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A framework for the exergy analysis of future transport pathways: Application for the United Kingdom transport system 2010–2050

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ABSTRACT

Exergy analysis has been used to quantify the historical resource use efficiency and environmental impact of transport systems. However, few exergy studies have explored future transport pathways. This study aims to, (a) develop a conceptual framework for the exergy analysis of multiple future transport and electricity pathways, (b) apply this framework to quantify future resource consumption and service delivery patterns, (c) discuss the policy-relevant results that exergy studies of future transport systems can offer. Multiple transport and electricity pathways developed by the UK Government are used to explore changes in energy use, useful work delivery and greenhouse gas emissions. In passenger transport, ambitious electrification results in a 20% increase of useful work delivery, whilst reducing GHG emissions and energy consumption by 65%. For freight, international shipping and aviation, smaller exergy efficiency improvements make useful work delivery and greenhouse gas emissions highly dependent on transport demand. Passenger transport electrification brings a step-change in useful work delivery, which if accompanied by low-carbon electricity, significantly reduces greenhouse gas emissions. The efficiency of low-carbon electricity systems is significant for useful work delivery, but not dominant across the scenarios explored. High penetration of renewables and electrified transport is the most resource-efficient combination in this context.

1. Introduction

In most OECD economies the transport sector is an important end-user of final energy (mainly of liquid hydrocarbons), and at the same time a major source of GHGs (greenhouse gases) and atmospheric pollutants.[1] Interconnected policy realities such as energy security and climate change have made the reduction of resource/energy use and carbon intensity from the transport sector a policy imperative across the OECD [2], including the UK [3]. Under the Climate Change Act of 2008 [4] the UK has committed to reduce by 2050 its GHG emissions by 80% compared to 1990 levels. The transport sector is considered to be key in this effort, as it was responsible in 2013 for 38% of the UK's final energy use [5] and 21% of GHG emissions [6].

Two main dimensions are targeted when aiming to decrease transport-related energy use and GHG emissions: i) the scale of transport demand and activity, and ii) the energy efficiency of the different transport modes. Other factors such as network efficiency, passenger occupancy and congestion can also affect transport-related energy use and emissions, but are essentially endogenous to the two dimensions mentioned above. A third important dimension that must be considered is the resource use efficiency of the electricity production system becomes, particularly for highly electrified transport systems. This is because different electricity systems, even if attaining the same low emissions intensity, will have different resource use efficiencies and subsequent impacts on the environment (Section 2.2.2).

In its 2050 Pathways Analysis [3] and Carbon Plan [7], the UK DECC (Government Department of Energy and Climate Change) set out a range of policy options and pathways to reduce national GHG emissions, to meet the targets of the Climate Change Act 2008 [4].

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With emissions reduction as the primary aim of the Government's policy-analysis exercise, transport efficiency was expressed as the ratio of energy used per vehicle-km, (or per seat-km for trains and aircrafts).

However while this ratio of useful output to energy input reflects the first law of thermodynamics (conservation of energy), it does not reflect potential sectoral improvements both in terms of technical efficiency of the end-use component (e.g. vehicles) and resource use efficiency of the energy sector (e.g. electricity system) [8].

Contrary to first-law efficiency (energy efficiency), the second-law efficiency (exergy efficiency) (ε) relates the actual useful energy outputs against the theoretical minimum inputs in a given thermodynamic system. This ratio reflects both the first and second laws of thermodynamics and it is bounded by $0 \leq \varepsilon \leq 1$, showing the distance of a given system to the theoretical ideal [9] [1]. For this reason, exergy analysis has been considered a powerful analytical tool for quantifying the resource consumption of (and the physical service delivered from) transport systems, as well as their improvement potential [10].

As mentioned above, the service provided by transport systems is conventionally measured as the product of goods/passengers transported by the conveyed distance (i.e. vehicle-km or seat-km), which is not expressed in energy units. However, in exergy analysis the service delivery from a transport system depends on the flow of useful work (or useful exergy) at the end-use stage [11]. Despite the ontological distinction between service delivery and energy use, useful work may therefore be acknowledged as a proxy for the contribution of the energy system to the transport service delivered [12]. In this respect, exergy analysis offers the closest assessment of transport services delivered in energy terms.

Exergy analysis is increasingly used to quantify the resource use efficiency of national economies, with the transport sector usually featuring as a distinct sub-component of the economy in most of these studies. Some of the earliest examples include studies Reistad for the US [13] and Wall for Sweden [14] and Japan [15]. Exergy studies in the context of the UK national economy have identified century-long trends in the transport sector [16]; trends over multiple decades with sectoral disaggregation [17]; and the effect of transport-related resource consumption on the broader sustainability of UK society [18]. Several authors have conducted comparative exergy analyses including. Brockway et al. that revealed divergent trends in the UK and US [19], Serrenho et al. that compared trends in EU-15 countries [11] and Ertesvåg that collected and compared results for multiple countries [20]. The transport sector has also featured as a sub-component of the economy in several extended exergy analyses including those of Italy [21], Norway [22], China [23], and the UK [18].

Exergy analysis has also been used in transport-dedicated studies. China has received particular attention with Ji and Chen studying four key transport sub-sectors [24]; Zhang et al. considering additional modes and sub-sectors using Reistad's approach [25]; and, Dai et al. performing an extended exergy analysis of the transport system [26]. Other transport dedicated exergy studies have been conducted for Greece [27], Jordan [28], Turkey [29] and the UK [30] among several others. Yet to the authors' best knowledge exergy analysis has rarely, if ever, been used outside academia to convey the impact of transport systems on resource consumption and the environment to policy-makers. Furthermore, whilst most transport exergy studies investigate the historical evolution of the sector's impacts, only a few studies have investigated the potential impact of future transport systems. The works of Motasemi et al. for Canada [31] and Zarifi et al. for Iran [32] use recent trends to forecast to 2035, However there seems to be a critical lack of exergy studies that consider the effects of different low-carbon electricity production systems, on resource use and GHG emissions of future transport pathways.

More importantly, as demonstrated above, the contribution of energy use in a given transport service depends only on the useful work delivered rather than on the primary or final energy use itself. However only the latter is used in most conventional future transport studies conducted by national policy bodies such as DECC in the UK [3]. Furthermore, given the ambition to decarbonize the transport sector through electrification, it is important to consider the exergy efficiency of both the electricity generation and the actual modes of transport, especially when investigating the potential of future electrified and hybrid transport systems [13].

In the authors' view omitting robust exergy thinking from the analysis of future transport pathways is a missed opportunity for identifying possible resource-use efficiency gains (or losses) and emissions reductions from the transport sector. Considering the above, the aim of this study is to:

(a) Develop a conceptual framework for the exergy analysis of future transport pathways that takes into account different possible electricity generation pathways;
(b) Apply this framework to the UK transport and electricity generation sectors (2010–2050)
(c) Demonstrate the relevance of exergy analysis in current sustainability discourses in the transport sector by identifying and discussing policy-relevant results.

The paper starts by developing a conceptual framework for operationalizing exergy analysis for the study of multiple future transport pathways (Section 2). A key consideration throughout the development of this framework has been its compatibility with conventional studies of future transport and electricity generation systems. Subsequently an exergy analysis of four future transport scenarios, that build on DECC's 2050 Pathways for energy and transport [3,7,33–35] is conducted (Section 3). These scenarios were deliberately chosen to demonstrate how the proposed exergy analysis framework can be linked to (and complement) conventional transport studies, essentially offering additional layers of policy-relevant information. For each scenario, the energy consumption and useful work delivery of the transport sector to 2050 is compared, disaggregated by transport mode and energy vector (Section 3.1). The sensitivity of useful work and GHG emissions on five alternative electricity generation pathways is then discussed (Sections 3.2–3.3). Section 4 brings together the policy-relevant insights of this exercise, using them to scrutinise future policy options for both the transport and the electricity generation systems.

2. Methodology

2.1. Conceptual framework

The exergy analysis of a future transport system needs to combine assumptions about the transport system itself, as well as of the future primary and secondary energy system. In the present study projections of future transport use (and its resulting energy demand) (Section 2.3.1) are matched to alternative future energy pathways (Section 2.3.2). Assumptions about future exergy

[1] The exergy of a system or a resource is defined as the “maximum amount of useful work that can be obtained from this system or resource when it is brought to equilibrium with the surroundings through reversible processes in which the system is allowed to interact only with the environment” [9].

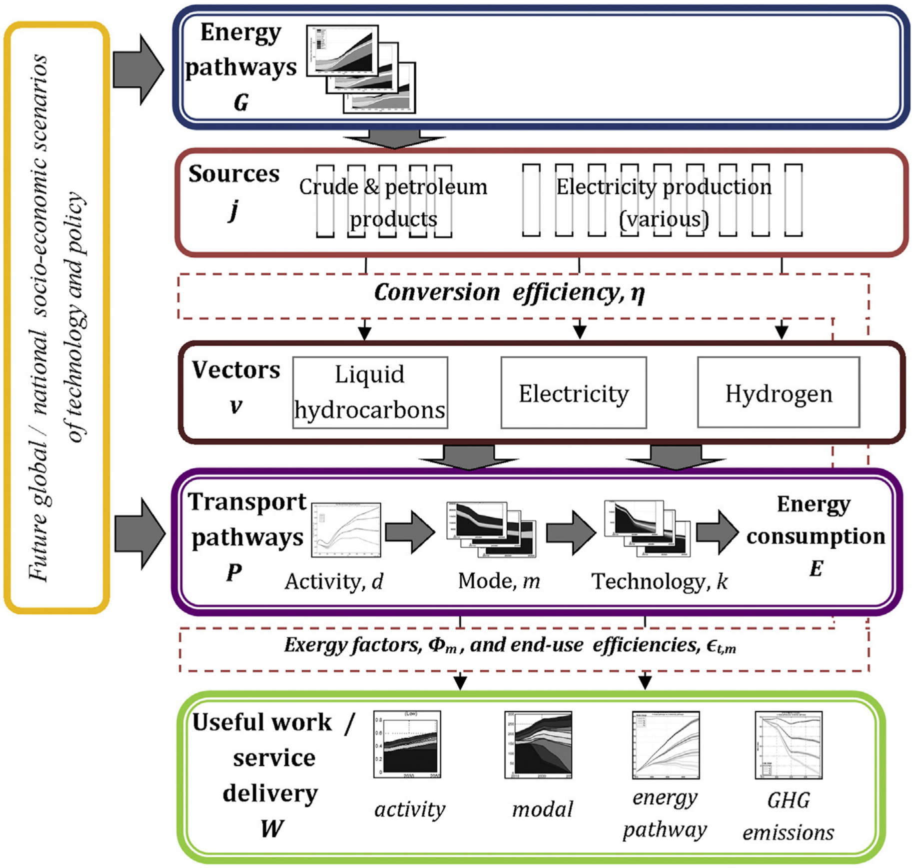

Fig. 1. Conceptual framework for the exergy analysis of future transport systems.

efficiencies are then used to calculate the useful work delivered by the sector (Section 2.2).

Fig. 1 summarizes the proposed conceptual framework for the exergy analysis of future transport systems. Future economy-wide energy pathways (G) are disaggregated to primary energy sources (j) and their projected consumption. The transformation of primary energy (j) into energy vectors (otherwise known as energy carriers) (v) is governed by the conversion efficiency (η) of these energy transformation processes. Different future transport pathways (P) are responsible for the variable consumption of energy vectors (v), depending on the transport activity levels (d), the modal split (m) and the conversion technology (k) of each of these transport modes.

Formally, future energy pathways are defined by an $n_t \times n_j \times n_v$ matrix G whose elements $g_{t,j,v}$: $t = 1, \ldots n_t$, $v = 1, \ldots n_v$, $j = 1, \ldots n_j$, denote the amount of an energy vector v that is produced by an energy source j in year t. Transport pathways are similarly defined by an $n_t \times n_m \times n_v$ matrix P, whose elements $p_{t,m,v}$: $t, m = 1, \ldots n_m, v$, denote the amount of an energy vector v used by transport mode m, in year t. The $n_t \times n_r$ matrix η (with elements $\eta_{t,j}$: t, j) defines the conversion efficiency at which a primary fuel source j is converted to an energy vector v, e.g. coal to electricity or crude oil to gasoline, as well as (where appropriate) transmission and distribution losses. The mean efficiency η_{n_j} of energy production weighted by volume across all sources for each energy vector is calculated as:

$$\eta_{n_j} = \sum_{j=1}^{n_j} \frac{g_{t,j,v}\eta_{t,j}}{\sum_{j=1}^{n_j} g_{t,j,v}} \tag{1}$$

The useful work (exergy), is defined as an $n_t \times n_m \times n_v$ matrix W, calculated as the element-wise product of final energy use $E_{t,m,v}$, exergy factor[2] $\Phi_{m,v}$, and end-use exergy efficiency $\varepsilon_{t,m,v}$. The sum of W for all transport modes over each energy vector gives the annual useful work:

$$\sum_v W_{t,m,v} = \sum_v E_{t,m,v}\phi_{m,v}\varepsilon_{t,m,v} \ . \tag{2}$$

2.2. Calculation of future useful work for each transport mode

Regarding the first two variables in Eq. 2, for each scenario the present study uses the energy consumption (E) projected by DECC [3] (Section 2.3.1) and the exergy factors (ϕ_m) found elsewhere in the literature [36,37] (Section 2.3.1).

Regarding the third variable in Eq. 2, the DECC model estimates future energy consumption based on assumptions of technological efficiency in terms of fuel efficiency. This type of technological efficiency is not directly linked to exergy efficiency (ε) as discussed in Section 1 and in Serrenho et al. (2013) [38]. While fuel efficiency depends on exergy efficiency and other vehicle factors such as aerodynamics, it is assumed in the present study that all these other factors, besides exergy efficiency remain constant for all transport modes using liquid hydrocarbons or hydrogen as energy vectors. Hence the relationship between vehicles' fuel efficiency and exergy efficiency becomes:

$$\varepsilon_{t,m} = \varepsilon_{t-1,m}(1 + \Delta\%F_{t,m}), \tag{3}$$

[2] An exergy factor is commonly defined as the ratio of exergy to energy. Usually, this is calculated as the ratio of exergy to the lower heating value of the energy vector.

where $F_{t,m}$ is the fuel efficiency of transport mode m in year t from the DECC projections and depends on initial efficiencies for 2010. The initial efficiencies and the evolution of future efficiencies for vehicles using liquid hydrocarbons is included in the supplementary material (Table SI6).

For Fuel Cell Vehicles (FCVs) the second-law efficiency is calculated following [39],:

$$\varepsilon \approx \eta_{theoretical\ maximum} \prod_{i=1}^{4} \alpha_i \tag{4}$$

where $0 \le \alpha_i \le 1,\ \forall\ i$ are coefficients that denote the bias from real to ideal use settings [38] for fuel cell/friction/accessories/transmission losses (Table SI7 in supplementary material) and $\eta_{theoretical\ maximum} = 83\%$ [40]. Furthermore, an exergy efficiency factor of 62% was used for hydrogen production from electricity assuming steam-methane reforming/advanced-technology electrolysis [41].

Historical technology efficiencies usually follow an S-shaped curve [42]. The efficiency of electric motors in plug-in hybrid electric vehicles and buses, electric and diesel-electric trains and fuel-cell vehicles has not improved significantly over the past decades, exhibiting high values of around 80%–90% [43]. It is assumed that the future efficiency of electric motors will stabilize around a high value of 95%. The following function is then derived by adjusting an exponential function that fulfills these above conditions and exhibits faster efficiency improvements, when fuel efficiency values are assumed by the DECC model to increase faster:

$$\varepsilon_{t,EV} = \varepsilon_{2010,EV} + \frac{0.95 - \varepsilon_{2010,EV}}{\left[1 + ke^{-0,2(t-2035)}\right]^{\frac{1}{k}}}\ , \tag{5}$$

where $k = 2.54 \times 10^{-12}$ and $\varepsilon_{t,EV}$ stands for the exergy efficiency of electric motors in the year t.

Diesel-electric trains combine both an electric generator and an electric motor that provides mechanical drive. Aggregate exergy efficiency combines the electric motor's efficiency obtained through Eq. (5) above and the average efficiency of electricity generation from the diesel motor:

$$\varepsilon_t = \varepsilon_g \varepsilon_{t,EV}, \tag{6}$$

where $\varepsilon_g = 39.9\%$, [44] and $\varepsilon_{t,EV}$ is the electric engine efficiency as calculated through Eq. (5).

2.3. Transport and energy pathways

2.3.1. Transport pathways

Four transport scenarios are derived to 2050 used in this study from DECC [3,33–35]. The classification used in the DECC Pathways model [35] is adopted, grouping the transport system into two sub-sectors: passenger transport and freight/international transport. Passenger transport (PT) includes all domestic transport by the public, including domestic aviation. FI (Freight/international transport) includes all freight transport within the UK, international shipping, and international aviation.

For each sub-sector, four trajectories represent different 'ambition' levels of change to 2050. PT consists of separate trajectories for both demand and technological change, whilst FI trajectories combine the two. "Level 1" equates to minimal policy interventions, whilst "Level 4" is extremely ambitious, relying on strong policy and technological breakthroughs. Ambition levels were developed by DECC in a highly consultative manner through workshops and expert elicitation.

For PT, the four ambition levels represent upper and lower boundaries of per capita passenger transport demand at a 2.5% annual GDP (gross domestic product) growth rate. While the levels of passenger demand can strongly influence the overall energy demand, changes in per capita passenger demand suggested by DECC are narrow, increasing from 14,079 passenger-kms per year (in 2010) to 14,076–15,363 passenger-kms per year (in 2050) [34]. For FI, only one set of trajectories is available. This is due to the apparent decoupling of freight and economic growth [3] as observed between 1997 and 2007 when freight volume increased by 11% whilst the GDP (gross domestic product) increased by 32% [45].

To reduce the number of potential PT (passenger transport) pathways (from 16 to 4), the levels of ambition across PT and FI (Table 1) are matched. This eliminates very unlikely (e.g. "level 4" in PT and "level 1" in FI, or vice versa) or very similar combinations (e.g. "level 2" in PT and "level 3" in FI). Such combinations are considered unlikely because the technological improvements achieved in one transport sub-sector (e.g. road personal transport), would most likely benefit, or be transferred, to other similar transport sub-sectors (e.g. freight road transport). Table 1 summarizes the narratives for the four transport scenarios considered in this study as derived from the DECC 2050 Pathways Excel model [35] and the Pathways Analysis 2010 main document [3].

Table 1
Transport scenarios of the UK transport system in 2050. Source [3,35].

Scenario	Sub-sector	Scenario description
T1	Passenger Transport	Conventional fossil fuelled cars and vans cover 80% of mileage
	Freight	Road haulage constitutes 73% of mileage, using conventional fossil fuel engines. Rail is entirely diesel
	International aviation	Annual improvement in plane fuel efficiency of 0.8%. Committee on Climate Change "likely" scenario
	International shipping	Follows International Maritime Organisation (IMO) global shipping forecast. GHG emissions are 3 times higher than present levels
T2	Passenger Transport	Road modal share is reduced by 50%. Greater hybridisation
	Freight	Some modal shift from road to rail and water, with more efficient engines. Rail is entirely electric
	International aviation	1% annual improvement in plane fuel efficiency. CCC "optimistic" scenario
	International shipping	Follows IMO global shipping forecast. GHG emissions are 3 times higher than present levels
T3	Passenger Transport	Plug-in, electric and fuel cell cars/vans constitutes 80% of passenger mileage
	Freight	Greater modal shift to rail and water. More efficient Heavy Goods Vehicles (HGVs). More efficient logistics
	International aviation	Same as T2
	International shipping	Fuel use increases to 101 TWh (from 42 TWh in 2007)
T4	Passenger Transport	All car and van travel is electrified. 20% use of fuel-cell range extenders
	Freight	Road modal share falls to half. Greater hybridisation. Rail freight is entirely electric
	International aviation	1.5% annual improvement in plane fuel efficiency. CCC "speculative" scenario
	International shipping	Fuel use increases to 91 TWh (from 42 TWh in 2007)

2.3.2. Energy pathways

Scenarios T3–T4 entail high penetration of electrified transport (Table 1). However, different decarbonized electricity systems in the UK can have different efficiencies and environmental impacts [46], even if GHG emissions are similar. Hence the exergy efficiency of the electricity generation system becomes important when considering useful work delivery through the entire transport system.

In this study, the four energy pathways presented by the UK Government in The Carbon Plan [7] are adopted, due to their explicit policy relevance, the range of future technologies explored and the ease of their implementation from the DECC Pathways model. As detailed in The Carbon Plan [7] these include UKM-326 a cost-optimized pathway, and CP1-REN, CP2-NUC and CP3-CCS that explore pathways with higher penetration of: renewables; nuclear power; and coal and gas with CCS (carbon capture and storage) technology, respectively (Table 2).

Taking the electricity generation from each pathway (including conversion and distribution losses) Eq. (1) calculates the mean exergy efficiency of grid electricity production weighted by generation type between 2010 and 2050. Pathways with high levels of renewables (particularly wind) and combined cycle gas turbines exhibit the highest efficiencies (CP1-REN, CP3-CCS), whilst the generally low efficiency of nuclear power (33%) and coal with CCS keeps efficiency lower (UKM-326, CP2-NUC) (Fig. 2). The higher penetration of renewables in the 2020s and 2030s helps increase the mean exergy efficiency. From the 2040s the expected exergy efficiency is reduced due to increasing levels of either nuclear or coal-CCS and gas-CCS, combined with decommission of some renewables (Table 2, Fig. 2). Electricity system-level transmission [47] and distribution [48] losses are proportionally fixed at 6%, whilst some conversion efficiencies change with time (coal, biomass and CCS generation) and are detailed in the supplementary information (Table SI3) and the DECC 2050 Pathways Excel model [35]. For the calculations in Section 3.1 the mean efficiency of electricity production is used.

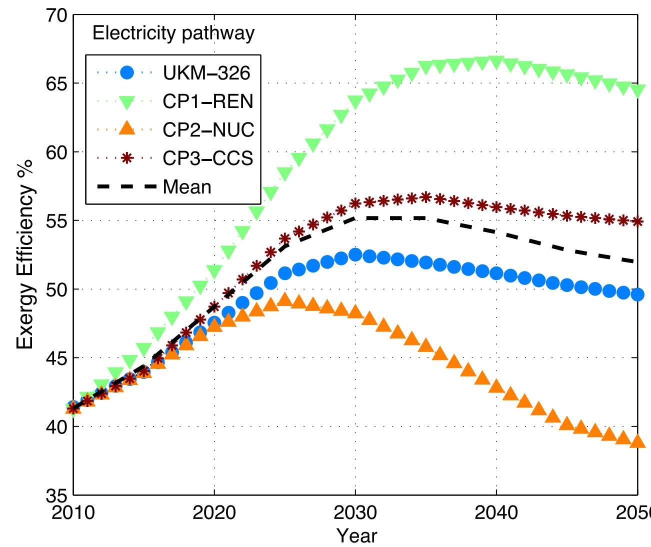

Fig. 2. Weighted exergy efficiency and mean exergy efficiency of electricity production for the four electricity generation pathways.

3. Results

3.1. Energy, exergy and useful work trends

Figs. 3–5 present the energy consumption and useful work delivery for the different scenarios between 2010 and 2050. Fig. 3 provides a comprehensive visualization by fuel and mode of transport, while Figs. 4–5 offer more aggregated visualizations by transport mode (Fig. 4) and by energy vector (Fig. 5).

For PT, overall energy demand decreases for all scenarios, from 1414 PJ/year (2010) to 817–495 PJ/year (2050) (Figs. 3a–5a). This corresponds to a 42–65% decrease in energy demand with the largest decrease observed in scenario T4. This consistent reduction

Table 2
Electricity generation pathways for 2050.

Energy pathway	Description	2050 electricity supply	TWh
UKM-326	Cost-optimized version of the UK MARKAL Elastic Demand model v3.26, that results in significant electricity demand reductions. It entails a balanced electricity mix of nuclear, renewables and CCS.	Unabated thermal	10
		CCS	162
		Nuclear	220
		Wind and solar	87
		Other renewables	58
		Other	24
		Total	560
CP1-REN	High level of renewable energy generation. It relies on significant behavioral change, energy efficiency increase and advances in energy storage	Unabated thermal	0
		CCS	87
		Nuclear	110
		Wind and solar	300
		Other renewables	28
		Other	0
		Total	525
CP2-NUC	Very high levels of nuclear power generation. It assumes no significant CCS deployment and less ambitious electricity demand reductions	Unabated thermal	0
		CCS	11
		Nuclear	525
		Wind and solar	68
		Other renewables	5
		Other	0
		Total	610
CP3-CCS	Balanced mix of renewables, nuclear and CCS generation. Higher levels of bioenergy use for heating and electricity production	Unabated thermal	36
		CCS	265
		Nuclear	137
		Wind and solar	97
		Other renewables	5
		Other	15
		Total	556

Source: Adapted from Ref. [7].

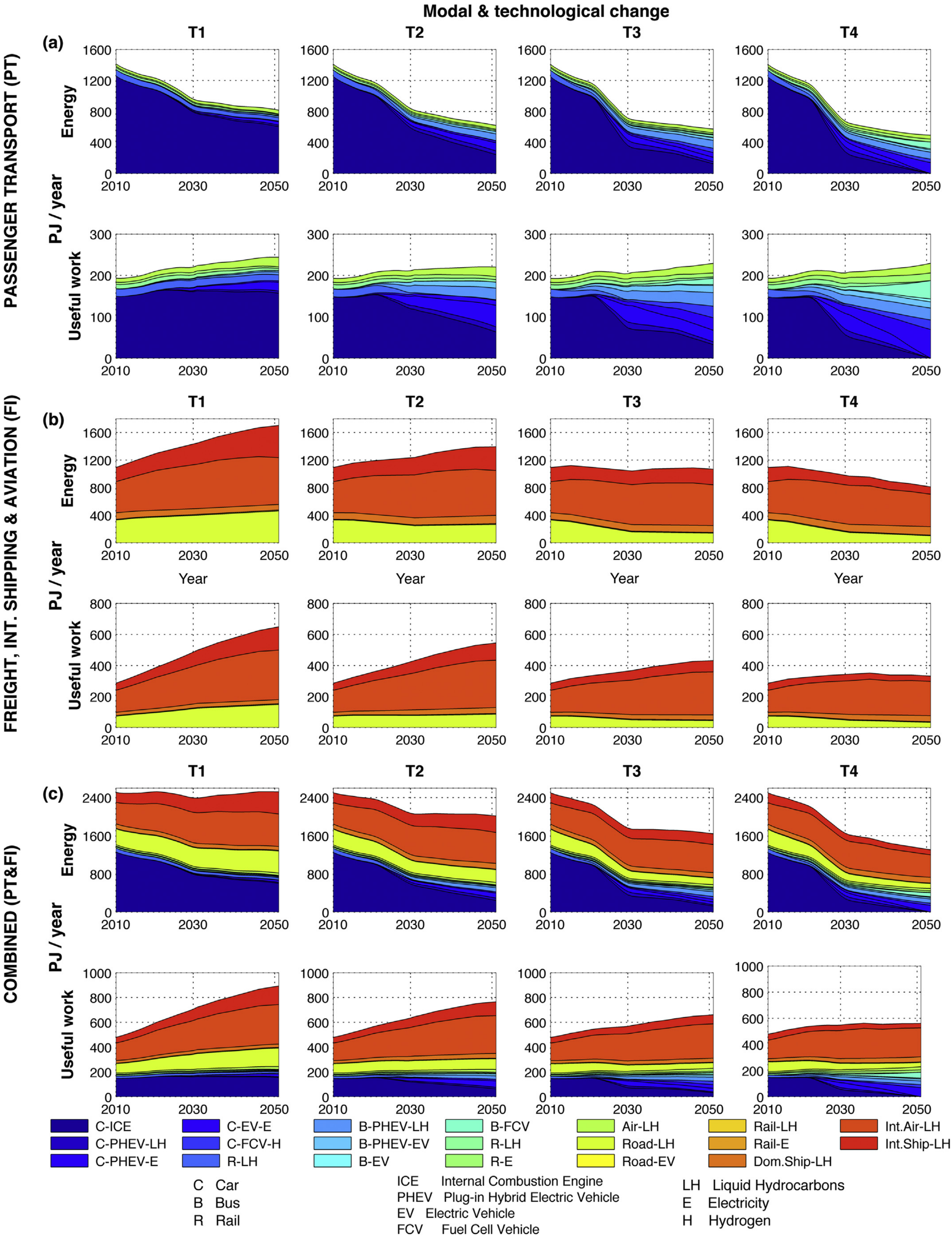

Fig. 3. Projections of future energy consumption and useful work delivery (in PJ/year) between 2010 and 2050, by fuel and mode for Passenger Transport (a), Freight and International shipping and aviation (b) and PT-FI combined (c).

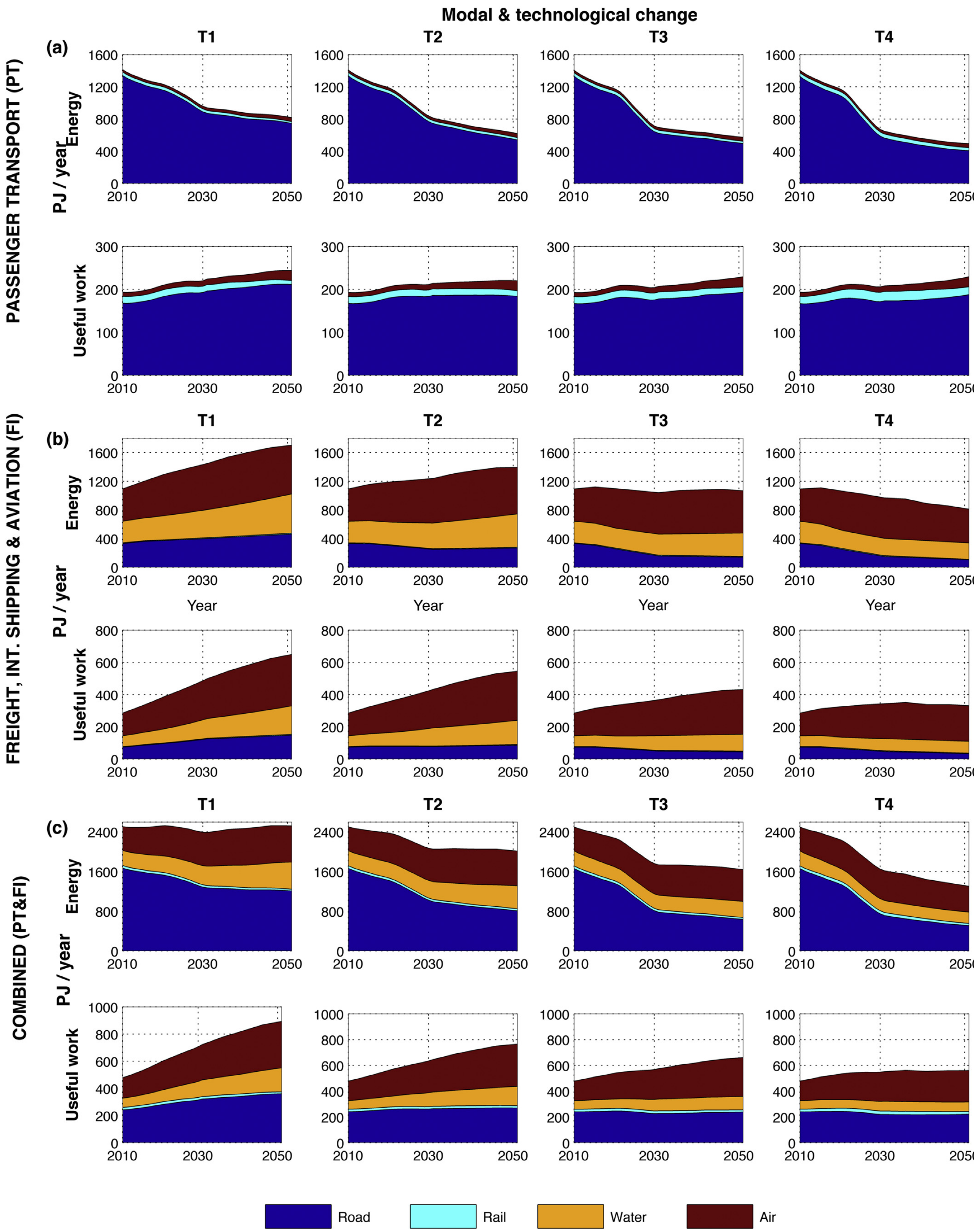

Fig. 4. Projections of future energy consumption and useful work delivery (in PJ/year) between 2010 and 2050 aggregated by road, rail, water and air transport.

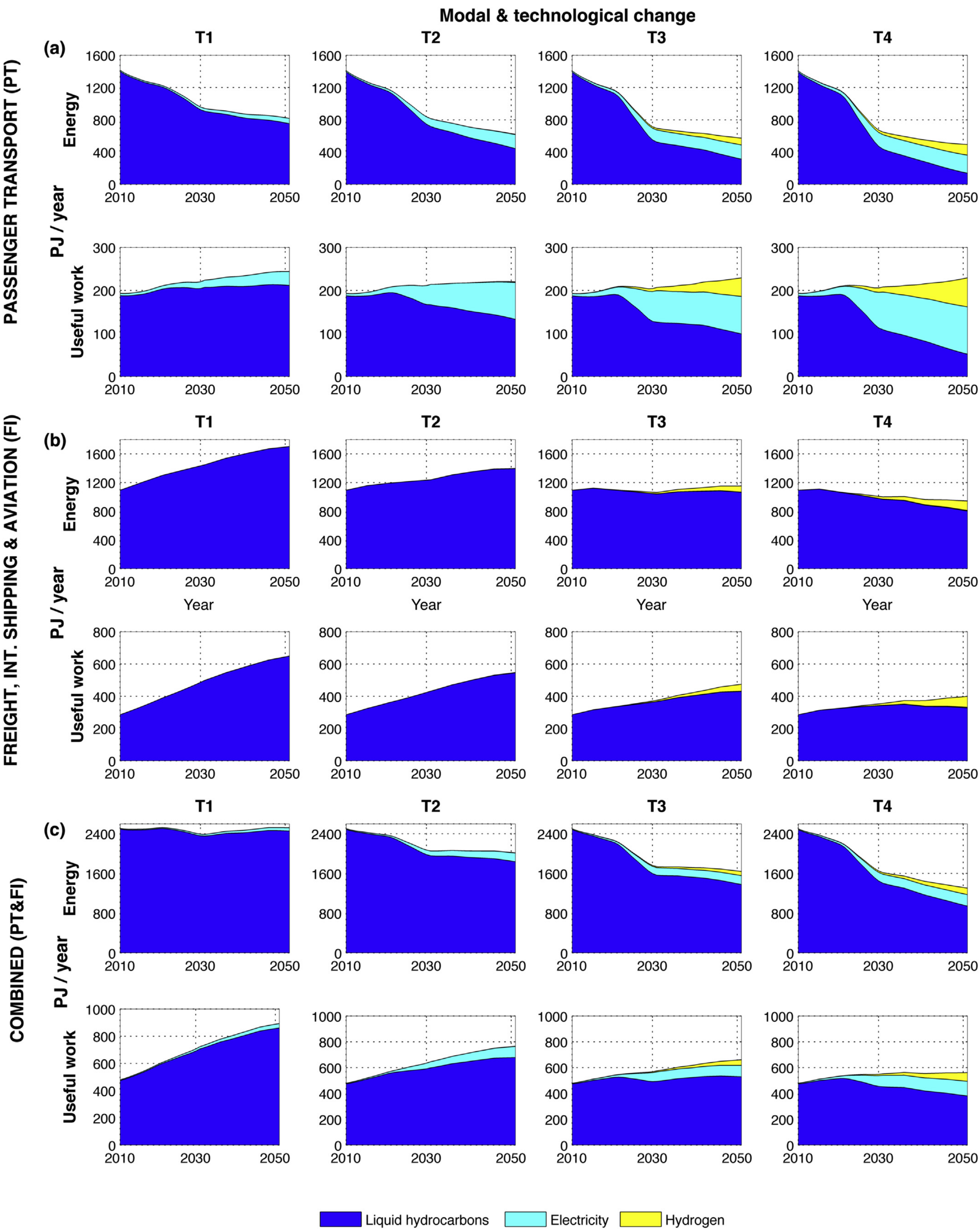

Fig. 5. Projections of future energy consumption and useful work delivery (in PJ/year) between 2010 and 2050 aggregated by energy vector.

across all four scenarios is almost entirely due to reductions in the use of liquid hydrocarbons in cars in favour of EVs (electric vehicles) and FCVs (fuel cell vehicles). The progressive technological change in scenarios T2–T4 results in an increasing energy consumption from other modes, e.g. 72% of total energy use in T4 in 2050 coming from EVs and FCVs.

At the same time, the delivery of useful work increases by 19–26% in all four scenarios by 2050, with 75% of the useful work delivered in T4 coming from EVs and FCVs. Similarly a high penetration of FCV buses and electrified rail is evident.

The results overall suggest that higher rates of technological and modal change away from liquid hydrocarbons exhibit the highest reductions of energy consumption, with only marginally lower increases in useful work delivery by 19% (T4), compared to a 26% increase in service delivery (T1).

Figs. 3b–5b show that depending on the scenario, energy demand from FI increases by 52% (T1) and 25% (T2), remains constant (T3) or decreases by 26% (T4). International aviation represents the largest share of this demand and practically dominates it in scenarios T3–T4. In T1, the growing demand for (and steadily improving efficiencies of) international shipping and aviation contribute greatly towards the 125% increase of useful work delivery for a 52% increase in energy consumption. By comparison in T4, a 25% reduction in energy consumption is accompanied by a 16% increase in useful work. Clearly, when future transport pathways are predominantly governed by demand and not technological change, it is only possible to increase the delivery of useful work by increasing energy consumption. The two significant technological changes in FI, i.e. electrified road (Road-EV) and rail (Rail-E) haulage, have limited penetration (~1%). This translates into negligible effects on energy consumption and useful work delivery, which are barely visible in Fig. 3b.

Figs. 3c–5c aggregate the heavy technological change in PT with the demand-driven growth of FI. Useful work delivery increases in all four scenarios between 2010 and 2050. However this increase is more prolonged for T1–T2 (87% and 60% respectively), and less significant for T3–T4 (38% and 18% respectively). The results highlight very different futures and a stark comparison: constant energy demand for ~75% gains in useful work (T1–T2) versus a halving energy demand for moderate (~30%) increase in useful work delivery (T3–T4).

It should also be noted that the growing contribution of hydrogen to PT only becomes meaningful in T3–T4 after 2035 (Fig. 5). Yet by 2050 hydrogen is expected to contribute 19–29% of total useful work delivered via fuel cells in personal cars and buses.

Fig. 6 plots the exergy efficiency of the entire transport sector and its sub-components. The results reiterate the general trends observed in Figs. 3–5, with exergy efficiency of PT increasing significantly, from 16% (in 2010) to 33–50% (in 2050) depending on the scenario (Fig. 6a). The greatest efficiency improvements occur for scenarios T2–T4 between the early 2020s and 2030s due to increasingly electrified PT. Exergy efficiency increases steadily after the 2030s for all four scenarios. The switch to hydrogen FCVs, with conversion efficiency estimated at 62% [42] marginally improves the exergy efficiency of PT when it displaces less efficient liquid hydrocarbons. However the effect is negative if FCVs were to replace electric vehicles given the high efficiency of electric motors. FI experiences more modest increases in exergy efficiency; from a higher 25% in 2010 to 37–40% in 2050 (Fig. 6b). This low exergy efficiency gain reflects the combined effect of liquid hydrocarbon dominance and the low (and late) penetration of viable alternatives such as electrified rail and road freight. As a result, overall exergy efficiency gains are a moderate compromise, with the exergy efficiency of the entire transport system increasing to 36–44% in 2050, from 23% in 2010 (Fig. 6c). This is a substantial change, considering that historical UK sector-wide exergy efficiency improved by less than a percentage point between 1970 and 2006 [30].

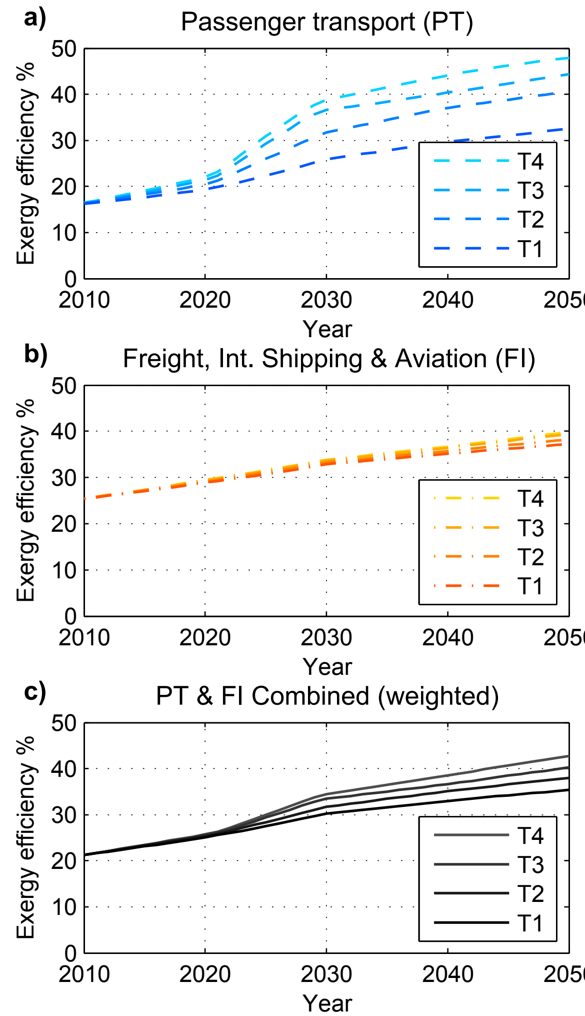

Fig. 6. Weighted exergy efficiency for Passenger Transport (a); Freight and International shipping and aviation (b); and the entire transport sector (c), for scenarios T1–T4.

3.2. *Sensitivity of useful work delivery to the electricity generation system*

As discussed in Section 2, the useful work delivered through different transport pathways can depend significantly on the characteristics of the future electricity generation system. This effect becomes significant for transport pathways that entail high penetration of electrified transport modes.

Fig. 7 visualizes the effects of the five different electricity generation pathways (Section 2.3.2) on the four transport scenarios (T1–T4). It shows the sensitivity of useful work delivery to changes in the exergy efficiency of electricity generation, which is expected to diverge from 42% (in 2010) to a range between 39% (CP2-NUC) and 65% (CP1-REN) in 2050 (Section 2.3.2, Fig. 2).

Scenarios with higher penetration of electric vehicles (T2–T4) show higher sensitivity to the different electricity pathways, whilst scenarios dominated by liquid hydrocarbons (T1) show lower sensitivity. The effect for the entire transport sector in 2050 between the least (CP2-NUC) and most efficient (CP1-REN) electricity pathway, is a difference of 17 PJ/year (for T1) compared to 59 PJ/year (for T4).

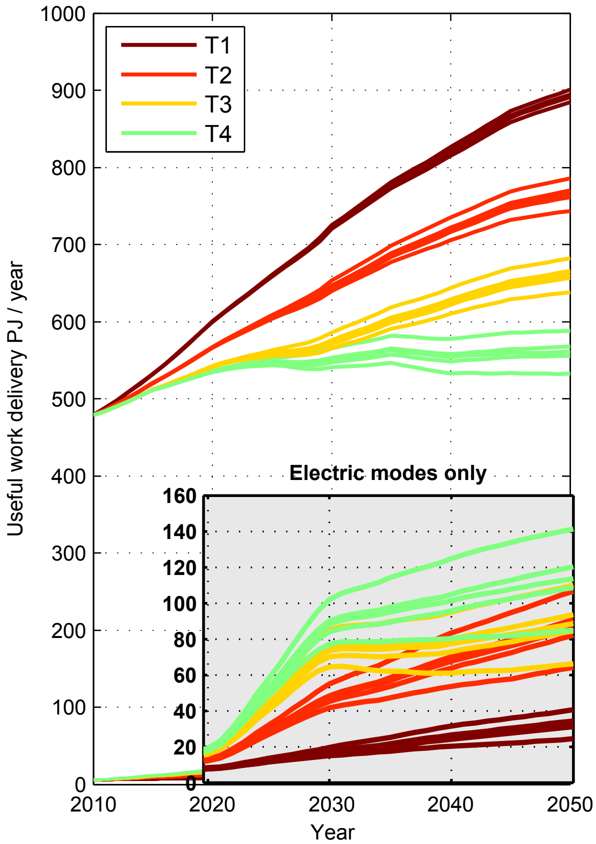

Fig. 7. Effects of the five electricity pathways on useful work delivery for the four transport scenarios. The upper plot displays effects on the total useful work delivery. The magnified inset plot displays the variation of useful work delivery for electric modes only.

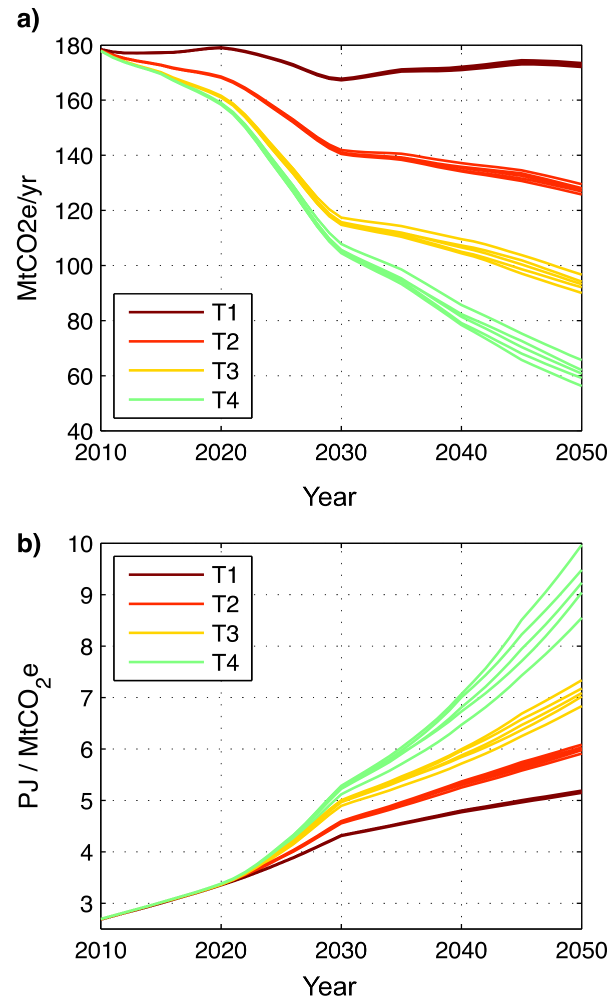

Fig. 8. GHG emissions (in $MtCO_2e$) (a) and useful work delivery per unit GHG emitted (in $PJ/MtCO_2e$) (b) between 2010 and 2050 for each of the five electricity pathways.

The inset in Fig. 7 gives a different insight by comparing the sensitivity effect for electric transport modes only. For T2–T4, the overlapping values in 2050 indicate that in terms of useful work delivery from electrified transport, grid efficiency is almost as important as the technological change of the transport scenarios themselves. In 2050, the three central electricity pathways for T2 perform as well as the worst performing electricity generation pathway (CP2-NUC) in T4. In T4, useful work delivery in 2050 from CP1-REN is 70% higher than CP2-NUC due to the higher electricity grid efficiency. Considering the whole system, the step change of electrification brought by the technological change in T2 or T3 brings the most immediate efficiency gains. Beyond this however, seeking improvements in grid efficiency delivers more useful work than obtaining improvements in the already high efficiency (~85–90%) of electrified transport. In fact increased grid efficiency would not only have benefits for the transport sector but the economy as a whole.

Note: The inverse relationship between total useful work and the amount of useful work obtained from electric modes. Upper strands of the same color correspond to more efficient electricity generation pathways, such as CP1-REN and CP3-CCS. The lower strand corresponds to the least efficient (CP2-NUC).

3.3. *Linking useful work and GHG emissions*

Fig. 8a summarizes the GHG emissions for each scenario and the useful work delivered per unit GHG emissions (Fig. 8b). Clearly evident is the potential of T4 to achieve significant emissions reductions, by as much as two-thirds by 2050 (Fig. 8a), accompanied by increases in useful work delivery per unit GHG emissions (Fig. 8b). The electrification of the transport system in tandem with decarbonization shows the potential for a trebling of useful work per unit of GHG emissions, from just under 3 PJ/$MtCO_2e$ (2010) to approximately 9 PJ/$MtCO_2e$ in 2050 for T4 (Fig. 8b). Even for the more conservative scenarios, T2–T3, more than a doubling in useful work per unit of equivalent CO_2 emissions is achieved.

While the effect of electrified transport on reducing transport emissions is pronounced, the electricity generation efficiency does not affect significantly the overall GHG emissions from the sector for any given scenario (Fig. 8a). In this sense GHG emissions are not as sensitive to differing electricity generation efficiencies (Fig. 8a) as useful work delivery (Fig. 7).

4. Discussion

4.1. *The step change of electrification*

The results clearly show that progressively ambitious transport pathways (in terms of technological change and modal switching), can achieve proportionally higher levels of useful work delivery (Figs. 3–5) and deep reductions in energy consumption (Figs. 3–5) and emissions (Fig. 8). In this respect the switch from liquid hydrocarbons to electrified motors and fuel cell vehicles offers a step change in exergy efficiency (Fig. 6).

A key finding is that useful work delivered by the UK transport system increases between 2010 and 2050 for all scenarios. However this increase in service delivery will come at the expense of differing energy consumption. It is reiterated that for T4 the 18% increase in useful work delivery in 2050 is accompanied by a 48% reduction in energy consumption, whilst for T1 the 87% increase in useful work delivery in 2050 is achieved with the same level of energy consumption and emissions as 2010. The above clearly highlights the added insights that an exergy analysis can offer for the study of future transport pathways compared to a conventional energy analysis.

The overall improvements in energy consumption and useful work delivery, particularly for T4, mainly manifest from efficiency improvements, modal change in road-based transport and higher share of aviation and shipping. Yet, these overall projections are the combined effect of decidedly different sectoral behaviors. For passenger transport, reductions in energy consumption are achieved progressively in T1–T4 from a reduction in dependency on liquid hydrocarbon for road transport (primarily cars). Despite the greater anticipated technological change and energy demand reduction in T4, the actual useful work delivery is approximately the same as T1, due to the higher exergy efficiency gains from technological change (Fig. 6). Freight transport projections exhibit a higher dependency on demand reduction, due to the only minor efficiency improvements and modal change. Modal change for freight has a particularly minor impact due to the similar exergy efficiencies across the technologies used (Fig. 6). This is exhibited in the generally positive correlation between energy consumption and useful work delivery for freight (Fig. 3b).

The above suggest the effectiveness that electrifying passenger transport can have for reducing energy demand and increasing service delivery. In this respect, policies that encourage step changes in efficiency should be prioritized (e.g. incentivizing scrappage of old vehicles and substitution with electric vehicles), over policies that offer only gradual and marginal changes (such as 5-year tailpipe emissions targets). In the authors' view, policies that tax inefficiency, even if progressively, remain at the mercy of elastic demand.

The lack of a step-change alternative for freight, shipping and aviation is clearly evident in Fig. 3b. Finally, considering the lower exergy efficiency of FCVs compared to EVs, in order to maintain increasing efficiency it is important that FCVs replace old liquid hydrocarbon vehicles before replacing EVs.

4.2. Sensitivity of transport demand and the DECC projections

The scale of transport demand is an important component not widely explored in this analysis. This is due to the relatively narrow range of DECC demand projections, compared to the projections of step-wise technological and modal change. Such narrow transport demand ranges however, were contested in the DECC consultations [34] and are quite different to other UK-based studies which have explored wider scenarios [53], expect steady growth [54], or argue that demand is saturating in developed economies [55,56].

In more detail, passenger transport distance travelled per passenger per year has increased by approximately 80% between 1970 and 2006 (with average annual GDP growth of 2.0%) [57]. Yet the DECC passenger transport demand projections only explore very moderate possible ranges of changes in transport demand: from 0% to +9% for 2010–2050.

While some studies suggest the saturation of passenger transport activity in wealthy industrialized nations [55], including the UK [56], other studies suggest that strong behavioral changes (in addition to technological innovation) should be an essential part of the policy options adopted to meet emissions targets [58]. Nonetheless, the importance of transport demand as a variable in studies that explore the decarbonization (or indeed proliferation) of the transport sector remains, and must not be forgotten from wider transport systems policy analysis. For example, the impact of freight and international transport demand growth for scenario T1 is particularly evident in the overall growth of useful work delivery at the cost of high energy consumption (Fig. 3) and GHG emissions (Fig. 8).

4.3. Decarbonization through electrification

The influence of the electricity system on the overall useful work delivery from the transport sector depends substantially on whether a sectoral or sub-sectoral perspective is adopted. When considering high penetrations of electrified transport, the level of technological and modal change is more significant for energy use, useful work delivery and GHG emissions, than the underlying low-carbon electricity pathways, e.g. for achieving the progress in T4 over T3 (Fig. 7).

That is not to say that the electricity generation pathway is insignificant. When considering only the electrified transport system for T2–T4 it is clear that the efficiency of the electricity generation system is almost as important as the level of electrification itself (Fig. 7, inset). In fact, the present analysis suggests that following the step-change to electrification, improvements in useful work delivery could be obtained more effectively by increasing the exergy efficiency of the electricity system than that of electric vehicles whose efficiency is already very high (Section 3.2).

While some studies have investigated the electricity generation and emissions of electric vehicles [3], both the exergy efficiency of the electricity generation system and the wider electrification of freight and non-car modes, are rarely considered. The present work complements this existing knowledge by demonstrating, at least for the UK, the relative merits for the transport sector of having a thermodynamically efficient, even if more variable, electricity system in terms of useful work delivery and GHG emissions. The decarbonization of the electricity system is likely to require significant and costly structural changes, not only to accommodate electrified transport, but also a higher penetration of renewables, electrified heating and smart grid systems [62]. Both energy and transport system planners should view this as an opportunity for coordinated action, both in the technological [62] and governance [70] senses, rather than a barrier to achieve wider systems' sustainability. If deep and absolute reduction in transport emissions are to be achieved in the UK, the present study confirms that moving towards electrified and hydrogen-based transport is the most productive way to do this.

4.4. Caveats of the study

There are three important caveats in this study. The first caveat has to do with the accuracy of the estimated results. The present

[3] Examples include studies in multiple national contexts [58], the global context [59], and plug-in hybrids in the US [60]. Other relevant studies include transport transitions and integration [59,61,62]; grid impacts on peak loading and demand, batteries, charging and vehicle-to-grid systems [63–65]; and the integration of electrified transport with intermittent renewable electricity generation [66], particularly wind power [67–69].

study is a scenario analysis of future transport pathways, with the specific scenarios derived from DECC [3] through a highly consultative process between academics, practitioners and policy-makers that reflected the expertise and policy needs of various stakeholders (Section 2). These scenarios vary drastically due to advances in technology, with conservative assumptions made in some areas and drastic in others, but all of them are within technological limits. These scenarios are treated not as predictions about the future of the transport system in the UK, but as an exploration or sampling of the space of possible futures. The wide variety of these scenarios makes them ideal for exploring radically different future transport pathways, policy options and their effect on resource consumption and GHG emissions. Methodological assumptions are well justified from the existing literature and have been cited throughout Section 2 and the supplementary electronic material. It is with this baseline picture of possible futures, that more elaborate decision-making and policy planning exercises can be applied, such as Robust Decision Making [71] and Dynamic Adaptive Policy Pathways [72].

The second caveat is with the perspective adopted in the present study. Exergy, as any other biophysical measure of sustainability, follows a rather eco-centric valuation perspective based on accounting for the amount of resources that have been appropriated within the transport system, as a proxy to environmental impact as has been discussed both in the sustainability assessment [49] and ecosystem services valuation [50] literature. Essentially, exergy analysis captures issues related to resource use and its efficiency very well, while other environmental impacts are captured in a rather derivative manner [51]. Whilst increases in exergy efficiency often result in better environmental performance [52], this is not always the case. For example, while PV electricity has a lower exergy efficiency (~20%) compared to coal-fired plants (~35%), it also has far lower GHG emissions. Furthermore, biophysical measures of sustainability, exergy included, cannot capture social dimensions of sustainability [51], including the social desirability of a given transport mode, electricity pathway or subsequent impacts on health. This means that the derived results capture only specific aspects associated with the sustainability of future transport systems and should be viewed as such.

The third is the conceptual limitations of exergy analysis when used for the optimization of thermal systems. In spite of being considered an effective analytical tool for quantifying the improvement potential of energy systems, exergy loss minimization is not always appropriate for the optimization of thermal systems, where methods such as entransy analysis [73,74] may be better suited to a variety of applications, such as cooling [75] and heat-work conversion [76].

5. Conclusions

The present study operationalizes exergy analysis for the study of future transport pathways. The developed conceptual framework was applied to four transport pathways of the UK transport system to the year 2050. By comparing future patterns of useful work delivery with energy consumption and GHG emissions a number of policy-relevant insights can be identified:

- Ambitious electrification of passenger transport can bring a 19–26% increase in useful work delivery, whilst reducing GHG emissions and energy consumption by up to 65%.
- For freight, international shipping and aviation, the smaller exergy efficiency improvements imply that energy consumption, useful work delivery and GHG emissions are highly dependent on transport demand.
- Electrification of passenger transport can bring a step-change in resource efficiency and useful work delivery, and can reduce GHG emissions if accompanied by low-carbon electricity.
- Following this step change of electrification, the efficiency of low-carbon electricity becomes significant, and in some cases it is more influential than seeking marginal exergy efficiency improvements in electrified transport.
- The high penetration of renewables and electrified transport is the most resource-efficient combination in the context of the range of scenarios and pathways explored in this study.

Whilst exergy analysis has been largely confined to the study of historical patterns of resource use and emissions from the transport sector, the present study indicates how exergy analysis can provide valuable and policy-relevant insights about the sustainability of multiple future transport pathways, which are often squarely focused on emissions. These insights demonstrate the added value of an exergy lens and how it can be used to add further layers of information to conventional transport-energy studies, both historical and forward-looking. For example the present study demonstrates that while the emissions from each electricity pathway are all effectively the same, overall transport-related improvements in useful work delivery could be achieved by a more exergy efficient electricity generation system.

The conceptual framework presented is compatible with mainstream studies of future energy and transport systems routinely produced by bodies such as the UK DECC [3], the U.S. Energy Information Administration [77], the Rocky Mountain Institute [78] and the European Commission [79]. As transport technologies diversify, the consideration of exergy in wider cross-sector analyses of the energy-transport relationship will become increasingly valuable. Nonetheless, it must be re-iterated that exergy analysis should be only one of the measures used when exploring the broader sustainability of future transport systems [80].

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2015.07.021.

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