Alternative Traction Energy Sources

Dr Zhongbei Tian (z.tian@bham.ac.uk)

Assistant Professor in Transportation Energy Systems

University of Birmingham

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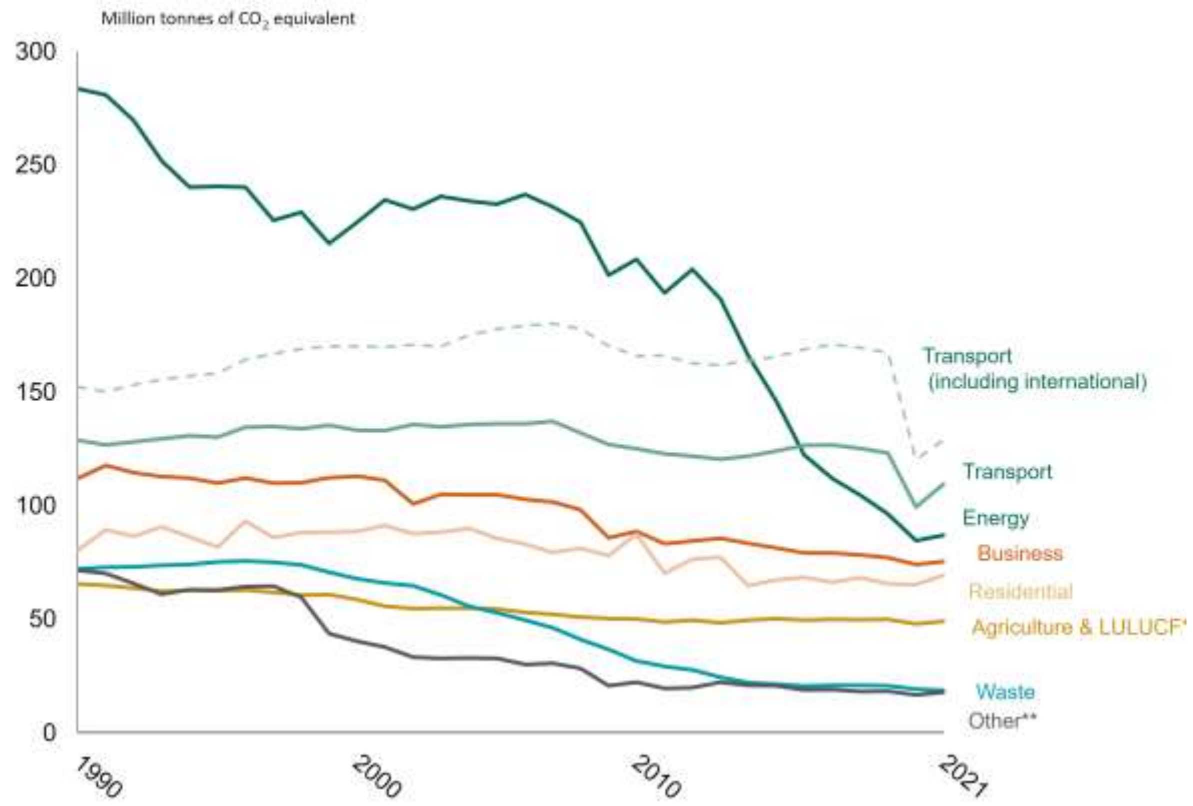
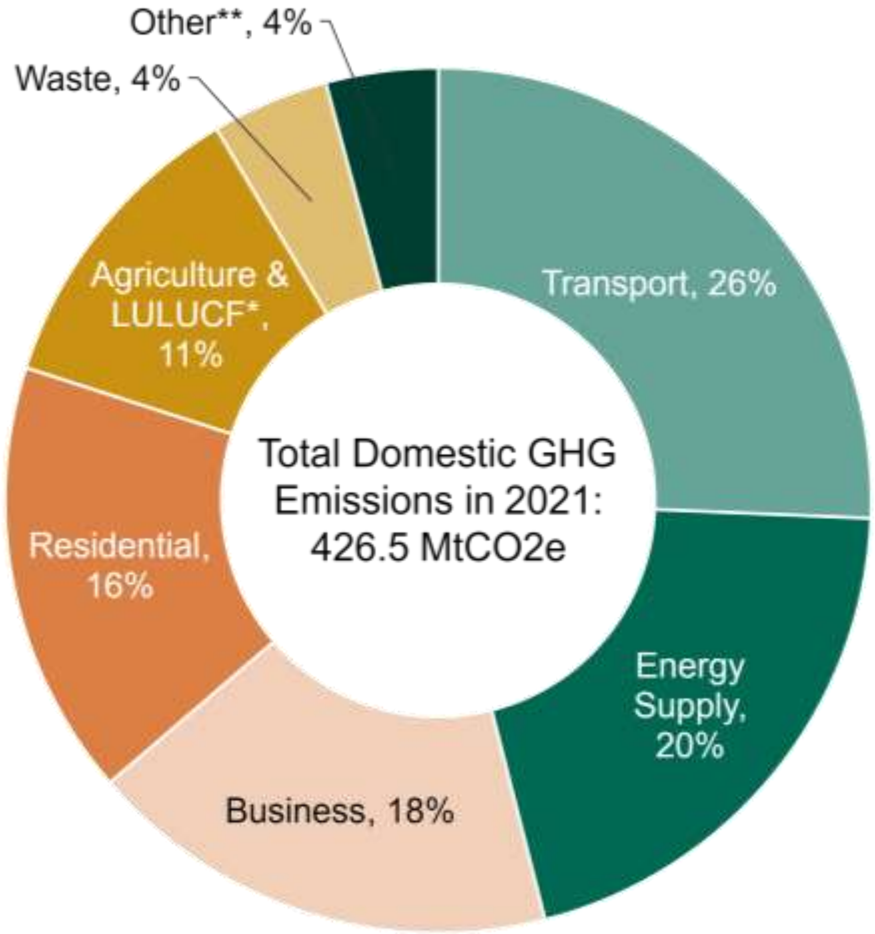
Background of Transport Emissions

- Transport is the largest contributor to UK domestic greenhouse gas (GHG) emissions, responsible for 27% in 2019.





Greenhouse gas emissions by sector, 2021 (DESNZ, 2023)

Decarbonising Transport in the UK

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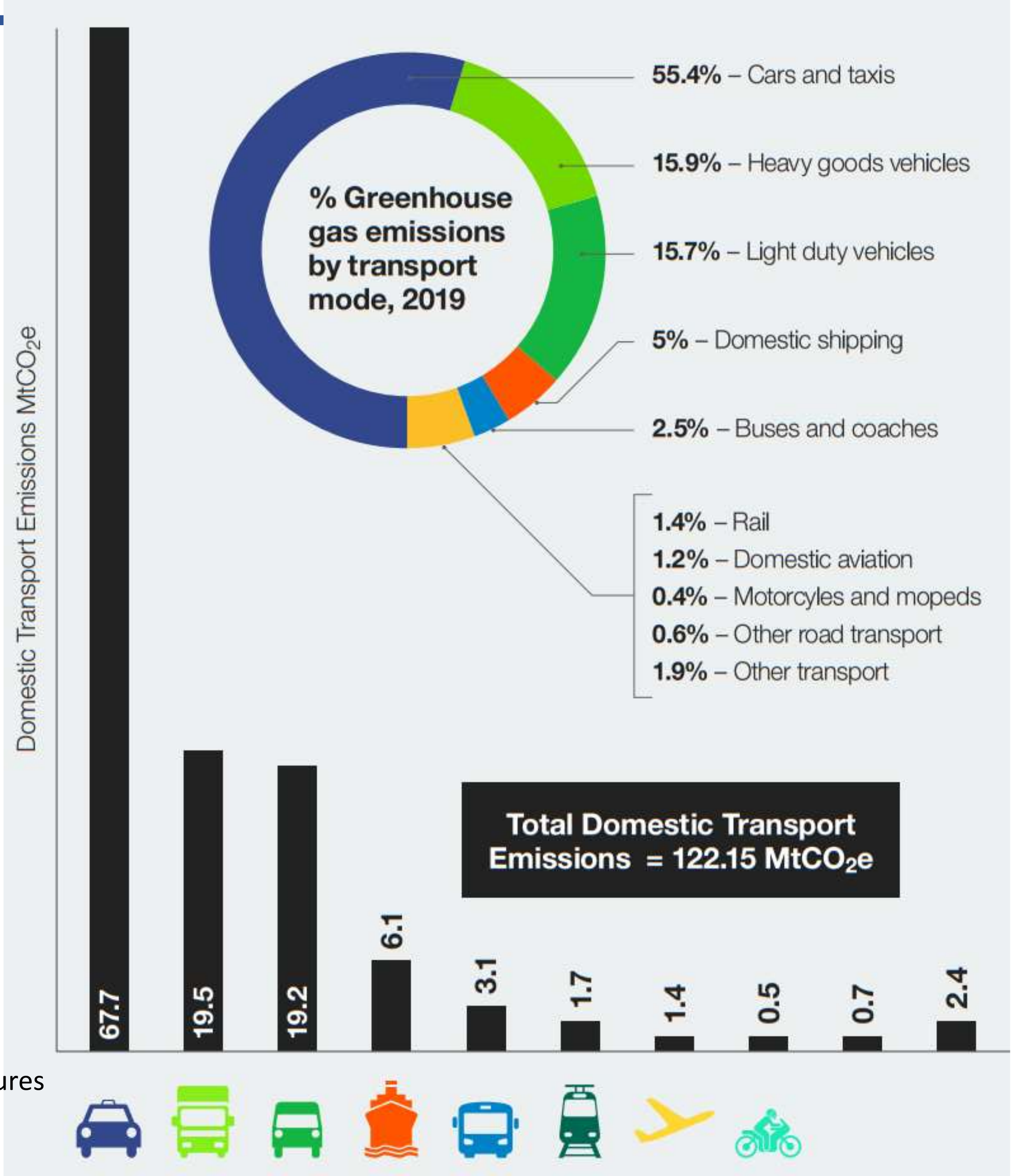
- ❑ UK domestic transport emissions 2019
- ❑ Carbon emissions are currently measured by
  - ➢ $kgCO_2e$ (kilograms Carbon Dioxide & its equivalent for other Greenhouse Gas)
  - ➢ tCO_2e (tonnes Carbon Dioxide & its equivalent for other Greenhouse Gas)
- ❑ Current annual carbon emissions for the UK:
  - ➢ Total ≈ 417 million tCO_2e
  - ➢ Transport ≈ 142 million tCO_2e
  - ➢ Rail ≈ 2.3 million tCO_2e (**1.4%** of all transport)
  - ➢ Distance travelled by rail increased steadily from 1983 onwards, which accounts for up to 9.5% (passenger-km).



Source

- Decarbonising Transport - A Better, Greener Britain, 2021
- UK Department for Energy Security & Net Zero (2023) – 2022 UK Greenhouse Gas Emissions, Provisional Figures
- Office or Rail & Road (2022) – Rail Emissions, April 2021 to March 2022
- Transport Statistics Great Britain: 2022 Domestic Travel

Railway decarbonisation plans

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- Currently, the main method of decarbonizing railways is through **EMU with OCL trains** .
- There are currently approximately 6,000 kilometers of electrified railways in the UK, accounting for 38% of all railway in the UK.
- Ambition is to remove all diesel-only trains (passenger and freight) from the network by 2040, and achieve a net zero emission rail network by 2050
- Network Rail's Traction Decarbonisation Network Strategy (TDNS).
- A holistic-level the technology deployment for 15,400 single track kilometres (STK) of unelectrified railway traction decarbonisation – recommendation for
  - 13,000 STKs of electrification.
  - Over 1,300 STKs for hydrogen train deployment
  - Over 800 STKs for battery train deployment
  - There are 300 STKs where a technology choice has not yet been made

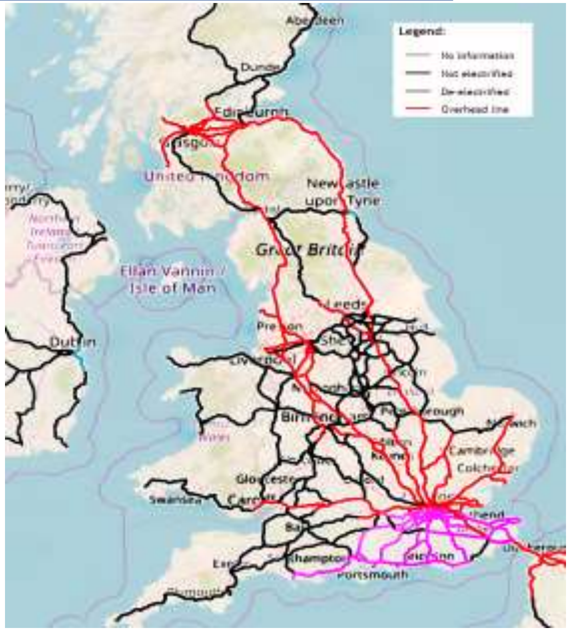
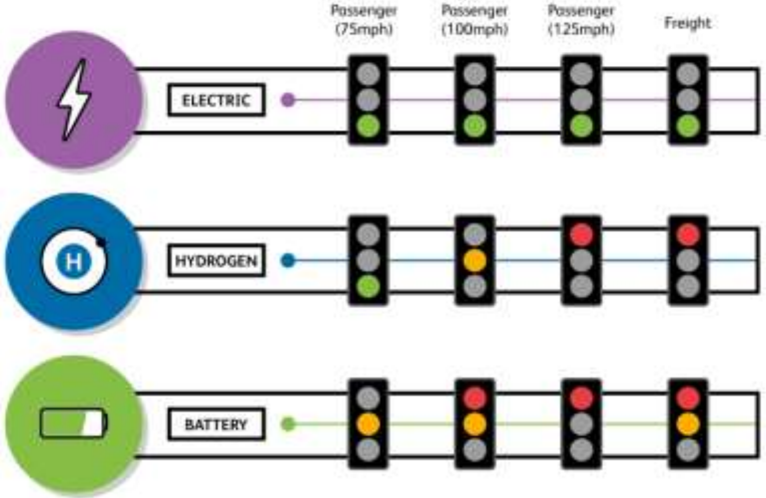
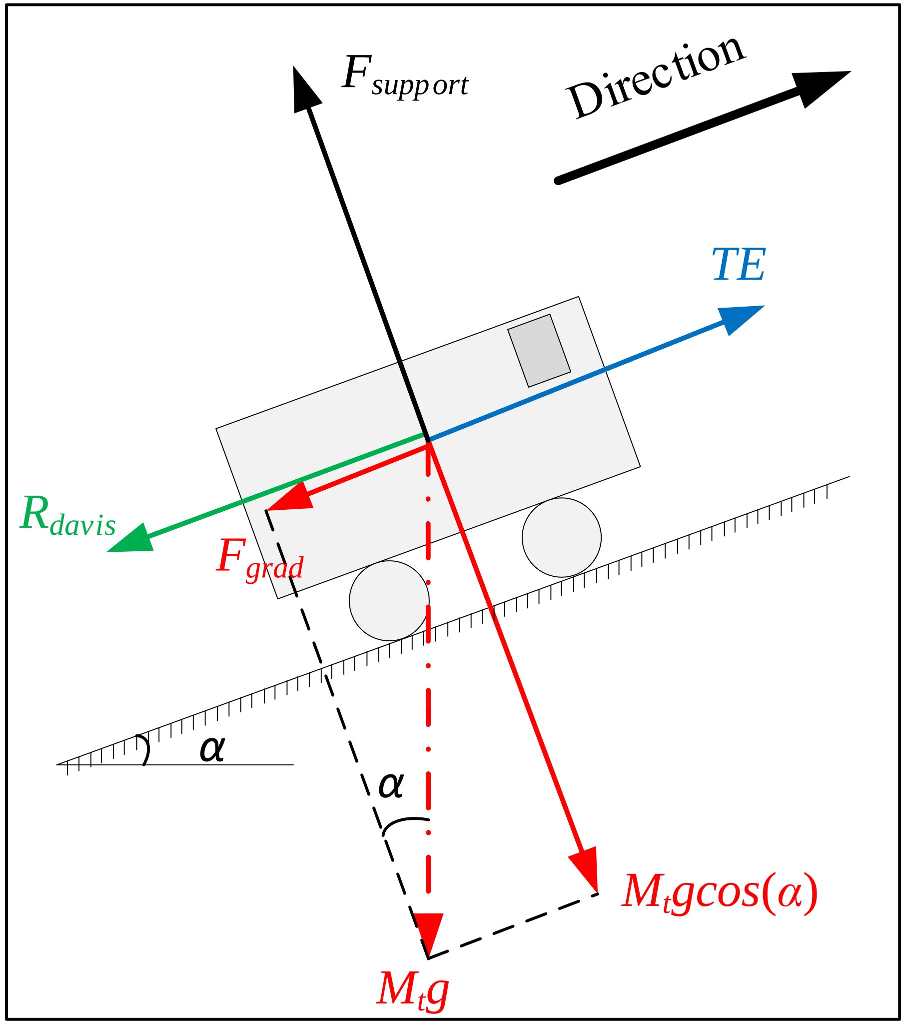


Fig. 1: Parts of the UK railway electrification distribution map [2].



[1] ORR Rail Infrastructure, 2019, Rail infrastructure and assets 2018-19, p. 3.
[2] (2023). Open railway map [Online]. Available: https://www.openrailwaymap.org/.
[3] Traction Decarbonisation Network Strategy (TDNS), 2021

Principles of railway traction energy systems



The Railway Traction Duty

Train Resistance Equation

$$R(v) = A + B \times v + C \times v^2 + M_t \times g \times grad$$

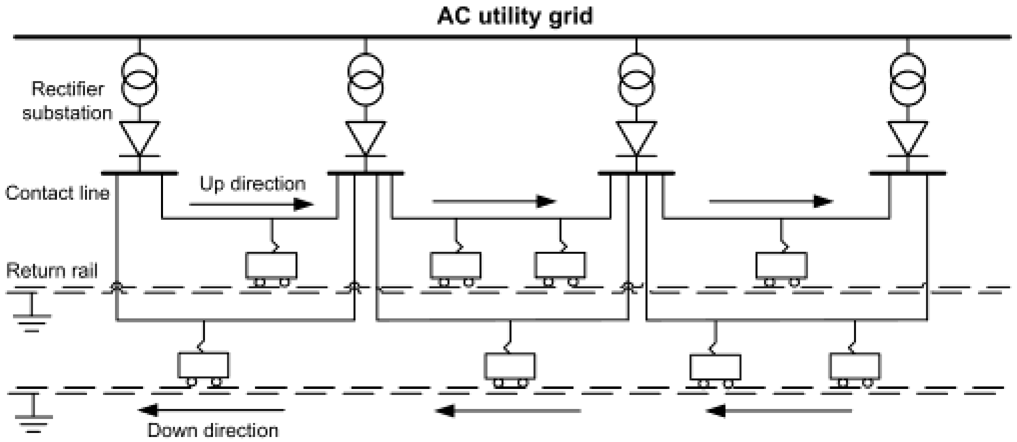
R: Train Resistance
v: Velocity of Train
A, B, C: Davies Coefficients
M_t: Mass of Train
TE: Tractive Effort
g: Gravitation (9.81m/s^2)
grad: Gradient in %
a_t: Acceleration of Train

Acceleration as a function of v

$$a_t(v) = [TE(v) - R(v)] \div M_t$$

The traction power sources

- Onboard power sources
  - Diesel
  - Battery
  - Hydrogen Fuel Cell
- Overhead line systems
  - DC electrification
  - AC electrification (Classic feeding, Booster transformer, Autotransformer)
  - Renewable energy sources
  - Way-side energy storage



Train traction system

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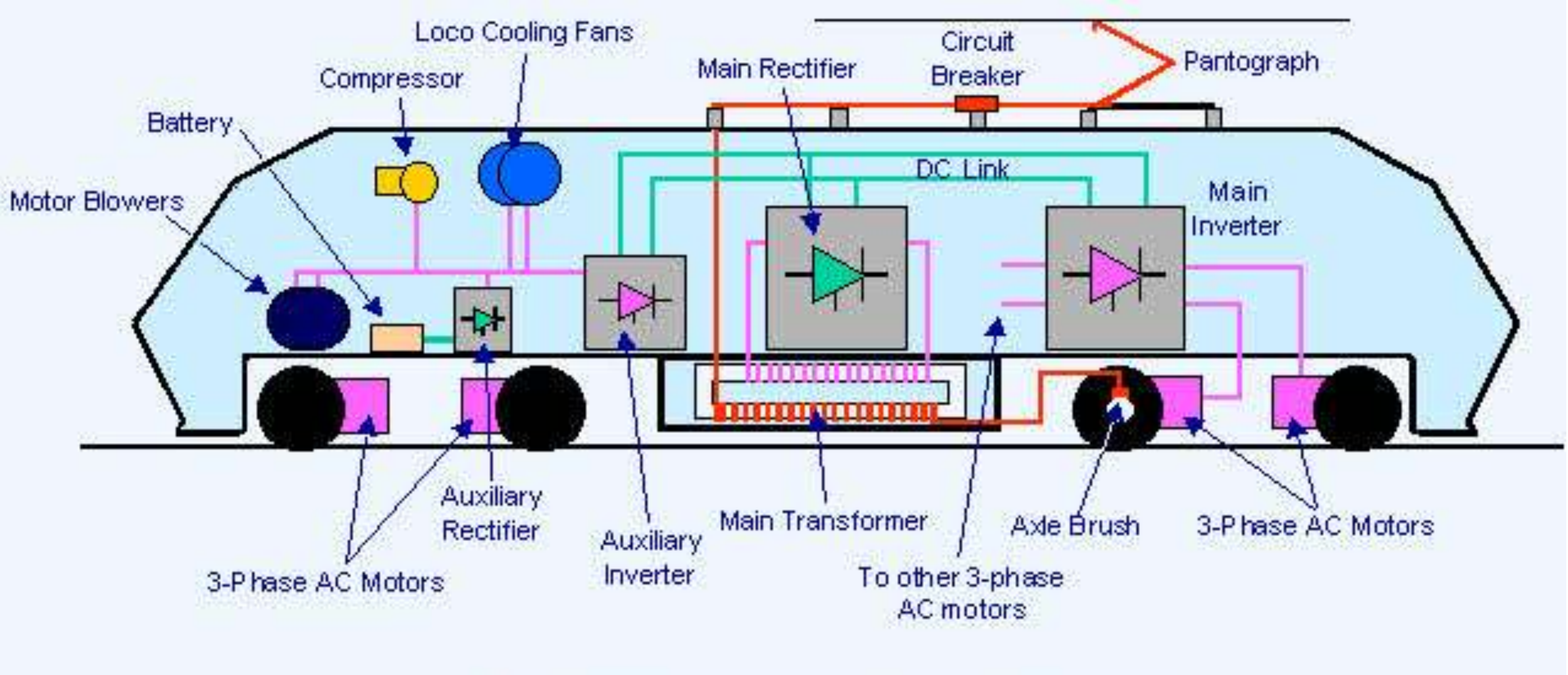
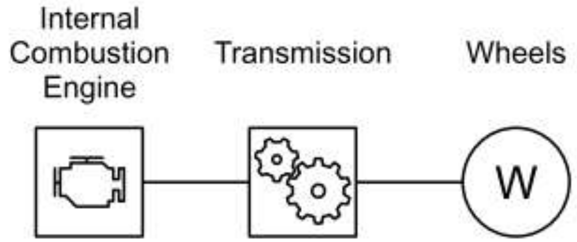


Block Diagram of Modern AC Electric Locomotive

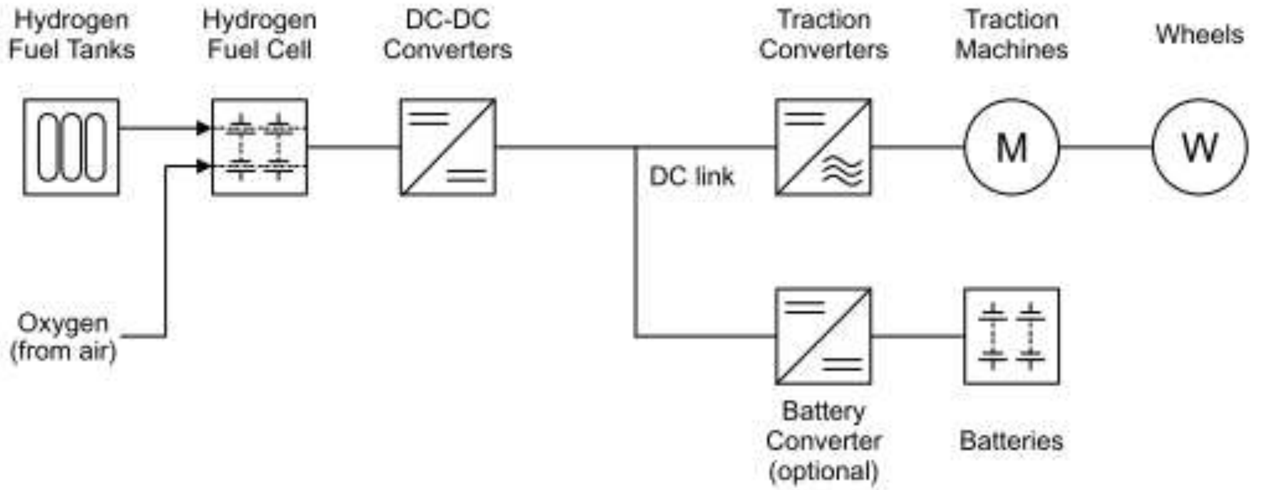
@www.railway-technical.com

Train traction system

- Diesel train structure:
  - Diesel-mechanical
  - Diesel-electrical (DEMU)



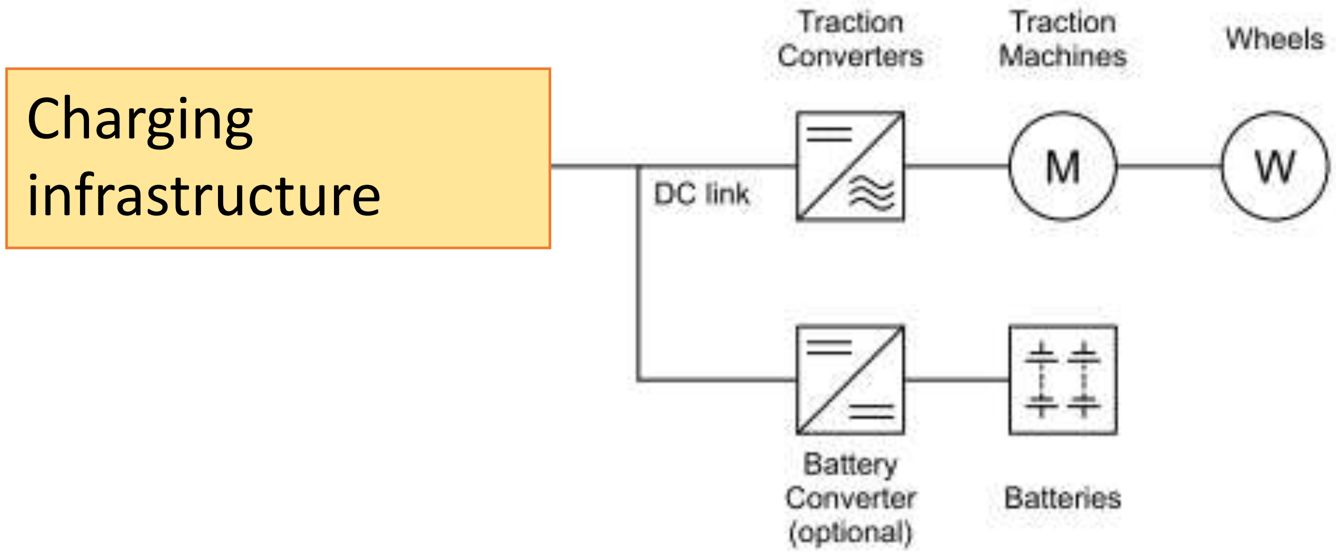
- Hydrogen fuel cell train structure with battery energy storage system



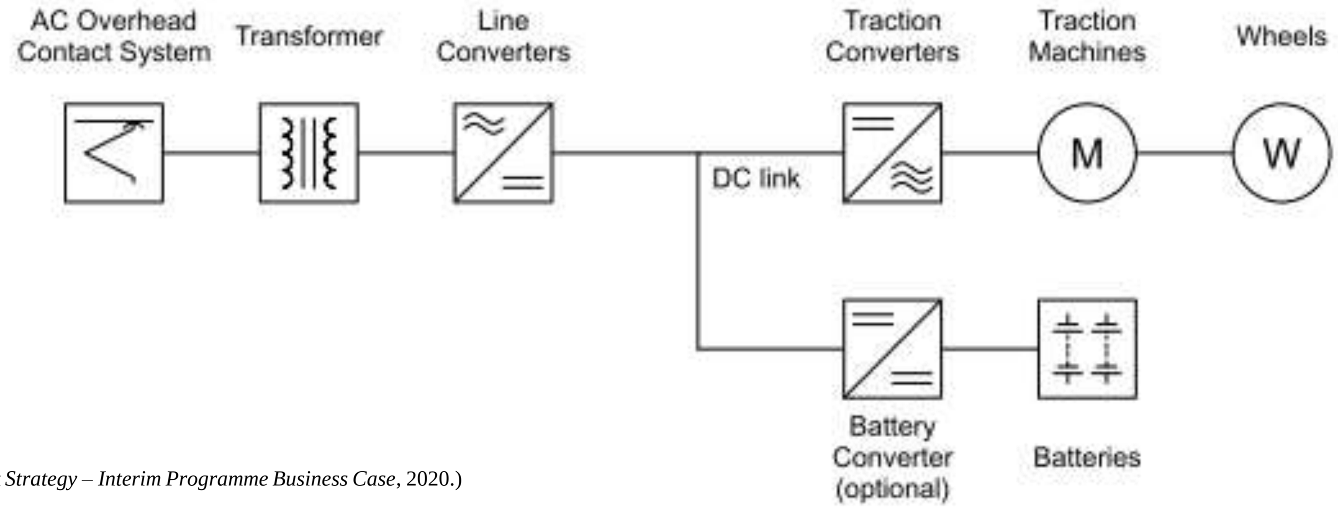
Source: (Traction Decarbonisation Network Strategy – Interim Programme Business Case, 2020.)

Train traction system

- Battery train structure



- Bi-mode or multi-mode train structure



Source: (*Traction Decarbonisation Network Strategy – Interim Programme Business Case*, 2020.)

The importance of alternative fuels

- The cost of rail operations is one of the parameters that operators are focusing on.
- For lines with low traffic density, it is difficult for the EMU solution to recover investment costs and make a profit.
- Rail operators may refuse or delay decarbonization upgrades for these lines.
- BEMU trains and HEMU trains can effectively solve the decarbonization problem of low traffic density lines.

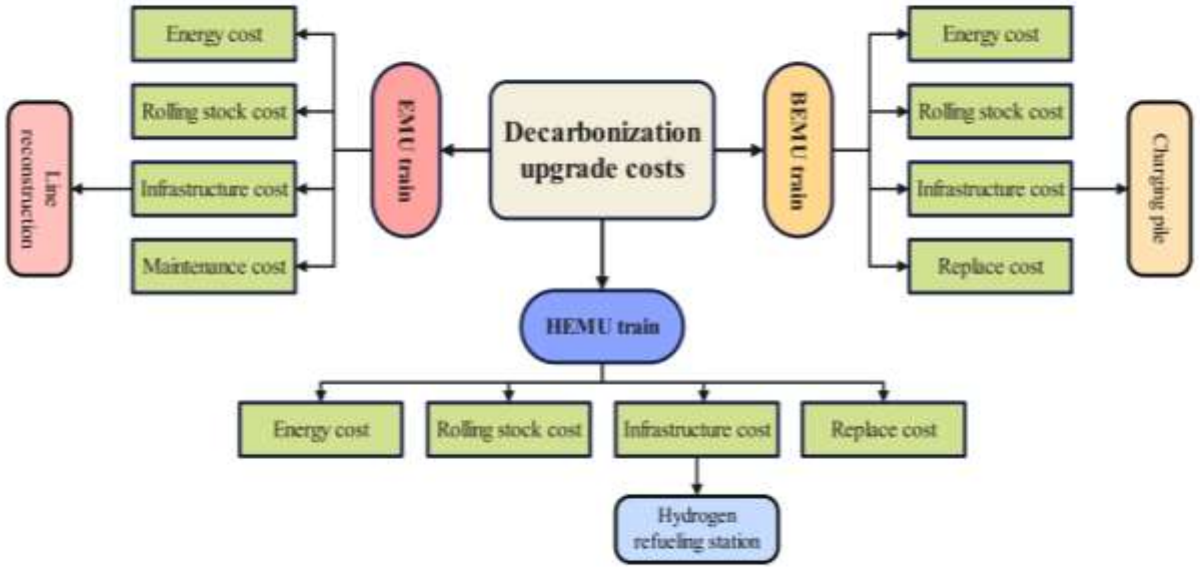


Fig. 2: Main components of the cost of rail decarbonisation options.

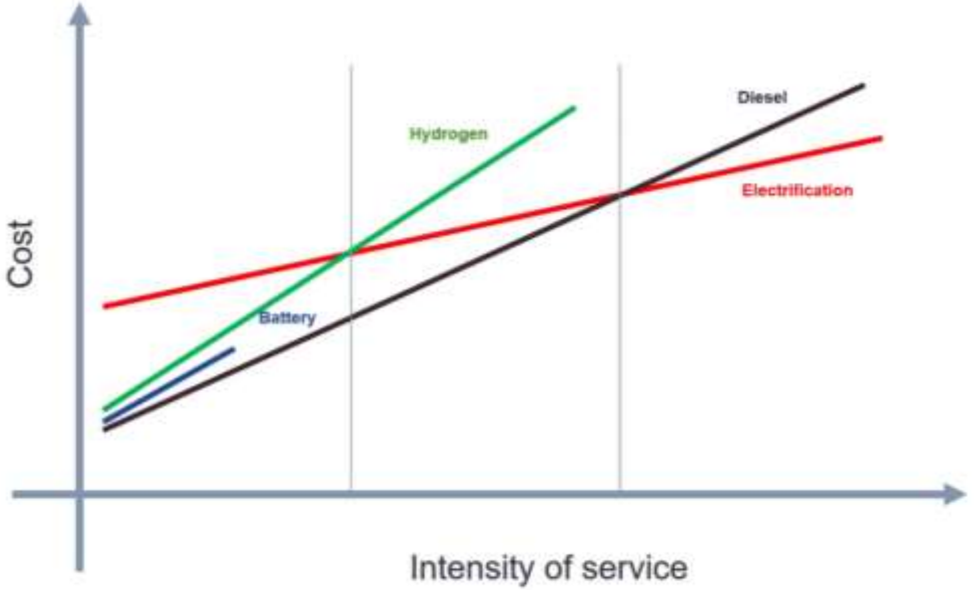


Fig. 3: Main components of the cost of rail decarbonisation options.

BEMU characteristics

- The battery pack supplies power to the motor to drive the train.
- Shorter train range (around 100km).
- Longer charging time.
- Shorter battery life.
- The energy conversion efficiency of BEMU trains can reach more than 90%.
- BEMU trains can replace diesel commuter trains serving short and idle routes.

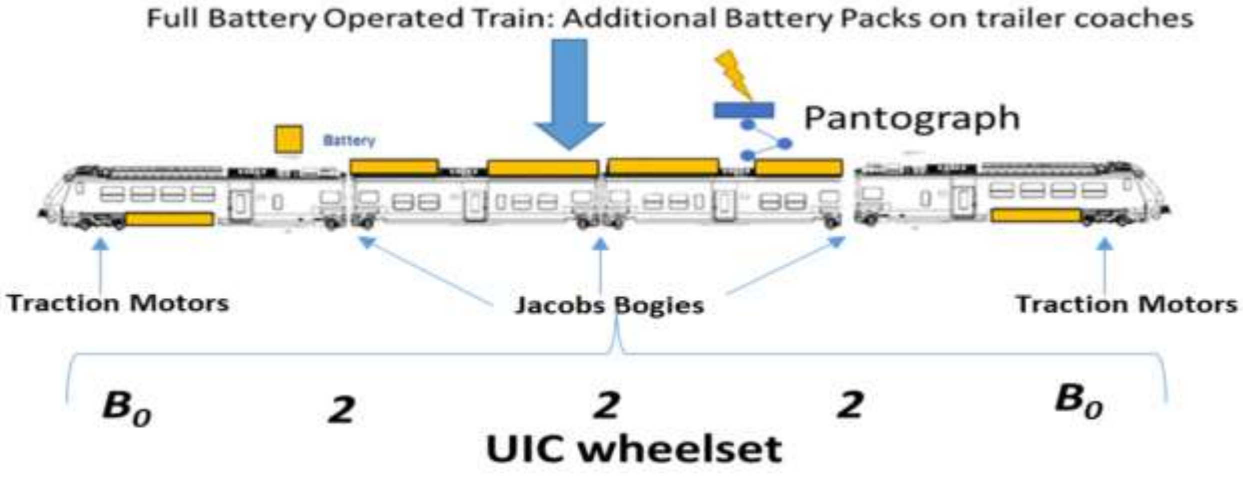


Fig. 4: Investigated BEMU derived from the original Hitachi Masaccio Platform.

Table 1: Main cost price of BEMU trains [5].

Objectives	Price
Battery system	£ 217/kWh
Fast Charging Electricity	£ 0.37/kWh
Fast charging pile	£ 486/kW
Electrical motor system	£ 23.5/kW

HEMU characteristics

- ❑Hydrogen fuel cells cannot respond quickly to changes in power.
- ❑All current HFC trains need to be equipped with storage batteries to provide a power buffer for the hydrogen fuel cells.
- ❑The energy conversion efficiency of hydrogen fuel cells is between 40% and 60% [7].
- ❑The refueling time is similar to that of traditional diesel trains.
- ❑The endurance of HEMU trains can exceed 1,000km.

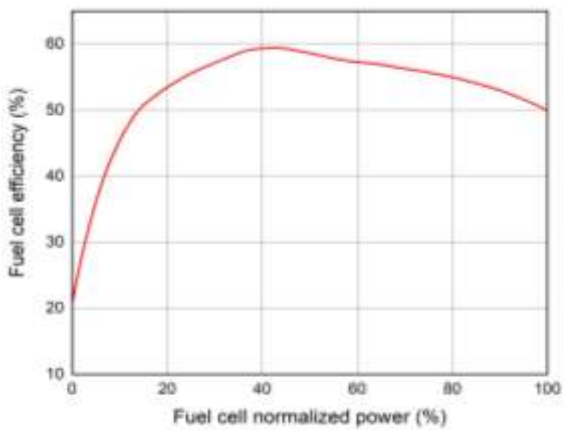


Fig. 6: HFC output power and energy conversion efficiency characteristic curve [7].

Table 2: Main cost price of HEMU trains.

Objectives	Price
Fuel cell system	£ 810/kW
Hydrogen tank	£ 8/kWh
Hydrogen fuel	£ 0.23/kWh (7.7£/kg)
Hydrogen refueling station	£ 15960k

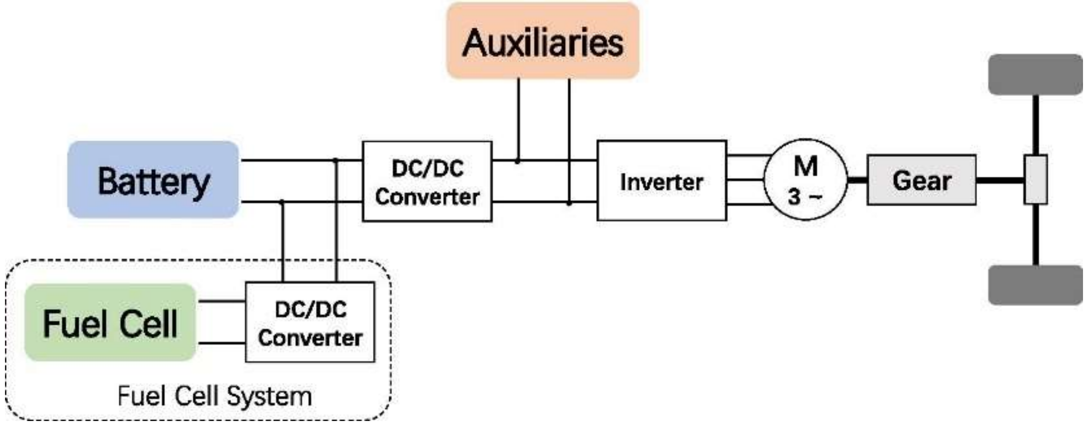


Fig. 5: HEMU trains basic structure schematic diagram [6].

[9] H. Peng et al., "Offline optimal energy management strategies considering high dynamics in batteries and constraints on fuel cell system power rate: From analytical derivation to validation on test bench," Applied Energy, vol. 282, 2021.
[10] G. Meng, C. Wu, B. Zhang, F. Xue, and S. Lu, "Net Hydrogen Consumption Minimization of Fuel Cell Hybrid Trains Using a Time-Based Co-Optimization Model," Energies, vol. 15, no. 8, 2022.

BEMU trains case studies

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- ❑ **Class 230 BEMU trains**
- ❑ The class 230 is a converted London Underground D78 unit
- ❑ In 2015, Vivarail started its retrofitting project aimed to convert five three-car D78 trains into the diesel-battery hybrids.
- ❑ In 2020, this culminated in the battery powered unit running a distance of 40 miles using battery power alone, a first for a train in the UK
- ❑ It can be re-engineered as a battery-only train, with each coach having two 70kWh battery packs that could be recharged in 10 minutes using the company's patented fast charge system, and that this offered a range of at least 80 miles.
- ❑ In 2024, a three-car Class 230 train used only 45% of the charge to travel 113 km autonomously to a depot in Reading Such long journeys show that a single charge would be sufficient for the train to travel more than 193 km.

Class 230001 for COP26

https://www.modernrailways.com/article/viva-venturer-battery-230-visits-scotland
https://www.railengineer.co.uk/trains-on-show-at-cop26/

BEMU trains case studies

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Class 230 BEMU trains

Operating lines: Greenford–West Ealing line.

- Each motor car is now fitted with three German Hoppecke lithium-ion traction batteries with a total capacity of 504 kWh, converters and traction and charging control systems.
- This train is fast-charged via the third rail. The contact rail is only energized when a train is passing directly over it. This technology allows for quick installation.
- To prevent the external catenary from overloading during fast charging, the charging station is equipped with batteries, so the input current does not exceed 63 A.

Assessed branch lines in the Thames Valley for Class 230 trains (enlarge). Source: GWR

Line length	Design Speed	Maximum charging output power	Onboard battery capacity	Recharge mileage	Charging speed
2.4 miles	97km/h	2000KW	504kWh	135km	3.5 min - 30%

Rolling Stock, "GWR to start operating battery Class 230 train," On available: https://rollingstockworld.com/passenger-cars/gwr-to-start-operating-battery-class-230-train/.

BEMU trains case studies

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- **Class 777 in Merseyrail**
- In 2023, the UK's first battery powered trains made their maiden trip from the new station at Headbolt Lane in Kirkby.
- These units, which Stadler refer to as "independently powered" EMUs, will be numbered in subclass 777/1.
- Charging can be performed from the third-rail supply, as well as from regenerative braking. Stadler claim that the battery packs will have a lifespan of at least eight years or 10,000 charge/discharge cycles.
- The initial off-third-rail section will be a one-mile extension from Kirkby to a new station at Headbolt Lane, but there is an ambition to extend to other locations such as Wrexham.
- The first production Class 777 BEMU delivered an encouraging 135km range which shows what is possible.

Traction power	6x350 kW (2.1 MW)
Battery technology	LTO-NMC
Total battery capacity	320 kWh
Battery operating voltage	386 V DC
Expected battery lifetime	at least 8 years
Nominal battery range	34 miles (55 km)
Max speed in battery mode	62 mph (100 km/h)

https://stadlerrail.com/media/pdf/mmer_ipemu0922e.pdf
https://www.railengineer.co.uk/mersey-electrics-class-777-and-system-upgrade/

BEMU - Nova 1/Class 802 train

- Testing of the UK's first intercity battery train commenced on May 24, 2024
- Hitachi Rail, Transpennine Express and Angel Trains have begun a UK first trial testing a battery powered intercity train converted from diesel power.
- The Nova 1/Class 802 train will be used to demonstrate the real-world viability of running a 100% battery-electric intercity train up to distances of 100km in battery mode, allowing it to bridge the gap between non-electrified sections on intercity routes.
- Hitachi’s predicts that the installation of the single battery unit will reduce emissions and fuel costs by around 30% on their intercity trains
- Allow operators to enter and depart non-electrified stations in battery mode to improve air quality and reduce noise.

The 700kw battery was manufactured in Sunderland. Credit: Hitachi Rail

https://www.railmagazine.com/news/2024/05/24/trials-begins-on-uk-first-intercity-battery-train
https://www.railway-technology.com/news/hitachi-uk-battery-converted-intercity-train/?cf-view
https://www.hitachi.com/New/cnews/month/2024/05/240524.html

UK HEMU trains case studies

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HydroFLEX Hydrogen Train

Design Speed	Hydrogen capacity	Maximum output power	Recharge mileage	Hydrogen storage method
150km/h	277 kg	800kW	500km	35 MPa CH2 vessel

- The first hydrogen-powered train in the UK, the University of Birmingham's Centre for Railway Research and Education (BCRRE) and rolling stock solutions provider Porterbrook are responsible for the implementation.

- HydroFLEX can also be operated using power from a 750V DC third rail or a 25kV overhead supply without a change in its operating system, offering a smooth transition.

[11] Railway Technology, "HydroFLEX Hydrogen Train," On available: https://www.railway-technology.com/projects/hydroflex-hydrogen-train/?cf-view.

EU HEMU trains case studies

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Alstom Coradia iLint Hydrogen Train

Line length	Design Speed	Maximum output power	Recharge mileage	Rated passenger capacity
51 miles	140km/h	960KW	1200km	300

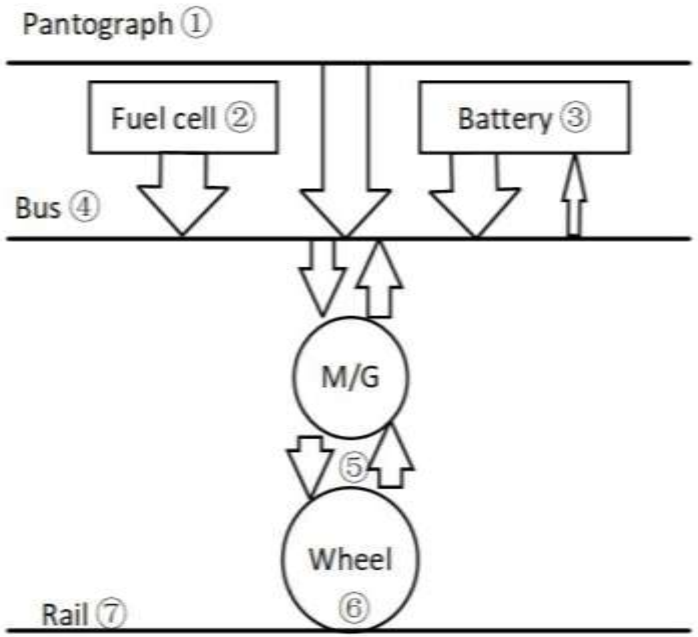
On the route between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude.

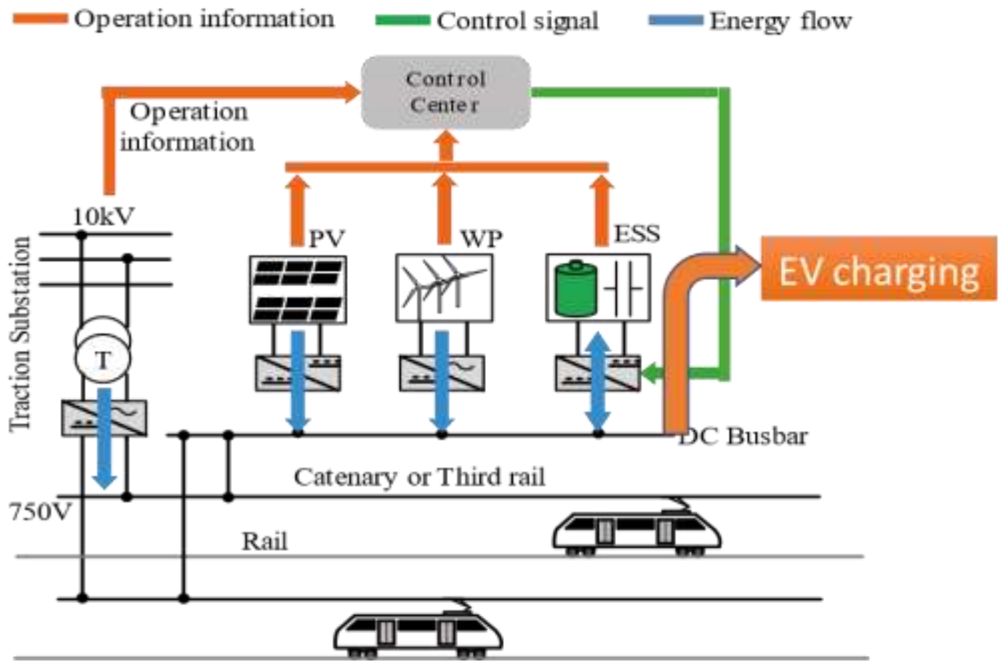
- In 2018, the Coradia iLint entered into commercial service in Germany.
- The Linde facility in Bremervörde contains sixty-four 500-bar high-pressure storage tanks with a total capacity of 1,800 kilograms, six hydrogen compressors and two fuel pumps.
- The use of hydrogen as a fuel for trains noticeably reduces the burden on the environment, as one kilogram of hydrogen replaces approximately 4.5 litres of diesel fuel.

[12] Alstom, "Towards clean and future-oriented mobility," On available: https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-passenger-train.

Recent research at UoB

- ❑ Multi-mode traction power supply network modelling and cost analysis
- ❑ Energy management strategy for discontinuous electrification routes
  - ➢ Onboard traction system
  - ➢ Charging infrastructure
  - ➢ Train operation strategies





Source (Y. Zhang, Z. Tian, C. Roberts, S. Hillmansen, and M. Chen, "Cost optimization of multi-mode train conversion for discontinuously electrified routes," International Journal of Electrical Power & Energy Systems, vol. 138, pp. 107993, 2022/06/01/, 2022.)

Case study - Results

- Under the current hydrogen price conditions, the HFC train decarbonization option does not cost-effective for line lengths of 1 to 100 km.
- Due to limitations of battery technology, BEMU trains are currently not suitable for lines exceeding 100km.

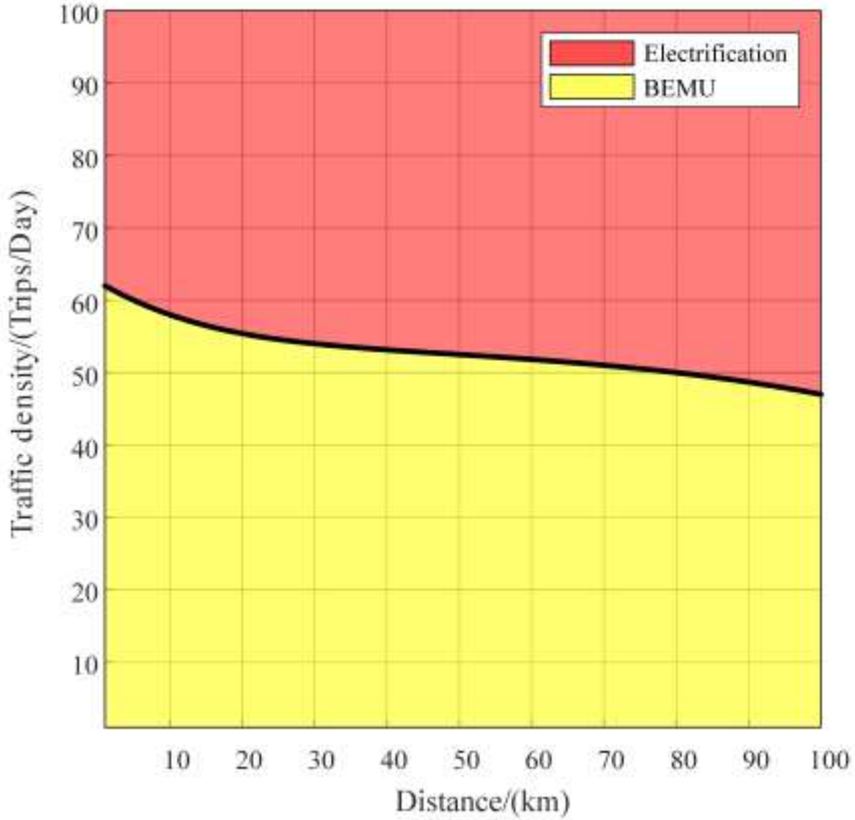


Fig. 15: The cost advantage area of railway decarbonization options with line length in 1~100km.

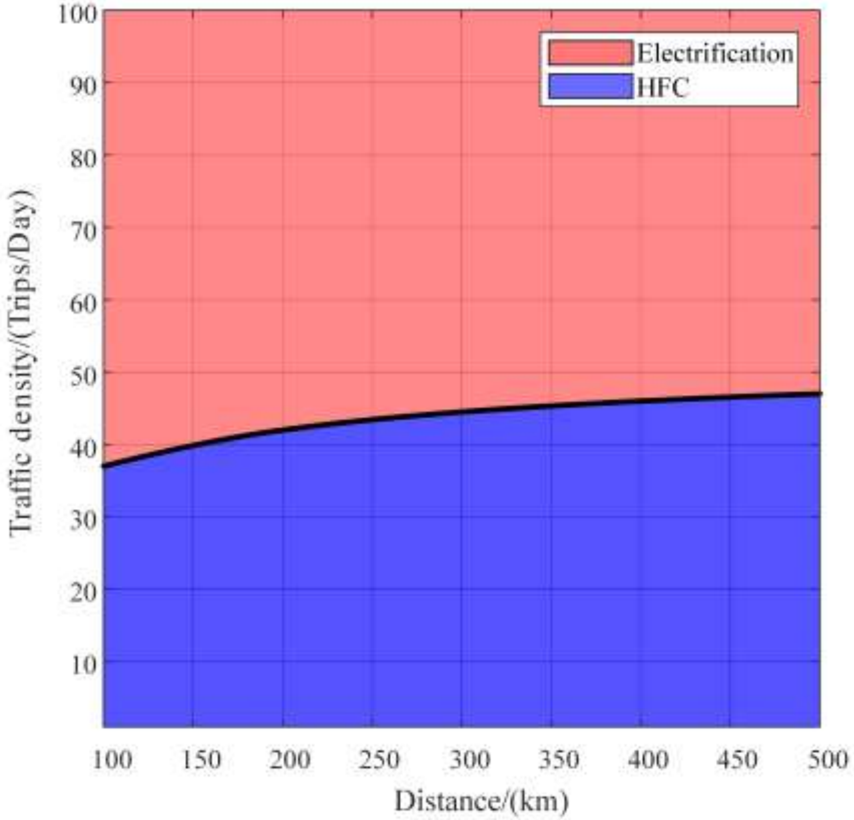


Fig. 16: The cost advantage area of railway decarbonization options with line length in 100~500 km.

Case study - Results

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- With the continuous development of the hydrogen economy and the expansion of the industrial chain, the market price of hydrogen will drop to 4.5 £/kg by 2030.

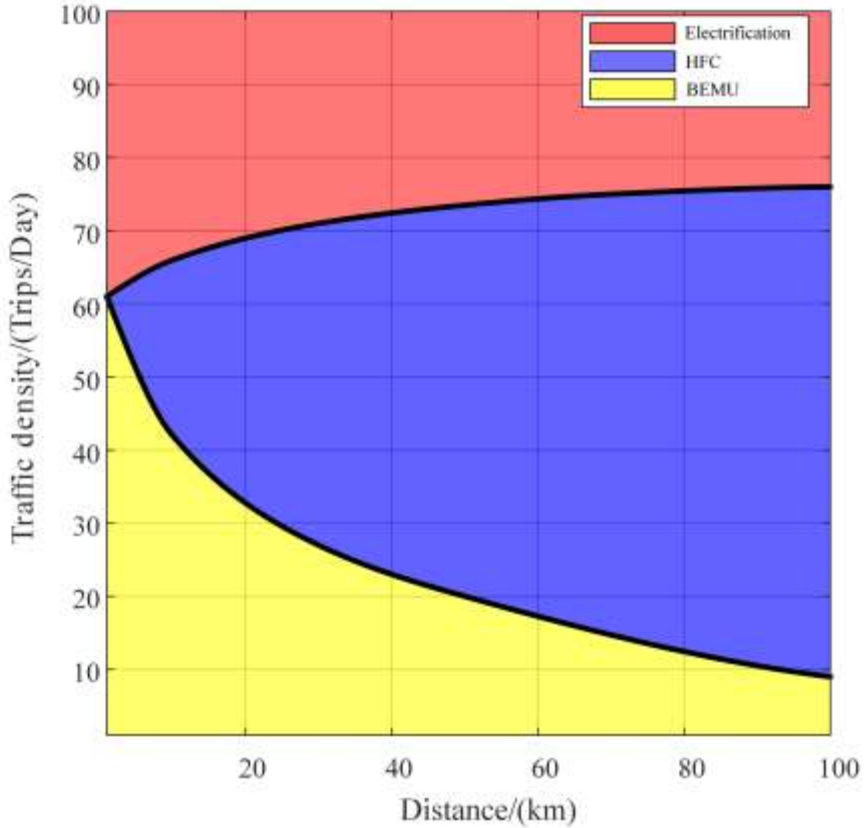

Fig. 17: When the hydrogen price is 5.7 £/kg, the cost advantage areas of railway decarbonization options are for routes ranging from 1 to 100 km.

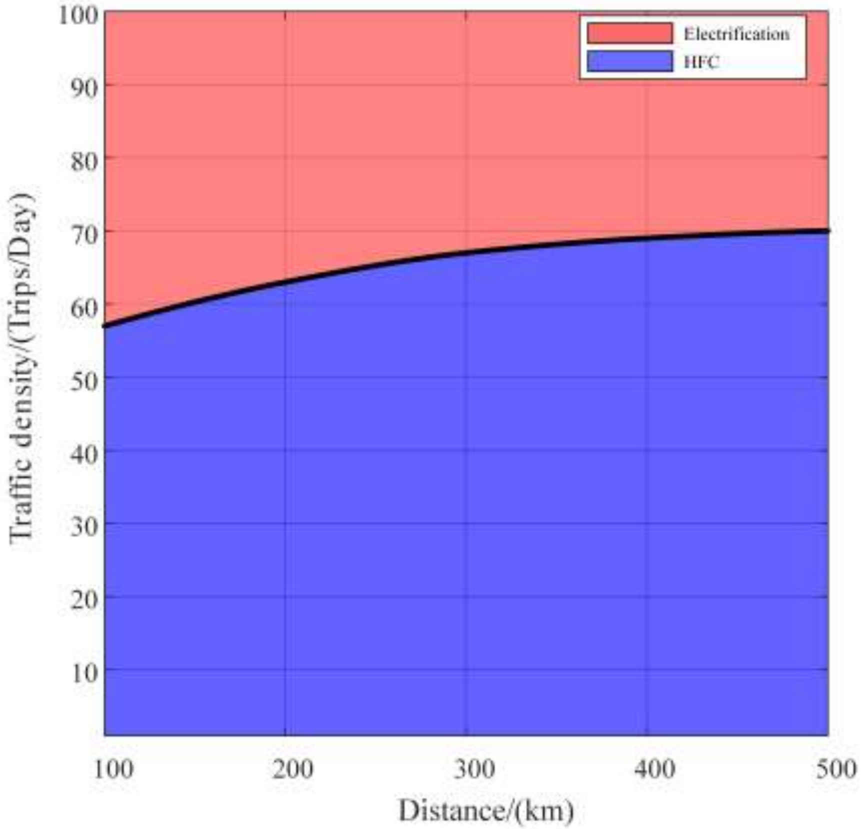

Fig. 18: When the hydrogen price is 5.7 £/kg, the cost advantage areas of railway decarbonization options are for routes ranging from 100 to 500 km.

Conclusion

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- Review of railway power supply and decarbonization plans.
- BEMU trains are suitable for decarbonizing short-distance routes with low traffic density. HEMU trains are suitable for decarbonizing long-distance routes with low traffic density.
- At present, there are relevant studies that BEMU trains can be used in the transition phase of electrified lines.
- With the development of solid-state battery technology and the hydrogen industry chain, large-scale commercialization of BEMU and HEMU trains will become possible.
- More case study results can be found:

  - K Jiang, Z Tian, T Wen, S Hillmansen, Y Zhang, 'Cost modelling-based route applicability analysis of United Kingdom passenger railway decarbonization options', International Journal of Electrical Power & Energy Systems 160, 110094, 2024
  - Y. Zhang, Z. Tian, C. Roberts, S. Hillmansen, and M. Chen, "Cost optimization of multi-mode train conversion for discontinuously electrified routes," International Journal of Electrical Power & Energy Systems, vol. 138, pp. 107993, 2022.
  - T Kamel, P Amor, N Polater, Y Zhang, Z Tian, S Hillmansen, P Tricoli, 'Development of a smart hybrid drive system with advanced logistics for railway applications', International Journal of Hydrogen Energy, 52, 559-576, 2023. [11]
  - T Din, Z Tian, SMAM Bukhari, S Hillmansen, C Roberts, 'Hybrid railway vehicle trajectory optimisation using a non-convex function and evolutionary hybrid forecast algorithm', IET Intelligent Transport Systems, 00, 1–19 (2023). https://doi.org/10.1049/itr2.12406

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- Dr Zhongbei Tian (z.tian@bham.ac.uk)

Thank you!