

1 A Framework For The Exergy Analysis Of Future
2 Transport Pathways: Application For The United
3 Kingdom Transport System 2010-2050

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5 **Edward A. Byers^{a,*}, Alexandros Gasparatos^{b,c}, André C. Serrenho^d**

6 a. School of Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU,
7 UK. e.a.byers@ncl.ac.uk +44 (0) 191 208 4880

8 b. Integrated Research System on Sustainability Science (IR3S), University of Tokyo, Tokyo, Japan.
9 gasparatos@ir3s.u-tokyo.ac.jp

10 c. Department of Zoology, University of Oxford, Oxford, OX1 3PS, UK.

11 d. Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, UK. ag806@cam.ac.uk

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13 ***Corresponding Author current address:** Edward A. Byers

14 **Address:** Environmental Change Institute,
15 School of Geography and the Environment
16 University of Oxford
17 Oxford, OX1 3QY, UK

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19 **Telephone:** +44 (0) 1865 614941

20

21 **Email:** edward.byers@ouce.ox.ac.uk

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28 **Abstract**

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

44 **Keywords:** exergy analysis; transport; useful work; scenario analysis; GHG emissions; UK

45 **Highlights**

- 46 • Develop an exergy analysis framework of future transport pathways and apply it to UK
- 47 • Electrification of personal transport brings step change in useful work delivery
- 48 • Efficiency of electricity supply becomes significant once transport is electrified
- 49 • High electrification increases useful work (+20%) and reduces emissions (-65%)
- 50 • High penetration of renewables and electrified transport is most resource efficient

51

52 **1 Introduction**

53

54 In most OECD economies the transport sector is an important end-user of final energy (mainly of
55 liquid hydrocarbons), and at the same time a major source of greenhouse gases (GHGs) and atmospheric
56 pollutants.[1] Interconnected policy realities such as energy security and climate change have made the
57 reduction of resource/energy use and carbon intensity from the transport sector a policy imperative
58 across the OECD[2], including the UK.[3] Under the Climate Change Act of 2008[4] the UK has
59 committed to reduce by 2050 its GHG emissions by 80% compared to 1990 levels. The transport sector
60 is considered to be key in this effort, as it was responsible in 2013 for 38% of the UK's final energy use
61 [5] and 21% of GHG emissions[6].

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

70 In its *2050 Pathways Analysis*[3] and *Carbon Plan*[7], the UK Government Department of Energy and
71 Climate Change (DECC) set out a range of policy options and pathways to reduce national GHG
72 emissions, to meet the targets of the Climate Change Act 2008 [4]. With emissions reduction as the
73 primary aim of the Government's policy-analysis exercise, transport efficiency was expressed as the
74 ratio of energy used per vehicle-km, (or per seat-km for trains and aircrafts).

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

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

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

93 Exergy analysis is increasingly used to quantify the resource use efficiency of national economies,
94 with the transport sector usually featuring as a distinct sub-component of the economy in most of these
95 studies. Some of the earliest examples include studies Reistad for the US [13] and Wall for Sweden [14]

ⁱ 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]

96 and Japan [15]. Exergy studies in the context of the UK national economy have identified century-long
97 trends in the transport sector [16]; trends over multiple decades with sectoral disaggregation[17]; and the
98 effect of transport-related resource consumption on the broader sustainability of UK society[18]. Several
99 authors have conducted comparative exergy analyses including. Brockway *et al.* that revealed divergent
100 trends in the UK and US[19], Serrenho *et al.* that compared trends in EU-15 countries [11] and Ertesvåg
101 that collected and compared results for multiple countries[20]. The transport sector has also featured as a
102 sub-component of the economy in several extended exergy analyses including those of Italy [21],
103 Norway [22], China [23], and the UK [18].

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

116 More importantly, as demonstrated above, the contribution of energy use in a given transport service
117 depends only on the useful work delivered rather than on the primary or final energy use itself. However
118 only the latter is used in most conventional future transport studies conducted by national policy bodies

119 such as DECC in the UK [3]. Furthermore, given the ambition to decarbonize the transport sector
120 through electrification, it is important to consider the exergy efficiency of both the electricity generation
121 and the actual modes of transport, especially when investigating the potential of future electrified and
122 hybrid transport systems[13].

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

- 126 (a) develop a conceptual framework for the exergy analysis of future transport pathways that takes
127 into account different possible electricity generation pathways;
- 128 (b) apply this framework to the UK transport and electricity generation sectors (2010-2050)
- 129 (c) demonstrate the relevance of exergy analysis in current sustainability discourses in the transport
130 sector by identifying and discussing policy-relevant results.

131 The paper starts by developing a conceptual framework for operationalizing exergy analysis for the
132 study of multiple future transport pathways (Section 2). A key consideration throughout the
133 development of this framework has been its compatibility with conventional studies of future transport
134 and electricity generation systems. Subsequently an exergy analysis of four future transport scenarios,
135 that build on DECC's 2050 Pathways for energy and transport[3,7,33,34,35] is conducted (Section 3).
136 These scenarios were deliberately chosen to demonstrate how the proposed exergy analysis framework
137 can be linked to (and complement) conventional transport studies, essentially offering additional layers
138 of policy-relevant information. For each scenario, the energy consumption and useful work delivery of
139 the transport sector to 2050 is compared, disaggregated by transport mode and energy vector (Section
140 3.1). The sensitivity of useful work and GHG emissions on five alternative electricity generation
141 pathways is then discussed (Sections 3.2-3.3). Section 4 brings together the policy-relevant insights of

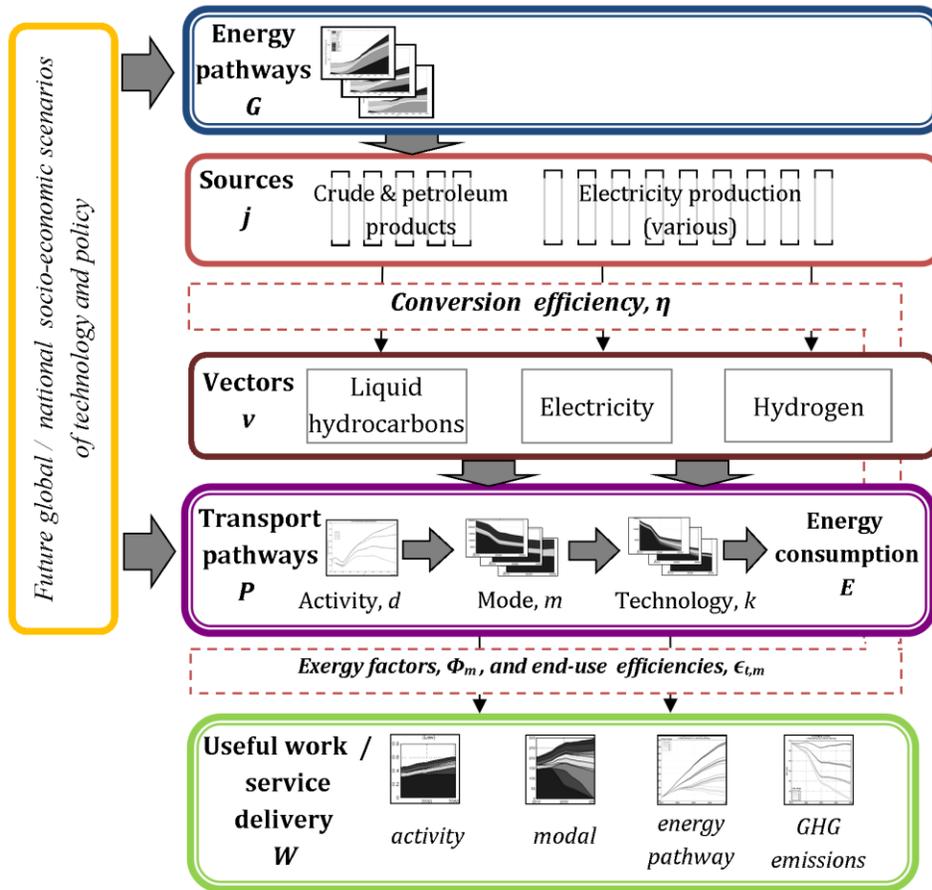
142 this exercise, using them to scrutinise future policy options for both the transport and the electricity
143 generation systems.

144 **2 Methodology**

145 **2.1 Conceptual framework**

146 The exergy analysis of a future transport system needs to combine assumptions about the transport
147 system itself, as well as of the future primary and secondary energy system. In the present study
148 projections of future transport use (and its resulting energy demand) (Section 2.3.1) are matched to
149 alternative future energy pathways (Section 2.3.2). Assumptions about future exergy efficiencies are
150 then used to calculate the useful work delivered by the sector (Section 2.2).

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



158

159 **Figure 1.** Conceptual framework for the exergy analysis of future transport systems. (1.5 or 2-column
 160 figure)

161 Formally, future energy pathways are defined by an $n_t \times n_j \times n_v$ matrix \mathbf{G} whose elements $g_{t,j,v}$: $t=1, \dots, n_t$,
 162 $v=1, \dots, n_v$, $j=1, \dots, n_j$, denote the amount of an energy vector v that is produced by an energy source j in
 163 year t . Transport pathways are similarly defined by an $n_t \times n_m \times n_v$ matrix \mathbf{P} , whose elements $p_{t,m,v}$: t ,
 164 $m=1, \dots, n_m$, v , denote the amount of an energy vector v used by transport mode m , in year t . The $n_t \times n_r$
 165 matrix η (with elements $\eta_{t,j}$: t, j) defines the conversion efficiency at which a primary fuel source j is
 166 converted to an energy vector v , e.g. coal to electricity or crude oil to gasoline, as well as (where

167 appropriate) transmission and distribution losses. The mean efficiency η_{n_j} of energy production
 168 weighted by volume across all sources for each energy vector is calculated as:

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

169 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
 170 final energy use $E_{t,m,v}$, exergy factorⁱⁱ $\Phi_{m,v}$, and end-use exergy efficiency $\epsilon_{t,m,v}$. The sum of W for all
 171 transport modes over each energy vector gives the annual useful work:

$$\sum_v W_{t,m,v} = \sum_v E_{t,m,v} \phi_{m,v} \epsilon_{t,m,v} \quad (2)$$

172
 173 **2.2 Calculation of future useful work for each transport mode**

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

177 Regarding the third variable in Eq. 2, the DECC model estimates future energy consumption based on
 178 assumptions of technological efficiency in terms of fuel efficiency. This type of technological efficiency
 179 is not directly linked to exergy efficiency (ϵ) as discussed in Section 1 and in Serrenho *et al.* (2013)
 180 [38]. While fuel efficiency depends on exergy efficiency and other vehicle factors such as aerodynamics,
 181 it is assumed in the present study that all these other factors, besides exergy efficiency remain constant
 182 for all transport modes using liquid hydrocarbons or hydrogen as energy vectors. Hence the relationship
 183 between vehicles' fuel efficiency and exergy efficiency becomes:

ⁱⁱ 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.

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

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

187 For Fuel Cell Vehicles (FCVs) the second-law efficiency is calculated following [40] ,:

$$\epsilon \approx \eta_{theoretical\ maximum} \prod_{i=1}^4 \alpha_i \quad (4)$$

188 where $0 \leq \alpha_i \leq 1, \forall i$ are coefficients that denote the bias from real to ideal use settings [38] for fuel
 189 cell/friction/accessories/transmission losses (Table SI7 in supplementary material) and
 190 $\eta_{theoretical\ maximum} = 83\%$ [43]. Furthermore, an exergy efficiency factor of 62% was used for
 191 hydrogen production from electricity assuming steam-methane reforming/advanced-technology
 192 electrolysis [44].

193 Historical technology efficiencies usually follow an S-shaped curve [45]. The efficiency of electric
 194 motors in plug-in hybrid electric vehicles and buses, electric and diesel-electric trains and fuel-cell
 195 vehicles has not improved significantly over the past decades, exhibiting high values of around 80%-
 196 90% [42]. It is assumed that the future efficiency of electric motors will stabilize around a high value of
 197 95%. The following function is then derived by adjusting an exponential function that fulfills these
 198 above conditions and exhibits faster efficiency improvements, when fuel efficiency values are assumed
 199 by the DECC model to increase faster:

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

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

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

$$\epsilon_t = \epsilon_g \epsilon_{t,EV} , \quad (6)$$

204 where $\epsilon_g = 39.9\%$, [46] and $\epsilon_{t,EV}$ is the electric engine efficiency as calculated through Eq. 5.

205 **2.3 Transport and energy pathways**

206 **2.3.1 Transport pathways**

207 Four transport scenarios are derived to 2050 used in this study from DECC [3,33,34,35]. The
208 classification used in the DECC Pathways model [35] is adopted, grouping the transport system into two
209 sub-sectors: passenger transport and freight/international transport. Passenger transport (PT) includes all
210 domestic transport by the public, including domestic aviation. Freight/international transport (FI)
211 includes all freight transport within the UK, international shipping, and international aviation.

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

217 For PT, the four ambition levels represent upper and lower boundaries of per capita personal transport
218 demand at a 2.5% annual Gross Domestic Product (GDP) growth rate. While the levels of passenger
219 demand can strongly influence the overall energy demand, changes in per capita passenger demand
220 suggested by DECC are narrow, increasing from 14,079 passenger-kms per year (in 2010) to 14,076-
221 15,363 passenger-kms per year (in 2050) [34]. For FI, only one set of trajectories is available. This is
222 due to the apparent decoupling of freight and economic growth [3] as observed between 1997 and 2007

223 when freight volume increased by 11% whilst the Gross Domestic Product (GDP) increased by 32%
 224 [47].

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

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

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

234 **2.3.2 Energy pathways**

235 Scenarios T3-T4 entail high penetration of electrified transport (Table 1). However, different
 236 decarbonized electricity systems in the UK can have different efficiencies and environmental impacts
 237 [48], even if GHG emissions are similar. Hence the exergy efficiency of the electricity generation
 238 system becomes important when considering useful work delivery through the entire transport system.

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

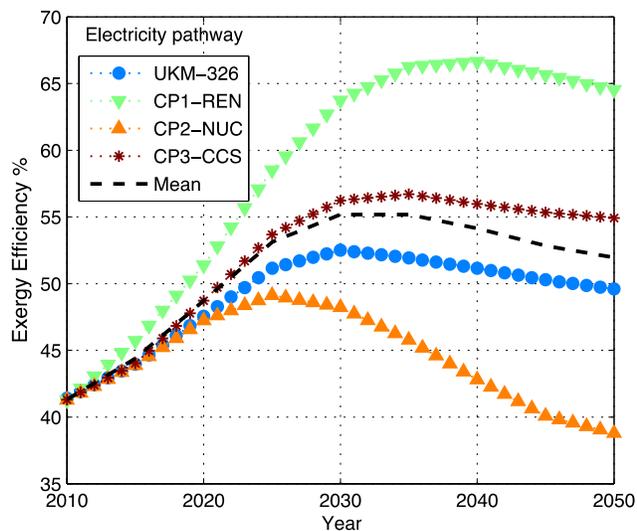
245 **Table 2.** Electricity generation pathways for 2050.

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

246 Source: Adapted from [7]

247 Taking the electricity generation from each pathway (including conversion and distribution losses) Eq.
248 1 calculates the mean exergy efficiency of grid electricity production weighted by generation type
249 between 2010-2050. Pathways with high levels of renewables (particularly wind) and combined cycle
250 gas turbines exhibit the highest efficiencies (CP1-REN, CP3-CCS), whilst the generally low efficiency
251 of nuclear power (33%) and coal with CCS keeps efficiency lower (UKM-326, CP2-NUC) (Figure 2).
252 The higher penetration of renewables in the 2020s and 2030s helps increase the mean exergy efficiency.
253 From the 2040s the expected exergy efficiency is reduced due to increasing levels of either nuclear or
254 coal-CCS and gas-CCS, combined with decommission of some renewables (Table 2, Figure 2).
255 Electricity system-level transmission [49] and distribution [50] losses are proportionally fixed at 6%,
256 whilst some conversion efficiencies change with time (coal, biomass and CCS generation) and are
257 detailed in the supplementary information (Table SI3) and the DECC 2050 Pathways Excel model [35].
258 For the calculations in Section 3.1 the mean efficiency of electricity production is used.



259

260 **Figure 2.** Weighted exergy efficiency and mean exergy efficiency of electricity production for the four
 261 electricity generation pathways. (1-column figure)

262 **3 Results**

263

264 **3.1 Energy, exergy and useful work trends**

265

266 Figures 3-5 present the energy consumption and useful work delivery for the different scenarios
 267 between 2010 and 2050. Figure 3 provides a comprehensive visualization by fuel and mode of transport,
 268 while Figures 4-5 offer more aggregated visualizations by transport mode (Figure 4) and by energy
 269 vector (Figure 5).

270 For PT, overall energy demand decreases for all scenarios, from 1414 PJ/year (2010) to 817-495
 271 PJ/year (2050) (Figure 3a-5a). This corresponds to a 42-65% decrease in energy demand with the largest
 272 decrease observed in scenario T4. This consistent reduction across all four scenarios is almost entirely
 273 due to reductions in the use of liquid hydrocarbons in cars in favour of Electric Vehicles (EVs) and Fuel
 274 Cell Vehicles (FCVs). The progressive technological change in scenarios T2-T4 results in an increasing

275 energy consumption from other modes, e.g. 72% of total energy use in T4 in 2050 coming from EVs and
276 FCVs.

277 At the same time, the delivery of useful work increases by 19-26% in all four scenarios by 2050, with
278 75% of the useful work delivered in T4 coming from EVs and FCVs. Similarly a high penetration of
279 FCV buses and electrified rail is evident.

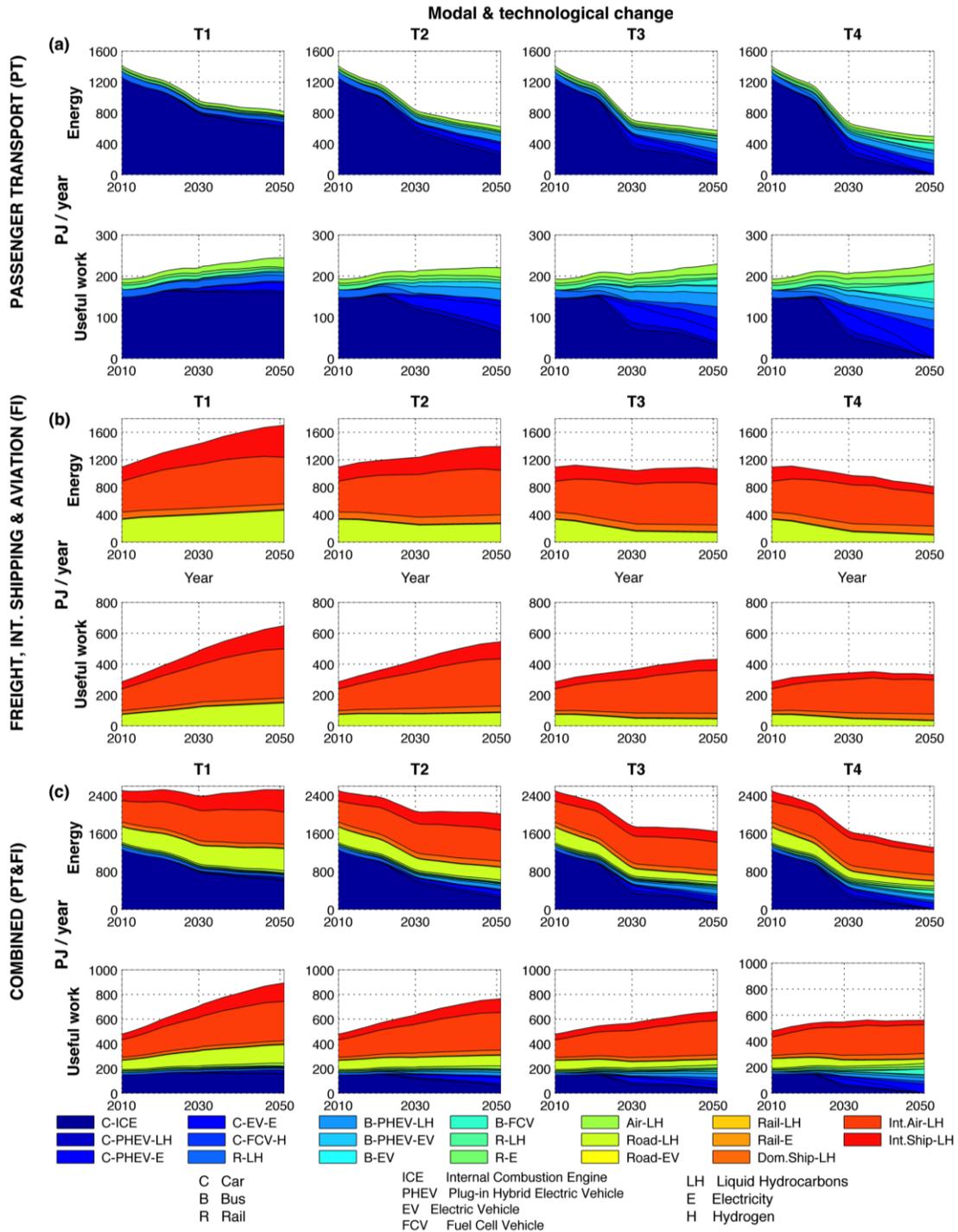
280 The results overall suggest that higher rates of technological and modal change away from liquid
281 hydrocarbons exhibit the highest reductions of energy consumption, with only marginally lower
282 increases in useful work delivery by 19% (T4), compared to a 26% increase in service delivery (T1).

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

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

298 demand for ~75% gains in useful work (T1-T2) versus a halving energy demand for moderate (~30%)
299 increase in useful work delivery (T3-T4).

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

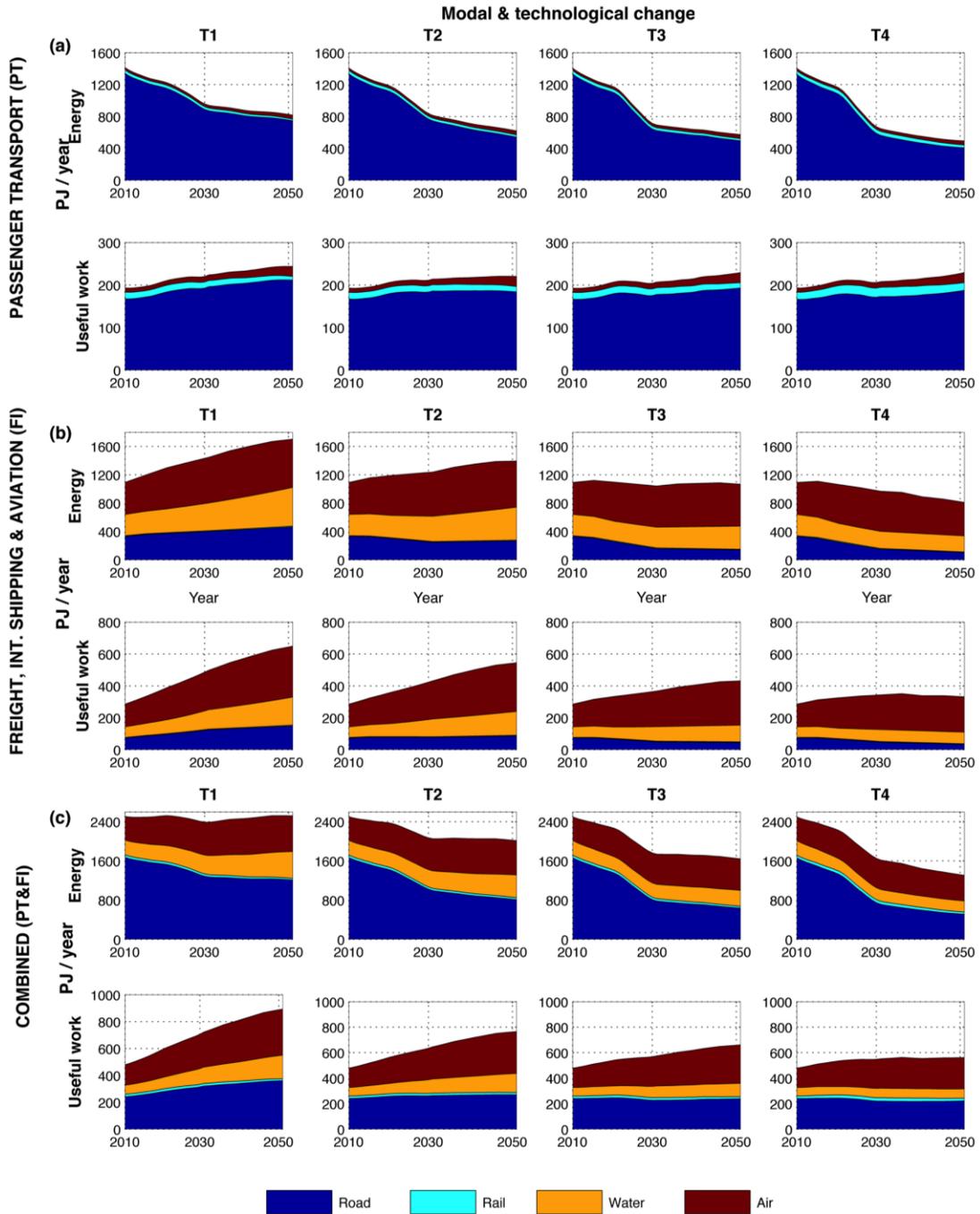


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304 **Figure 3.** Projections of future energy consumption and useful work delivery (in PJ/year) between 2010-

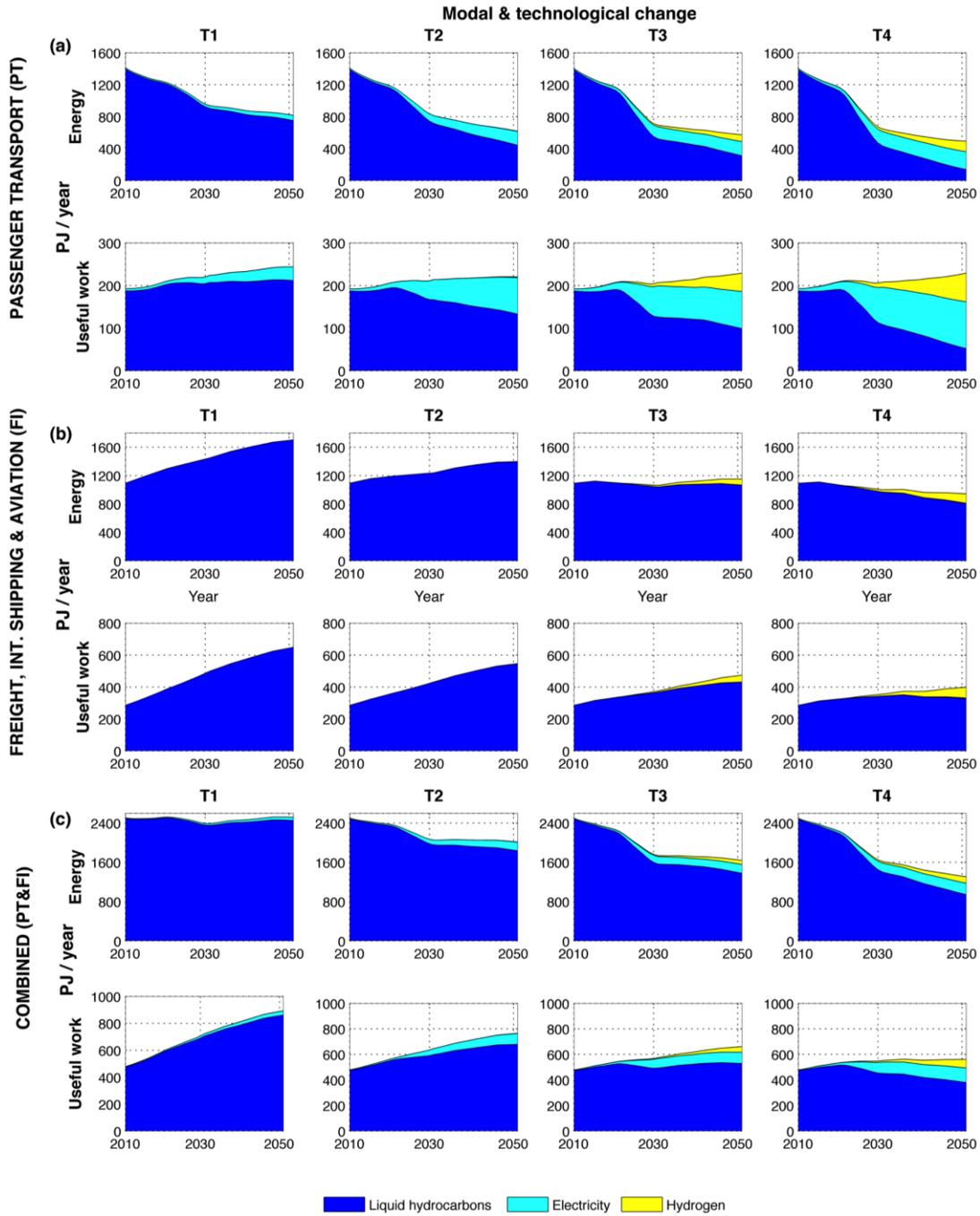
305 2050, by fuel and mode for Passenger Transport (a), Freight and International shipping and aviation (b)

306 and PT-FI combined (c). (2-column figure, low-res version)



307

308 **Figure 4.** Projections of future energy consumption and useful work delivery (in PJ/year) between 2010-
 309 2050 aggregated by road, rail, water and air transport. (2-column figure, low res version)

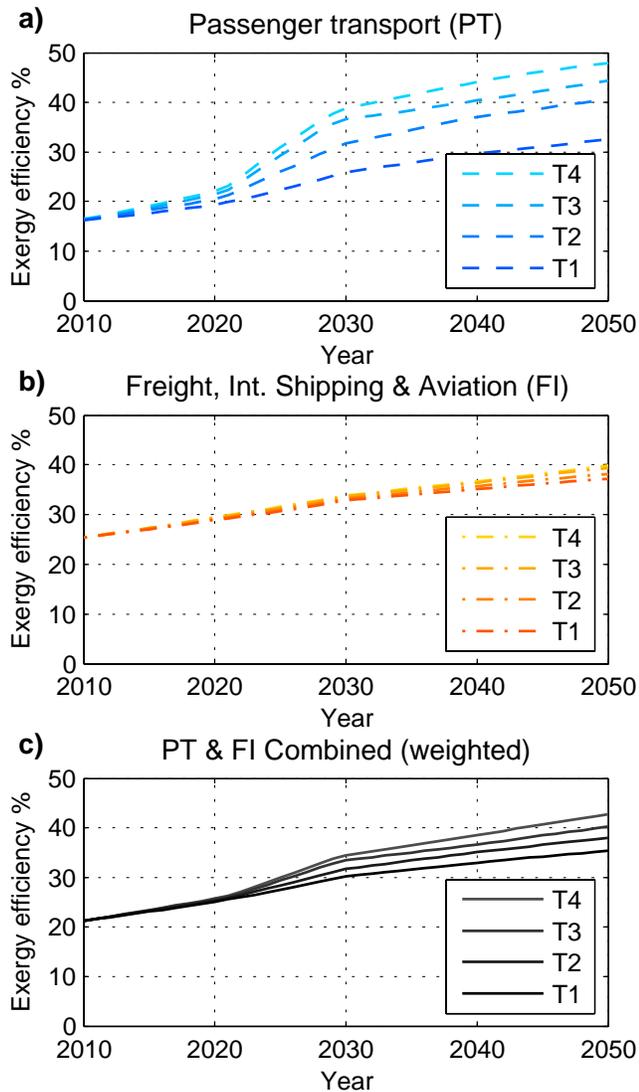


310

311 **Figure 5.** Projections of future energy consumption and useful work delivery (in PJ/year) between 2010-
 312 2050 aggregated by energy vector. (2-column figure, low res version)

313 Figure 6 plots the exergy efficiency of the entire transport sector and its sub-components. The results
 314 reiterate the general trends observed in Figures 3-5, with exergy efficiency of PT increasing

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



328

329 **Figure 6.** Weighted exergy efficiency for Passenger Transport (a); Freight and International shipping
 330 and aviation (b); and the entire transport sector (c), for scenarios T1-T4. (1-column figure)

331

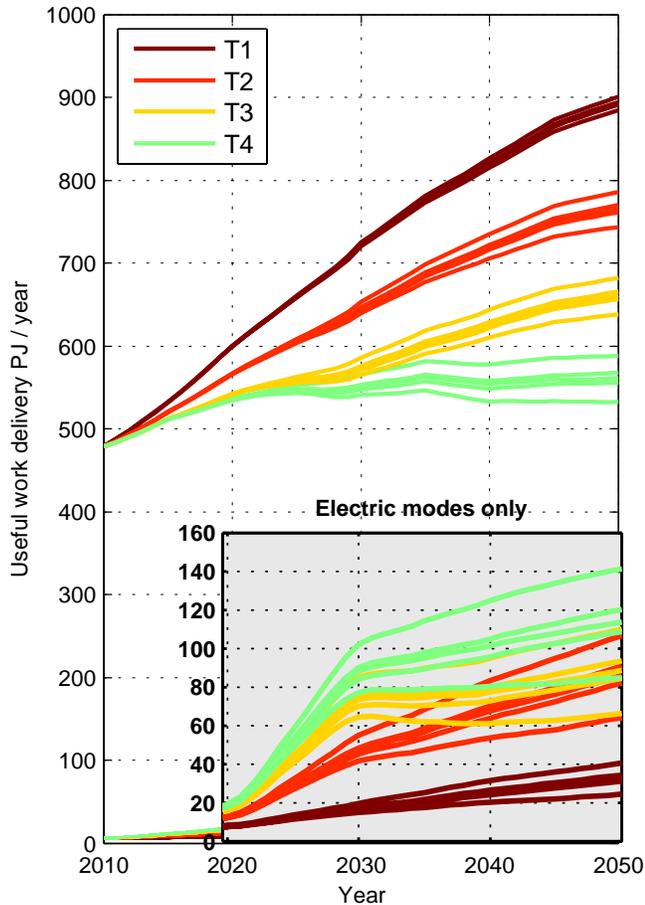
332 3.2 Sensitivity of useful work delivery to the electricity generation system

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

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

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

344 The inset in Figure 7 gives a different insight by comparing the sensitivity effect for electric transport
345 modes only. For T2-T4, the overlapping values in 2050 indicate that in terms of useful work delivery
346 from electrified transport, grid efficiency is almost as important as the technological change of the
347 transport scenarios themselves. In 2050, the three central electricity pathways for T2 perform as well as
348 the worst performing electricity generation pathway (CP2-NUC) in T4. In T4, useful work delivery in
349 2050 from CP1-REN is 70% higher than CP2-NUC due to the higher electricity grid efficiency.
350 Considering the whole system, the step change of electrification brought by the technological change in
351 T2 or T3 brings the most immediate efficiency gains. Beyond this however, seeking improvements in
352 grid efficiency delivers more useful work than obtaining improvements in the already high efficiency
353 (~85-90%) of electrified transport. In fact increased grid efficiency would not only have benefits for the
354 transport sector but the economy as a whole.



355

356 **Figure 7.** Effects of the five electricity pathways on useful work delivery for the four transport
 357 scenarios. The upper plot displays effects on the total useful work delivery. The magnified inset plot
 358 displays the variation of useful work delivery for electric modes only. (1-column figure)

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

363

364

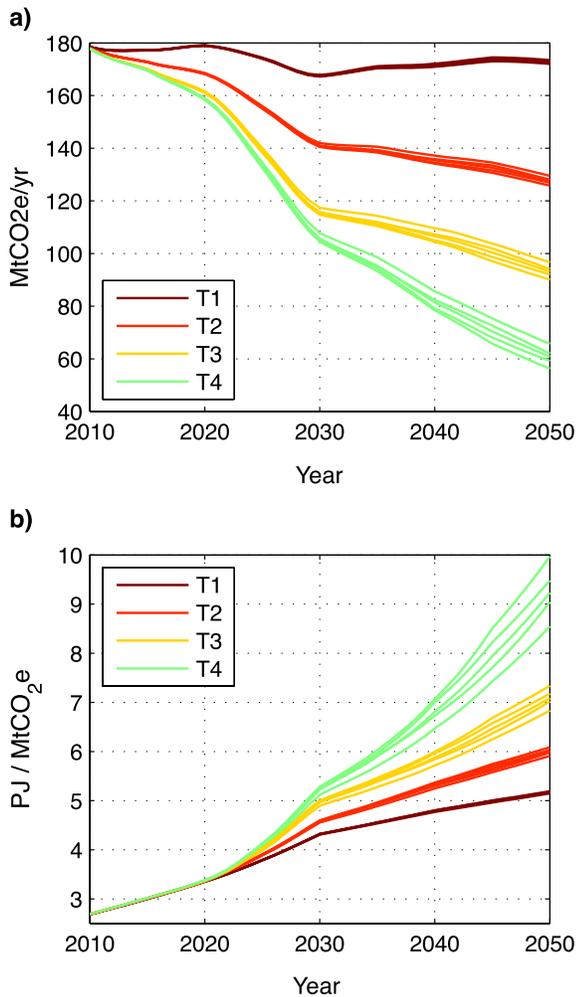
365

366 3.3 Linking useful work and GHG emissions

367

368 Figure 8a summarizes the GHG emissions for each scenario and the useful work delivered per unit
369 GHG emissions (Figure 8b). Clearly evident is the potential of T4 to achieve significant emissions
370 reductions, by as much as two-thirds by 2050 (Figure 8a), accompanied by increases in useful work
371 delivery per unit GHG emissions (Figure 8b). The electrification of the transport system in tandem with
372 decarbonization shows the potential for a trebling of useful work per unit of GHG emissions, from just
373 under 3 PJ/MtCO_{2e} (2010) to approximately 9 PJ/MtCO_{2e} in 2050 for T4 (Figure 8b). Even for the more
374 conservative scenarios, T2-T3, more than a doubling in useful work per unit of equivalent CO₂
375 emissions is achieved.

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



380

381 **Figure 8.** GHG emissions (in MtCO₂e) (a) and useful work delivery per unit GHG emitted (in
 382 PJ/MtCO₂e) (b) between 2010-2050 for each of the five electricity pathways. (1-column figure)

383

384 4 Discussion

385

386 4.1 The step change of electrification

387 The results clearly show that progressively ambitious transport pathways (in terms of technological
 388 change and modal switching), can achieve proportionally higher levels of useful work delivery (Figure
 389 3-5) and deep reductions in energy consumption (Figure 3-5) and emissions (Figure 8). In this respect

390 the switch from liquid hydrocarbons to electrified motors and fuel cell vehicles offers a step change in
391 exergy efficiency (Figure 6).

392 A key finding is that useful work delivered by the UK transport system increases between 2010 and
393 2050 for all scenarios. However this increase in service delivery will come at the expense of differing
394 energy consumption. It is reiterated that for T4 the 18% increase in useful work delivery in 2050 is
395 accompanied by a 48% reduction in energy consumption, whilst for T1 the 87% increase in useful work
396 delivery in 2050 is achieved with the same level of energy consumption and emissions as 2010. The
397 above clearly highlights the added insights that an exergy analysis can offer for the study of future
398 transport pathways compared to a conventional energy analysis.

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

411 The above suggest the effectiveness that electrifying passenger transport can have for reducing energy
412 demand and increasing service delivery. In this respect, policies that encourage step changes in

413 efficiency should be prioritized (e.g. incentivizing scrappage of old vehicles and substitution with
414 electric vehicles), over policies that offer only gradual and marginal changes (such as 5-year tailpipe
415 emissions targets). In the authors' view, policies that tax inefficiency, even if progressively, remain at
416 the mercy of elastic demand.

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

421

422 **4.2 Sensitivity of transport demand and the DECC projections**

423

424 The scale of transport demand is an important component not widely explored in this analysis. This is
425 due to the relatively narrow range of DECC demand projections, compared to the projections of step-
426 wise technological and modal change. Such narrow transport demand ranges however, were contested in
427 the DECC consultations [34] and are quite different to other UK-based studies which have explored
428 wider scenarios [55], expect steady growth[56], or argue that demand is saturating in developed
429 economies[57,58].

430 In more detail, passenger transport distance travelled per passenger per year has increased by
431 approximately 80% between 1970-2006 (with average annual GDP growth of 2.0%) [59]. Yet the DECC
432 personal transport demand projections only explore very moderate possible ranges of changes in
433 transport demand: from 0% to +9% for 2010-2050.

434 While some studies suggest the saturation of passenger transport activity in wealthy industrialized
435 nations[57], including the UK [58], other studies suggest that strong behavioral changes (in addition to

436 technological innovation) should be an essential part of the policy options adopted to meet emissions
437 targets [59]. Nonetheless, the importance of transport demand as a variable in studies that explore the
438 decarbonization (or indeed proliferation) of the transport sector remains, and must not be forgotten from
439 wider transport systems policy analysis. For example, the impact of freight and international transport
440 demand growth for scenario T1 is particularly evident in the overall growth of useful work delivery at
441 the cost of high energy consumption (Figure 3) and GHG emissions (Figure 8).

442

443 **4.3 Decarbonization through electrification**

444

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

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

456 While some studies have investigated the electricity generation and emissions of electric vehiclesⁱⁱⁱ,
457 both the exergy efficiency of the electricity generation system and the wider electrification of freight and
458 non-car modes, are rarely considered. The present work complements this existing knowledge by
459 demonstrating, at least for the UK, the relative merits for the transport sector of having a
460 thermodynamically efficient, even if more variable, electricity system in terms of useful work delivery
461 and GHG emissions. The decarbonization of the electricity system is likely to require significant and
462 costly structural changes, not only to accommodate electrified transport, but also a higher penetration of
463 renewables, electrified heating and smart grid systems [64]. Both energy and transport system planners
464 should view this as an opportunity for coordinated action, both in the technological [64] and governance
465 [72] senses, rather than a barrier to achieve wider systems' sustainability. If deep and absolute reduction
466 in transport emissions are to be achieved in the UK, the present study confirms that moving towards
467 electrified and hydrogen-based transport is the most productive way to do this.

468

469 **4.4 Caveats of the study**

470 There are three important caveats in this study. The first caveat has to do with the accuracy of the
471 estimated results. The present study is a scenario analysis of future transport pathways, with the specific
472 scenarios derived from DECC [3] through a highly consultative process between academics,
473 practitioners and policy-makers that reflected the expertise and policy needs of various stakeholders
474 (Section 2). These scenarios vary drastically due to advances in technology, with conservative

ⁱⁱⁱ Examples include studies in multiple national contexts [61], the global context [62], and plug-in hybrids in the US [63]. Other relevant studies include transport transitions and integration [61,64,65]; grid impacts on peak loading and demand, batteries, charging and *vehicle-to-grid* systems [66,67,68]; and the integration of electrified transport with intermittent renewable electricity generation [69], particularly wind power [70,71].

475 assumptions made in some areas and drastic in others, but all of them are within technological limits.
476 These scenarios are treated not as predictions about the future of the transport system in the UK, but as
477 an exploration or sampling of the space of possible futures. The wide variety of these scenarios makes
478 them ideal for exploring radically different future transport pathways, policy options and their effect on
479 resource consumption and GHG emissions. Methodological assumptions are well justified from the
480 existing literature and have been cited throughout Section 2 and the supplementary electronic material. It
481 is with this baseline picture of possible futures, that more elaborate decision-making and policy planning
482 exercises can be applied, such as *Robust Decision Making* [73] and *Dynamic Adaptive Policy Pathways*
483 [74].

484 The second caveat is with the perspective adopted in the present study. Exergy, as any other
485 biophysical measure of sustainability, follows a rather eco-centric valuation perspective based on
486 accounting for the amount of resources that have been appropriated within the transport system, as a
487 proxy to environmental impact as has been discussed both in the sustainability assessment [51] and
488 ecosystem services valuation [52] literature. Essentially, exergy analysis captures issues related to
489 resource use and its efficiency very well, while other environmental impacts are captured in a rather
490 derivative manner [53]. Whilst increases in exergy efficiency often result in better environmental
491 performance [54], this is not always the case. For example, while PV electricity has a lower exergy
492 efficiency (~20%) compared to coal-fired plants (~35%), it also has far lower GHG emissions.
493 Furthermore, biophysical measures of sustainability, exergy included, cannot capture social dimensions
494 of sustainability [53], including the social desirability of a given transport mode, electricity pathway or
495 subsequent impacts on health. This means that the derived results capture only specific aspects
496 associated with the sustainability of future transport systems and should be viewed as such.

497 The third is the conceptual limitations of exergy analysis when used for the optimization of thermal
498 systems. In spite of being considered an effective analytical tool for quantifying the improvement
499 potential of energy systems, exergy loss minimization is not always appropriate for the optimization of
500 thermal systems, where methods such as entransy analysis [75,76] may be better suited to a variety of
501 applications, such as cooling[77] and heat-work conversion [78].

502 **5 Conclusions**

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

- 507 • Ambitious electrification of passenger transport can bring a 19-26% increase in useful work
508 delivery, whilst reducing GHG emissions and energy consumption by up to 65%.
- 509 • For freight, international shipping and aviation, the smaller exergy efficiency improvements
510 imply that energy consumption, useful work delivery and GHG emissions are highly
511 dependent on transport demand.
- 512 • Electrification of passenger transport can bring a step-change in resource efficiency and
513 useful work delivery, and can reduce GHG emissions if accompanied by low-carbon
514 electricity.
- 515 • Following this step change of electrification, the efficiency of low-carbon electricity becomes
516 significant, and in some cases it is more influential than seeking marginal exergy efficiency
517 improvements in electrified transport.

- 518 • The high penetration of renewables and electrified transport is the most resource-efficient
519 combination in the context of the range of scenarios and pathways explored in this study.

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

529 The conceptual framework presented is compatible with mainstream studies of future energy and
530 transport systems routinely produced by bodies such as the UK DECC [3], the U.S. Energy Information
531 Administration [79], the Rocky Mountain Institute [80] and the European Commission [81]. As
532 transport technologies diversify, the consideration of exergy in wider cross-sector analyses of the
533 energy-transport relationship will become increasingly valuable. Nonetheless, it must be re-iterated that
534 exergy analysis should be only one of the measures used when exploring the broader sustainability of
535 future transport systems [82].

536

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546 **7 Appendix A: Supplementary material**

547 The supplementary material includes additional data and specific details used to incorporate our work
548 into the generalized framework methodology.

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