydrogen production process, its utilization results in an increase of the WTW energy use in all scenarios. Despite its high energy demand, when produced from wind power-based electrolysis, hydrogen use leads to reduced GHG emissions by about 89–90% in hybrid-electric, 90–91% in fuel cell hybrid-electric, and 93–94% in plug-in hybrid-electric system when combined with green electricity. Finally, the best performance in both energy use and GHG emissions reduction is provided by the battery-electric system running on green electricity, offering a cut in WTW energy use by 65–71% depending on the vehicle series, and carbon–neutral trains operation. However, it is essential to note that more advanced systems, such as plug-in hybrid-electric, fuel cell hybrid-electric and battery-electric, require significant investments in the development of supporting infrastructure, in addition to further rolling stock retrofit.

Future research efforts will take on a broader perspective on sustainability by applying Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods to capture the environmental impacts and overall costs associated with the technology production and the infrastructure development. Furthermore, policy mechanisms such as carbon taxes in facilitating the transition towards carbon–neutral railways operation will be analyzed.

CRediT authorship contribution statement

Marko Kapetanović: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Alfredo Núñez:** Supervision, Writing – original draft, Writing – review & editing. **Niels van Oort:** Project administration, Supervision, Writing – original draft, Writing – review & editing. **Rob M.P. Goverde:** Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used is provided in a separate supplementary file. Some of the data is confidential and marked as such.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2024.118202.

Appendix B. Overall estimates of fuel and/or electricity consumption from trains operation

Vehicle	Prop. system	Energy carrier	Unit	Mean	Max	Min
GTW 2/6	DE	Diesel	l/km	0.989	1.595	0.723
	HE (ZESC)	Diesel		0.905	1.236	0.696
		FAME		0.979	1.334	0.753
		HVO		0.945	1.286	0.726
		LNG	kg/km	0.660	0.899	0.508
		Hydrogen		0.270	0.368	0.208
	HE (FSMC)	Diesel	l/km	0.900	1.236	0.699
		FAME		0.974	1.339	0.757
		HVO		0.941	1.292	0.730
		LNG	kg/km	0.656	0.903	0.510
		Hydrogen		0.268	0.369	0.209
	PIHE	Diesel / Electricity	l/km, kWh/km	0.560 / 1.368	0.823 / 4.004	0.179 / 0.280
		FAME / Electricity		0.605 / 1.367	0.888 / 4.004	0.196 / 0.280
		HVO / Electricity		0.586 / 1.356	0.859 / 4.004	0.205 / 0.280
		LNG / Electricity	kg/km, kWh/km	0.408 / 1.372	0.598 / 4.005	0.131 / 0.278
		Hydrogen / Electricity		0.167 / 1.362	0.245 / 4.004	0.054 / 0.280
	FCHE	Hydrogen	kg/km	0.243	0.391	0.187
	BE	Electricity	kWh/km	3.073	9.167	0.000
GTW 2/8	DE	Diesel	l/km	1.063	1.669	0.749
	HE (ZESC)	Diesel		0.995	1.304	0.734
		FAME		1.079	1.414	0.795
		HVO		1.039	1.361	0.767
		LNG	kg/km	0.729	0.952	0.536
		Hydrogen		0.298	0.390	0.219
	HE (FSMC)	Diesel	l/km	0.995	1.302	0.743
		FAME		1.078	1.410	0.804
		HVO		1.037	1.360	0.776
		LNG	kg/km	0.728	0.953	0.543
		Hydrogen		0.298	0.389	0.222
	PIHE	Diesel / Electricity	l/km, kWh/km	0.654 / 1.387	0.948 / 4.118	0.222 / 0.280
		FAME / Electricity		0.707 / 1.386	1.027 / 4.118	0.236 / 0.281
		HVO / Electricity		0.680 / 1.400	0.989 / 4.118	0.229 / 0.280
		LNG / Electricity	kg/km, kWh/km	0.478 / 1.381	0.692 / 4.118	0.163 / 0.280
		Hydrogen / Electricity		0.195 / 1.394	0.283 / 4.118	0.065 / 0.280
	FCHE	Hydrogen	kg/km	0.268	0.421	0.196
	BE	Electricity	kWh/km	3.465	9.936	0.000
WINK	HE (ZESC)	Diesel	l/km	1.263	1.591	0.898
		FAME		1.369	1.712	0.972
		HVO		1.319	1.657	0.938
		LNG	kg/km	0.921	1.157	0.655
		Hydrogen		0.378	0.472	0.268
	HE (FSMC)	Diesel	l/km	1.305	1.609	0.949
		FAME		1.416	1.739	1.027
		HVO		1.363	1.676	0.992
		LNG	kg/km	0.953	1.171	0.692
		Hydrogen		0.391	0.480	0.283
	PIHE	Diesel / Electricity	l/km, kWh/km	0.882 / 2.123	1.209 / 7.770	0.340 / 0.398
		FAME / Electricity		0.956 / 2.123	1.310 / 7.766	0.368 / 0.399
		HVO / Electricity		0.925 / 2.109	1.273 / 7.782	0.368 / 0.399
		LNG / Electricity	kg/km, kWh/km	0.645 / 2.115	0.883 / 7.766	0.247 / 0.399
		Hydrogen / Electricity		0.266 / 2.097	0.364 / 7.769	0.101 / 0.398
	FCHE	Hydrogen	kg/km	0.352	0.604	0.227
	BE	Electricity	kWh/km	5.121	16.689	0.000

Legend: DE = Diesel-electric, HE = Hybrid-electric, PIHE = Plug-in hybrid-electric, FCHE = Fuel cell hybrid-electric, BE = Battery-electric, ZESC = Zero-emission station control, FSMC - Finite state machine control, FAME = Fatty Acid Methyl Ester, HVO = Hydrotreated vegetable oil, LNG = Liquefied natural gas.

Appendix C. Overall estimates of Tank-to-Wheel (TTW) energy use per distance and seat-distance

Vehicle	Prop. system	Energy carrier	Overall estimates per distance (MJ/km)			–	Overall estimates per seat-distance (kJ/skm)			Rel. range[a] (%)
			Mean	Max	Min		Mean	Max	Min	
GTW 2/6	DE	Diesel	35.468	57.201	25.943		334.600	539.636	244.743	88
	HE (ZESC)	Diesel	32.435	44.329	24.942		305.994	418.197	235.303	60
		FAME	32.397	44.152	24.932		305.631	416.524	235.205	59
		HVO	32.446	44.150	24.932		306.092	416.511	235.206	59
		LNG	32.401	44.147	24.931		305.667	416.477	235.202	59
		Hydrogen	32.399	44.149	24.945		305.652	416.497	235.328	59
	HE (FSMC)	Diesel	32.278	44.329	25.059		304.513	418.197	236.407	60
		FAME	32.242	44.334	25.050		304.166	418.241	236.322	60

(continued on next page)

(*continued*)

Vehicle	Prop. system	Energy carrier	Overall estimates per distance (MJ/km)			Overall estimates per seat-distance (kJ/skm)			Rel. range[a] (%)
			Mean	Max	Min	Mean	Max	Min	
		HVO	32.299	44.330	25.050	304.707	418.206	236.323	60
		LNG	32.193	44.328	25.053	303.709	418.187	236.345	60
		Hydrogen	32.186	44.334	25.065	303.646	418.247	236.461	60
	PIHE	Diesel / Electricity	25.021	34.037	15.749	236.044	321.106	148.576	73
		FAME / Electricity	24.938	34.084	15.737	235.265	321.548	148.466	74
		HVO / Electricity	25.007	33.948	15.748	235.920	320.260	148.566	73
		LNG / Electricity	24.955	33.990	15.751	235.423	320.658	148.595	73
		Hydrogen / Electricity	24.955	34.021	15.751	235.426	320.957	148.594	73
	FCHE	Hydrogen	29.180	46.918	22.413	275.284	442.620	211.440	84
	BE	Electricity	11.062	33.001	0.000	104.357	311.329	0.000	298
GTW 2/8	DE	Diesel	38.132	59.866	26.857	231.102	362.827	162.770	87
	HE (ZESC)	Diesel	35.665	46.764	26.318	216.154	283.416	159.506	57
		FAME	35.718	46.802	26.317	216.474	283.649	159.498	57
		HVO	35.669	46.724	26.320	216.175	283.175	159.517	57
		LNG	35.789	46.725	26.324	216.906	283.184	159.542	57
		Hydrogen	35.732	46.762	26.318	216.556	283.407	159.501	57
	HE (FSMC)	Diesel	35.671	46.675	26.632	216.189	282.878	161.408	56
		FAME	35.690	46.682	26.632	216.304	282.918	161.403	56
		HVO	35.602	46.678	26.637	215.771	282.899	161.438	56
		LNG	35.730	46.777	26.639	216.548	283.498	161.451	56
		Hydrogen	35.710	46.673	26.636	216.426	282.866	161.429	56
	PIHE	Diesel / Electricity	28.433	39.335	17.659	172.320	238.396	107.026	76
		FAME / Electricity	28.393	39.343	17.700	172.076	238.440	107.272	76
		HVO / Electricity	28.389	39.284	17.581	172.056	238.086	106.554	76
		LNG / Electricity	28.432	39.363	17.660	172.314	238.563	107.031	76
		Hydrogen / Electricity	28.379	39.369	17.680	171.992	238.602	107.152	76
	FCHE	Hydrogen	32.133	50.575	23.505	194.748	306.513	142.455	84
	BE	Electricity	12.475	35.769	0.000	75.605	216.784	0.000	287
WINK	HE (ZESC)	Diesel	45.281	57.059	32.195	295.955	372.936	210.423	55
		FAME	45.335	56.683	32.177	296.309	370.475	210.305	54
		HVO	45.271	56.858	32.188	295.889	371.619	210.380	54
		LNG	45.232	56.809	32.137	295.636	371.298	210.048	55
		Hydrogen	45.383	56.619	32.178	296.621	370.057	210.316	54
	HE (FSMC)	Diesel	46.789	57.708	34.035	305.808	377.174	222.452	51
		FAME	46.867	57.590	34.016	306.318	376.407	222.326	50
		HVO	46.776	57.518	34.033	305.725	375.934	222.438	50
		LNG	46.771	57.517	33.967	305.691	375.926	222.008	50
		Hydrogen	46.948	57.552	34.009	306.852	376.154	222.284	50
	PIHE	Diesel / Electricity	39.259	53.164	25.443	256.593	347.477	166.291	71
		FAME / Electricity	39.294	53.227	25.444	256.821	347.889	166.299	71
		HVO / Electricity	39.331	53.180	25.420	257.067	347.584	166.144	71
		LNG / Electricity	39.262	53.181	25.403	256.612	347.589	166.032	71
		Hydrogen / Electricity	39.463	53.191	25.420	257.928	347.651	166.147	70
	FCHE	Hydrogen	42.195	72.488	27.252	275.783	473.778	178.118	107
	BE	Electricity	18.437	60.079	0.000	120.504	392.675	0.000	326

Legend: DE = Diesel-electric, HE = Hybrid-electric, PIHE = Plug-in hybrid-electric, FCHE = Fuel cell hybrid-electric, BE = Battery-electric, ZESC = Zero-emission station control, FSMC - Finite state machine control, FAME = Fatty Acid Methyl Ester, HVO = Hydrotreated vegetable oil, LNG = Liquefied natural gas, **Note:** [a] Calculated as $((\text{Max - Min})/\text{Mean})\cdot 100\%$.

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