Applied Energy 401 (2025) 126561

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apen

Insights from the evolution of transport technologies, 1800–2020: Energy use, transitions, and efficiency

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HIGHLIGHTS

- A transition to renewables-based transport is underway to reduce CO_2 emissions.
- We develop a 1800–2020 world transport dataset to view previous energy transitions.
- Final and useful energy use in transport rose 300 and 460-fold from 1850 to 2019.
- Transitions in transport increased energy use, despite improvements in efficiency.
- The quality of energy services was also an important driver of past transitions.

ARTICLE INFO

Keywords:
Transport
Energy transitions
Energy efficiency
Energy history
Rebound effect

ABSTRACT

The replacement of fossil fuels by electricity and other alternative fuels in transport will not be that sector's first energy transition. Using transport history as an analogue for the future can offer helpful insights for today's policymakers. The present work investigates the evolution of world energy use in the transport sector, identifying its energy transitions (at the final and useful stages), and evaluating the impact of past transitions on energy use over the period 1800–2020. To perform these analyses, a novel long-run dataset of energy use and efficiencies of water, rail, road, and air transport was developed. Our main findings are: (1) final energy use in transport increased 300-fold between 1850 and 2019, while useful energy rose 460-fold over the same period, (2) final-to-useful efficiency of the transport sector improved from 15 % to 23 % in the period 1850–2019, (3) the transport sector has experienced 3 transitions: from renewables to coal, from coal to oil products, and from oil to electricity and biofuels (ongoing), all of which lasted for several decades, and (4) past energy transitions in transport resulted in growth of final energy use, regardless of changes in final-to-useful energy efficiency (backfire). Moreover, this work concludes that the quality of energy services was an important driver of past transitions, a factor to be explored when adopting new technologies.

1. Introduction

1.1. Motivation

Before the 19th century, no forms of motorized transport existed, so transport relied mainly on animals and sailing boats [1]. Since then, great improvements have been made in speed, reliability, and energy efficiency while consuming enormous amounts of natural resources, particularly fossil fuels. Today, the transport sector faces a new challenge: delivering affordable, low-carbon, and high-quality transportation to a growing population in an increasingly globalized world. Insights into this complex issue may be gleaned from the past.

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https://doi.org/10.1016/j.apenergy.2025.126561
Received 27 November 2024; Received in revised form 12 July 2025; Accepted 30 July 2025

In 1970, the transport sector emitted around 2.8Gt of CO_2, which corresponded to 19 % of total CO_2 emissions [2,3]. Since then, transport emissions have been rising, reaching 7.95 Gt of CO_2 in 2022 (around 22 % of total emissions) [3,4]. The rise in the share of transport in total emissions highlights the need for climate policies in this sector. Insights from energy history are important for designing energy policies, identifying opportunities for reducing energy consumption and environmental impacts, and recognizing drivers and obstacles to the energy transition. Furthermore, estimating and analyzing historical energy data enables future studies to explore deeper relationships between energy use, transport services, and the economy. This work addresses this shortcoming by reconstructing world energy since 1800 in transport and analyzing the speed and drivers of major past energy transitions.

1.2. Global transport transition studies lack long-run historical data

Previous energy transitions in the transport sector have been explored by several studies. The replacement of sailing ships by steam has been of particular interest since it had a substantial impact on the growth of international trade and migration [5–9]. These studies conclude that the wind-to-steam transition was initially motivated by the need to solve the unreliability of wind power, but as the steam technology progressed it also became a faster and cheaper alternative that allowed heavier loads to be transported. Another important transition was the replacement of coal with oil products as the primary energy source across both water and rail transport modes, coupled with the development of oil-fueled internal combustion engines for road transport [10–13]. The cost reduction caused by the introduction of oil products created further business opportunities, such as the development of the automobile industry and the expansion of international trade.

The historical evolution of energy use in the transport sector has already been partially studied; however, the lack of data remains an important obstacle. For the years after 1971, the IEA developed a dataset with world energy use by sector [4], which has been used to characterize the transport sector in specific countries [14,15]. However, the years prior to 1971 remain understudied. Tostes et al. [10] covered part of this issue by developing a world long-run energy dataset focused exclusively on rail transport. De Stercke [16] pioneered a long-run dataset of primary to useful energy (from the raw energy source to the energy past the end-use conversion device) from 1900 to 2014, which included the transport sector. However, by excluding the 19th century dataset does not allow one to understand major transport transitions such as the sail-steamboat transition and the beginnings of rail transport. In addition, De Stercke's dataset does not incorporate important energy sources (such as wind) and has the shortcoming of using GDP per capita to extrapolate energy efficiencies rather than using thermodynamic-based energy conversion efficiencies.

On a country level, Fouquet [17] developed a dataset of energy consumption in the UK from 1800 to 2008 for several economic sectors, including transport. Each sector's energy use is further divided by energy carrier (e.g., coal, oil) and transport mode (e.g., road, rail). Fouquet [17] addresses key aspects regarding energy transitions in the UK including the birth of the demand for transport services, the role of animal transport in the 18th and 19th century, the “Railway Mania”, and the consolidation of road transportation. Fouquet [17] concluded that the investment in infrastructure, the declining price of fossil fuels, and the increase in efficiency were crucial to reducing the cost of transport since the 19th century. However, Fouquet [17] does not quantify the useful energy stage, which is essential for understanding the impact of the evolution of final-to-useful efficiency in past transitions.

1.3. Towards a historical understanding of energy transitions

Authors use a variety of criteria to define energy transitions. Hirsh and Jones [18] restricted the definition to a change in fuel, along with a shift in the associated technologies. O'Connor [19] uses a broader definition, considering energy transitions as a change in energy use patterns affecting primary resources, final energy carriers, conversion devices, and energy services. Fouquet and Pearson [20] define energy transitions through the lens of economics, focusing on the shift of the economic system from dependence on one set of fuels and technologies to another. Smil [21] aligns with the definition of energy transitions presented by Hirsh and Jones [18], adding the layer of the duration required for a particular primary energy source or prime mover to gain a significant market share.

According to Sovacool [22], two important aspects of energy transitions should be analysed: first is the full spectrum from primary energy sources to energy services, and second is the timespan. Regarding the first, the research in energy transitions is mainly focused on primary energy carriers (e.g., crude oil), as opposed to useful energy flows (e.g., mechanical work used for transport) and energy services (e.g., passenger-kilometers), partially due to the lack of historical data [23]. The lack of studies exploring the useful stage applies not only to the economy-wide scale but also at the sectoral level (e.g., transport).

Grubler [23] summarized three important insights into past energy transitions. First, Grubler argues that the introduction of novel or vastly improved energy services acts as a key catalyst for energy transitions, especially when combined with higher efficiencies and declining costs. Then, Grubler points out that large markets and infrastructure requirements contribute to slower rates of change, while a multidimensional comparative advantage and the pre-existence of small markets accelerate transitions. Lastly, Grubler [23] argues that scaling up technologies requires a series of steps, from an extended period of experimentation and learning to industry scale and technology diffusion through globalization.

Regarding the complex relation between energy services, efficiency, and cost (highlighted as the first insight of Grubler [23]), several studies conclude that improvements in energy efficiency reduce the marginal cost of energy services, which in turn increases their demand [24,25]. As a result, final energy use does not necessarily decrease as expected and may even rise. This phenomenon is called rebound effect [26]. In transport, the direct rebound effect is well documented by several econometric studies, however, none of them explore rebound at a timescale long enough to cover past energy transitions [27–29]. A notable exception is Fouquet [30], who found the magnitude of passenger transport rebound effects declined from the mid-19th century until the 1970s and appears to decline with economic development.

The literature presents three levels of rebound effects: direct rebound, indirect rebound, and economy-wide rebound effects. The direct rebound effect occurs when energy savings from increased efficiency lead to lower costs, encouraging higher energy consumption (e.g., driving more due to a fuel-efficient car). The indirect rebound effect is defined as the phenomenon by which the money saved from energy efficiency is spent on other goods and services that also use energy. Lastly, the economy-wide rebound effect corresponds to broader systemic impacts, such as the increased economic activity that resulted from efficiency gains, leading to overall higher energy demand. These effects can partially or fully offset the anticipated energy savings from energy efficiency improvements [31,32].

As for the duration of transitions (second insight of Grubler [23]), various authors have employed different thresholds to define energy transitions [33] as extensively discussed. In the present work, we apply the energy transition thresholds proposed by Fouquet [34], where the transition begins when an energy carrier reaches 5 % of total energy use and ends at 80 %. If the carrier does not reach the 80 % threshold, the year of peak consumption is considered the endpoint of the transition. The application of these thresholds is described in Section 2.7.

1.4. Aim and structure

Although previous global energy studies have examined the evolution of energy use in the transport sector, there remains a lack of an integrated historical analysis of energy use (at both final and useful stages) across water, rail, road, and air transport sectors over an extended timescale. As discussed in previous sections, most studies focus on final energy use, yet quantifying the useful energy stage is essential to assess the role of final-to-useful efficiency in energy transitions. Furthermore, as climate change is a global environmental problem, it is important to assess energy transitions from a global perspective. If we were to restrict our analysis to national or regional scales, we would not comprehend the full scope, which is so important for tackling global environmental challenges. To address these gaps, we answer the following questions: (1) How has the use of final and useful energy evolved at the global level in the transport sector? (2) What are the final and useful energy transition periods? (3) What are the long-term final-to-useful conversion efficiencies for various transport modes, and how do these efficiencies impact energy use? (4) What implications can be drawn for future energy transitions?

To answer these questions, the aim of this study is to gain a deeper understanding of the historical evolution of the global transport sector, focusing on the efficiency of energy use and energy transitions. We developed a long-term global dataset on energy usage that offers an overview of final and useful energy, as well as energy efficiencies. While the study provides a global, long-term perspective, it does not include national-level data, separate freight from passenger transport, nor cover pre-rail periods and traditional energy sources. This dataset, together with a rebound state map, was used to identify and characterize past energy transitions.

This paper contains 4 more sections. Section 2 describes the methods used to develop the dataset. Section 3 presents and discusses the main results while answering the first three research questions. Section 4 explores insights from the evolution of transport and their implications, addressing the last research question. Section 5 concludes.

2. Data and methods

We first provide a brief overview of the energy conversion chain and the main analytical framework used in this work. Following this, we describe the methods and data sources used to develop the dataset for each transport mode.

2.1. Overview of the energy conversion chain

The final energy stage corresponds to the energy delivered to the final consumer. Final energy serves as an input to a conversion device operated by the energy consumer, where one form of energy is transformed into heat and/or mechanical work. When the final energy carrier is a fuel, the input is the chemical energy, which is released as heat during combustion. This heat is used to warm a fluid, causing it to move a piston and, in turn, spin a shaft. When electricity is the final energy carrier, electric motors are used to transform one form of work (electrical) into another (mechanical). In sailing ships, the kinetic energy of the wind is converted into mechanical work using aerodynamic drag and lift forces.

Conversion devices receive final energy, but only part of it is used to deliver useful energy due to inefficiencies in the conversion of energy within the conversion device (e.g., friction, heat dissipation). The last stage where energy can be measured before delivering services is called useful energy. The ratio between the energy output (useful energy) and input (final energy) of a conversion device is the final-to-useful efficiency. It is important to clearly define the boundary for the useful energy stage, as it significantly impacts results. Our definition of useful energy for each transport mode is as follows:

- **Water transport (sailing):** The useful energy is the mechanical energy delivered by the sail.
- **Water transport (motorized):** The propeller spins, pushing the water in the opposite direction of the ship's movement, creating a force that propels the boat forward. The useful energy is the energy delivered by the propeller.
- **Rail transport:** One locomotive produces mechanical work, pulling the other carriages, connected by a drawbar. The useful energy is the energy delivered at the drawbar.
- **Road transport**: The mechanical power produced by the engine is carried through the gearbox and the driveshaft to the tires. The useful energy is the energy delivered at the tires.
- **Air transport:** In jet aircraft, the engine compresses and heats the air, which increases its velocity as it is expelled in the opposite direction of the aircraft's movement, generating a thrust force that drives the aircraft forward. Propeller aircraft operate in a similar way to motorized ships, pushing the air in the opposite direction of the aircraft, generating a thrust force. The useful energy is the energy delivered by the jet engine.

To estimate useful energy, we multiplied the final energy use by the final-to-useful efficiency. Final-to-useful efficiencies were estimated separately for each transport mode and using different methods, reflecting differences in the availability and type of information.

Useful energy is delivered into passive systems, where useful energy is dissipated as heat to provide a certain energy service [35]. In the case of transport, energy service is measured as transport turnover, i.e., product of the tons of freight or number of passengers and the distance traveled. Transport turnover statistics are divided into freight and passenger, which are accounted for as ton-km (tkm) and passenger-km (pkm). Fig. 1 illustrates the energy stages previously described using internal combustion road vehicles as an example. The following subsections explore the data sources and methods used to quantify each energy stage, efficiencies, and intensities of world transport.

2.2. Water transport (sailing): 1800–1960

Defining the boundary of the final energy stage in sailing boats is a complicated task since the wind is a free renewable energy source, so energy is not purchased by the final consumer. We considered the final energy to be equal to the energy content of the primary energy resource

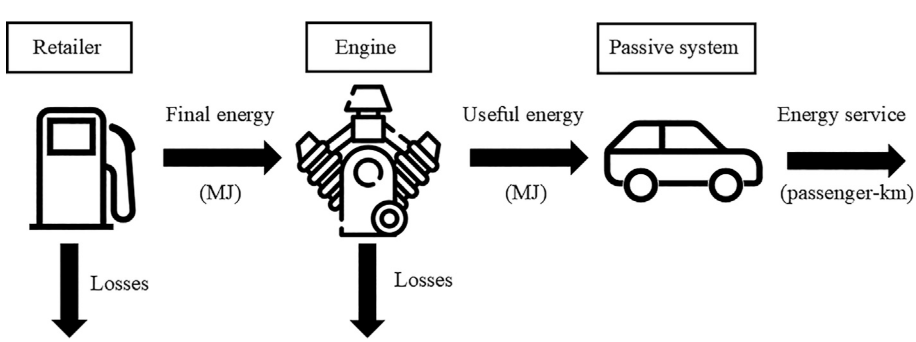

Fig. 1. Energy conversion chain applied to internal combustion road vehicles. Authors own construction.

(energy as found in nature), which in this case is the kinetic energy of the wind. Therefore, the final energy used by the global fleet of sailing boats over the course of one year is expressed as

$$E_f = \frac{\rho \times V_a^3 \times A \times \Delta t}{2} \times N_{ships}, \quad (1)$$

where ρ is the density of the air (1.293 kg/m^3), V_a is the apparent wind speed (in m/s), A is the mean sail area of global fleet of sailing ships (in m^2), Δt is the sailing time per ship per year (in seconds), and N_{ships} is the number of ships [36].

We estimated the sail area using gross register tonnage (GRT). The GRT is a historical measure of the internal volume of a ship (1 GRT = 100 ft^3 = 2.83 m^3). We used GRT as a proxy for sailing ships, as ships with larger internal volumes require greater sail areas. Based on technical data of historical sailing vessels, each ship requires around 1.2 m^2 of sail area per GRT [37–42]. This value was multiplied by the world GRT, obtained from Mitchell [43–45].

The apparent wind speed is defined as the speed of the wind in the frame of reference of the ship which is calculated by

$$V_a = \sqrt{V_B^2 + V_T^2 + 2 \times V_B \times V_T \times \cos\theta}, \quad (2)$$

where V_B is the ship speed, V_T is the true wind speed (relative to the Earth), and θ is the angle between the true wind speed and the ship speed.

We estimated the final energy use by sailing ships in four wind conditions: light breeze (< 8 knots), moderate breeze (8–16 knots), fresh breeze (16–21 knots), and strong breeze (> 21 knots). Kelly and Ó Gráda [46] estimated the evolution of the average speed of East India Company sailing ships under different true wind conditions. We calculated V_a by assuming $\theta = 90°$ for each wind condition using the average value of the interval (in the case of the first and last interval we used 6 and 22 knots respectively).

According to Mao and Rychlik [47], the true wind speed follows a Weibull distribution described by

$$P(V_T > v_T) = exp\left[-\left(\frac{v_T}{\lambda}\right)^k\right], v_T \geq 0, \quad (3)$$

where λ and k are parameters. Mao and Rychlik [47] estimated $\lambda = 8.53$ and $k = 2.18$ with on-board measurements based on 40 common ship routes. The probability of the occurrence of each wind condition (see Table 1) was multiplied by a total of 3500 working hours per year, as suggested by Dewhurst [48] and supported by other sources [49,50], to determine the number of hours sailing ships were subjected to each wind condition.

Several studies have estimated energy efficiencies of historical sailing ships, though the lack of data and physics-based methods remains their main limitation [48,51,52]. For example, Dewhurst [48] suggests that the final-to-useful efficiency of sailing boats is 50 %. However, this value seems to be unrealistic, considering the Betz limit, which states that the maximum energy that can be extracted from the wind is 59.3 % of its kinetic energy [53].

Since there is very limited data regarding the technological evolution of sailing ships in the 19th century, we calculated the final-to-useful efficiency in a specific condition and assumed it constant through time.

Table 1
Probability of a ship being exposed to different wind conditions. Probabilities were calculated based on the method proposed by Mao and Rychlik [47].

Breeze	Speed (knots)	Expression	Probability
Light	< 8	$1 - P(W > 8)$	0.1847
Moderate	8–16	$P(W > 8) - P(W > 16)$	0.4189
Fresh	16–21	$P(W > 16) - P(W > 21)$	0.2089
Strong	> 21	$P(W > 21)$	0.1875

Morin Scott [54] studied the substitution of engines by sail power in sail-assisted motor boats, in which a value of 0.04 useful horsepower per square feet of sail is suggested as a rule of thumb for ship design under the Beaufort 5 wind condition (17—21 knots, fresh breeze). This suggests that a boat with A square feet of sail area, receiving kinetic energy from wind at Beaufort scale 5, delivers the same mechanical power as a (similar) boat equipped with a diesel engine supplying $0.04 \times A$ horsepower. This information was used to estimate the final-to-useful efficiency. Mathematically, this is represented by

$$\eta_{FU} = \frac{E_u}{E_f} = \frac{0.04 \times A \times \Delta t \times k}{\frac{1}{2} \times \rho \times V_a^3 \times A \times \Delta t} = \frac{0.04 \times k}{\frac{1}{2} \times \rho \times V_a^3} = 23.8\ \%, \quad (4)$$

where $k = 8026.71$ W · ft^2/(hp · m^2) (conversion from horsepower to Watt and squared feet to m^2) and V_a is the apparent wind speed determined with Eq. (2), in which $V_T = 19$ knots (9.77 m/s, mean value of Beaufort 5) and $V_B = 16$ knots (8.23 m/s, sailing ships in the 20th century reached around this speed when in Beaufort 5 [55]). These assumptions resulted in $V_a = 12.8$ m/s. The total final energy was multiplied by η_{FU} to estimate the total useful energy for sailing boats.

2.3. Water transport (motorized): 1814–2020

After 1971, the IEA [4] has data on fuel consumption for navigation purposes per energy carrier divided into domestic and international use. Endresen et al. [56] reviewed different sources for the worldwide sales of marine fuel bunkers (coal and oil products) between 1925 and 2002. For the period 1925–1949, linear interpolation was used for years with missing data. To estimate the fuel use for domestic navigation, we assumed following Endresen [56] that national consumption was approximately 27 % of international consumption.

For the period from 1814 to 1925, we found data only on coal consumption by steamships in the UK. [57]. To estimate the world coal consumption, we scaled the consumption in the UK by the number of registered ships [43–45]. According to Fletcher [58], 96.6 % of the world merchant fleet was coal-powered in 1914 (excluding wind-powered ships). We considered that motor ships were exclusively coal-powered between 1814 and 1914, after which the fraction of oil increased proportionally to the share of diesel and fuel oil-powered ships in the world merchant fleet until 1925 [58].

The conversion from final to useful energy in motor ships includes the following processes: (a) conversion of chemical energy of the fuel into mechanical work by the engine, (b) transmission from the engine to the propeller, and (c) rotation of the propeller into propulsive energy (useful energy). The final-to-useful efficiency of motor and steamboats is expressed as

$$\eta_{FU} = \eta_{Eg} \times \eta_T \times \eta_{Prop}, \quad (5)$$

where η_{Eg} is the efficiency of the engine, η_T is the transmission efficiency, and η_{Prop} is the propulsion efficiency.

The engine energy performance is usually quantified as the mass flow of fuel per unit of power produced at the shaft (also referred to as specific fuel consumption). These values were converted into energy units using the heating value of the fuels. Table 2 summarizes the specific fuel consumption reported in previous studies.

The estimation of the engine efficiency (ratio of the engine energy output to input) was divided into three different periods: 1814–1915, 1915–1950, and 1950–2020. For the latest period, 1950–2020, we used the time series provided by Olesen et al. [62] for medium-sized oil-burning ships between 1950 and 2008. From 2008 to 2020 linear extrapolation was applied.

Between 1915–1950, the engine efficiency was estimated based on the values suggested by Baker [59] and Le Mesurier and Humphreys [60]. Average values for different technologies using the same energy carrier were used to determine the engine efficiency of coal and oil-burning ships in 1915 and 1935. Linear interpolation was used to estimate the engine efficiency between 1915–1935 and 1935–1950.

Table 2
Summary of the different specific fuel consumption (SFC, pounds of fuel per horsepower-hour) and the respective engine efficiency (η_{E_g}) of motor and steamboats.

Type	Fuel	Reference	Year	SFC	η_{E_g}
Steam engine	Coal	[59]	1915	1.54	6.8 %
Steam engine	Coal	[60]	1935	1.35	7.8 %
Steam turbine	Coal	[59]	1915	2.4	4.4 %
Steam turbine	Coal	[60]	1935	1.13	9.4 %
Steam engine	Oil products	[60]	1935	0.9	16.4 %
Steam engine	Oil products	[61]	1988	1.15	12.8 %
Steam turbine	Oil products	[60]	1935	0.75	19.7 %
Steam turbine	Oil products	[61]	1988	0.49	30.2 %
Motor	Oil products	[59]	1915	0.47	31.5 %
Motor	Oil products	[60]	1935	0.36	41.1 %
Motor	Oil products	[61]	1988	0.33	44.8 %
Motor	Oil products	[62]	1950–2008	0.42–0.31	35.2 %–47.7 %

Table 3
Summary of the data sources for gasoline (G), diesel (D), biofuels (B), electricity (E), and unspecified motor fuel (MF) consumption on roads (final energy).

Energy carrier	Time span	Region covered	Reference
G	1910–1918	USA	[66,67]
G	1918–1935	USA	[68]
MF	1936–1959	USA	[68,69]
MF	1910–2018	UK	[17]
G	1932–1959	Canada	[70]
G, D	1952–1959	France	[71]
G, D, B, E	1960–1970	OECD	[4]
G, D, B, E	1971–2018	World	[4]

For the period 1814–1915 we assumed that the engine efficiency of steamships was proportional to the boiler pressure. According to Graham [63], the boiler pressure increased from 5 psi in the 1830s, to 10 psi in the 1840s, 20 psi in the 1850s, 30 psi in the 1860s, reaching 70 psi in 1870s. Between 1870 and 1915, since no reliable data source was found, linear interpolation was applied.

Since there are no historical records available for η_T and η_{Prop}, it is not feasible to accurately quantify their evolution. We assumed their values to be constant at 0.95 and 0.65, respectively [64]. This assumption is expected to create an upward bias in the values of efficiency in the 19th and early 20th century since propulsion systems experienced great developments around that time [65].

2.4. Rail transport: 1840–2020

Tostes et al. [10] developed a publicly available dataset that covers final and useful energy use and energy efficiencies of rail transport from 1840 to 2020. As such, we retrieved our data directly from Tostes et al. [10], not requiring further estimations.

2.5. Road transport: 1910–2020

The first step in estimating final energy use by road vehicles was to collect statistics from different countries. Table 3 summarizes the data sources of final energy use. Supplementary Information I provides a more detailed description of these sources.

The values for which no data were found were estimated based on the gallons per vehicle metric. The final energy use data listed in Table 3 were converted into gasoline gallons and divided by the number of vehicles in use, taken from Mitchell [43–45], to calculate the gallons per vehicle for each country, as shown in Fig. 2.

We observed that gallons per vehicle remained fairly constant for every country, therefore we applied the naïve method. The naïve method is one of the simplest backcasting methods in which the backcasts are

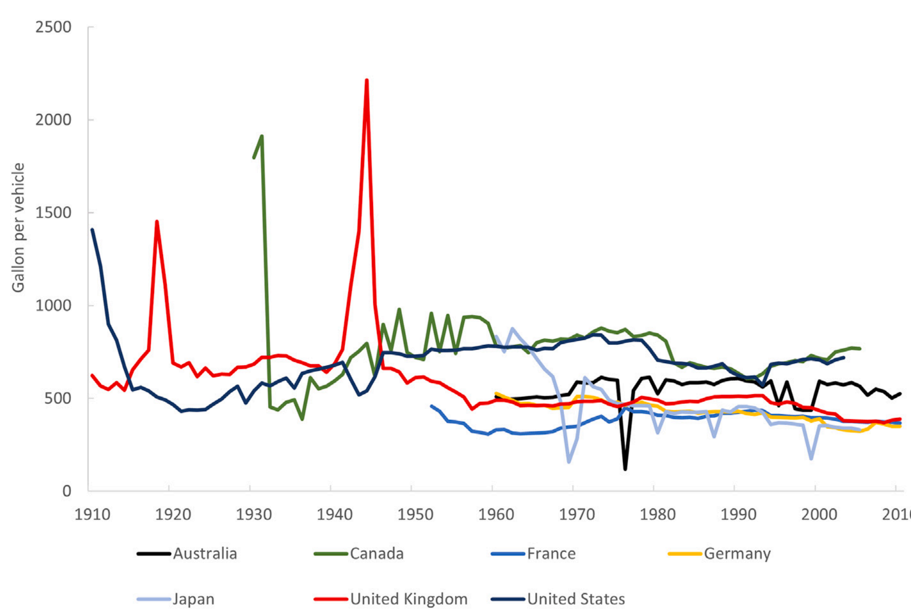

Fig. 2. Gallons per vehicle for selected countries.

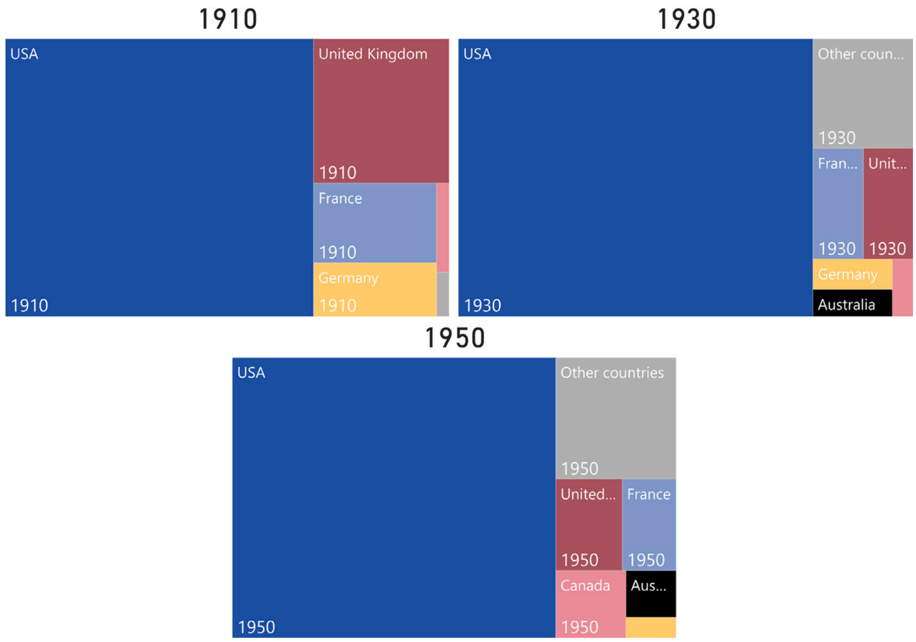

Fig. 3. Most relevant countries in terms of number of vehicles and their proportion to the world total.

estimated as equal to the last observation. If we assume that residuals have constant variance, are uncorrelated, and follow a normal distribution, then the naïve method states that the backcasts are normally distributed, centered on the last observation.

The following steps were taken to estimate fuel consumption prior to 1971 (except for the US and UK, as their time series were complete): (1) identify countries to be estimated at different time spans (most relevant in terms of the number of vehicles, see Fig. 3), (2) remove outliers and replace them with linear interpolation (e.g., peaks in gallons per vehicle during the First and Second World Wars), (3) apply the naïve method to estimate gallons per vehicle for each country ($\widehat{gpv}_{t,c}$), and (4) sum the product of gallons per vehicle and vehicles in use ($Nv_{t,c}$) for the n different countries, represented by

$$E_f(t,c) = \sum_{c=1}^{n} \widehat{gpv}(c) \times Nv(t,c). \tag{6}$$

Outliers in time series data can significantly impact model performance, leading to biased estimations and misleading trends. In the case of gallons per vehicle, historical events such as World Wars and the 1929 economic crisis caused abrupt and temporary deviations from the long-term trend. These anomalies do not represent the typical behavior of the series and can distort the model fitting and residuals analysis. Removing these outliers helps to improve model fit, reduce variability, and ensure more reliable confidence intervals. This approach is a standard practice in time series analysis to enhance the robustness and interpretability of results.

We divided the estimation of final energy use into 2 periods: 1910–1959 and 1960–1970. In the period 1960–1970, we found data for OECD countries [4], as shown in Table 3 (no estimation needed). The remaining countries (non-OECD) were estimated in an aggregated way. Gallons per vehicle for non-OECD countries were calculated from 1971 to 2018 (training data) and then backcasted from 1971 to 1960. After that, Eq. (6) was applied to determine final energy use of non-OECD countries.

Between 1910 and 1959, we applied the naïve method to the countries listed in Fig. 3 until 1910 (France, Germany, Australia, and Canada), backcasted gallons per vehicle, and applied Eq. (6). Similarly to the time span 1960–1970, we estimated the remaining countries in an aggregated way, as together they represent a small fraction of the number of vehicles (8.8 % in 1930 and 17.3 % in 1959). The estimation of the confidence interval, residual analysis, and hypothesis tests are described in Supplementary Information I.

After estimating the total final energy use, we estimated the contribution of each energy carrier. In 1971, the sum of liquid biofuels, natural gas, and other petroleum products (OPP) represented less than 1 % of the final energy use at the world scale. For this reason, we did not estimate their fraction prior to 1971. Between 1971 and 2007, the fraction of diesel in the road transport final energy use increased following a linear trend [4]. Based on these results we backcasted the diesel fraction with a linear model. The estimated parameters are in Supplementary Information I. After 2007 the fraction of diesel stabilized, so these points were not included in the linear regression model.

The estimated fraction of diesel was multiplied by the total final energy use to calculate the diesel consumption before 1971. The remaining final energy was assumed to be 100 % gasoline.

The naïve method and the linear regression model were implemented using the Darts library [72] in Python and Excel, respectively.

For estimating the final-to-useful efficiencies of road vehicles, we applied the loss factor method to exclude the influence of passive system characteristics from the efficiency calculation [73]. In the loss factor approach, the maximum theoretical efficiency (η_{th}) is multiplied by loss factors (α_i). Each loss factor represents a specific energy loss along the conversion from final to useful energy. Mathematically, the loss factor approach is given by

$$\eta_{FU} = \eta_{th} \times \prod_{i=1}^{n} \alpha_i. \tag{7}$$

Table 4
Theoretical efficiency (η_{th}) of spark ignition (SI), compression ignition (CI), and electric engines.

Engine	Equation	Fuel
SI	$\eta_{th} = 1 - \frac{1}{r^{k-1}}$	Gasoline, natural gas, biogasoline
CI	$\eta_{th} = 1 - \frac{1}{r^{k-1}} \left[\frac{r_c^k - 1}{k(r_c - 1)} \right]$	Diesel, biodiesel
Electric	1	Electricity

Table 5
Loss factors used to compute final-to-useful efficiency, their meaning, sources, and description.

α_i	Meaning	Values	Source	Description
1	Working fluid	0.75	[74]	Fluid is not an ideal gas.
2	Incomplete combustion	0.90 (SI); 0.98 (CI)	[75]	SI engines work at slightly rich conditions, while CI engines work in excess of air.
3	Heat losses	0.75	[74]	Heat losses through the cylinder wall.
4	Friction	0.7–0.9	[76], [75]	Power to pump the gas and the friction in the driveshaft.
5	Accessories	0.9	[76]	Other uses apart from transportation, such as lighting, cooling, and heating.
6	Transmission	0.85 (autom.); 0.9 (manual)	[74]	Torque converter increases the energy losses in automatic transmission vehicles.

Road vehicle engines may be divided into three types: spark ignition (SI), compression ignition (CI), and electric. The equations for the maximum efficiency of each type of engine are shown in Table 4. A detailed description of the estimation of η_{th} is in the Supplementary Information I.

We attributed 6 loss factors to move from the theoretical efficiency to the actual final-to-useful efficiency of internal combustion engines. Their descriptions, sources, and values are in Table 5.

We attributed different α_2 coefficients for SI and compression-ignition engines since they work in air-to-fuel ratios lower and higher than stoichiometric, respectively [75].

Many authors suggest that friction losses have significantly reduced over the years, though it is difficult to quantify them [74,76–78]. We assumed that α_4 increased linearly between 0.7 and 0.9 [76].

To estimate transmission losses (α_6), the vehicles in use should be divided into automatic and manual, as these two technologies have different efficiencies (Table 5). According to Statista [79], since the 1950s the popularity of automatic cars has been increasing, reaching 34 % in 2015. We modeled the fraction of automatic cars (f_{ac}) as a linear function, described by

$$f_{ac}(t) = -10.2 + 5.23 \times 10^{-3} \times t, \tag{8}$$

assuming there were no automatic cars when $t = 1950$.

The coefficients α_1, α_3, and α_5 were assumed to be constant throughout the years. The first one depends on the properties of the working fluid, which depend on the working air-to-fuel ratio. At stoichiometric conditions, Ross [74] approximates α_1 to 75 %. Heat losses through the cylinder are also difficult to measure, so we assumed the same value as Ross [74]. Energy allocated to non-transport services, such as lighting, cooling, and heating, is also highly variable and difficult to account for. We opted to use the value from Serrenho et al. [76].

In electric engines, the maximum efficiency is 100 % since, theoretically, electrical energy can be fully converted into mechanical work. The coefficients α_1, α_2, and α_3 are not applicable. We estimated the final-to-useful efficiency by multiplying the engine efficiency of electric motors [80] by the α_4 and α_5 used in internal combustion vehicles, a battery efficiency of 0.92 [81], and the transmission efficiency (α_6). The transmission in electric vehicles differs significantly from that of internal combustion vehicles, as most electric cars typically have only a single gear. We assumed $\alpha_6 = 0.92$, which is an average value in the range suggested by Břoušek and Zvolský [82].

To determine the amount of useful energy, the estimated final energy for each energy carrier was multiplied by its respective final-to-useful efficiency.

2.6. Aviation: 1940–2020

After 1971, the IEA [4] has data for fuel consumption by airplanes per energy carrier divided into domestic and international aviation. Between 1940–1971, Sausen and Schumann's [83] CO_2 emissions estimations from the aviation sector were used to determine final energy use. We validated their estimations by comparing them with the existing historical data for the OECD for the period 1960–1971 and for the USA between 1940 and 1960 [4,84]. The CO_2 emissions (m_{CO2}) and final energy use (E_f) are related by

$$E_f = m_{CO2} \times \left(\frac{f_{avg}}{CF_{avg}} + \frac{1 - f_{avg}}{CF_{jet}} \right), \tag{9}$$

where f_{avg} is the fraction of emissions from aviation gasoline, and CF_{avg} and CF_{jet} are the carbon emission factors of aviation gasoline and jet fuel. Between 1940 and 1957, only piston airplanes were used ($f_{avg} = 1$). For the period 1957–1971, we assumed f_{avg} was approximately the fraction of piston airplanes in the USA, calculated from the number of piston and jet airplanes available in the "Air Transport Facts and Figures" [84]. The carbon emission factors of aviation gasoline and jet fuel were obtained from the IPCC [85].

Final energy use for the period 1940–1971 was also divided into domestic and international aviation. The fraction of fuel consumption in domestic aviation has decreased over the years since international flights gained more relevance. We assumed a linear decrease from 80 % of domestic flights in 1940 (fraction determined for the USA based on the American Historical Census [68]) to 50 % in 1971 (based on IEA [4] data).

The final-to-useful efficiency (η_{FU}) of airplanes was defined as the ratio between the energy flow associated with the thrust force delivered by the jet engine (useful energy) and the energy content of the fuel (final energy), which is expressed as

$$\eta_{FU} = \frac{T \times v_{aircraft}}{\dot{Q}_{fuel}} = \frac{v_{aircraft}}{TSFC}, \tag{10}$$

where T is the thrust force, $v_{aircraft}$ is the velocity of the aircraft, $\dot{Q}_{fuel}$ is the fuel energy flow, and $TSFC$ is the thrust specific fuel consumption (fuel mass flow per unit of thrust force produced [kg/N s]). We assumed that the velocity of aircraft was equal to the average velocity of airplanes in the USA, reported by the American Historical Census [68] for international and domestic trips between 1940–1970. After 1970, the average velocity stabilized, so we considered its value constant until 2020 [86].

As for the $TSFC$, the IPCC [86] estimated a range for jet engines during the period 1960–1995. We calculated the average value of the upper and lower bounds to determine an average value of $TSFC$. Linear extrapolation was applied for the period 1995–2020 since no time series data were found. For piston engines, we assumed that the estimations of fuel consumption per seat-kilometer from Peeters et al. [87] were proportional to their $TSFC$. Finally, the average yearly $TSFC$ was calculated by

$$TSFC = TSFC_{piston} \times f_{avg} + TSFC_{jet} \times (1 - f_{avg}). \tag{11}$$

The final-to-useful efficiency was then determined with Eq. (10) for both international and domestic aviation. Finally, useful energy was calculated by multiplying the final energy use in domestic and international aviation by their respective final-to-useful efficiencies.

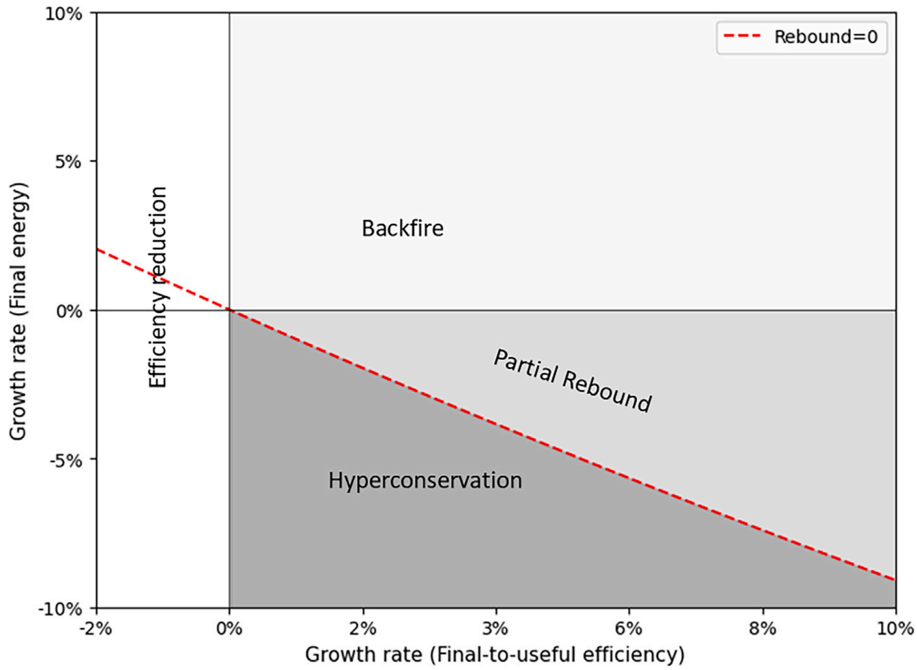

Fig. 4. Energy rebound state map for identifying partial rebound, hyperconservation, backfire, and efficiency reduction. Adapted from Aramendia et al. [88].

2.7. Energy transitions and rebound

Having all the energy data presented in the previous sections, we were able to determine energy transition periods within each transport mode and in the transport sector. We used the definition of energy transition from Fouquet [34], from 5 % to 80 % of energy consumption. If the energy carrier does not reach 80 %, its peak is used as the last year of transition. We applied these limits to both final and useful energy in order to explore the differences between transitions in these two energy stages.

For each energy transition identified, we evaluated whether there may be a rebound effect associated with it. We utilize the concept of a rebound state map, as earlier defined and set out by Aramendia et al. [88], which consisted of plotting the annual growth rates of final energy vs. final-to-useful efficiency (see Fig. 4). We applied this state map to our different transport modes to determine different periods when rebound effects (when efficiency is increasing) may be classified as being in states of hyperconservation (rebound <0 %), partial rebound (0-100 % rebound) or backfire (>100 % rebound), or a state of efficiency reduction (when efficiency is decreasing).

We finally note that we are not reporting causal relationships between efficiency improvements and energy consumption, as our approach does not involve econometric analysis to disentangle effects of income, population, or economic growth, of supply-side vs. demand-side factors, or of policy changes.

3. Results

3.1. Final and useful energy: evolution and transitions

Fig. 5 shows the evolution of the world final energy use by rail, road, air, and water transport, as well as their sum (overall transport). Fig. B.3 shows the fraction of final energy per transport mode. Water transport was the most relevant mode until the 1870s when rail transport surpassed it. Road transport has been increasing sharply since the 1910s, exceeding the final energy use of water transport in the 1930s

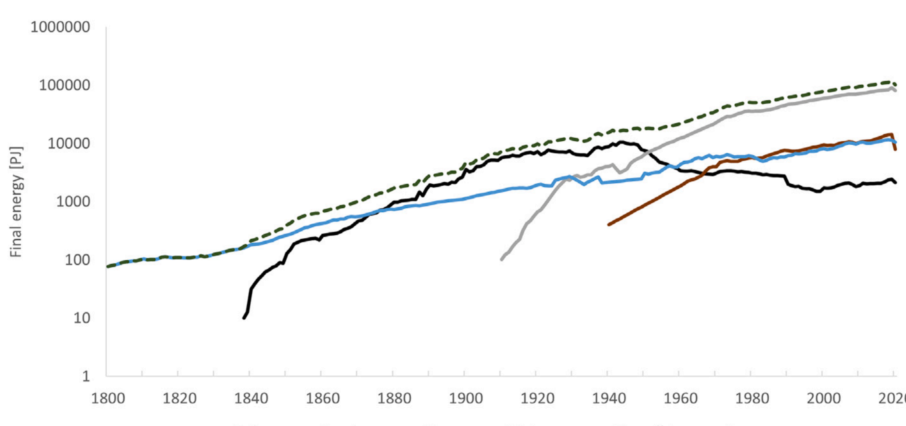

Fig. 5. World final energy use per transport mode (log scale): 1800–2020.

Table 6
Average annual growth rates of final energy per transport mode.

Timespan	Water	Rail	Road	Air	Overall transport
1800–1820	1.8 %	–	–	–	1.8 %
1820–1840	2.6 %	–	–	–	3.4 %
1840–1860	4.3 %	11.2 %	–	–	6.0 %
1860–1880	2.8 %	6.9 %	–	–	4.7 %
1880–1900	2.2 %	6.7 %	–	–	5.2 %
1900–1920	2.7 %	3.6 %	–	–	3.7 %
1920–1940	0.5 %	1.0 %	9.4 %	–	2.3 %
1940–1960	3.6 %	−4.7 %	5.7 %	8.0 %	1.8 %
1960–1980	1.6 %	−0.5 %	5.4 %	5.7 %	4.2 %
1980–2000	1.5 %	−2.9 %	2.6 %	2.6 %	2.3 %
2000–2020	1.3 %	1.1 %	1.5 %	−0.8 %	1.3 %
Average	2.2 %	2.0 %	4.9 %	3.7 %	3.3 %

and rail in the 1950s. Air transport also emerged in the 20th century and has sharply increased its fuel consumption ever since. Final energy use in global transport (excluding animal and human muscle power) increased from 1800 to 2019, with an average annual growth rate of 3.4 %. The average annual growth rates by transport mode are presented in Table 6.

Fig. 6 shows the fraction of final energy carriers, as well as the periods of final energy transitions in world transport. During the 19th century, traditional renewable energy sources (wind and wood) had their share reduced due to the general increase in coal consumption. By the beginning of the 20th century, oil products were starting to become dominant. The share of coal products reduced from 98 % of total final energy use in the 1900s, to 50 % in the 1940s, and 3 % in the 1970s. The beginning of the oil boom was mainly led by gasoline use in road vehicles. Around the 1970s, diesel started to grow its share, especially in road transport. Alternative fuels, namely natural gas, electricity, and biofuels have been growing their share since the early 2000s, however, they still have not exceeded 5 % of final energy use.

Fig. 7 shows the useful energy use by transport mode. Fig. B.4 shows the fraction of useful energy per transport mode. One of the main differences from the final energy use graph (Fig. 5) is that while the final energy use by railways peaked in the 1940s, the useful energy has not yet peaked [10]. The remaining transport modes present an even greater increase in useful energy than they do in final energy use. Between 1850 and 2019, useful energy demand in the transport sector increased 460-fold (2.84 % per year), while final energy use grew 300-fold (2.64 % per year). This discrepancy is due to an improvement in final-to-useful

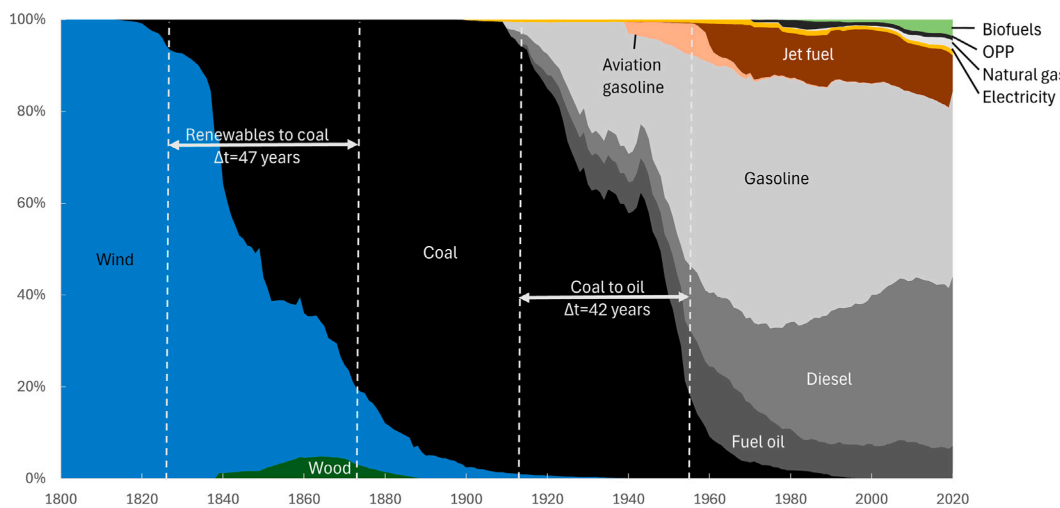

Fig. 6. Fraction of final energy carriers in world transport: 1800–2020.

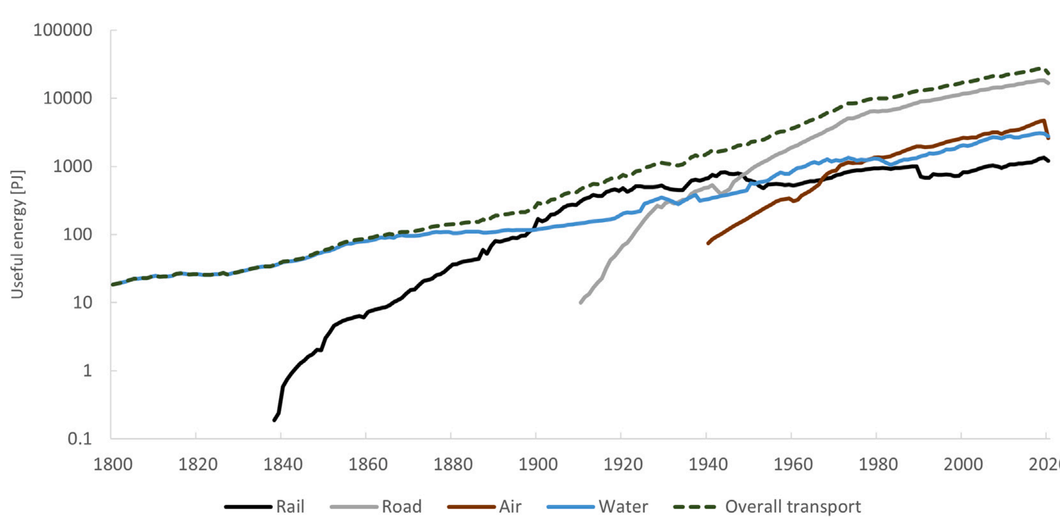

Fig. 7. World useful energy use per transport mode (log scale): 1800–2020.

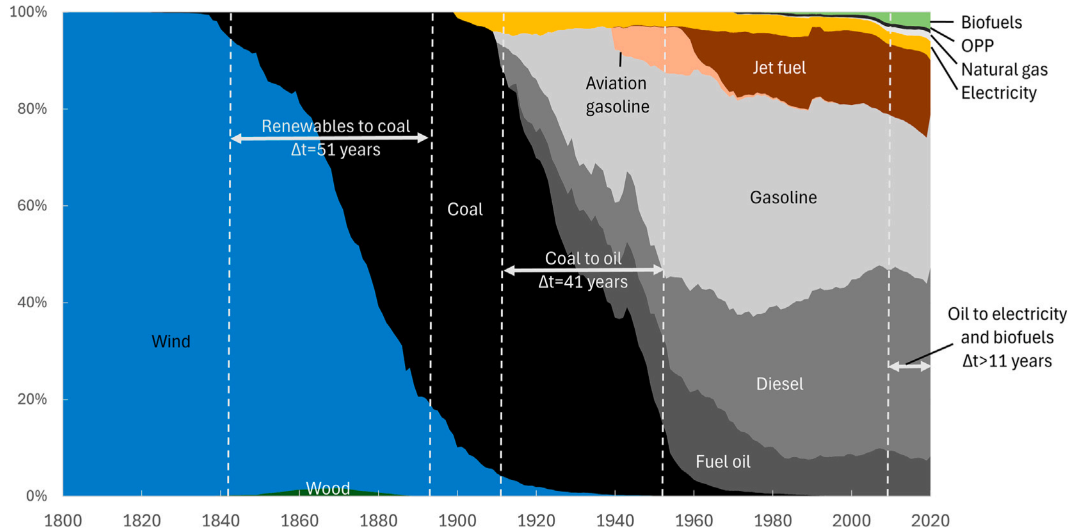

Fig. 8. Fraction of useful energy output from final energy carriers in world transport: 1850–2020.

Table 7
Average annual growth rates of useful energy per transport mode.

Timespan	Water	Rail	Road	Air	Overall transport
1800–1820	1.8 %	–	–	–	1.8 %
1820–1840	2.1 %	–	–	–	2.2 %
1840–1860	3.6 %	13.4 %	–	–	4.0 %
1860–1880	1.4 %	8.4 %	–	–	2.4 %
1880–1900	0.6 %	8.0 %	–	–	3.6 %
1900–1920	2.7 %	5.4 %	–	–	4.9 %
1920–1940	2.5 %	1.7 %	10.3 %	–	3.8 %
1940–1960	4.9 %	−1.2 %	7.1 %	7.4 %	4.3 %
1960–1980	2.0 %	2.9 %	6.2 %	7.7 %	5.2 %
1980–2000	2.4 %	−0.7 %	3.0 %	3.4 %	2.7 %
2000–2020	1.5 %	2.0 %	1.8 %	−0.1 %	1.5 %
Average	2.2 %	2.8 %	5.2 %	4.3 %	3.2 %

energy efficiency, which rose from 15 to 23 %. The average annual growth rates by transport mode are presented in Table 7.

Fig. 8 shows the fraction of each useful energy carrier and the transition periods determined with useful energy. In 1850, wind provided 60 % of total useful energy, much higher than the 25 % share in final energy use. Another important difference is the transition from coal to oil products, which happened a few years earlier in useful energy. Coal had declined to 50 % of useful energy sources in transport by the 1930s, but it took more than ten years to decline to 50 % of final energy. Electricity consumption also presents a higher share compared to Fig. 6, since the final-to-useful efficiency of electric engines is much higher than that of internal combustion engines (although not necessarily in terms of primary-to-useful efficiency). As a result, in useful energy terms the transition from oil to electricity and biofuels began in 2009, while in final energy terms, it has not yet begun.

Energy transitions within each transport mode for final and useful energy were also identified, along with the most likely driving factors, as shown in Table 8. The fractions of final and useful energy carriers per transport mode are in Appendix B. The driving factors considered were: better service (e.g., speed, comfort, or reliability), cost, and environment. The transition from wind to coal in water transport is one of the clearest examples of a better service driving an energy transition. Even though sailing ships did not present any fuel expenditure, low-efficiency steamships replaced them due to their reliability. Air transport also experienced a service-driven transition as jet engines, although less energy efficient than piston engines in their early days, could fly at higher altitudes and speeds [86]. Cost played a major role in the replacement of steam trains, as diesel and electric trains worked at a much higher final-to-useful efficiency [10]. Environment-driven transitions are the most recent ones, such as the partial replacement of gasoline by diesel in road transport [89,90] and the replacement of oil products with biofuels and electricity in both rail and road transport.

By comparing Fig. 6 with Fig. 8 and the timespan columns in Table 8, we noticed a significant difference between defining energy transitions with final or useful energy. Although final energy has a clear economic value, which is a good reason to use it to define energy transitions, when comparing technologies with vastly different final-to-useful efficiencies, final energy offers a limited understanding of energy use. The first transition in transport, from renewables to coal, appeared to have ended in 1873 while sailing boats were still providing more than 50 % of the total useful energy. Twenty years later, in 1893, coal would conclude its transition by reaching 80 % of useful energy. If animal and human-powered transport were included, the transition would be completed even later. Another example is the electrification of rail transport, which accounted for 5 % of final energy use in railways by 1960, even though it had already contributed 5 % of rail useful energy as early as 1908. We also observe a similar behavior in the ongoing energy transition to electricity and biofuels. As of 2020, the transition in terms of final energy had not yet begun at both the road and overall transport scales, whereas in terms of useful energy, it started in 2016 for the road sector and in 2009 for the transport sector. Therefore, when assessing the current energy transition solely in terms of final energy, it may appear that only a small amount of electricity and biofuels is being used for transport. However, in reality, these fuels are providing a much higher amount of mechanical work at the useful stage.

3.2. Final-to-useful energy efficiencies and potential rebound effects

Fig. 9 and Table 9 show the evolution of the final-to-useful efficiency of the different transport technologies. In the 19th century, sailing ships presented the highest final-to-useful efficiency, as the steam engines used in ships and locomotives were not very efficient. In the 20th century, several types of oil engines emerged across all transport modes. Compared to steam and sailing ships, oil-fueled ships presented a much higher efficiency.

Table 8
Energy transitions identified across the different transport modes, their timespan in terms of final (Δt_{final}) and useful (Δt_{useful}) energy and the most likely driving factor.

Transition	Mode	Δt_{final}	Δt_{useful}	Better service	Cost	Envir.
Wind to coal	Water	1826–1903 (77 years)	1859–1908 (49 years)	✓		
Coal to oil	Water	1915–1948 (33 years)	1914–1944 (30 years)	✓	✓	
Coal to oil and elec.	Rail	1954–1997 (43 years)	1924–1986 (62 years)	✓	✓	
Electrification	Rail	1960–present (>60 years)	1908–present (>112 years)		✓	✓
Gasoline to diesel	Road	1955–2012 (57 years)	1952–2007 (55 years)	✓		✓
Oil to elec. and biofuels	Road	–	2016–present (>4 years)			✓
Piston to jet engines	Air	1957–1971 (14 years)	1957–1971 (14 years)	✓		

Table 9
Average annual growth rates of final-to-useful efficiency per transport technology.

Tec.	1860–1880	1880–1900	1900–1920	1920–1940	1940–1960	1960–1980	1980–2000	2000–2020
CI engines	–	–	–	–	–	0.19 %	−0.22 %	0.05 %
Coal-fueled ships	–	0.52 %	0.47 %	1.49 %	0.39 %	0.00 %	0.00 %	0.00 %
Diesel-electric locomotive	–	–	–	0.28 %	0.48 %	1.08 %	1.06 %	0.44 %
Domestic aviation	–	–	–	–	–	−1.09 %	1.74 %	0.79 %
Electric locomotive	–	–	–	0.27 %	0.48 %	0.40 %	0.31 %	0.31 %
Electric vehicle	–	–	–	0.00 %	0.00 %	0.00 %	0.00 %	0.52 %
International aviation	–	–	–	–	–	−0.17 %	0.86 %	0.72 %
Oil-fueled ships	0.00 %	0.00 %	0.00 %	0.00 %	1.04 %	0.29 %	0.51 %	0.73 %
Sailing ships	0.00 %	–	–	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
SI engines	0.00 %	1.25 %	1.00 %	0.53 %	1.09 %	0.79 %	0.17 %	0.29 %
Steam locomotive	0.00 %	1.25 %	1.00 %	0.83 %	0.00 %	0.00 %	0.00 %	0.00 %

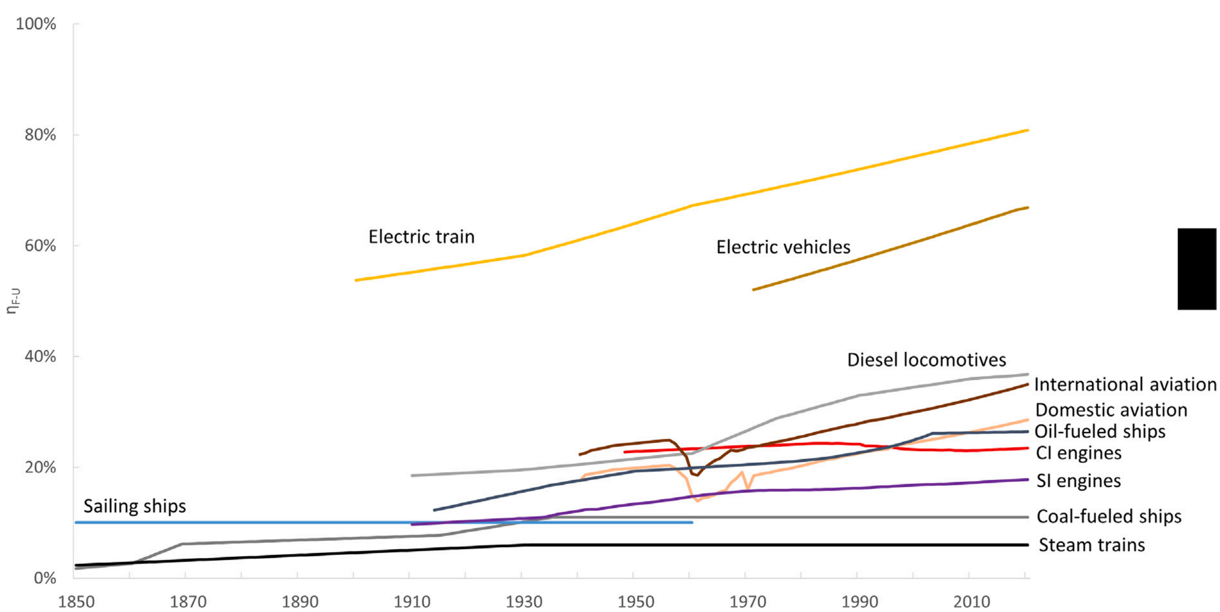

Fig. 9. World final-to-useful efficiency (η_{F-U}) per transport technology: 1850–2020. SI: spark-ignition, CI: compression-ignition.

In road transport, gasoline-fueled spark-ignition engines were the first type of internal combustion engine to be used. Later in the 1950s, compression-ignition engines began to be more widely used in road vehicles. The evolution of the final-to-useful efficiency of road vehicles has been highly dependent, not only on technological development but also on pollutant regulations (e.g., the American Clean Air Act of 1970 banned lead additives from gasoline, forcing car manufacturers to drastically reduce their compression ratio) [78].

The final-to-useful efficiency of both international and domestic aviation increased in the years following the increase in air transport, followed by a drastic decline around 1960, associated with the replacement of the piston by jet engines. When jet airplanes were introduced, they presented a lower efficiency compared to piston ones. However, as their technology improved, the efficiency of jet engines surpassed that of the predecessor technology.

The highest values of final-to-useful efficiency are observed in electric engines, both in rail and road transport. Electric vehicles present a slightly lower final-to-useful efficiency, due to higher friction losses and the inefficiency of the battery. Most trains are grid-connected, resulting in a higher final-to-useful efficiency. It is important to remember that although electric engines present higher final-to-useful efficiencies compared to internal combustion ones, there are significant losses in electricity production which should be accounted for when comparing the environmental benefits and burdens of transport technologies.

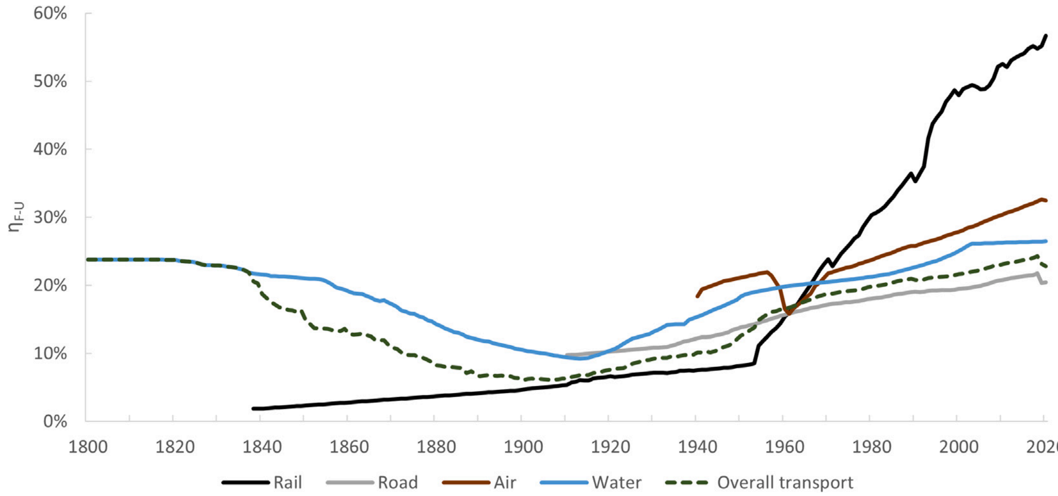

Fig. 10. World final-to-useful efficiency (η_{F-U}) per transport mode: 1800–2020.

Pinto et al. [91] estimated that in 2017, the primary to final energy efficiency of world electricity was around 40 %.

Fig. 10 shows the evolution of the final-to-useful efficiency per transport mode, as well as the overall transport. Rail transport is the transport mode that faced the highest increase in final-to-useful efficiency, mainly due to the replacement of steam trains by diesel and electric ones [10]. The final-to-useful efficiency has been rising for all transport modes, except during the end of the 19th century when sailing ships were being replaced by steamships in water transport and at the beginning of the transition from piston to jet engines in air transport around the 1960s.

Fig. 11 shows the growth rates of final energy and final-to-useful efficiency by transport mode, where energy transitions are identified according to useful energy. Fig. 11 can be used to identify states of potential rebound, i.e., where efficiency increases may be associated with hyperconservation, partial rebound, and backfire (Fig. 4). The transition from wind to coal in water transport shows a distinct behavior since steamships were less energy efficient than sailing ones. This reduction in the final-to-useful efficiency is associated with a more than proportional increase in final energy (most observations are above the red dashed line). The following transition from coal to oil presented high growth rates of final-to-useful efficiency, from 2 to 4 % per year, while final energy also presented high positive growth rates (backfire). In some years, hyperconservation was observed, however, these are related to the 1929 economic crisis, so they can be considered outliers. This is consistent with the findings of many authors that hyperconservation only happens during times of major crises where GDP growth rates are negative [92–94].

The rail plot in Fig. 11 shows two overlapped transitions: the replacement of coal with oil products and electrification. When coal was being replaced, some countries invested in electrifying their lines (e.g., Japan), while others chose to switch to diesel locomotives (e.g., USA) [10]. In the coal to oil and electricity transition, most observations of annual efficiency and energy changes are located in the partial rebound area. Hyperconservation is potentially observed during the Great Depression, a phenomenon also present in the replacement of steamships, and in the years following World War II (1946–1953). During the war, the limited supply of oil products led to an increase in rail activity, while road transport experienced a significant reduction in usage. After the oil restrictions were abolished, it would be expected that railways might experience hyperconservation, as there was a reduction in rail transport demand and final-to-useful efficiency kept increasing. During the period of electrification, a similar pattern is observed: potential states of backfire and rebound are the most dominant cases, except for periods of economic recession, where hyperconservation is observed. As the electrification of rail transport began in 1908 according to our definition of transition, it captured several economic recessions that were associated with potential hyperconservation: World War I, the Great Depression, both oil shocks, the dissolution of the USSR, and the 2007–2008 global financial crisis.

In road transport, two transitions were identified (in both final and useful stages): gasoline to diesel and the ongoing replacement of oil products by biofuels and electricity. The first transition was mainly motivated by the goal of reducing CO_2 emissions per kilometer [95], as compression-ignition engines present a higher efficiency than SI ones (Fig. 9). By analyzing Fig. 11, the introduction of diesel had the opposite effect, resulting in high growth rates of final energy use (an average of 4 % per year) and associated CO_2 emissions. The current renewable transition has been presenting a similar behavior: even though the increase in final-to-useful efficiency is motivated by the need to reduce final energy use, the increase in efficiency has been associated with higher final energy use.

Finally, the air transport plot in Fig. 11 presents the transition from piston to jet engines. Independently of the behavior of final-to-useful efficiency, final energy kept increasing at high growth rates. As a result, this transition is mainly located in the backfire region, apart from the first few years of efficiency reduction. In all cases, there were no reductions in final energy use associated with this transition. Air transport was still developing at that time, therefore it is expected that gains in efficiency would be used to expand air travel instead of reducing fuel consumption.

Fig. 12 shows the growth rates of final-to-useful and final energy of the four transport modes combined. The first transition identified is the replacement of renewables (wind and wood) with coal products. Since this transition mainly affected water transport, we observe the same behavior of efficiency reduction. The second transition, from coal to oil, involves the replacement of technology (steam locomotives and ships with oil-fueled ones) and the rise of a new type of service (road transport). At the transport scale, this transition is mainly associated with a state of potential backfire, as the final energy demand increased at the same time as the increase in efficiency provided by internal combustion engines. The periods of potential hyperconservation also coincide with economic recessions, mainly the years affected by the Great Depression. The ongoing transition towards renewable energy sources is still in its early stages (started in 2009). Even though the electrification of rail transport began in 1908, it was only when road transport started to adopt

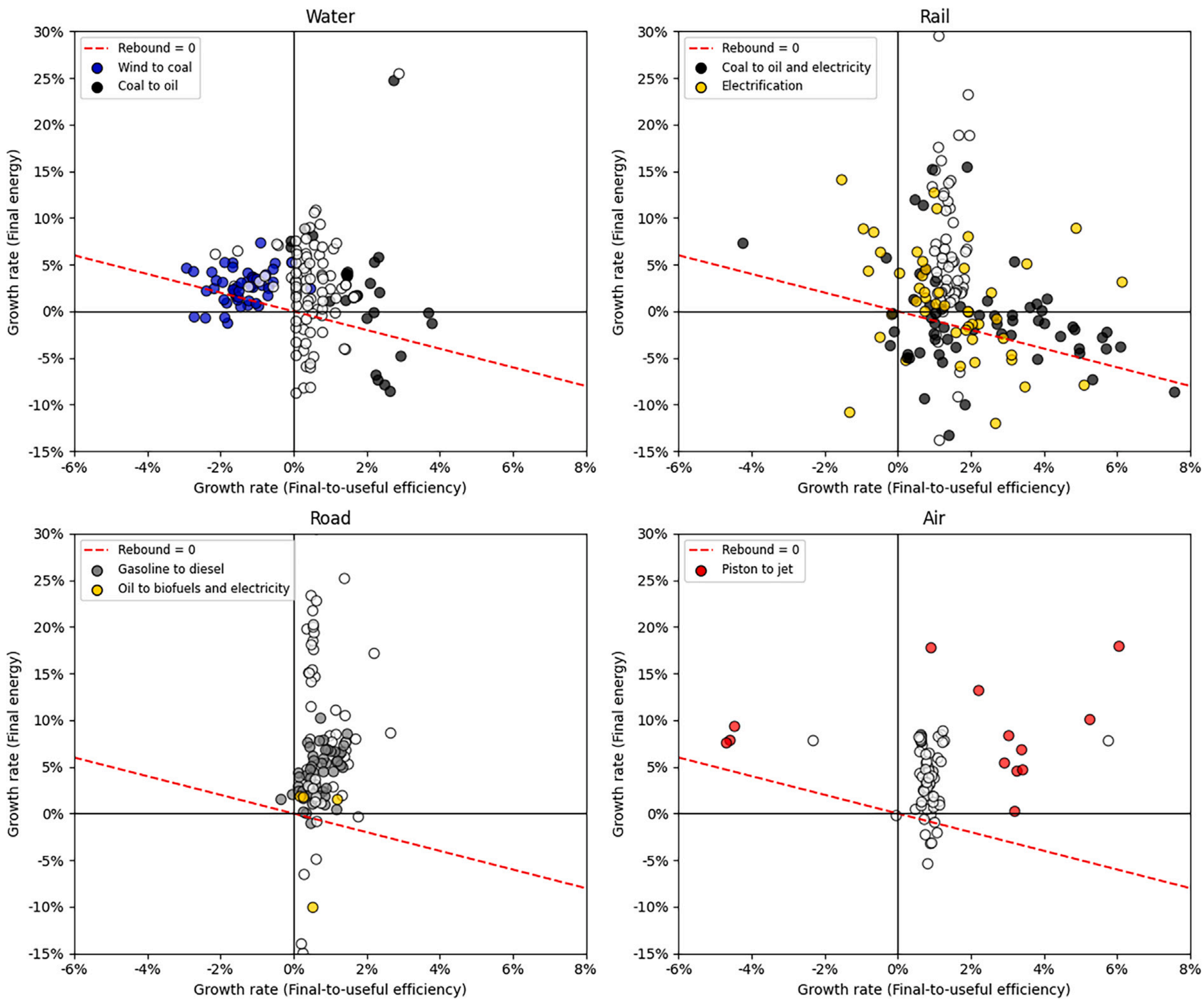

Fig. 11. Potential rebound state map: annual growth rates of final-to-useful efficiency and final energy use of each transport mode during past energy transitions. White circles are years not attributed to any energy transition.

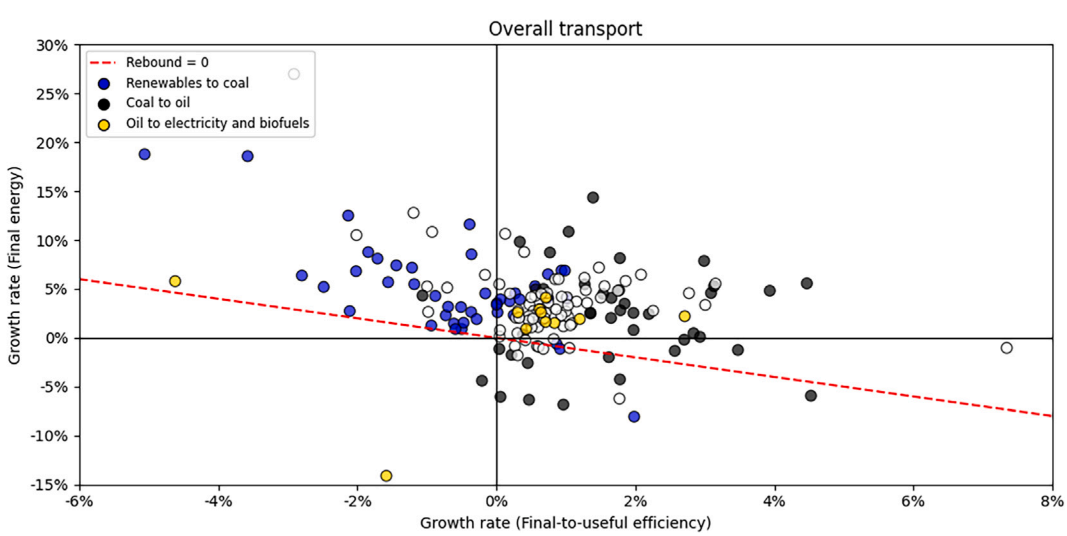

Fig. 12. Potential rebound state map: annual growth rates of final-to-useful efficiency and final energy use of the transport sector during past energy transitions.

these alternative fuels that the transition at the sector scale began. Until 2020, the increase in final-to-useful efficiency observed has not been associated with reductions in final energy demand, which suggests the introduction of electricity and biofuels is backfiring.

We have one point of comparison, with the long-run transport studies of the UK by Fouquet [17,30]. In our analysis, we find global final energy growth is consistent (seen by the approximately straight overall line in Fig. 5), while overall final-to-useful efficiency in Fig. 10 reduces from ∼25 % to 10 % during the 19th century (growth rate of −1 % per year), and a similar but opposite increase in the 20th century efficiency. Thus we find consistent increases in final energy use at around 3.5 %/year since 1800 whether efficiency was increasing or decreasing, which like Fouquet (2008) [17] we suggest indicates many other factors are at play beyond a choice simply to improve efficiency to reduce cost.

3.3. Limitations

The results from this work reveal meaningful insights into the evolution of energy use in transport history, however, they have limitations and present opportunities for improvements in future work. First, we focused on world aggregate data instead of analyzing on a national scale. While national-scale data would enhance the value of the study, creating an opportunity to assess the introduction of specific policies, the methodology relied on aggregate world-level estimates for most transport modes. Estimating energy use at the national level would require a more detailed assessment, which falls outside the scope of this study.

A second limitation consists in the aggregation of passenger and freight transport energy use. This choice did not directly affect the quality of our results, as service data were not used in any estimation method. The present study focused on final and useful energy use, the shift in energy carriers, energy efficiency, and long-term transitions rather than on the transport services provided. While disaggregating energy use by transport service would be a valuable addition, such detail is generally not available in energy statistics—most notably, the IEA [4] reports freight and passenger final energy use in aggregate form. Extending the analysis to the level of transport services could provide additional insights, not only about their historical evolution, but also into how they relate to efficiency trends.

A third limitation is that the present work excludes human and animal-powered transport, which represents an important limitation of this study. Including these forms of transport would certainly enrich the analysis, nevertheless, there are many methodological challenges involved. The diversity of animals used for transport across regions, each potentially serving multiple purposes beyond mobility (e.g., agriculture or leisure), makes it difficult to isolate their energy use for transport alone. Moreover, estimating the share of final energy (in the form of food or feed) dedicated to muscle work introduces a high degree of uncertainty, limiting its inclusion within the current framework. As with many long-run energy transition studies, the exclusion of animal and human-powered transport reflects data limitations but also implies that early phases of the transition may appear more abrupt or complete than they actually were [9].

Fourth, there is also uncertainty in the quantification of final and useful energy, particularly in relation to historical sailing ships. This arises from limited data on key factors such as wind speed, the evolution of sailing ship speeds over time, and the number of hours ships were in operation. These variables significantly influence both the energy input required and the useful energy output, yet historical records rarely capture them. As a result, estimates related to sailing transport involve considerable approximations, which contribute to the overall uncertainty in the energy assessment.

Fifth, the estimation of final-to-useful energy efficiency also presents notable limitations. Data on this aspect are scarce, especially for earlier periods. As a result, some parameters—such as specific loss factors in the efficiency of road vehicles— had to be assumed constant over time. This simplification, while necessary, may not fully reflect historical improvements or variations. Furthermore, national differences in technologies were not accounted for, which could lead to deviations in actual efficiency results.

Finally, an important limitation concerns the estimation of air transport efficiency. While the final-to-useful efficiency of other transport modes was estimated independently from losses in the passive system, this was not possible for air transport. In this case, efficiency is directly dependent on air velocity, which is equal to the aircraft's own velocity. This introduces a methodological inconsistency in how efficiency was determined compared to other modes. Nevertheless, the definition of useful energy remains consistent across all modes, ensuring that the resulting values are still comparable.

4. Discussion

Regarding the identification of past energy transitions, our results show a significant disparity in their duration. While the transition from piston to jet engines was extremely fast ($\Delta t_{final} = \Delta t_{useful} = 14$ years), the electrification of railways has been lasting much longer ($\Delta t_{final} > 60$ years; $\Delta t_{useful} > 112$ years). Apart from these two examples, the fastest and slowest transitions, the remaining transitions in the transport sector have required several decades to accomplish.

These results have significant implications for the future transition. The fastest transition happened at a moment when air transport infrastructure was still developing. Nevertheless, current transport systems have long passed this stage. In developed countries, transportation systems are currently mature, therefore it is not reasonable to expect that the current energy transition could be as fast as the historical example in air transport. However, the transition from piston to jet engines also shows that when transport systems are still developing, especially regarding infrastructure, the speed of transition can be relatively fast. Consequently, if appropriate incentives are provided, developing countries could achieve faster transitions.

Moreover, the only previous example of electrification, in rail transport, is the longest energy transition observed in the past. The prolonged duration of rail transport electrification is due to many countries choosing to replace steam locomotives with diesel ones, which ultimately became an intermediate technology. In the current transition, natural gas is often viewed as an intermediate technology in several sectors; however, historical evidence shows that intermediate technologies could delay electrification for several decades.

On the other hand, the renewable transition in other economic sectors could catalyze the transport sector's transition. If the use of fossil fuels is stopped completely in industry, domestic heating, electricity generation, and transport, so will the demand for transporting fossil fuels. Therefore, the transport energy demand could be reduced, especially in water where in 2022, approximately 31 % of the world's gross tonnage was attributed to oil, gas, and chemical tankers [96].

Increasing energy efficiency is often touted as one of the main strategies for reducing final energy use. However, we find that past improvements in efficiency are typically associated with higher (not lower) energy use, raising concerns about the potential effectiveness of this strategy. In the transport sector, all three transitions identified in Fig. 12 have featured higher energy use, even the transition that was not associated with increasing efficiency. We identified one transition at the mode level (replacement of coal in rail transport) that was associated with a potential state of partial rebound, even with the rising competition of road and air transport in short and long-distance travel, respectively. This transition led mainly to partial rebound, even with the rising competition of road and air transport in short and long-distance travel, respectively.

By increasing the share of electricity in the final energy mix for transport, final-to-useful efficiency is expected to rise, since electric motors are typically more efficient than internal combustion engines (Fig. 9). If the increase in efficiency is not accompanied by additional policies to ensure a reduction in final energy demand, our results suggest that the replacement of oil products could lead to higher than expected energy use, raising key questions about GHG emission mitigation if the transition to renewables succeeds. Even though a 100 % renewable final energy mix would result in no direct CO_2 emissions, higher energy use is still a problem because the transition would be more costly to achieve and it would increase the material demand. The increasing demand for materials could cause geopolitical and environmental problems besides CO_2 emissions (such as water demand, noise, air pollution, and biodiversity loss). According to Pinto et al. [91], achieving full electrification of society by 2050 would require tripling electricity production—a rate of increase that has no historical precedent.

Although a state of potential backfire is the most common case, hyperconservation is occasionally indicated, coinciding mainly with economic recessions. Therefore, the energy savings are associated with a reduction in transport demand, not the transition in energy carriers, rise in final-to-useful efficiency, or environmental concerns. This result challenges the idea of reducing final energy use while maintaining economic growth, as there is no precedent for it in the transport sector.

Energy efficiency played a key role in replacing coal in water and rail transport and in increasing diesel consumption in road transport; however, many transitions have been primarily driven by improvements in energy services. The substitution of sailing ships is a curious example. Sailing ships were more energy efficient and relied on wind power with zero variable cost. Steamships replaced them mainly due to their reliability. Until the advent of the steamship, it was not possible to create timetables or accurately predict the time of travel. Although more expensive and materially demanding, a better and more reliable service opened new trade opportunities. Air transport also experienced a transition not driven by efficiency. Jet engines allowed airplanes to fly higher and faster, reducing the travel time and the need for refueling stops, both of which drove the replacement of piston engines.

These examples in transport history highlight the importance of the quality of services in energy transitions, one of Grubler's main conclusions [23]. By improving the quality of energy services in a transition, the demand side tends to catalyze the adoption of novel technologies. In the current energy transition, exploring opportunities to improve the speed and reliability of transport systems while introducing shared and electric mobility could be an important factor in their adoption.

5. Conclusion

This work explored the evolution of the final and useful energy use of water, rail, road, and air transport during the period 1800–2020. We used these results to identify past energy transitions in the transport sector and gain insights from the extension to the useful stage. Our results suggest that:

- Final energy use in transport (excluding animal and human transport) increased 300-fold from 1850 to 2019, while useful energy rose 460-fold in the same period;
- The transport sector has experienced two transitions: from renewables to coal and from coal to oil products. Another transition is underway from oil to electricity and biofuels;
- Identifying energy transitions between technologies with significantly different final-to-useful efficiencies exclusively in terms of final energy gives incomplete results. Useful energy provides additional insights into transitions;
- Past energy transitions in transport always involved higher final and useful energy consumption, regardless of whether there was an increase or decrease in final-to-useful efficiency;
- The quality of energy services was an important driver of past transitions, which is a blueprint for how to accelerate the adoption of new technologies in the current transitions.

This work reveals important insights from past energy transitions; however, there is an important aspect of transport history that is still to be addressed: CO_2 emissions and the environmental impact of transport technologies. It is well known that carbon emissions from transport have been rising, though quantifying these emissions and their positive and negative drivers is still to be explored. In addition, several factors are evolving in parallel to energy transitions, such as population, transport demand, energy prices, and GDP growth, all of which should be considered when analyzing transitions. Based on this work and the historical evidence gathered on transportation, little evidence was found to suggest that efficiency gains will successfully reduce final energy use in future transitions.

CRediT authorship contribution statement

Bernardo Tostes: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthew Kuperus Heun:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Sofia T. Henriques:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Paul E. Brockway:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Tânia Sousa:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.

Acknowledgments

This work was supported by FCT/MCTES (PIDDAC) through projects LARSyS - FCT Pluriannual funding 2020–2023 UIDB/EEA/50009/2020 and UIDP/EEA/50009/2020. Bernardo Tostes' work was supported by Project LARSyS - FCT Pluriannual funding LA/P/0083/2020 - MARETEC, funded by FCT. The work was also supported by Elsevier through the project "Development and publication of a World Primary-Final-Useful (WPFU) energy & exergy database from 1800 to 2020". Sofia Henriques acknowledges the support of Centro de Economia e Finanças (CEF.UP), financed by Portuguese public funds through FCT - Fundação para a Ciência e Tecnologia, I.P. Paul Brockway's time was funded by the UK Research and Innovation (UKRI) Council, supported under EPSRC Fellowship award EP/R024254/1.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.apenergy.2025.126561.

Appendix B. Auxiliary graphs

See Figs. B.1–B.4.

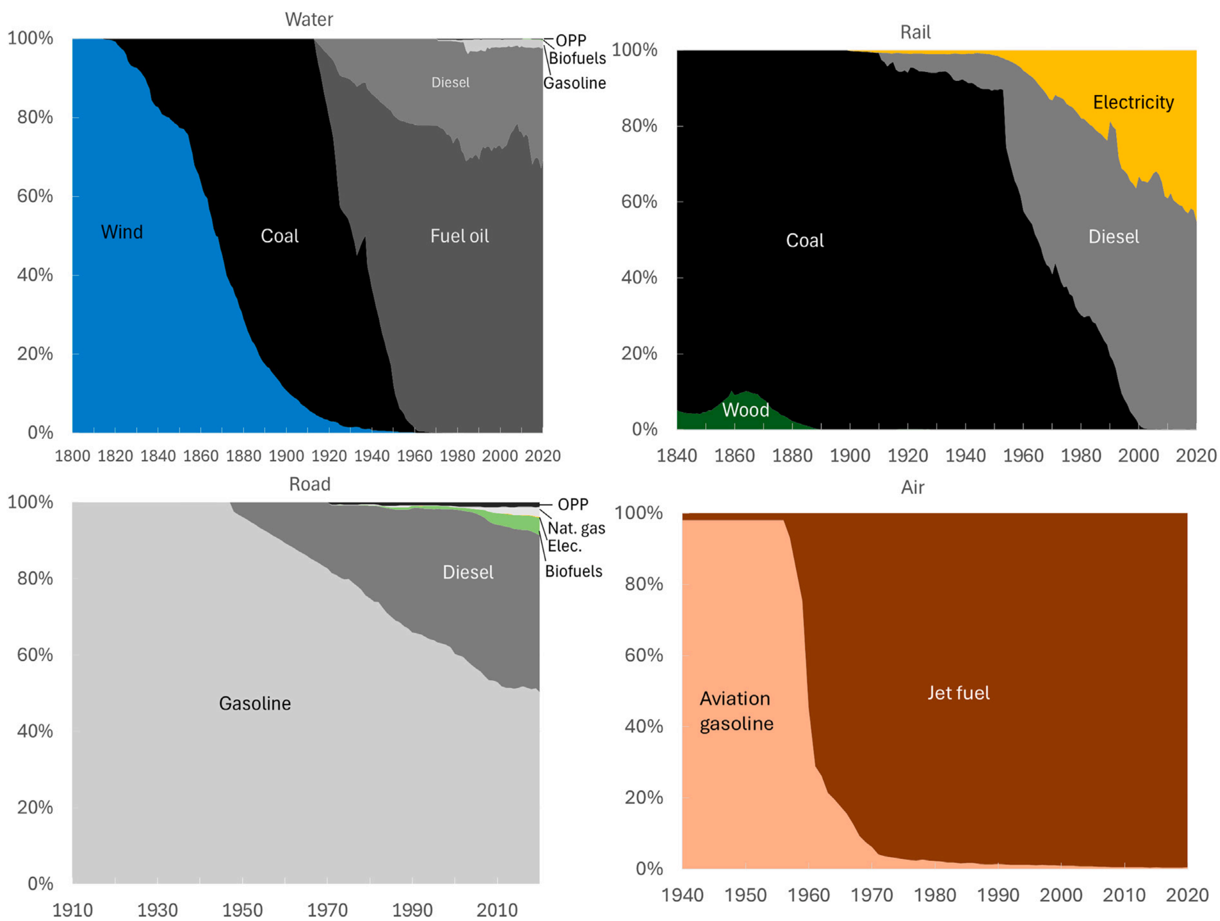

Fig. B.1. Fraction of final energy carriers in world transport by mode.

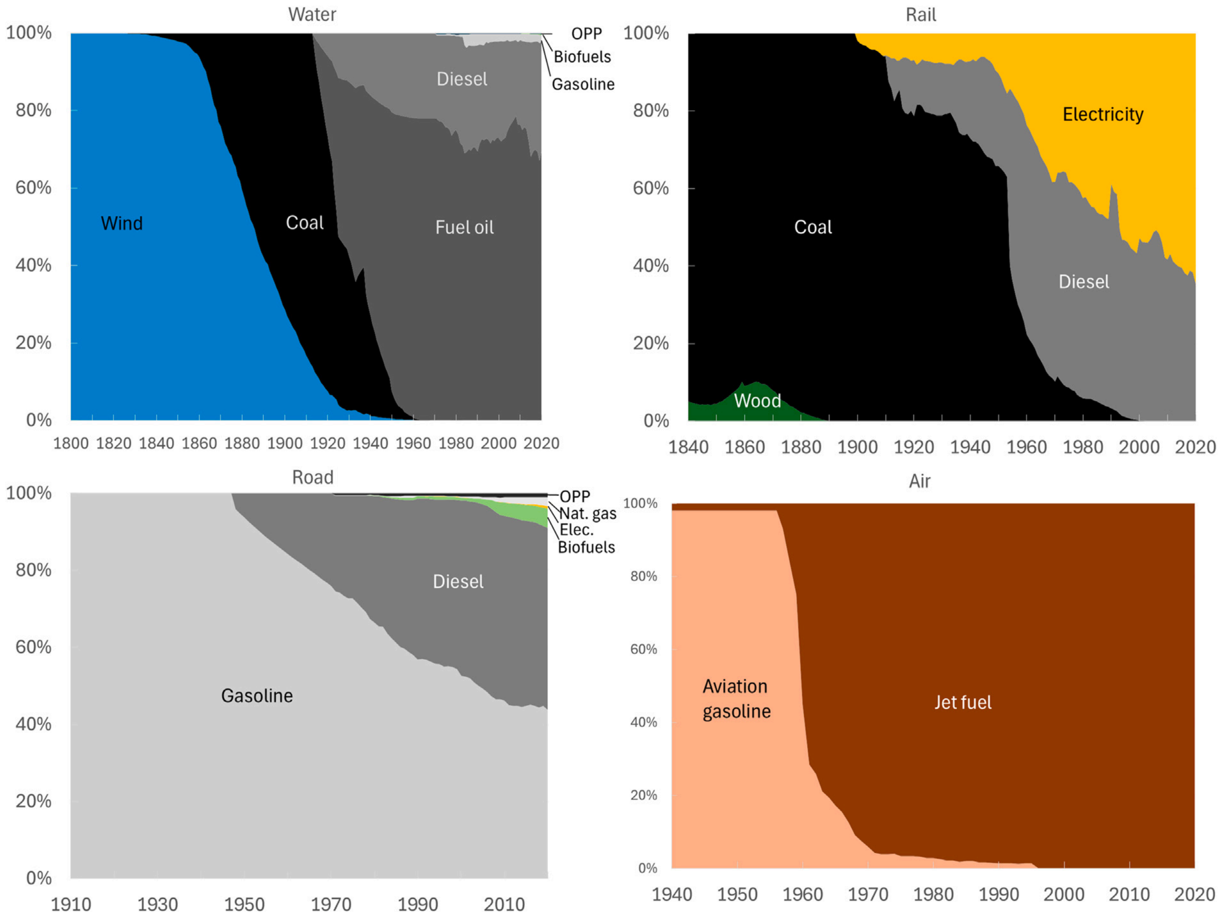

Fig. B.2. Fraction of useful energy output from final energy carriers in world transport by mode.

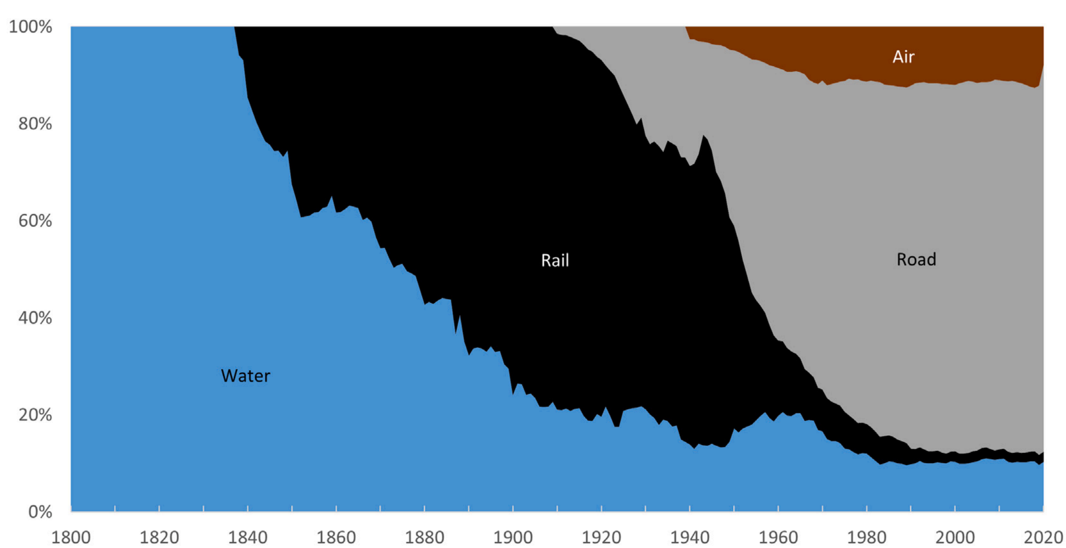

Fig. B.3. Fraction of final energy by transport mode: 1800–2020.

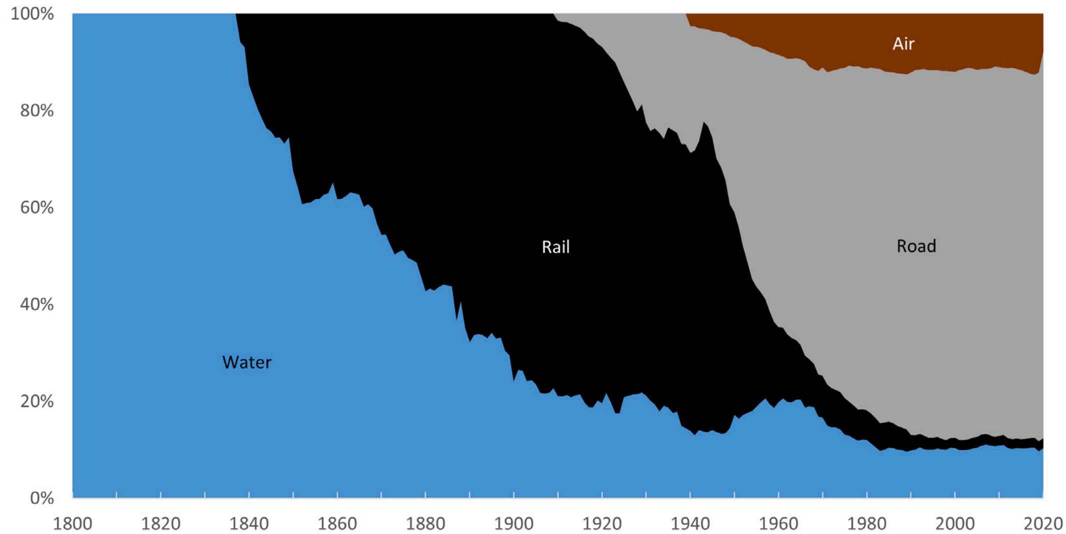

Fig. B.4. Fraction of useful energy by transport mode: 1800–2020.

Data availability

Supplementary Information contains the data used to build the graphs displayed in this paper. More detailed data will be made available upon request.

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