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

Marko Kapetanović[1], Alfredo Núñez[2], Niels van Oort[1], Rob M.P. Goverde[1]

[1]Delft University of Technology, Department of Transport and Planning, Delft, The Netherlands

[2]Delft University of Technology, Section of Railway Engineering, Delft, The Netherlands

Content

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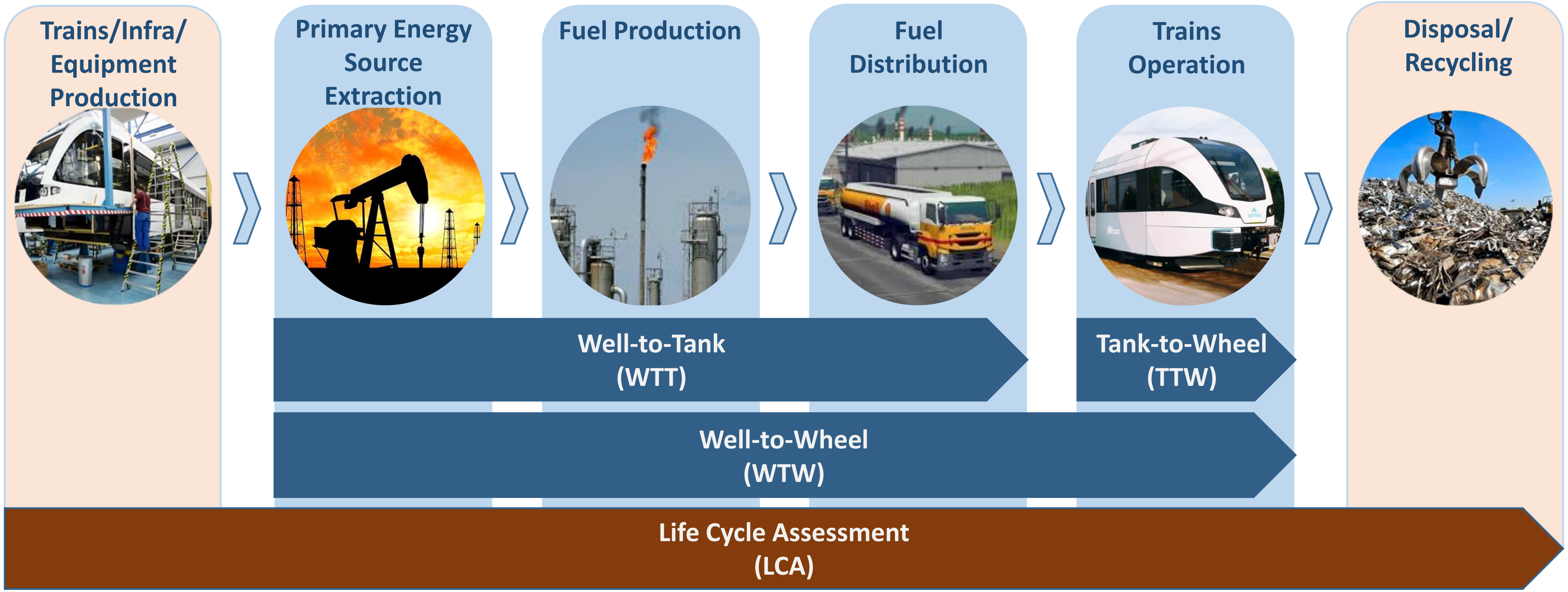
Introduction

- **Non-electrified regional railway networks** require identification of alternative traction options to meet stringent emission regulations and defined targets.
- Transition (retrofit) of existing diesel-driven rolling stock to their low-emission counterparts requires in-depth analyses that include **identification, design, modelling, and assessment of potential alternatives**, with respect to the particular case-related constraints imposed by infrastructure, technical and operational constraints.
- Direct vs. indirect emissions:



Introduction

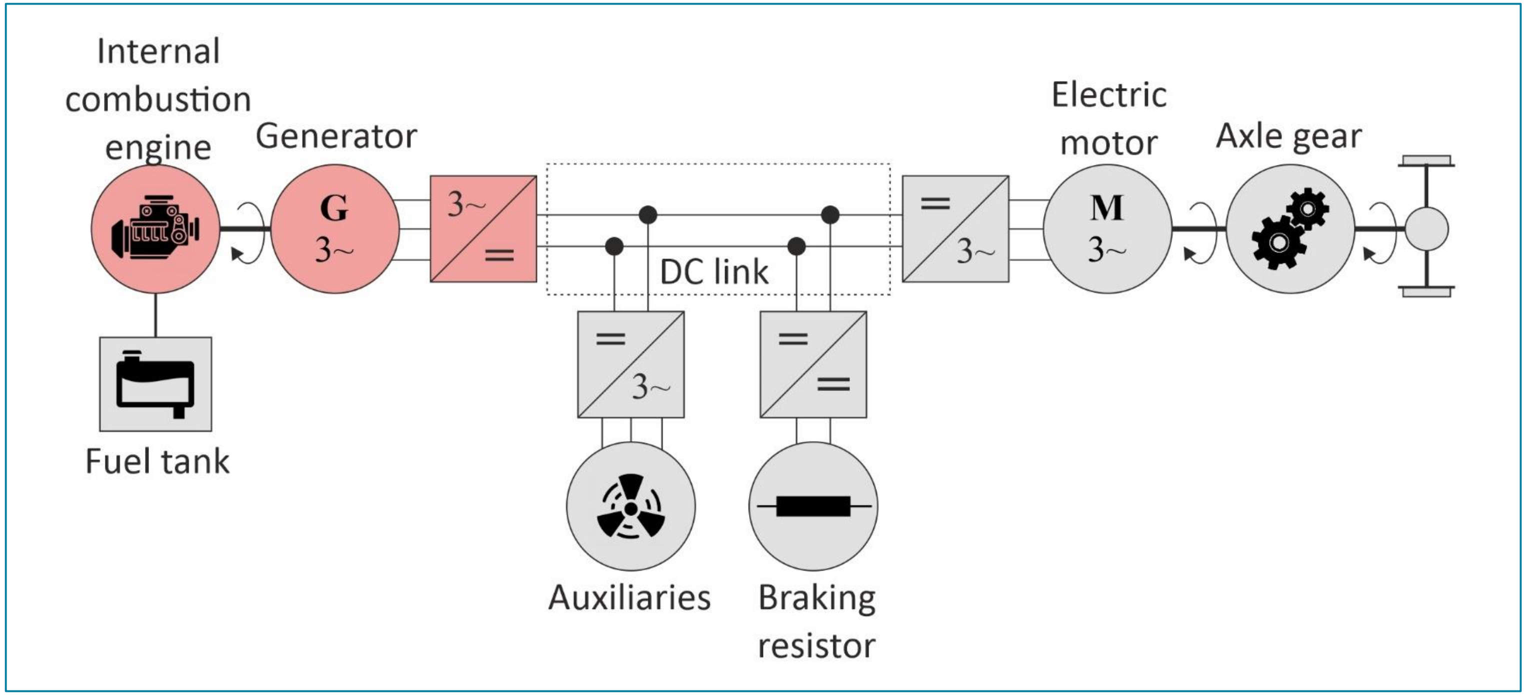
- Scope and context of the study:
    - ✓ Greenhouse gas (GHG) emissions
    - ✓ Regional railway services and rolling stock in the northern Netherlands
    - ✓ Concession period 2025-2035

- Aim of the study:
    - ✓ Model-based analysis of standard DEMU vehicle conversion to its low-emission counterparts
    - ✓ Assessment of potential reduction of life cycle GHG emissions compared to the current (baseline) scenario

Content

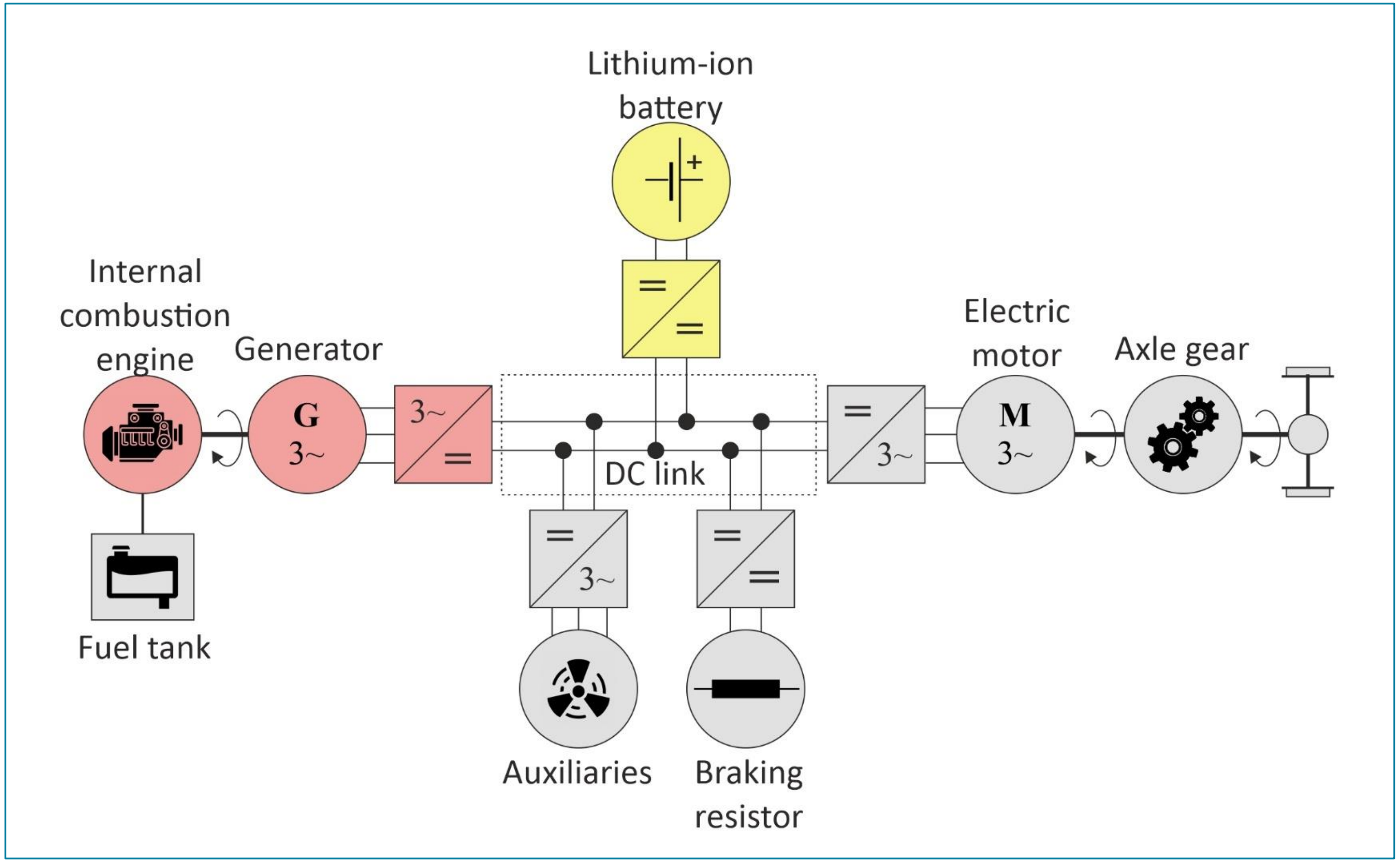
Alternative propulsion system configurations

Standard (Diesel-Electric)



Alternative propulsion system configurations

Hybrid-Electric



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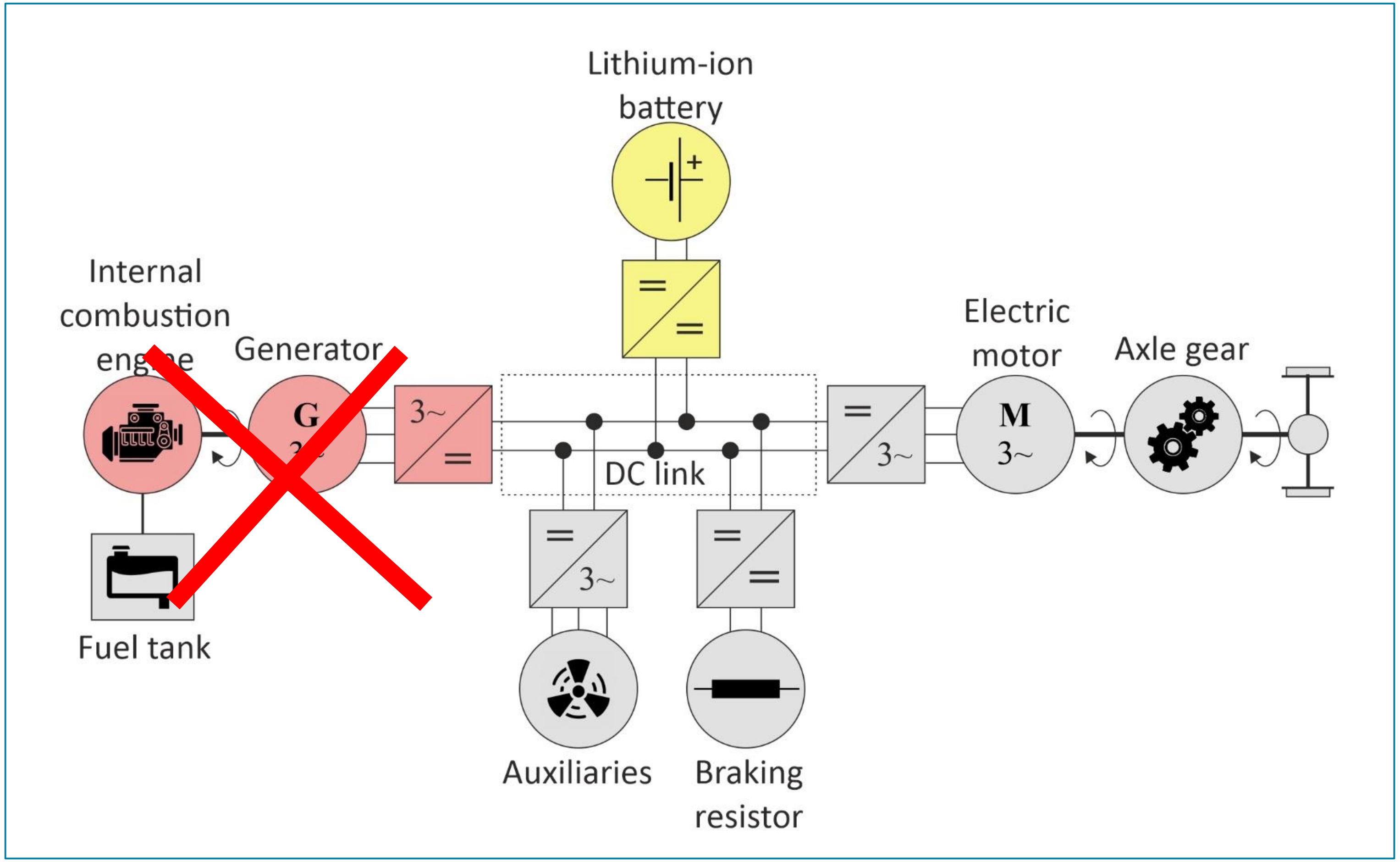
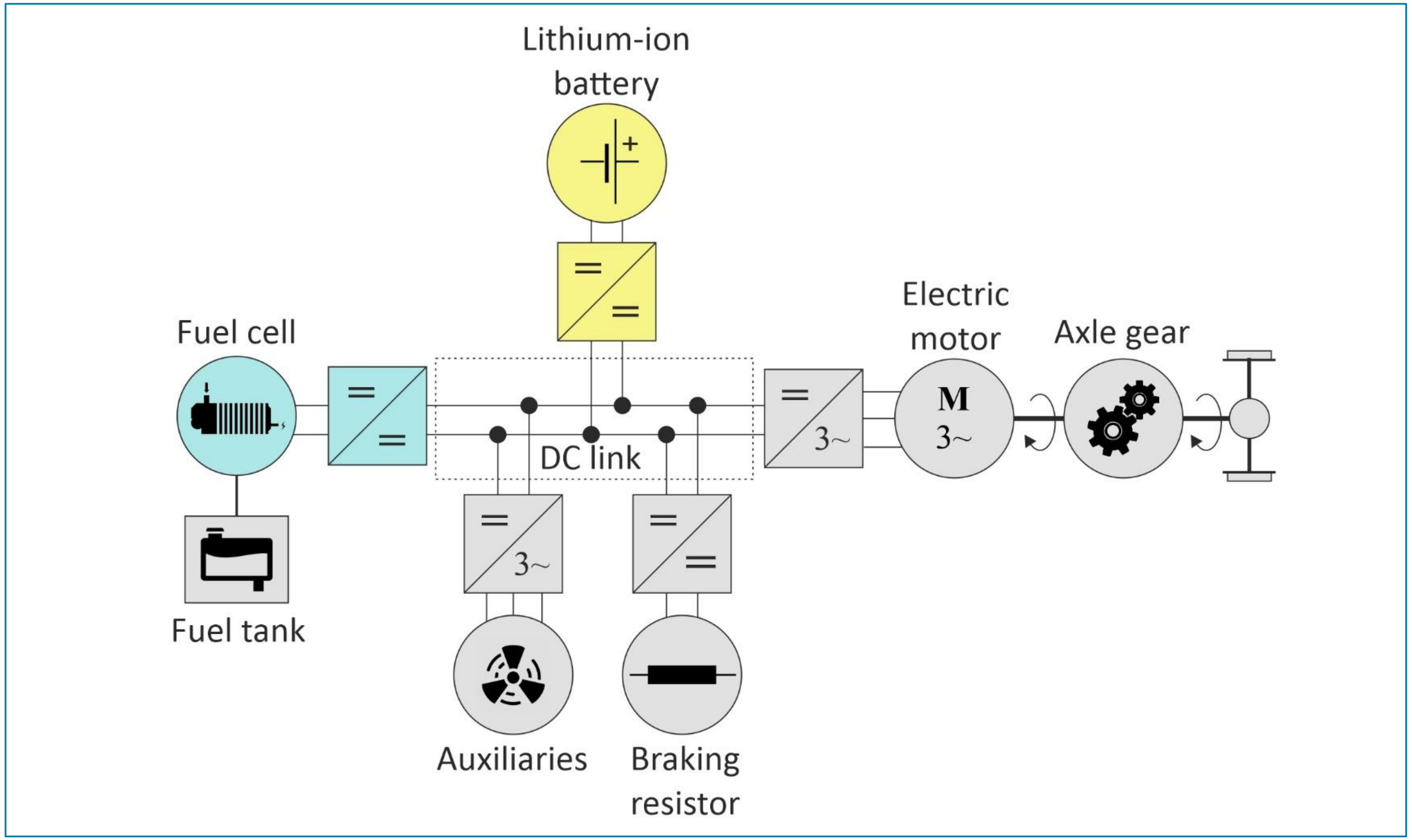
Hybrid-Electric



Alternative propulsion system configurations

Fuel Cell-Electric



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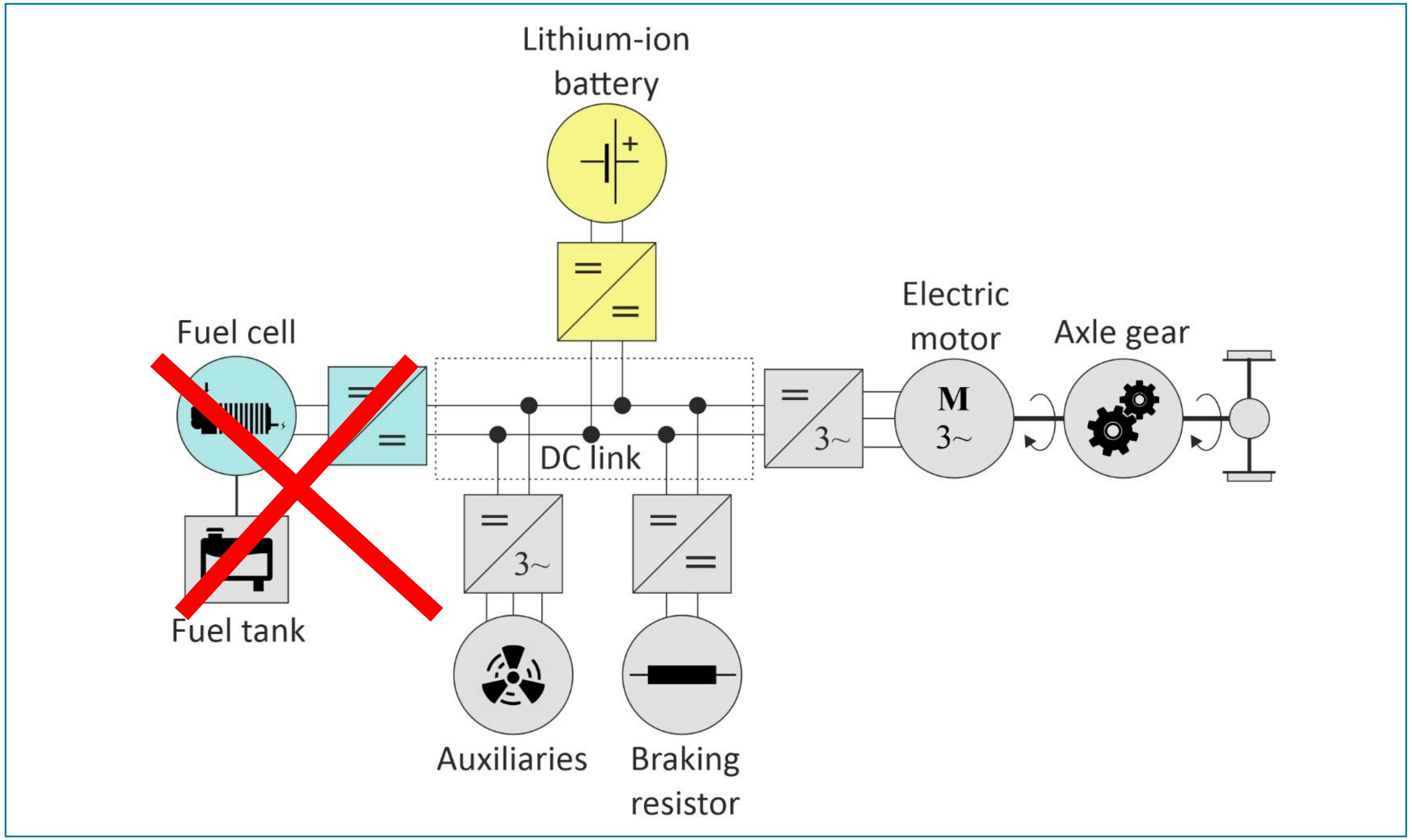
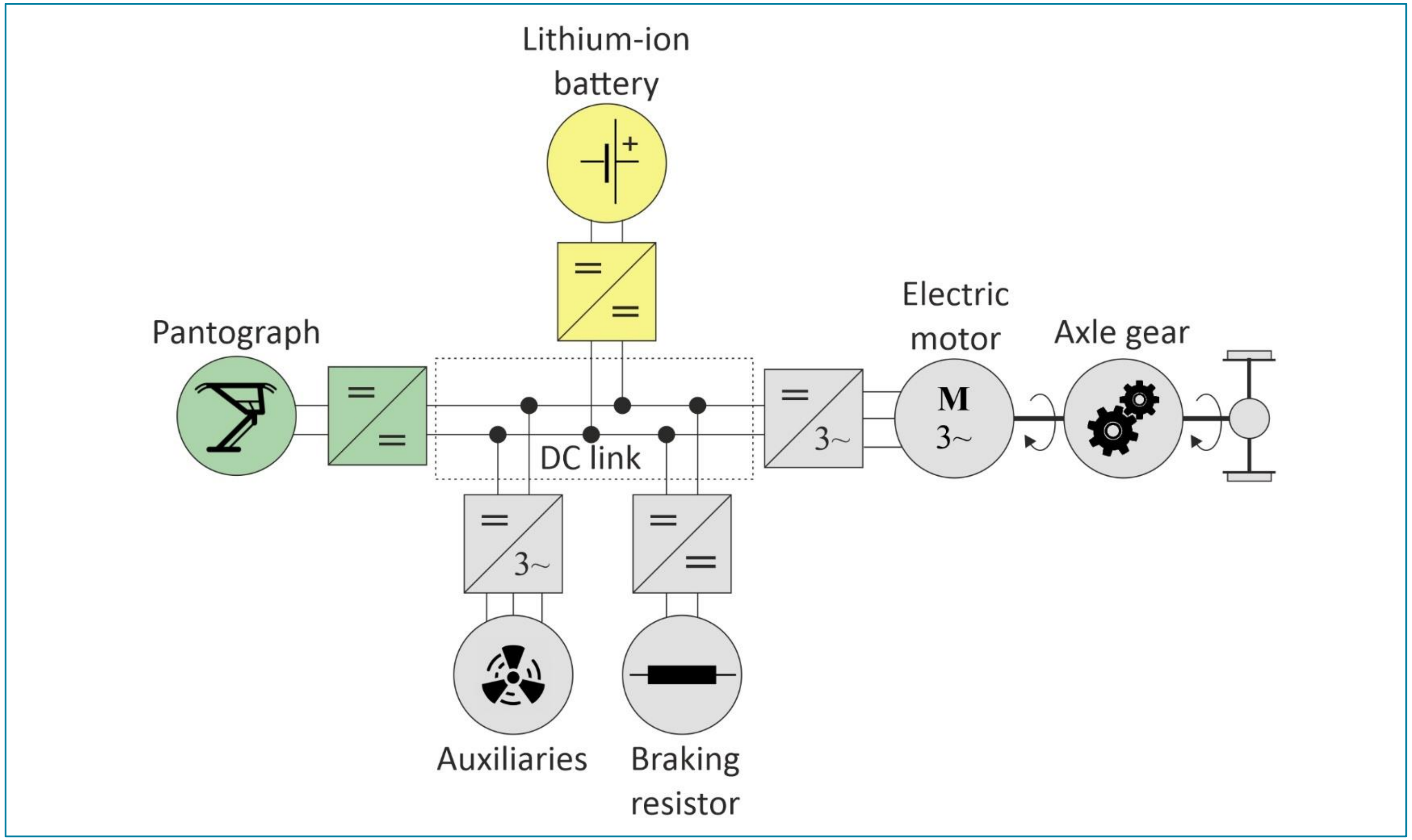


Alternative propulsion system configurations

Battery-Electric



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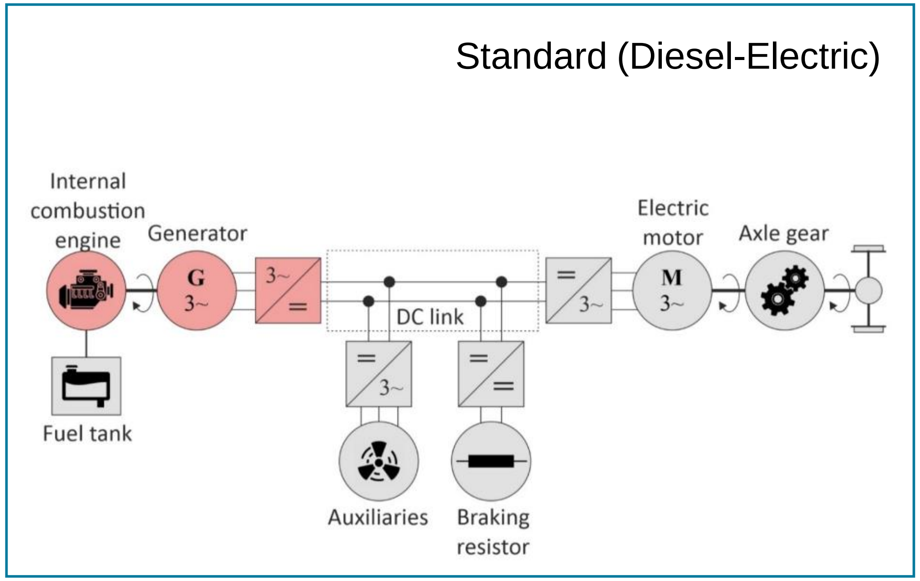
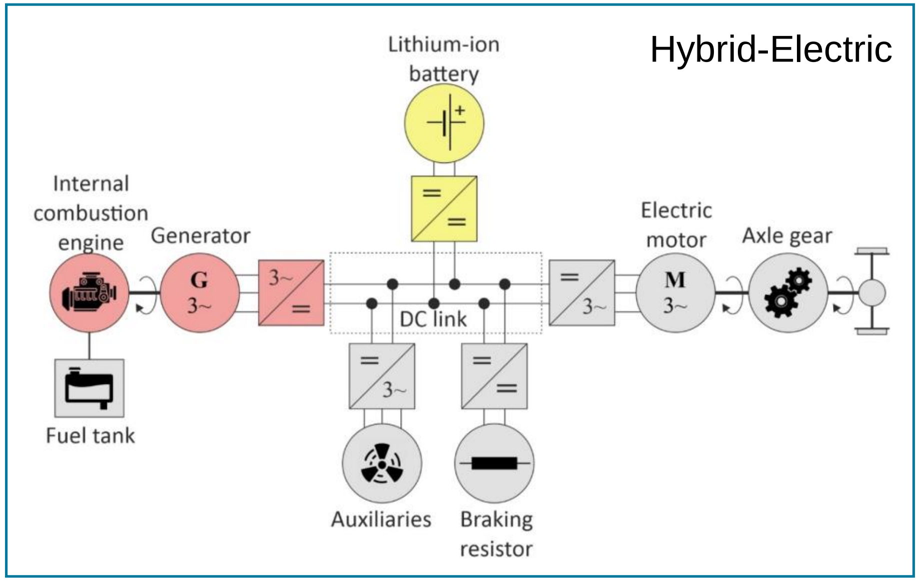
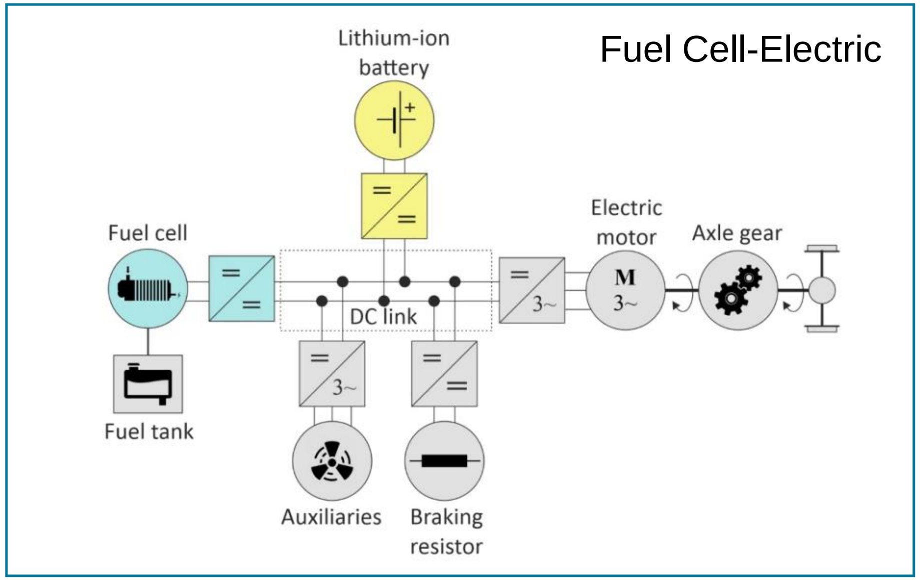
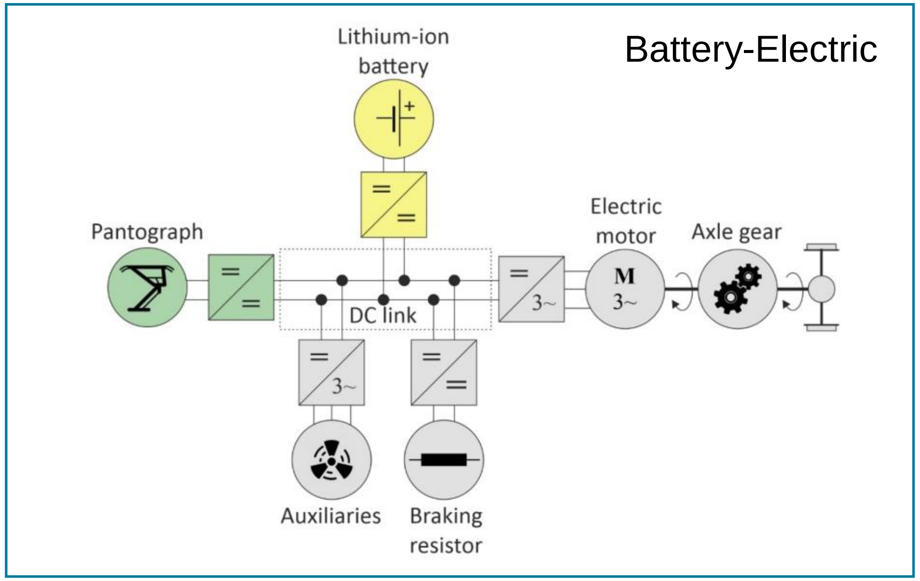
Alternative propulsion system configurations









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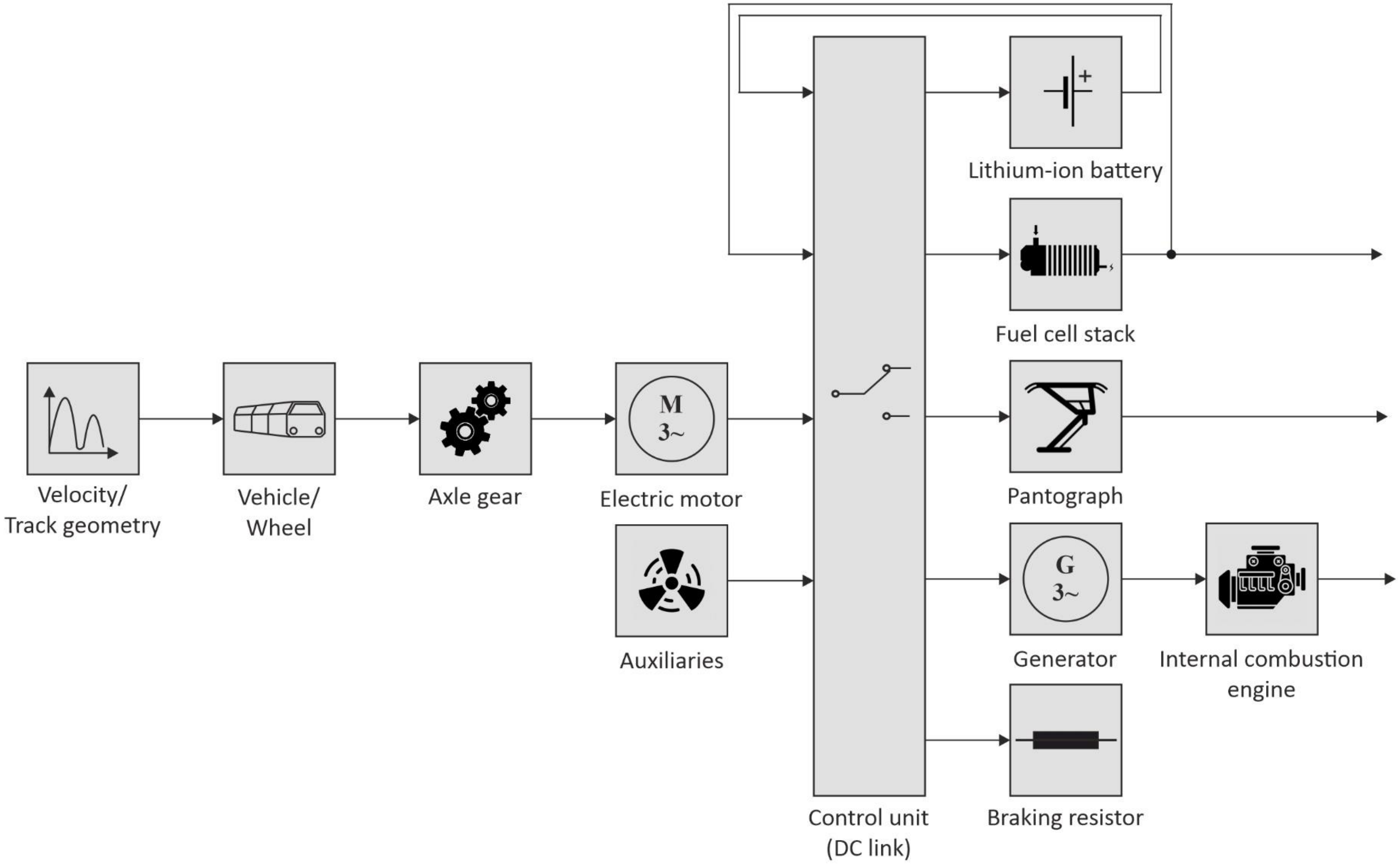
Content

Modelling of Alternative Propulsion Systems

- Backward-looking quasi-static simulation approach [1]
- MATLAB®/Simulink© environment
- OPEUS Simulink toolbox [2,3]



1. Kapetanović, M., Nunez, A., van Oort, N., & Goverde, R. (2021). Reducing fuel consumption and related emissions through optimal sizing of energy storage systems for diesel-electric trains. Applied Energy, 294, 117018.
2. L. Pröhl, "OPEUS Deliverable DO2.1 - OPEUS simulation methodology", EU-project OPEUS (S2R-OC-CCA-02-2015), 2017.
3. L. Pröhl, "OPEUS Deliverable DO2.2 - OPEUS simulation tool", EU-project OPEUS (S2R-OC-CCA-02-2015), 2017.

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Modelling of Alternative Propulsion Systems

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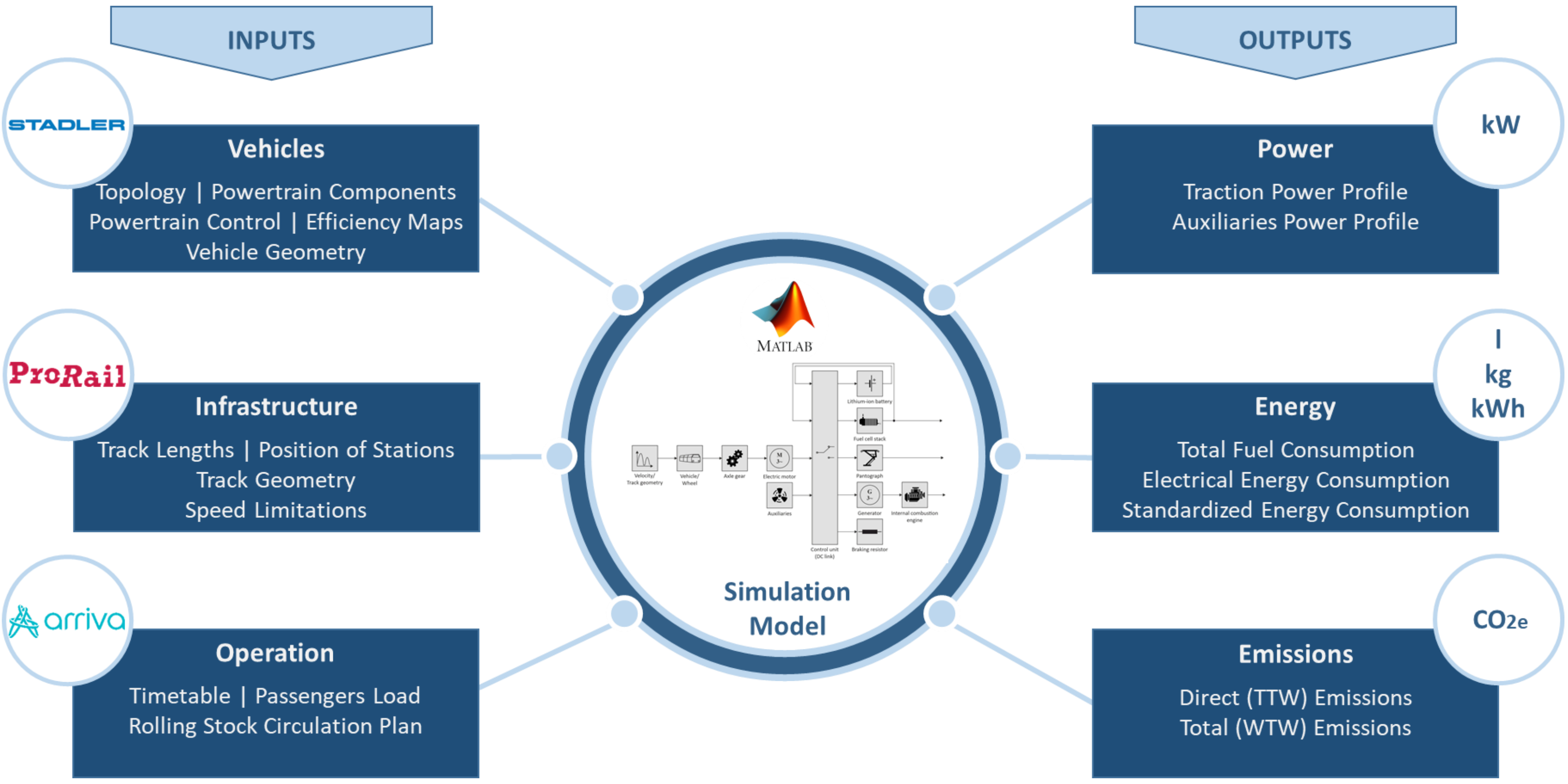
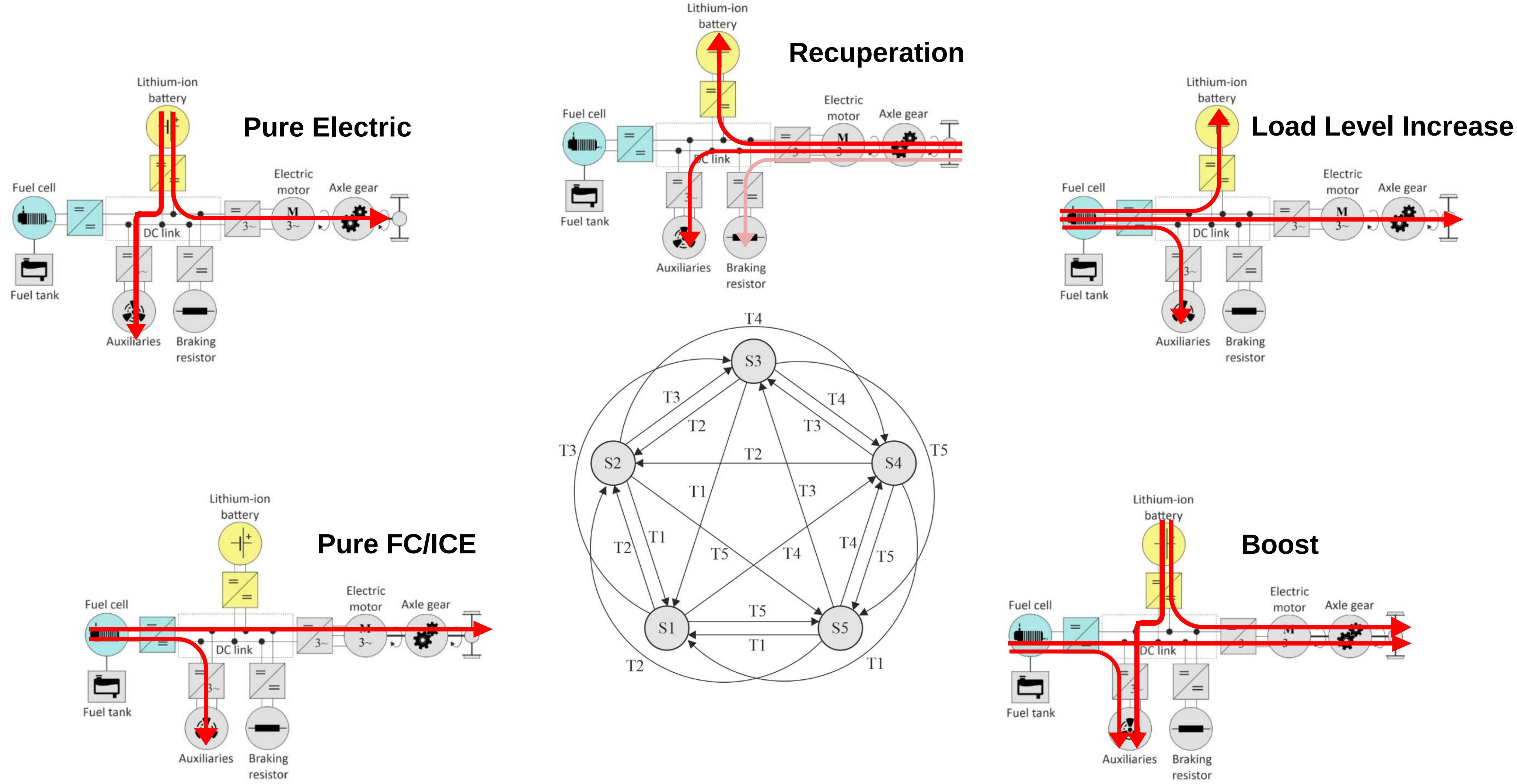


Control of Alternative Propulsion Systems



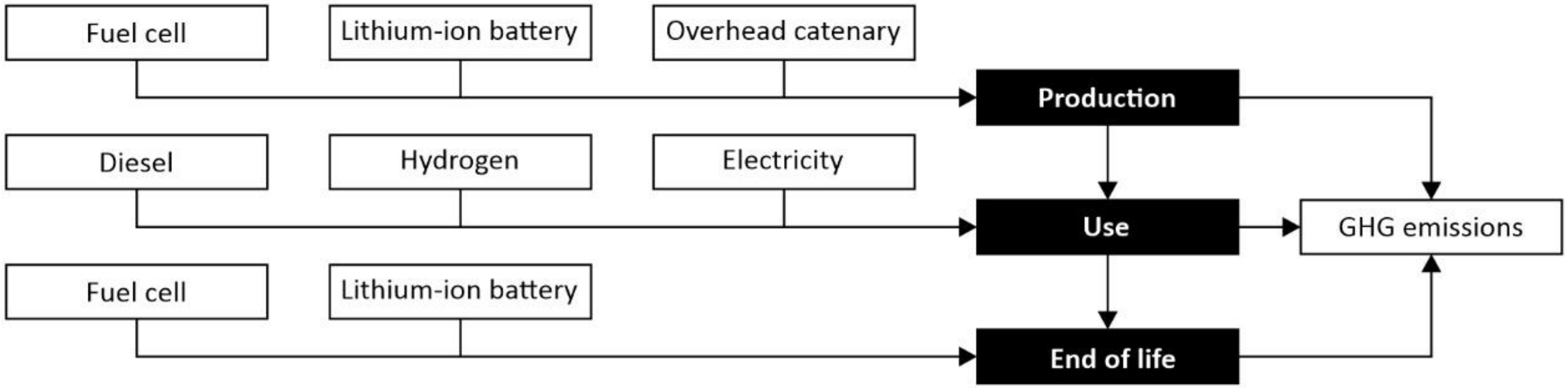
4. Kapetanović, M., Vajihi, M. and Goverde, R.M.P. (2021), "Analysis of Hybrid and Plug-In Hybrid Alternative Propulsion Systems for Regional Diesel-Electric Multiple Unit Trains", Energies, 14(18), 5920.
5. Kapetanović, M., Nunez, A., van Oort, N. and Goverde, R.M.P. (2022), "Analysis of hydrogen-powered propulsion system alternatives for diesel-electric multiple unit regional trains", J. Rail Transp. Plan. Manag.

Content

- Introduction
- Alternative Propulsion System Configurations
- Modelling and Control of Alternative Propulsion Systems
- Assessment of Life Cycle GHG Emissions
- Conclusions

Assessment of Life Cycle GHG Emissions

System boundary for the LCA



Assessment of Life Cycle GHG Emissions

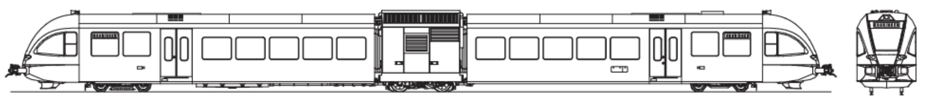
GHG emission factors for energy carriers and alternative technology components

Component / Energy carrier	Unit	Value	Source
Fuel cell	$kgCO_2e/kW$	43	[6]
Lithium-ion battery	$kgCO_2e/kWh$	83.5	[7]
Track electrification	$kgCO_2e/km/year$	1750	[8]
Diesel	$kgCO_2e/l$	3.303	[9]
Hydrogen (SMR)	$kgCO_2e/kg$	15.900	[9]
Hydrogen (electrolysis)	$kgCO_2e/kg$	0.432	[9]
Electricity (EU mix 2030)	$kgCO_2e/kWh$	0.259	[9]
Electricity (wind energy)	$kgCO_2e/kWh$	0	[9]

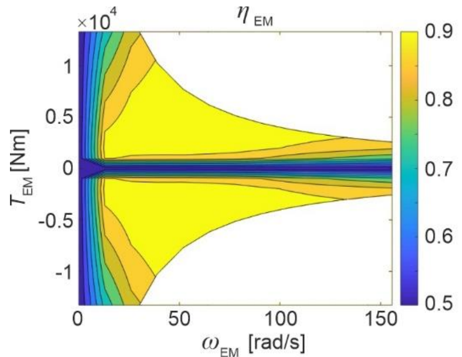
6. M. Pehnt, "Life-cycle assessment of fuel cell stacks", Int. J. Hydrogen Energy, vol. 26 (1), pp. 91–101, 2001.
7. Ö. Andersson and P. Börjesson, "The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications", Appl. Energy, vol. 289, p. 116621, May 2021.
8. T. Baron, M. Tuchschmid, G. Martinetti, and D. Pepion, "High Speed Rail and Sustainability. Background Report: Methodology and results of carbon footprint analysis", UIC, Paris, 2011.
9. JRC, "JEC Well-to-Tank report v5. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context", Luxembourg, 2020.

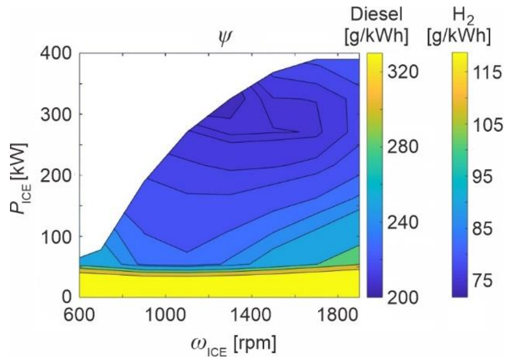
Benchmark Vehicle

Stadler GTW 2/6 diesel-electric multiple unit



Parameter	Unit	Value
Tare weight	t	70.4
Rotating mass factor	-	0.05
Total passengers weight	t	7
Davis equation coefficient (constant term)	N	1001
Davis equation coefficient (linear term)	N/(km/h)	22.3
Davis equation coefficient (quadratic term)	$N/(km/h)^2$	0.1
Powered wheel diameter	m	0.86
Axle gear ratio	-	1.7218
Axle gear efficiency	-	0.97
Maximum velocity	km/h	140
Maximum acceleration	m/s^2	1.05
Maximum deceleration	m/s^2	-1
Maximum (starting) tractive effort	kN	80
Maximum power at the wheel	kW	600
EM rated power	kW	2×400
ICE rated power	kW	2×390
Constant auxiliaries power	kW	50
Cooling power coefficient	-	0.01





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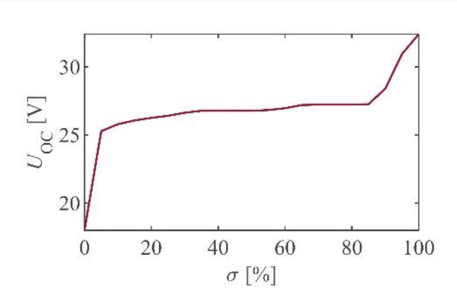
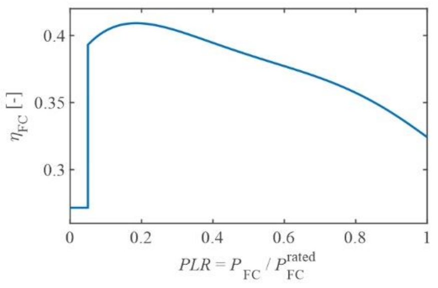
Technology Selection

Toshiba SCiB™ module
Type 1-23 (NMC/LTO)
24 cells (2x12)

Ballard FCmove™-HD
Based on
FCgen®-LCS stack

Luxfer G-Stor™ H2
Model W322H35
(350bar)

Component	Parameter	Unit	Value
Lithium-ion Battery Module 	Nominal capacity	Ah	45
	Minimum/maximum continuous current	A	-160/160
	Minimum/maximum pulse current	A	-350/350
	Allowed time for pulse current	s	10
	Minimum/maximum voltage	V	18/32.4
	Internal resistance charge/discharge	Ω	0.006/0.006
	Nominal SoC	%	50
	Minimum/maximum SoC	%	10/90
	Energy content	kWh	1.24
	Usable energy content	kWh	0.922
	Minimum/maximum power at nominal SoC	kW	-4.130/4.437
	Volume	m^3	0.00857
	Weight	kg	15
Fuel-Cell Module 	Rated power	kW	70
	Idle power	kW	8
	Volume	m^3	0.61362
	Weight	kg	250
Hydrogen Storage	Storage capacity	kg	7.8
	Volume	m^3	0.418
	Tank weight	kg	141

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Assessment of Life Cycle GHG Emissions

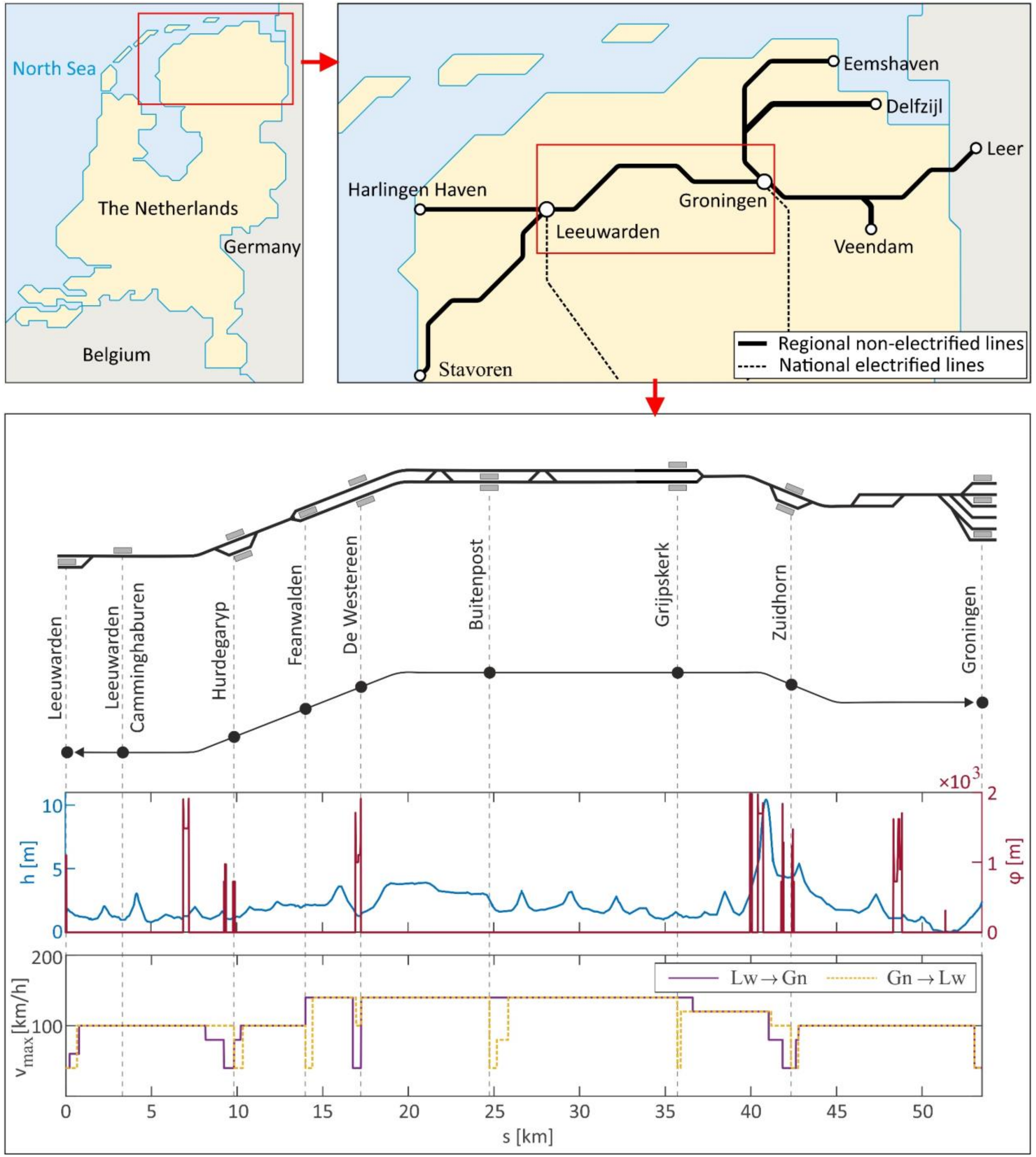
Technical specifications of alternative propulsion system configurations

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

Benchmark Railway Line

Departure times for the vehicle round trip based on the periodic timetable:

Stop	Lw - Gn	Gn - Lw
Leeuwarden	hh : 51	hh+2 : 40 (arrival)
Leeuwarden C.	hh : 54	hh+2 : 35
Hurdegaryp	hh+1 : 01	hh+2 : 30
Feanwalden	hh+1 : 05	hh+2 : 25
De Westereen	hh+1 : 08	hh+2 : 20
Buitenpost	hh+1 : 16	hh+2 : 15
Grijskerk	hh+1 : 23	hh+2 : 06
Zuidhorn	hh+1 : 30	hh+2 : 01
Groningen	hh+1 : 39 (arrival)	hh+1 : 51



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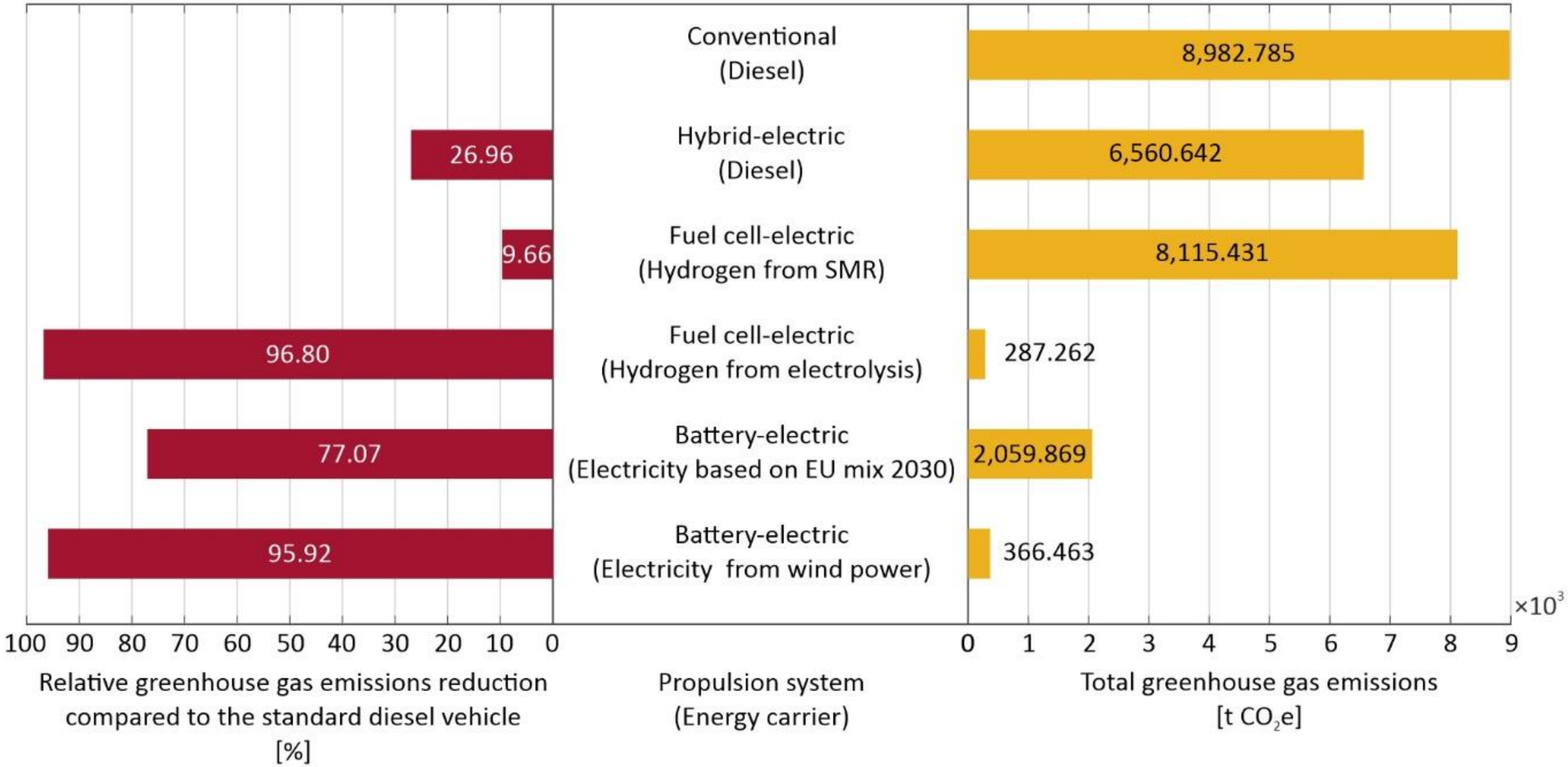
Assessment of Life Cycle GHG Emissions

Estimated energy consumption from train's operation

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

Assessment of Life Cycle GHG Emissions



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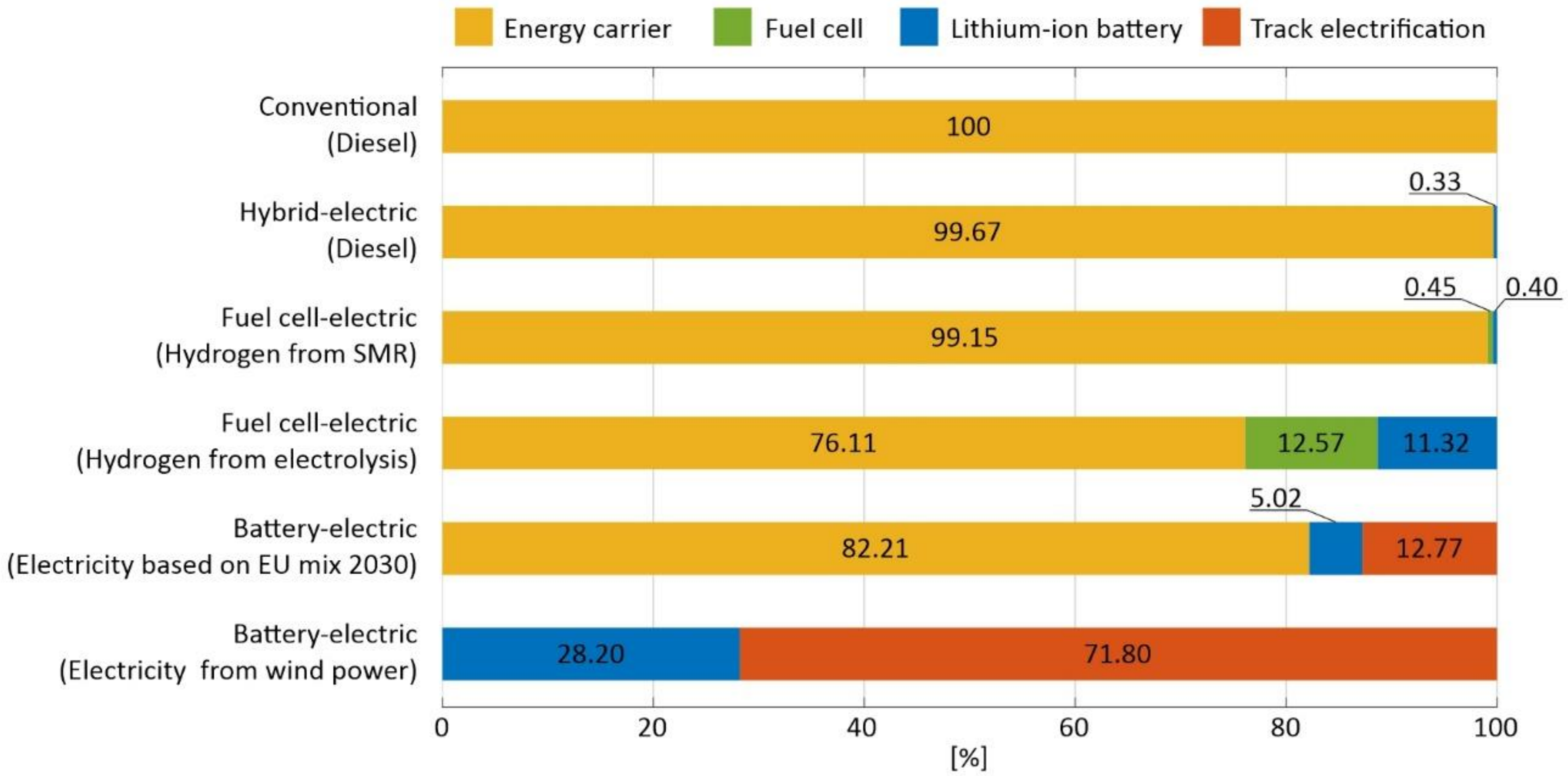
Assessment of Life Cycle GHG Emissions



Relative contribution of different components to the overall greenhouse gas emissions

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Conclusions

- Significant impact of the **production pathways** for the alternative energy carriers.
- Highest potential benefits identified for the **fuel-cell electric system running on electrolysis-based hydrogen**.
- Similar performance is obtained for the **battery-electric vehicle using green electricity** from wind power.
- 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.
- Extensions of the present research:
  - ✓ Consideration of alternative fuels, e.g., **HVO, synthetic fuels**.
  - ✓ Consideration of alternative technology, e.g., **supercapacitors, flywheels**.
  - ✓ Consideration of fixed costs for infrastructure/equipment production in a comprehensive **life cycle costs analysis**.

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Thank you for your attention!

Marko Kapetanović

M.Kapetanovic@tudelft.nl

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