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Life Cycle Assessment of Alternative Traction Options for Non-Electrified Regional Railway Lines

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Abstract

The railway sector is facing significant challenges in addressing the increasing concerns related to climate change, environmental pollution and scarcity of resources. This especially applies to often non-electrified regional railway networks, with passenger services provided by diesel-driven vehicles. Innovative propulsion system concepts offer significant improvement of energy efficiency and reduction of overall environmental impact from train operation. This study presents a life cycle assessment of greenhouse gas emissions linked to the implementation of alternative powertrain systems in conventional diesel-electric multiple-unit vehicles employed on the regional railway lines in the northern Netherlands. The analysis encompassed the retrofit of a standard vehicle to its hybrid-electric, fuel cell-electric and battery-electric counterparts, and a comparative assessment of life cycle emissions during a ten-year time horizon. Results indicated significant impact of the production pathway for alternative energy carriers to diesel, namely hydrogen and electricity. The largest reduction in total emissions (96.80%) is obtained for a fuel cell-electric vehicle running on hydrogen produced from electrolysis, with slightly lower performance shown by the battery-electric configuration using green electricity produced from wind power (95.92%). Maintaining the diesel engine in the hybrid-electric alternative leads to a potential overall emission reduction of about 27%, as a result of improved fuel economy offered by the implemented energy storage system, and could be considered as a cost-effective transition solution towards carbon-neutral trains operation.

Keywords: regional railways, greenhouse gas emissions, life cycle assessment, alternative propulsion systems

1. Introduction

Regional railway passenger transport in the EU is often characterized by non-electrified lines, and diesel-electric multiple unit (DEMU) vehicles as the only traction option. Complete electrification of such lines is often not economically viable due to high capital investments required and low transport demand compared to the main corridors. Facing stringent emission regulations [1], railway undertakings are thus seeking alternative traction options to improve their environmental impact. Potential solutions are sought in advanced vehicle powertrains, with hybrid-electric, hydrogen fuel cell-electric, and battery-electric propulsion systems [2, 3] being the most prominent technology. Through improved fuel economy and/or use of renewable fuels, these systems offer significant reduction of well-to-wheel greenhouse gas (GHG) emissions and potentially zero-emission trains operation. However, to date, specific studies investigating the life cycle impacts of such solutions hardly exist.

Focussing on a case of regional railway services provided in the northern Netherlands, the aim of the present study is to assess and compare the life cycle GHG emissions resulting from the implementation of the three aforementioned alternative propulsion systems in the conventional DEMU vehicle. Hybridization of a standard vehicle can be achieved by implementing an energy storage system, typically a Lithium-ion battery, that would allow for the utilization of regenerative braking energy, reduced fuel consumption and related emissions. A catenary-free fuel cell-electric system can be implemented by replacing the engine-generator unit with a hydrogen fuel cell system, together with an appropriately sized energy storage system that would make up for the slow dynamic responses of a fuel cell. Due to the lack of an on-board power plant, a battery-electric system requires partial track electrification for charging the energy storage system, with stored energy later utilized on non-electrified track sections. The results presented in the remainder of the study will provide railway undertaking and decision makers with essential input in planning rolling stock and infrastructure investments.

2. Methodology

A life cycle assessment (LCA) approach is used in assessing the GHG emissions linked to the alternative propulsion systems implementation, namely hybrid-electric, fuel-cell electric and battery electric. A ten-years' time horizon is considered, from 2025 until 2035, which denotes the end of the ongoing concession period and the end of current vehicles' service life. Due to the comparative nature of the study, and considered retrofit of existing vehicles with electrification of already built railway lines, the analysis is restricted to the subsystems and components varying with the alternative vehicle configurations. This approach also contributes to handling the complexity, which is inherently high when the analysis entails infrastructure construction and vehicle production from scratch. The system boundary (Figure 1) includes emissions resulting from: (i) production of the system components used in converting the conventional vehicle, i.e., fuel cells and Lithium-ion batteries, as well as the track electrification equipment required for the operation of battery-electric multiple units; (ii) the vehicle-use phase, covering upstream emissions related to the production and distribution of fuel/electricity, and direct emissions produced during vehicle operation; and (iii) the end-of-life phase that encompasses recycling and/or disposal of particular vehicle components. Due to the much longer service life of railway infrastructure (typically 60 years) than the observed time horizon, end-of-life processes for track electrification equipment are omitted.

Depending on the nominal power of the fuel cell system, energy capacity of Lithium-ion battery and/or length of the electrified track, corresponding life cycle emissions are estimated using emission factors provided in Table 1. Although hydrogen and electricity utilization in vehicle propulsion does not produce direct emissions, the overall environmental impact of these energy carriers largely depends on the upstream processes related to their production and distribution. To investigate the impact of these processes, and to allow for fair comparison with the baseline diesel fuel, various production pathways are considered using a well-to-wheel approach. Alternative hydrogen production pathways include steam methane reforming (SMR) and electrolysis of water using green electricity obtained from wind power, while electricity production scenarios encompass a predicted EU power mix for 2030, or renewable electricity obtained solely from wind power. Corresponding emission factors are given in the remainder of Table 1, which are then coupled with the estimated fuel or electricity consumption from vehicle operation in assessing the overall GHG emissions from the vehicle use phase.

Taking into account the significance and contribution of the use phase to the overall environmental impact over a ten-years period, it is essential to obtain reliable estimates of the fuel or electricity consumption during the train's operation. For this aim, detailed MATLAB/Simulink individual train models based on a backward looking quasi-static simulation approach [4] is employed. The modular structure and programming environment allows for relatively easy development or customization of train propulsion system configurations and implemented on-board power management [5]. We extend previous work on the model of a hybrid-electric [6] and fuel cell-electric system [7] with a newly developed model of a battery-electric train. The simulation model requires technical specifications for a variety of system components and infrastructure related characteristics, and provides an estimate of fuel or electricity consumption during observed trips as an output. The obtained estimates are then coupled with information on the annual days of operation, maintenance frequencies, and the number of cycles performed per day in assessing the overall energy consumption during a ten years period.

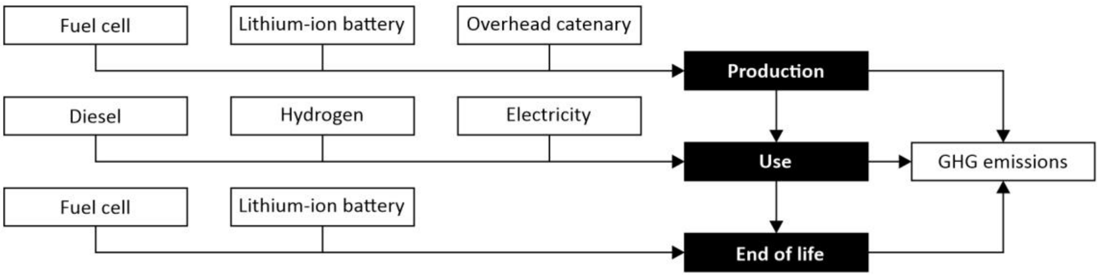

Figure 1: System boundary for the LCA

Component/Energy carrier	Unit	Value	Reference
Fuel cell	$kgCO_2e/kW$	43	[8]
Lithium-ion battery	$kgCO_2e/kWh$	83.5	[9]
Track electrification	$kgCO_2e/km/year$	1750	[10]
Diesel	$kgCO_2e/l$	3.303	[11]
Hydrogen (SMR)	$kgCO_2e/kg$	15.9	[11]
Hydrogen (electrolysis)	$kgCO_2e/kg$	0.432	[11]
Electricity (EU mix 2030)	$kgCO_2e/kWh$	0.259	[11]
Electricity (wind energy)	$kgCO_2e/kWh$	0	[11]

Table 1: Greenhouse gas emission factors for energy carriers and alternative technology components

3. Case Study of Regional Railways in the Northern Netherlands

The methodology proposed in the previous section was applied in estimating the energy consumption for each of the considered alternative propulsion systems, followed by the calculation of related life cycle GHG emissions. The following sub-sections provide the description of the selected benchmark DEMU and railway line, followed by a comparative analysis of the different scenarios.

3.1 Reference Vehicle and Railway Line

The presented LCA approach is applied in a case of a two-coach DEMU GTW 2/6 from Stadler, employed on the network's main railway line connecting the cities Leeuwarden and Groningen. Due to the difference in line resistances and maximum speed limits for the two opposite directions (Figure 2), the vehicle round trip is analysed, based on the actual periodic timetable and vehicle circulation plan provided by the railway undertaking. A vehicle performs eight round trips during working days, and six round trips during weekends. A three weeks out-of-operation period is assumed per year for maintenance purposes. Commercially available fuel cell modules from Ballard [12] and Lithium-ion batteries from Toshiba [13] are used in vehicle retrofit, with the number of modules determined from the estimated power and energy demand, while satisfying the maximum weight and volumetric space constraints [7]. With stations Leeuwarden and Groningen already connected to the national traction grid, the battery-electric scenario considers electrification of the first track sections stretching from these two stops, namely Leeuwarden – Leeuwarden Camminghaburen and Groningen – Zuidhorn. Table 2 provides the main specifications for alternative scenarios. In addition to the initial retrofit, both fuel cells system and Lithium-ion battery energy storage system are to be replaced once during the observed ten-years period due to the limited service life of these technologies, i.e. number of working hours or charge/discharge cycles.

Component	Propulsion system			
	Conventional	Hybrid-Electric	Fuel Cell-Electric	Battery-Electric
Diesel engine	2×390 kW	2×390 kW	-	-
Fuel cell system	-	-	6×70 kW	-
Lithium-ion battery	-	106×1.24 kWh	157×1.24 kWh	499×1.24 kWh
Electrified track	-	-	-	15.036 km

Table 2: Technical specifications of alternative propulsion system configurations

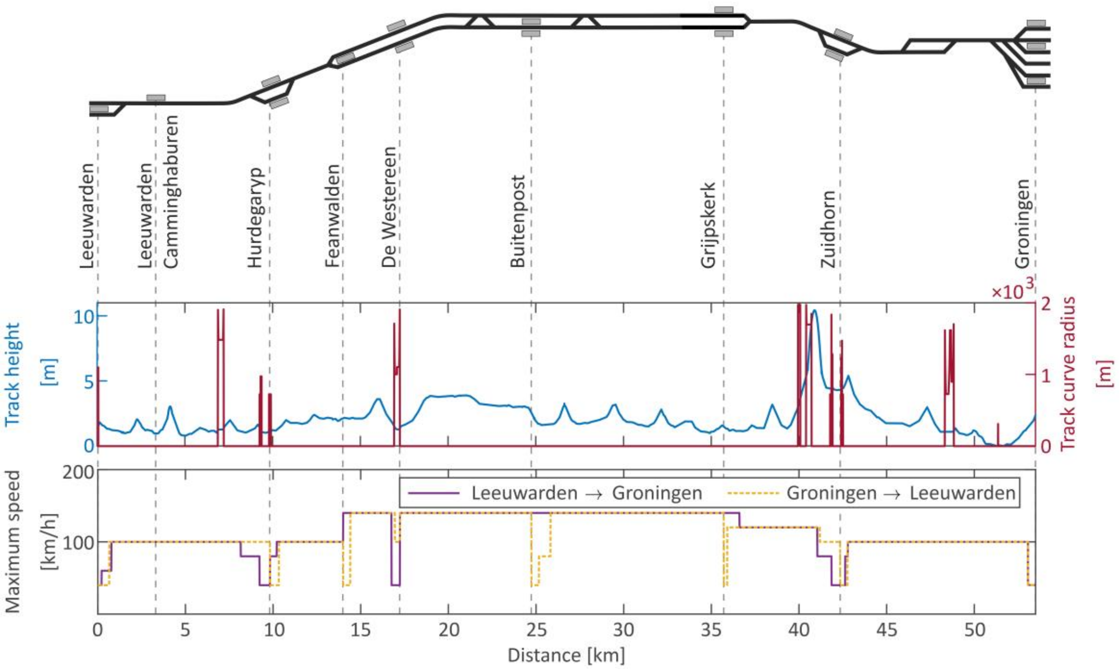

Figure 2: Railway line Leeuwarden-Groningen: track layout, geometry, and speed limits

3.2 Results

The estimated fuel or electricity consumption per single trip and for the overall ten-years period is provided in Table 3. The total life cycle GHG emissions are further calculated using emission factors (Table 1), propulsion system configurations (Table 2) and the assumptions related to the periodic replacement of components, with estimates for the six scenarios summarized in Figure 3. Figure 3 also shows the relative GHG emissions reduction potential of alternative systems compared to a baseline conventional DEMU vehicle as the highest emitter, with estimated total GHG emissions of almost 9 million tons of CO_2e, attributed completely to the vehicle use phase (production and consumption of diesel fuel).

Conversion of a conventional DEMU to its hybrid-electric counterpart leads to a potential overall emissions reduction of about 27%, as a result of improved fuel economy offered by the implemented energy storage system. A significant impact of upstream processes related to the production and distribution of an energy carrier is most evident in the case of fuel cell-electric vehicle configuration, which demonstrated both, the lowest (9.66%) and the highest (96.80%) emission reduction potential if hydrogen produced from SMR and electrolysis is used, respectively. A slightly higher emission level compared to the aforementioned best alternative is shown for the battery-electric powertrain with green electricity used for traction and charging the energy storage system. A high contribution of the energy carrier pathway is notable here as well, with emission savings potential reduced to about 77% for electricity based on the 2030 EU mix, as still significant part of the electricity production is expected to rely on fossil energy such as coal and natural gas [11].

Propulsion system	Energy carrier	Per trip	Over 10 years
Conventional	Diesel [l]	106.40	2,719,584
Hybrid-electric	Diesel [l]	77.45	1,979,622
Fuel cell-electric	Hydrogen [kg]	19.80	506,088
Battery-electric	Electricity [kWh]	255.80	6,538,248

Table 3: Estimated energy consumption from train’s operation

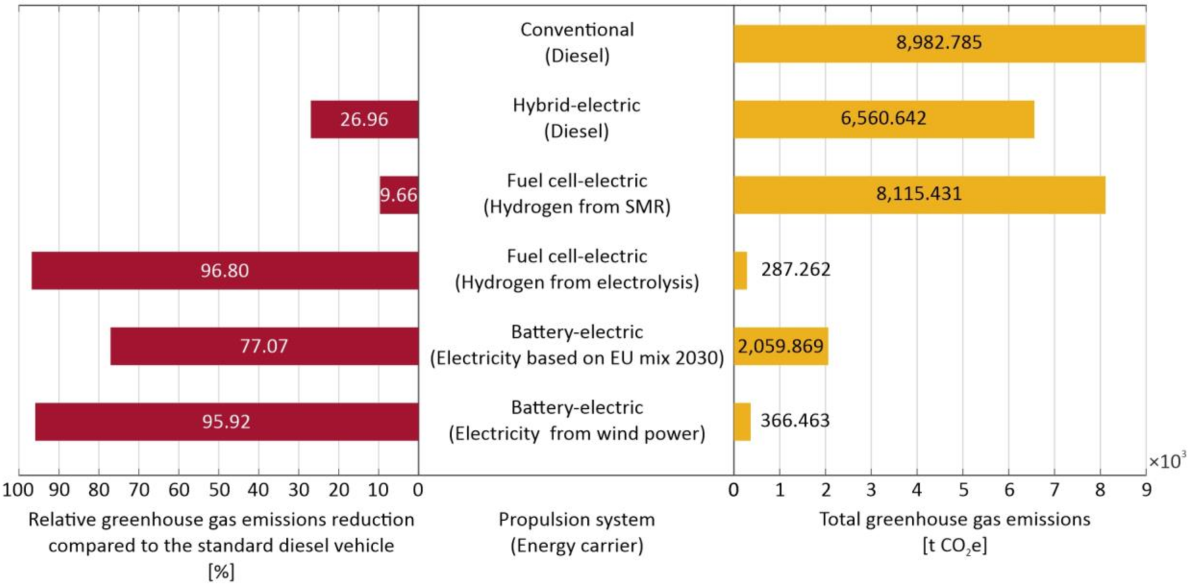

Figure 3: Total life cycle greenhouse gas emissions produced during the observed period and relative greenhouse gas emissions reduction compared to the standard diesel vehicle

Regarding the relative share of different components to the overall GHG emissions produced during the observed period (Figure 4), the vehicle use phase (energy carrier production, distribution and consumption) has the far largest contribution in all scenarios, except for the battery-electric vehicle running on green electricity – as the only alternative that offers net-zero emissions from a well-to-wheel perspective. The fuel cell system is linked with slightly higher life cycle impact than the considered Lithium-ion battery for this powertrain configuration. Although the battery-electric configuration considers a significantly larger battery system, its life cycle emissions are almost three times lower than those associated with the track electrification.

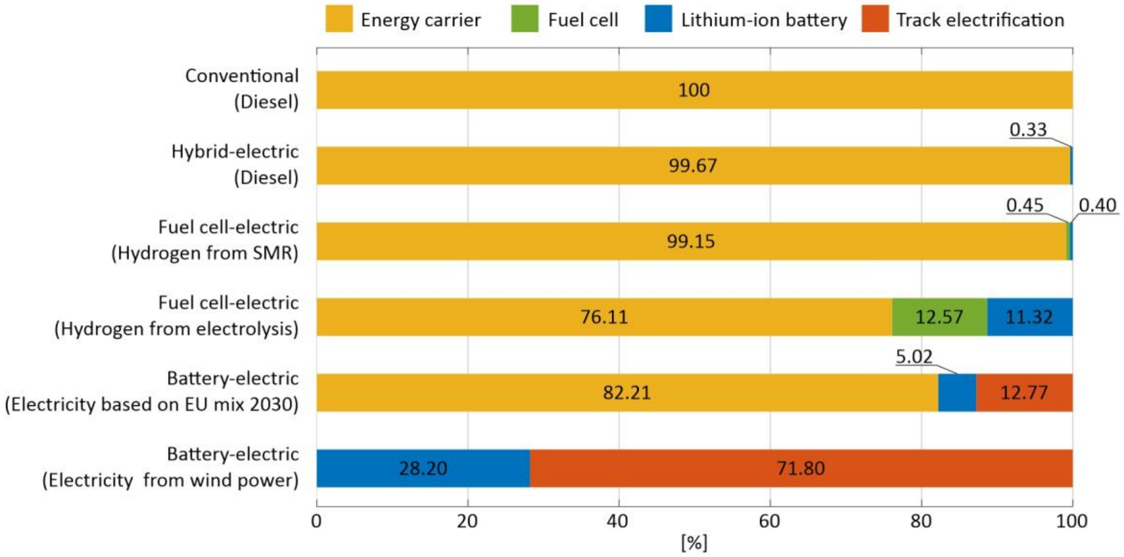

Figure 4: Relative contribution of different components to the overall greenhouse gas emissions produced during the observed period

4. Conclusion

This study presented a comparative assessment of life cycle GHG emissions related to the implementation of various alternative powertrain configurations in a conventional diesel regional train, namely hybrid-electric, fuel-cell-electric and battery-electric. The results indicated significant impact of the production pathways for the alternative energy carriers, with the highest potential benefits identified for the fuel-cell electric system running on green hydrogen. Similar performance is obtained for the battery-electric vehicle using green electricity from wind power. Although internal combustion engines produce other harmful emissions such as local pollutants, a vehicle retrofit solely by hybridization of a conventional powertrain demonstrated significant fuel savings and emission reduction, and could be considered as a cost-effective transition solution towards carbon neutral trains operation. Future research will include economical aspects related to the implementation of presented propulsion systems, together with the alternative production pathways for hydrogen and electricity, by an integrated LCA and life cycle costs (LCC) approach.

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