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INDUSTRY ARTICLE

Radical technology innovations for high-speed transport; ePlanes to replace rail?

Paul H. Riley[1] | **Michele Degano**[2] | **Chris Gerada**[2]

[1]Belsa Power Electronics Ltd, Ilkeston, UK

[2]The University of Nottingham, Nottingham, UK

Correspondence

Paul H. Riley, Belsa Power Electronics Ltd, 5 Weybridge Close, West Hallam, Ilkeston DE7 6NL, UK.

Email: paul@IT9.biz

Abstract

This paper evaluates various modes of transport against the dual requirements of Net-Zero carbon emissions and user convenience, in particular, speed of travel and cost of transportation. Results show that when operated across a whole country, battery-powered ePlanes have the lowest energy use as measured by well-to-wing efficiency of other high-speed transport systems such as the UKs HS2 and conventional diesel rail systems. This condition may not hold for extremely high passenger numbers per hour as seen in metropolitan areas with high density populations. Various proposed disruptive technologies lower cost of ownership when combined with changes in the transport paradigm that has rarely been explored in other papers.

KEYWORDS

ePlane, high-speed transport, hPlane, Net-Zero transport, well-to-wing energy efficiency

1 | INTRODUCTION

In recent years, lightweight battery technology based on Lithium have made all electric aircraft [1] or ePlanes a reality, with certification of both fixed wing, for example, the 19-seater ES-19 [2] and Joby aerospace VTOL (Vertical take-off and landing) [3] due around 2026. Present cell technology is limiting the range of battery-powered aircraft to about 150 miles, so other fuel technologies such as hydrogen power and synthetic fuels [4] are proposed for longer ranges to meet the net-zero targets [5] set by many countries. However, the well-to-wing (wheel) efficiency [6] of the alternative fuels is much lower than batteries, making them more expensive to operate. Not only has the Net-Zero goal-driven technological innovations, such innovations have themselves the potential to open up new markets as summarised in this paper.

This paper presents a systematic review of available data to explore the hypothesis that modern transport technologies, such as battery-powered planes (ePlanes), can deliver Net-Zero high-speed transport at a capital and operating cost that is competitive with present modes.

The results of this paper do not imply that the thousands of miles of existing rail should be torn up and replaced by ePlanes; rather, it is intended to present a more rigorous analysis of the various options rather than repeating 'rail is always best for high-speed transport'. The evidence shows that where passenger numbers are high throughout the day so that trains run at high capacity, trains do offer a low-energy solution. However, for high-speed transport over an entire country such as the United Kingdom, these condition often do not apply. It is beyond the scope of this paper to define exactly which routes would benefit by swapping from rail to ePlane or electric bus, but consider Dr. Beeching who in 1965 wrote a report [7] that resulted in the closure of many railway routes as they were not competitive. Despite the controversy of that decision, he did understand that rail has its limitations.

1.1 | Markets

A transport goal is to transfer people or goods from one place to another with zero carbon emissions, at low-cost and in the shortest time. From the perspective of a country, this goal should apply to all transport systems whilst minimising any effect on the population or balance of payments. Initiatives, such as working from home as seen in the Covid-19 pandemic, have a significant impact on country energy use and are being encouraged by some governments, but are only one aspect of a viable long-term transport strategy [8]. Government transport policy thinking is highly influenced by the past, and often outdated, modes of transport, sometimes called stove pipe thinking. So, for example, rail is seen as a low-carbon mode of transport and widely promoted. This paper argues that rail is inappropriate outside metropolitan regions and even modern technological improvements are unlikely to make it a contender for net-zero, high-speed transport. Recent years have seen a paradigm shift in transport markets with companies such as Uber, Deliveroo and Amazon introducing different ways of moving people and delivering goods. When combined with technological changes such as pilotless drones and Vertical Take-off and Landing aircraft (VTOL), transport of the future will look quite different to that of the last century. The UK government is supporting new transport modes through initiatives, such as Future Flight, that are investing not only in vehicle technology but also in the change in infrastructure needed for support. Air Traffic Control (ATC), influences on the environment and population demographic changes are all included in the research. The use of battery-powered planes (ePlanes) has been discussed in various fora and is gaining interest [9]. The European market for short-haul planes is significant but as Filipponi [10] correctly asserts, current planes contribute significantly to pollution levels. Modern technology is therefore needed to reach Net-Zero.

1.2 | Technology improvements

Electric propulsion is generally seen as the solution for Net-Zero for transport with wind, solar and hydro being the main primary energy sources although some argue that nuclear and biomass are also renewable energy sources [11]. There are two main contenders for storing the electrical energy for transport, batteries and hydrogen, with research work on other fuels, such as ammonia [12], also being undertaken. Lithium-ion batteries presently dominate the Electric Vehicle car market with hydrogen proposed for longer-range transport solutions despite its poor well-to-wheel efficiency. As battery cell chemistry improves the parasitic mass of containing the battery and power electronics for motor drive and battery charging becomes more significant [13]. A new topology of battery arrangements was proposed by Tolbert [14] in the late 1990s, where low-voltage modules are switched in and out of a series circuit using a cascaded H bridge. More recently, the Modified Multi-Level converter (M^2lec) has shown the potential to reduce the mass of power electronics by a factor of 5 [15] and Falcon electric Ltd. is evaluating whether M^2lec can reduce overall parametric mass by 25% with help from AerospaceUP [16].

2 | MATERIALS AND METHODS

This paper evaluates two contenders for net-zero high-speed transport compared with conventional diesel trains:

1. Battery-powered aircraft: ePlanes
2. Hydrogen-powered aircraft: hPlanes

by considering:

- Cost of ownership
- Total energy use at point of energy extraction
- User acceptance
- Scalability
- Certification challenges

Diesel trains are chosen as the comparator as particularly in the United Kingdom, much of the track has a relatively small loading gauge, making the necessary electrification for net-zero [17] difficult or expensive [18].

2.1 | Cost of ownership

The main cost of ownership [19] contributions that can be improved by technology for an airline are fuel, aircraft utilisation, and maintenance.

2.2 | Energy use

We compare fuel costs for Net-Zero options and existing fossil fuel transport systems by modelling the energy use at source, considering well-to-wheel [20], or in the aircraft case, well-to-wing efficiency (see Table A4 for variable definitions).

Energy at the source ('well') = *Es,* where

$$E_s = E_p * \eta_{\mathrm{pt}} * \eta_{\mathrm{WTT}} \tag{1}$$

and

$$\eta_{\mathrm{WTT}} = \eta_e * \eta_T \tag{2}$$

For *Es,* Table 1 defines the Energy Sources.

For fossil fuels and (green) hydrogen power, we define 'tank' as normal usage; for electric vehicles, the 'tank' is the storage battery. All definitions assume a net-zero world, except for the vehicle itself, to ensure like-for-like comparisons, that is, the road transport of the fuel, machines used in the digging of wells etc. are assumed to be powered by renewable means.

Where possible from external sources, E_p is defined as the average energy used per vehicle trip. Well-to-wheel comparisons η are extracted from Ref. [21], fossil-fuelled propulsive efficiency η_{pt} from Ref. [22], hydrogen efficiencies from Ref. [23] and other energy uses are referenced from this web page: [24].

Normalised energy use E_n per passenger journey is defined as either:

$$E_n = \frac{E_p}{P_a} \tag{3}$$

TABLE 1 Source energy definition

Type	Definition
Wind power	Produced at the shaft of the turbine
Solar power	Delivered from the solar panel
Fossil fuel	Extracted from the well
Hydrogen	*Es* extracted by electrolysis

where the vehicle carries the average number of passengers or more, as defined by Ref.[25], or

$$E_n = \frac{E_p}{P_t} \tag{4}$$

where the vehicle transports less than the fleet average number of passengers.

A definitive source for the average fuel consumption of diesel trains was unavailable at the time of writing, so this source was used for a Voyager train diesel fuel consumption [26] at 1.42 L per 100 passenger kilometres to compute Ep = 1.79 MJ/km for a long-distance diesel train. Consumption for a Euro6 bus, defined as 31 L per 100 km, can be found in Ref. [27], giving an Ep of 11 MJ/km. Calculations for an electric car are based on the consumption of an e-Niro [28], giving Ep = 0.6 MJ/km, and Appendix A1 calculates the consumption of an electric plane, giving Ep = 14 MJ/km. Full computations are available in this Excel™ file [29].

2.3 | Aircraft utilisation and maintenance

Commercial aircraft only generate income when flying, either passengers or freight. Historically short-haul small operations were uneconomic because the time between major overhaul was measured in hundreds of hours and maintenance could take more than 2 weeks. The charging time of battery-powered planes meant that charging rather than passenger load time dominated aircraft time on the ground.

The frequently asked questions (FAQ) page [30] of Heart Aerospace states 'When the engine cost-of-ownership can be the same for a 19-seater and a 70-seater, and engine wear is the same whether you fly a 100 km as a 1000 km route, flying short hops with small turboprop aircraft is simply not profitable to airlines…How does going electric change the economic equation? Our electric motor is about 20 times less expensive than a similarly-size turboprop, and about 100 times less expensive than the cheapest turbofan. More importantly, maintenance costs are more than 100 times lower. These lower operating costs will make 19-seater electric aircraft competitive to 70-seater turboprop aircraft.' Technology advancements, many driven by the requirements if airlines and particularly in energy storage systems have improved the cost of ownership for short-haul flight. Formerly with batteries fixed to the airframe, the charging time meant that planes spent considerable time on the ground. Additionally, components with a lower mean time between failure (MTBF) (the power electronics and high current connectors) or short service life (the batteries themselves) added considerably to cost of ownership. Droney, in Patent [31], describes a concept for charging the batteries off the aircraft, with the method being slightly slower than that proposed for the automotive sector in Patent [32], that uses a robotic arm for battery replacement. Although an improvement in aircraft on the ground time and removal of short lifetime components, these so-called battery swap techniques have the disadvantage that low MTBF components still reside on the aircraft. The concept in Patent [33] quickly removes the blade unit, power electronics, motor and battery systems, paving the way for an apron turn-round in the same time as it takes passengers to disembark and load onto the plane and a scheduled maintenance interval of 3000 h, as is common in larger kerosene-powered aircraft rather than the present 300 h of the 19-seater aircraft presently on the market. These technological changes reduce the cost of ownership considerably, making short-haul ePlanes much cheaper than high-speed rail and competitive with conventional diesel-powered units, as shown in the results section below.

2.4 | Scalability

This paper discusses scalability by comparing aircraft fleet capacity and aircraft range with examples of current railway capacity and passenger journey distances. As the main justification for HS2 is a lack of rail capacity [34], one could infer that there is an opportunity for ePlanes rather than laying new high-speed track for later stages of HS2. A comprehensive comparison is out of the scope of this paper, being a multivariable problem. However, by taking a few typical examples, any major inhibitors are highlighted and could form a basis for future research.

For a conventional airport, 564 flights per day are possible even with large jets. Using a conservative number of 30 flights per hour, a 75% load factor 19-seater ePlane could carry 1.6 million passengers from one point to another per year and with 45 seats 4.9 million passengers per year. The capacity of VTOL planes is not limited to runways, further increasing capacity. For comparison, the Virgin West Coastline (345 miles) carries 0.7 million passengers per year [35], needing two ePlane stops. The HS2 phase 1 report predicts 25 million return passenger journeys per year, although this is highly disputed and requires train travellers over an area 5 times the size of Birmingham to use HS2, see Appendix A2.

2.5 | Range

Conventional aircraft require fuel for all parts of the flight envelope plus sufficient reserves in cases of emergency [36]. Aircraft flying into larger airports require more reserves in case of congestion [37, 38]. Electric aircraft also need reserves of energy. However, there are some aspects unique to battery power that can reduce the size of that reserve. Some of the potential energy at altitude can be recovered on descent to charge the batteries rather than using air brakes to dissipate that energy as heat. VTOL designs can choose flight paths near to suitable landing locations, further reducing reserve requirements. The rest of this section ignores these advantages to give a range comparison on a like-for-like basis.

Although petrol and kerosene have roughly 50–100 times more specific energy density in the tank than 2020 lithium-ion batteries [39], electric propulsion systems are lighter, conversion of energy to thrust is more efficient [40] and electric propulsion offers improvements in aerodynamic efficiency not practical with conventional aircraft engines [41]. These factors give a rule of thumb that battery planes have a range of 10% compared with conventional power plants. This is borne out by the various flight demonstrations being undertaken:

The Heart ES90 FAQ page says '…Our first-generation aircraft will have a maximum range of up to 400 km (250 miles), which will increase as battery energy densities improve… Reserve, alternate, and contingency energy (fuel) requirements vary by geographical region, and by the type of operation being flown (VFR, IFR, etc). In addition, for short range operations, there are procedures for reduced contingency fuel, and for no alternate depending on the specific route. However, as a rule, a sizeable portion of the available energy on an electric aircraft needs to be reserved for missed approaches, adverse weather conditions, etc. Therefore, our early focus will be short routes. This is not a problem – the unit economics of electric aircraft will be better the shorter the route, as the recharge times will be shorter, the battery wear will be less, and more departures can be made in a day.'

'Beta Technologies … completed the longest crewed test flight of its Alia aircraft yet, clocking in at 205 miles[sic]' [42].

'The Wright Spirit builds on a proven 4-engine, 100 passenger platform: the BAe 146 … one hour flight…' [43].

2.6 | Certification, aircraft and air traffic control

The UK government is investing £125 M, matched by £175 M from industry, to develop greener ways to fly, such as all-electric aircraft and deliveries by drone, by advancing electric and autonomous flight technologies [44]. The project is investing in the future of air mobility and technologies that will allow full electric flight in the United Kingdom and addressing challenges for the wider aviation system that new aircraft will operate within, including key infrastructure and air traffic management. The first two of the project's three phases is mostly complete (as of 2022), with phase 3 due to be complete in 2024. As well as technological advances, a key element of the project is the impact on certification legislation of the electric and autonomous technologies. The CAA is an integral partner tasked to both support the industry and highlight any changes to legislation required.

3 | RESULTS

3.1 | Energy

Fuel prices are quite volatile and susceptible to global economic and political conditions. This results section compares energy usage, as derived from the source, in order to make like-for-like comparisons for fuel costs.

Tables 2–8 plot the energy per passenger trip in kWh for a selection of transport modes for trip distance (km) against average passengers per hour. Tables make the following assumptions:

- Scheduled services run every hour
  - More frequent journeys increase energy consumption per passenger when passenger numbers per hour reduce the vehicle occupancy rate.
- Fleet average occupation is defined in Ref. [45].

TABLE 2 Long-distance diesel train, kWh ppt

Average Passengers per hr \ Distance, km	0.1	0.3	1	3	10	30	100	300	1000
10000					5	14	46	138	461
3000					5	14	46	138	461
1000					5	14	46	138	461
300					5	14	46	138	461
100					16	47	158	473	1576
30					53	158	525	1576	5254
10					158	473	1576	4729	15763
3					525	1576	5254	15763	52542
1					1576	4729	15763	47288	157625

TABLE 3 Euro6 diesel bus, kWh ppt

Average Passengers per hr \ Distance, km	0.1	0.3	1	3	10	30	100	300	1000
10000			0.2	0.6	2.1	6.3	21.1	63.3	
3000			0.2	0.6	2.1	6.3	21.1	63.3	
1000			0.2	0.6	2.1	6.3	21.1	63.3	
300			0.2	0.6	2.1	6.3	21.1	63.3	
100			0.2	0.6	2.1	6.3	21.1	63.3	
30			0.2	0.6	2.0	6.1	20.2	60.5	
10			0.6	1.8	6.1	18.2	60.5	181.6	
3			2.0	6.1	20.2	60.5	201.7	605.2	
1			6.1	18.2	60.5	181.6	605.2	1815.7	

TABLE 4 Electric vehicle, kWh ppt

Average Passengers per hr \ Distance, km	0.1	0.3	1	3	10	30	100	300	1000
10000		0.05	0.18	0.54	1.8	5.4	18.0		
3000		0.05	0.18	0.54	1.8	5.4	18.0		
1000		0.05	0.18	0.54	1.8	5.4	18.0		
300		0.05	0.18	0.54	1.8	5.4	18.0		
100		0.05	0.18	0.54	1.8	5.4	18.0		
30		0.05	0.18	0.54	1.8	5.4	18.0		
10		0.05	0.18	0.54	1.8	5.4	18.0		
3		0.05	0.18	0.54	1.8	5.4	18.0		
1		0.06	0.22	0.65	2.2	6.5	21.6		

TABLE 5 ePlanes, kWh ppt

Average Passengers per hr	0.1	0.3	1	3	10	30	100	300	1000
10000				1.0	3.4	10.3	34.2	102.6	410.5
3000				1.0	3.4	10.3	34.2	102.6	410.5
1000				1.0	3.4	10.3	34.2	102.6	410.5
300				1.0	3.4	10.3	34.2	102.6	410.5
100				1.0	3.4	10.3	34.2	102.6	410.5
30				1.0	3.4	10.3	34.2	102.6	410.5
10				1.5	4.9	14.6	48.8	146.3	585.0
3				4.9	16.3	48.8	162.5	487.5	1950.0
1				14.6	48.8	146.3	487.5	1462.5	5850.0

Distance, km

- ◻ Instant occupancy rate can increase above 100% (seating capacity) for trains and buses with standing passengers. The extra mass has a small effect on energy but is not considered significant to the results.
- External references define energy consumptions, except ePlanes, which is described in Appendix A1
- Tables are truncated due to practical limitations
- Grey areas represent vehicles whose passenger numbers are below the fleet average.
- E and hPlanes land to refuel beyond their range. Energy for such journeys is 120% higher.
  - ◻ The excess energy is due to losses during descent and climb, see Appendix A3

3.2 | Operating costs

The cost of an anytime single ticket from Nottingham to London St. Pancras in the United Kingdom was £100.50 in 2021. According to reference [9], an ePlane journey was predicted to cost £89.20 for a similar journey from Nottingham to London City airports.

In Table 9 the overhead and profit of 50% of operating costs is based on this report [46], adjusted to take advantage of the lower maintenance costs of ePlanes.

4 | DISCUSSION

The model in Section 2 and results from Section 3 show that real-world energy consumption is highly dependent on the service required by the passenger and passenger volumes per hour. The UK government has a 'levelling up' agenda to distribute wealth more fairly outside London. Within London, passenger numbers are high even outside normal rush hours, and during rush hours, many buses, trains and the underground system have standing passengers, thus decreasing energy per passenger. However, outside London and particularly in the suburban and rural areas, scheduled passenger services often run below capacity and are occasionally empty. Trains are particularly vulnerable to expending unwanted energy due to running a scheduled service due to their large passenger carrying capacity, with bus services similarly

TABLE 6 Cycling, kWh ppt

Average Passengers per hr	0.1	0.3	1	3	10	30	100	300	1000
10000		0.01	0.03	0.09	0.31				
3000		0.01	0.03	0.09	0.31				
1000		0.01	0.03	0.09	0.31				
300		0.01	0.03	0.09	0.31				
100		0.01	0.03	0.09	0.31				
30		0.01	0.03	0.09	0.31				
10		0.01	0.03	0.09	0.31				
3		0.01	0.03	0.09	0.31				
1		0.01	0.03	0.09	0.31				

Distance, km

TABLE 7 Walking, kWh ppt

Average Passengers per hr	0.1	0.3	1	3	10	30	100	300	1000
10000	0.006	0.02	0.06	0.18					
3000	0.006	0.02	0.06	0.18					
1000	0.006	0.02	0.06	0.18					
300	0.006	0.02	0.06	0.18					
100	0.006	0.02	0.06	0.18					
30	0.006	0.02	0.06	0.18					
10	0.006	0.02	0.06	0.18					
3	0.006	0.02	0.06	0.18					
1	0.006	0.02	0.06	0.18					

Distance, km

TABLE 8 hPlanes, kWh ppt

Average Passengers per hr	0.1	0.3	1	3	10	30	100	300	1000
10000				3.7	12.4	37.1	124	371	1486
3000				3.7	12.4	37.1	124	371	1486
1000				3.7	12.4	37.1	124	371	1486
300				3.7	12.4	37.1	124	371	1486
100				3.7	12.4	37.1	124	371	1486
30				3.7	12.4	37.1	124	371	1486
10				5.3	17.6	52.9	176	529	2117
3				17.6	58.8	176.4	588	1764	7057
1				52.9	176.4	529.3	1764	5293	21171

Distance, km

TABLE 9 ePlane journey predicted cost, per passenger journey

19 Seater running costs, ppj	
Pilot	£5.33
Fuel	£4.00
Battery amortisation	£3.98
A/C amortisation	£0.47
Landing charges per journey	£20.00
Marketing and sales costs	£6.76
Misc. costs	£4.05
Sub-total	**£44.59**
Overheads and profit	£44.59
Total	**£89.18**

affected. Cycling and walking do not suffer this problem and although cars only run when needed, they often only contain one passenger, and therefore run below their optimum capacity, with a quoted fleet average of 1.2 passengers per journey. Table 10 compares energy use for three scenarios ignoring any practicalities such as how far people are willing to walk, fleet average, full vehicle and what we call sparse passenger numbers typical of suburban or rural conditions; the notes column shows the energy multiplier used for this calculation.

Combining practical considerations and only looking at energy usage, we obtain Tables 11 and 12 that show which modes of transport give lowest energy for passenger numbers and journey length. These tables only consider one mode of transport. In a real-world case, most journeys comprise more than one mode, for example, walking, and the mode of transport is often influenced by overall journey time. Interestingly, the model shows that diesel trains are never the optimum form of transport considering energy use, somewhat contrary to conventional opinion. High-speed electric trains, such as the proposed HS2 in the United Kingdom have been excluded for two reasons: firstly, they consume more energy per vehicle km than diesel trains due to the losses at high-speed, and secondly, it does not offer a Net-Zero solution across the whole country. Battery-powered planes have both low-energy consumption and are able to cover the whole country. Newer modes of transport, such as VTOL electric planes, open other transport paradigms, such as point-to-point travel, that are both fast and more energy efficient than either fixed train and bus stations or sub-regional airports.

The multipliers in the Notes column are used to compute the Sparse column. They multiply the full vehicle energy by the figure in the Notes column to give an indication of energy usage for a part-occupied vehicle. For example, Sparse for a car would be 2 passengers, a bus one-third full and a train half full.

Considering high-speed medium distance alone, Figure 1 compares ePlanes, hPlanes and diesel train energy consumption. In all cases, ePlanes have the lowest energy and hPlanes the highest. At small numbers of passengers per hour, trains require elevated levels of energy per passenger.

TABLE 10 Well energy, kWh per 100 passenger km

	Fleet	Full	Sparse	Notes
Cycling	11	11	11	
Walking	22	22	22	
eCar	52	19	39	x2
ePlane	99	74	99	
Bus	40	37	112	x3
Diesel train	125	70	139	x2
hPlane	446	334	446	

TABLE 11 Lowest energy use considering practical limitations. (Well energy ppt kWh)

Average Passengers per hr \ Distance, km	0.1	0.3	1	3	10	30	100	300	1000
10000	0.006	0.01	0.03	0.09	0.3	5.4	18.0	63	411
3000	0.006	0.01	0.03	0.09	0.3	5.4	18.0	63	411
1000	0.006	0.01	0.03	0.09	0.3	5.4	18.0	63	411
300	0.006	0.01	0.03	0.09	0.3	5.4	18.0	63	411
100	0.006	0.01	0.03	0.09	0.3	5.4	18.0	63	411
30	0.006	0.01	0.03	0.09	0.3	5.4	18.0	61	411
10	0.006	0.01	0.03	0.09	0.3	5.4	18.0	146	585
3	0.006	0.01	0.03	0.09	0.3	5.4	18.0	488	1950
1	0.006	0.01	0.03	0.09	0.3	6.5	21.6	1463	5850

TABLE 12 Key to previous table

Key to lowest energy (max 1 hour journey)	
Walking	
Cycling	
Electric Plane, fixed wing	
Electric Car	
Single Decker Euro6 bus	
Diesel Trains	

5 | CONCLUSION

Meeting the Net-Zero carbon emission targets whilst preserving or improving living standards requires radical thinking enabled through disruptive technologies. In the case of country-wide high-speed transport systems, battery-powered ePlanes offer the lowest energy consumption and cost of ownership when compared with rail. With the advent of battery-powered VTOL aircraft, point-to-point

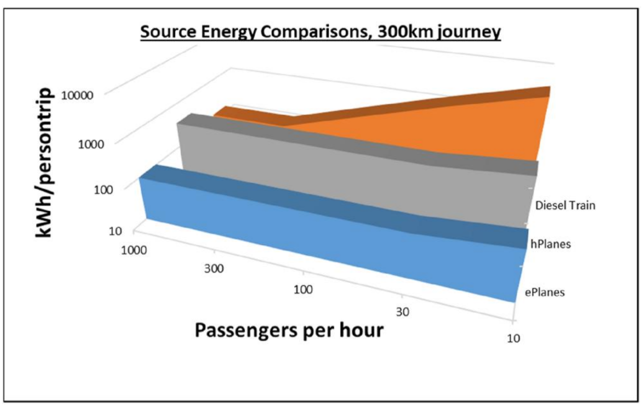

FIGURE 1 Energy comparison, planes and diesel trains.

(single mode) journeys are achievable, which would further reduce journey times and alleviate congestion from other modes of transport. This would remove the need for major environmental changes necessitated by high-speed rail systems, such as HS2.

The authors have found no technological barriers for implementation in this decade, that is, before 2030.

AUTHOR CONTRIBUTIONS

Paul H. Riley: Conceptualisation; Data curation; Formal analysis; Methodology; Project administration; Software; Writing – original draft. **Michele Degano:** Supervision. **Chris Gerada:** Funding acquisition.

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CONFLICT OF INTEREST

The authors are not aware of any conflicts of interest in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in ResearchGate. 'e-Plane energy comparisons with other modes of transport'. https://doi.org/10.13140/RG.2.2.11024.89605.

ORCID

Paul H. Riley https://orcid.org/0000-0002-1580-7689

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APPENDICES

A1 ePlane energy calculations

Reliable energy consumption figures for ePlanes are unavailable due to them being in their infancy. This paper uses the energy of similar kerosene-powered aircraft with reasonable adjustments of $Er = 30\%$ improvement in aerodynamic efficiency (from the NASA report [41]) due to the benefits of electrical propulsion from research into electric-powered flight to derive ePlane energy consumption figures.

$$E_j = \frac{E_{\mathrm{cl}} + E_{\mathrm{cr}} + E_d}{D_f} \tag{A1}$$

$$E_{\mathrm{cl}} = \frac{h_c.V_{\mathrm{ff}}.K_{\mathrm{cf}}.R_r}{60.V_c} \tag{A2}$$

$$E_{\mathrm{cr}} = \left(T_f - \frac{2.h_c}{V_c}\right)\frac{1}{60}(1 - E_r)V_{\mathrm{ff}}K_{\mathrm{cf}}R_r \tag{A3}$$

$$E_d = E_{\mathrm{cl}}R_d \tag{A4}$$

The equations of Appendix A1 use the parameters of a 30-seater Dornier 328 with a range of 1852 km as shown on Table A1 to give a value for energy requirement of an ePlane.

A2 HS2 calculations

The Transport Watch UK report [48] quotes the number of return passengers per day using phase 1 of HS2 (the Birmingham arm) as 69,000. Table A2 shows the variables, Equation (A5) the required catchment area for passengers and Equation (A6) the area multiplier needed.

Birmingham had in 2022 a population density of 4200 people per km^2 [49]. 3% of journeys are by train [50], 65% of adults travel to work [51] and there are 65% people of working age [52]. Therefore

$$C_a = \frac{H_{\mathrm{rpd}}}{B_{\mathrm{pop}D}A_{\mathrm{bt}}A_{\mathrm{tw}}A_{\mathrm{wa}}} \tag{A5}$$

and

$$M_a = \frac{C_a}{B_a} \tag{A6}$$

Meaning that train travellers over an area 5 times the size of Birmingham [53] would have to use HS2 each day, one assumes, to travel to London. Each one would have to travel to the HS2 station terminal. It is not surprising therefore that the HS2 passenger numbers are being disputed [34, 54].

A3 ePlane energy >300 miles

For distances greater than is currently possible with battery power, refuelling (recharging) is necessary. Hence an ePlane needs additional energy for the extra landing and take-off. The

TABLE A1 Dornier328 values [47]

Variable	Value	Units
Er	30%	%
Kcf	46	MJ/kg
Rd	−10%	%
Vc	1107	m/min
Vd	1200	m/min
Vff	817	kg/Hr

TABLE A2 Required catchment area for HS2

Ref	Description	Variable	Value	Units
[48]	Return passengers per day	*Hrpd*	69000	ppd
[49]	Birmingham population density	*BpopD*	4200	ppkm2
[50]	Percentatge adults travelling by trai	*Abt*	3%	
[51]	Percentage adults travel to work	*Atw*	65%	
[52]	percentage adults of working age	*Awa*	65%	
	Catchment area	*Ca*	1296	km2
[53]	Area Birmingham	*Ba*	268	km2
	Area multiplier	***Ma***	**5**	**#**

TABLE A3 ePlane longer haul

Longer haul		
(distance x2)	962	km
Energy no landing	3878	kWh
Net excess landing	471	kWh
Total with landing	4349	kWh
Ratio additional fuel (per landing)	112%	

energy calculations from the reference in Appendix A1 are shown on Table A3, showing 112% energy increase for one additional stop. Earlier calculations use a more conservative figure of 120% to account for queuing time in the air or ground taxiing.

A4 Nomenclature

TABLE A4 List of variables

	Description	Unit
h_c	Climb ceiling height	m
P_a	Average number of passengers on a vehicle journey as defined in Ref. [45]	#
P_t	Actual number of passengers on a vehicle journey	#
η_T	Energy used (lost) in transportation	%
η_{WTT}	Energy efficiency well to tank	%
η_e	Energy used (lost) to extract fuel from the source	%
η_{pt}	Energy efficiency tank to propulsion	%
Df	Flight distance	km
Ecl	Energy consumed during climb	kWh
Ecr	Energy consumed during cruise	kWh
Ed	Energy consumed during descent	kWh
Ej	Energy per vehicle journey per kWhr	kWh/km
En	Normalised energy use per passenger journey	kWh per Pj
Ep	Energy required for propulsion	MJ/km
ePlane	Battery-powered aircraft, fixed wing or VTOL	
Es	Energy at the source	MJ/km
hPlane	Hydrogen-powered plane	
Kcf	Calorific value of kerosene	kWh/kg
MTBF	Mean time between failure	
Pj	Passenger journey	
ppt	Per person trip	
Rd	Ratio of energy recovered during descent	#
Rr	Ratio of useful energy to fuel flow energy	#
Tf	Total flight time	min
Vc	Climb rate	m/min
Vd	Descent rate	m/min
Vff	Fuel flow	kg/hour

Abbreviation: MTBF, mean time between failure.