Supplementary Information

Added mass offset half of the efficiency gains in Europe's electric vehicles

Christopher R. Knittel

Equation, Extended Data, and figure numbers without the prefix "Supplementary" refer to the main paper.

Supplementary Tables 1 to 3 accompany the main text and the Methods. Supplementary Table 1 decomposes the change in consumption between each pair of years, Supplementary Table 2 repeats the decompositions from a 2020 base, and Supplementary Table 3 reports registration-weighted means by year.

Supplementary Note 1: Robustness of the decomposition

I investigate robustness along five dimensions. The first concerns the sample. The preferred estimates use only the registrations whose variant has a manufacturer-stated drag coefficient, drive configuration, and heat pump status. The decompositions further require usable battery capacity and motor power, which the mass frontier uses. The first check therefore drops the drag coefficient, puts frontal area and length in the load function in its place, and estimates the system on all 7.9 million registrations. Supplementary Table 4 reports the results in two specifications, one with mass alone and one with mass and body size.

The results are close to the preferred estimates. On the full sample, fleet-average consumption fell from 175 to 163 Wh/km. The technology factor is 0.85 to 0.87, so technology reduced consumption at 2019 attributes by 24 to 26 Wh/km, compared with 25 Wh/km in the preferred estimates. Heavier vehicles added back 11 to 15 Wh/km, compared with 13 Wh/km. As a result, attributes took about half of the progress, close to the 47 percent in the preferred estimates. The mass coefficient is 0.062 Wh/km per kilogram, compared with 0.057. The range decomposition produces similar estimates. Mean log range rose 39 log points on the full sample, of which larger batteries account for 24 to 25 and the efficiency frontier for 15 to 16. In the preferred estimates, the corresponding numbers are 25 and 15 of 38 log points.

The two samples end at different levels of consumption, and the difference comes from which vehicles are missing. The drag-coefficient sample covers 80 to 91 percent of registrations in every year. The decomposition sample also requires motor power, which comes from the specification data or, where they do not report it, from the registry, and it covers 80 percent of registrations

Supplementary Table 1. Technology and attribute effects by period

	Change in consumption	Technology effect	Mass effect	Drag, size, and drive	Share absorbed by attributes	Change in mass (kg)	Change in usable capacity (kWh)
Panel A: from each base year to 2025							
2019 to 2025	−13.1	−24.9	13.3	−1.5	0.47	271	16.5
2020 to 2025	−7.7	−19.2	13.5	−2.7	0.56	275	15.7
2021 to 2025	−5.9	−13.5	10.5	−3.5	0.52	214	13.1
2022 to 2025	−9.8	−11.5	4.3	−2.9	0.12	87	6.8
2023 to 2025	−6.6	−8.3	2.8	−1.2	0.19	56	5.1
Panel B: year to year							
2019 to 2020	−5.4	−5.9	−0.2	1.4	0.19	−4	0.8
2020 to 2021	−1.8	−6.1	3.3	0.8	0.67	61	2.7
2021 to 2022	3.8	−2.4	6.7	−0.6	2.54	127	6.3
2022 to 2023	−3.2	−3.2	1.6	−1.8	−0.08	31	1.7
2023 to 2024	−3.7	−4.2	1.7	−1.4	0.08	34	2.7
2024 to 2025	−2.9	−4.1	1.1	0.2	0.30	22	2.4

Notes: Decomposition of equation (7) with the preferred efficiency frontier, column (5) of Extended Data Table 2, between the years shown, on the decomposition sample. Consumption effects are in Wh/km; the technology effect is evaluated at the attributes of the first year and the attribute effects at the technology of the second. The share absorbed by attributes is the sum of the mass effect and the drag, size, and drive effect divided by minus the technology effect; it is not informative when the technology effect is small, as between 2024 and 2025.

Supplementary Table 2. The decompositions from a 2019 and a 2020 base

	Unconditional (5)		Constant price (6)	
Base year	2019	2020	2019	2020
Panel A: consumption (Wh/km)				
Fleet-average consumption, base year	174.5	169.1	174.5	169.1
Fleet-average consumption, 2025	161.4	161.4	161.4	161.4
Technology factor	0.857	0.887	0.882	0.902
Technology effect (Wh/km)	−24.9	−19.2	−20.6	−16.6
Mass effect (Wh/km)	13.3	13.5	9.5	9.7
of which larger batteries	7.3	6.9	3.3	3.1
Drag, size, and drive (Wh/km)	−1.5	−2.7	−1.0	−2.6
Share of the technology effect absorbed by mass	0.53	0.71	0.46	0.58
Share of the technology effect absorbed by all attributes	0.47	0.56	0.41	0.43
Panel B: range (log points)				
Change in mean log range	0.375	0.308	0.375	0.308
Larger batteries, net of mass penalty	0.252	0.222	0.224	0.167
of which battery frontier shift			0.221	0.115
Efficiency frontier shift	0.154	0.120	0.126	0.103
Mass frontier shift	−0.017	−0.009	−0.034	−0.020
Drag, size, drive, other	−0.015	−0.025	0.058	0.057

Notes: The 2019-base columns repeat Extended Data Tables 4 and 7; the 2020-base columns re-run the same decompositions from the 2020 fleet with the same frontier estimates. The decomposition sample has 0.17 million registrations in 2019 and 0.51 million in 2020, and consumption at fixed attributes fell by 3.4 log points between 2019 and 2020.

Supplementary Table 3. Registration-weighted mean attributes of new battery-electric vehicles, EU, Iceland and Norway

Year	Registrations	Wh/km	km/kWh	Mass (kg)	Power (kW)	0–100 (s)	Usable kWh	Range (km)
NEDC test cycle								
2013	20,949	153.9	6.58	1,475	51	–	–	–
2014	34,205	151.2	6.72	1,512	54	–	–	–
2015	54,235	158.9	6.56	1,592	77	–	–	–
2016	61,812	154.3	6.78	1,606	78	–	–	–
2017	90,814	146.7	7.01	1,609	79	–	–	–
WLTP test cycle (matched sample)								
2019	205,967	175.2	5.89	1,695	120	8.2	51.3	–
2020	573,628	171.4	6.00	1,736	101	8.5	54.6	370
2021	912,419	166.7	6.13	1,718	101	8.8	53.4	364
2022	1,227,613	169.4	6.01	1,838	144	8.1	59.7	397
2023	1,603,852	167.3	6.06	1,889	168	7.8	62.3	435
2024	1,531,416	164.8	6.14	1,954	184	7.1	66.4	470
2025^{p}	1,891,568	162.9	6.22	1,975	184	7.2	68.5	489

Notes: Means are weighted by registrations; km/kWh is the mean of km per kWh across specifications and is not the reciprocal of mean Wh/km. Wh/km, mass (mass in running order) and motor power are from the EEA registry; 0–100 km/h time and usable battery capacity are from EV Database variants matched to each registered specification. Consumption is measured at the charging point (it includes charging losses) on the NEDC cycle through 2017 and the WLTP cycle from 2019; 2018 mixes the two cycles and is omitted. Electric range is reported in the registry from 2020. ^{p} Provisional data.

in 2019 and 80 to 88 percent in later years. The vehicles outside it are lighter than the vehicles in it in both years. In 2019, they were slightly less efficient, at 178 against 175 Wh/km. In 2025, they were less efficient by more, at 169 against 161 Wh/km, and the largest among them are the Citroën ë-C3, the Dacia Spring, and the Peugeot 2008, for which no drag coefficient is published. The decomposition sample therefore starts from almost the same consumption as the full fleet in 2019, 174.5 against 175.2 Wh/km, ends at a lower one in 2025, 161.4 against 162.9 Wh/km, and shows a larger fall, 13.1 against 12.3 Wh/km. The technology effect is similar in the two samples, so the difference lies in the attributes of the vehicles rather than in the estimated progress.

The second check repeats the constant-price analysis on a larger sample. The system conditional on price in the Methods uses the drag-coefficient sample. Here I estimate the same three frontiers, conditional on real price, with frontal area and length in place of the drag coefficient, on all 7.9 million registrations with a matched price, usable capacity, and power. Supplementary Tables 20 to 22 report the estimates and the decompositions. The comparable specification is the one that controls for frontal area and length in all three frontiers, as the preferred specification does. In that specification, technology at constant price reduced consumption at 2019 attributes by 19 Wh/km, and heavier vehicles added back 8 Wh/km, against 21 and 9.5 on the drag-coefficient sample. The battery frontier shifted by 23 log points, against 24 on the drag-coefficient sample. The range decomposition agrees as well. On the larger sample, the shift of the battery frontier accounts for 21 log points of the increase in range, the efficiency frontier for 12, and lower real spending for −3. On the drag-coefficient sample, the corresponding numbers are 22, 13, and −2. Without frontal area and length in the frontiers, the battery-frontier shift is larger, at 32 log points. Vehicles became

larger over the period, and larger vehicles carry larger batteries, so without the size controls, the frontier absorbs part of the growth in body size.

The third check concerns the base year. The 2019 cohort is small. The registry records a consumption figure for 0.21 million battery-electric registrations of 73 variants in 2019, and the decomposition sample contains 0.17 million registrations of 32 variants. The Renault Zoe, the Tesla Model 3, and the BMW i3 account for nearly half of the 2019 decomposition sample. Consumption at fixed attributes also fell by 3.4 log points between 2019 and 2020 alone, one of the two largest changes of any year, so the choice of base year affects the size of the technology effect. Supplementary Table 2 re-runs the decompositions with 2020 as the base year. From 2020, the technology factor is 0.887, so technology reduced consumption at 2020 attributes by 19 Wh/km, compared with 25 Wh/km from 2019. The mass effect is about the same, 13.5 Wh/km rather than 13.3, because the average vehicle gained about as much mass from 2020 as from 2019, 275 kilograms rather than 271. Attributes therefore took 56 percent of the progress measured from 2020, compared with 47 percent measured from 2019, because the technology effect is smaller. The 2020-base share is less precise, with a bootstrap interval of 38 to 89 percent, because the technology effect from 2020 is smaller relative to its standard error. The main text explains why. The range decomposition keeps its shape. Measured from 2020, larger batteries account for 22 of the 31 log points of the increase in range, and the efficiency frontier for 12. I use 2019 as the base year because it is the first year of WLTP data, and I report the 2020 base so that the reader can see which results depend on the small first year.

The fourth check concerns the mass coefficient. The preferred specification holds the mass coefficient fixed over time and lets technology scale the whole load function. Supplementary Note 2 relaxes this by letting the mass coefficient vary by year. The energy cost of a kilogram then drifts down slightly, from 0.051 Wh/km in 2019 to 0.047 Wh/km in 2025, although the drift is not statistically significant, with a p-value of 0.79 against no drift. To see what the drift would mean for the decomposition, I repeat it with equation (S1), so that the added kilograms are priced at the 2025 mass coefficient. The technology effect at 2019 attributes is then 24 Wh/km rather than 25. The mass effect is 12.8 Wh/km rather than 13.3, and drag, body size, and drive configuration together reduce consumption by 1.5 Wh/km, as before. Mass therefore absorbs 52 percent of the progress rather than 53 percent. The difference is the part of the frontier shift that the year-specific model attributes to a flatter mass gradient. As Supplementary Note 2 discusses, a flatter gradient could reflect better tires and regeneration, but it could also reflect a change in which vehicles are heavy, so I do not treat it as technological progress in the preferred estimates.

The fifth check concerns the test cycle. Every estimate in the paper uses the WLTP rating from the registry. That is the rating on which manufacturers' compliance is measured, but it is not what drivers experience. Real-world consumption exceeds the rating by an amount that varies with temperature, speed, and driving style. If the gap between the two changed over the period, the frontier estimated on the rating could show technological progress that drivers never saw, or miss progress they did see.

To check this, I use a second measure of consumption. EV Database reports a real-world consumption figure for 82 of the variants in the matched data. These variants account for 3.0 million registrations, 44 percent of the decomposition sample. The figure has three limitations. First, it is not measured. EV Database models it for mild weather and a mix of city and highway driving. Second, it is the energy drawn from the battery, so it excludes the charging losses that the WLTP figure includes, and it is about 6 percent lower than the WLTP figure on average. Third, it is a single value for each variant, so it does not change across the years in which a variant was registered.

Because the real-world figure is available for only part of the sample, comparing it with the preferred estimates would mix the effect of the consumption measure with the effect of the sample. Supplementary Table 6 therefore holds the sample fixed. It re-estimates the preferred frontier and the decompositions on the registrations with a real-world figure twice, once with the WLTP rating and once with the real-world figure, so that the two columns differ only in how consumption is measured. The estimates in the first column differ from the preferred estimates because the subsample differs from the full sample. The comparison of interest is between the two columns.

With the WLTP rating, the technology factor on this subsample is 0.874. Technology reduced consumption at 2019 attributes by 22 Wh/km. Mass offset 40 percent of that progress, and the mass of larger batteries offset 24 percent. With the real-world figure, the technology factor is 0.855, so technology reduced consumption by 24 Wh/km, slightly more than with the rating. Mass offset 45 percent of the progress, and the mass of larger batteries 27 percent, nearly the same shares as with the rating. The mass coefficient is 0.039 Wh/km per kilogram with the WLTP rating and 0.051 with the real-world figure. The one share that differs is the share offset by all attributes together: 40 percent with the rating and 18 percent with the real-world figure. The difference arises because the drag, size, and drive terms reduce consumption by more when consumption is measured with the real-world figure, and those terms work in the opposite direction from mass.

The range decomposition is also similar under the two measures. Larger batteries account for 28 log points of the increase in range with the WLTP rating and 26 with the real-world figure. The efficiency frontier accounts for 14 and 16 log points.

The main conclusions therefore do not depend on the test cycle. Technology reduced consumption by about as much under either measure, mass offset about two-fifths of that progress, and larger batteries contributed more to range than the efficiency frontier. The caveat is that the real-world figure is itself the output of a model rather than a measurement, so the check shows that the results hold under a different way of rating consumption, not that they hold on the road.

The sixth check concerns the measure of range. The range decompositions use the range implied by equation (4) of the Methods, usable capacity divided by consumption, rather than the WLTP range in the registry. Because consumption is measured at the charging point, the implied range measures changes in range correctly only if the efficiency of charging did not change. The registry reports range from 2020, and Supplementary Table 7 compares the two measures on the 89 percent of the decomposition sample that has both. The reported range is about 15 percent above the

implied range, as charging losses of that size would imply. Between 2020 and 2025, the implied range rose 33 log points and the reported range rose 29. Within a variant, the ratio of the two hardly changed, falling by less than 1 log point over the period. The gap therefore comes from the variants that entered the market, which is consistent with newer models losing less energy in charging. Lower charging losses reduce consumption at the charging point, and so they are part of the shift of the efficiency frontier, but they do not add range on a charge. The implied range therefore overstates the growth in range per charge by about 4 log points, and the overstatement falls on the efficiency frontier rather than on the batteries. Measured as range per charge, and assuming that 2019 to 2020 was like the later years, the contribution of the efficiency frontier would be about 11 log points rather than 15, and the conclusion that larger batteries contributed more to range than the efficiency frontier is strengthened.

The seventh check concerns the matching of registrations to EV Database variants. The Methods chooses, among the variants whose name matches the registry's model, the one closest in mass and in the battery capacity implied by the registry's range and consumption. Because that implied capacity is built from range and consumption, the matching could tie the battery capacity used in the estimates to the outcomes the paper studies. Supplementary Table 8 repeats the matching with mass alone and with mass and power, and it re-estimates the preferred specification and the decompositions each time. With mass alone, the results are nearly unchanged. The technology effect is 25.0 Wh/km, mass offsets 52 percent of it, the mass of larger batteries 30 percent, and all attributes 47 percent. Larger batteries account for 26 log points of the increase in range and the efficiency frontier for 16. With mass and power, the shares are larger: mass offsets 63 percent of the technological progress and the mass of larger batteries 38 percent, because the mean battery in the decomposition sample grows by 22 kWh rather than 16.5. This difference comes from the sample rather than from the matching cue. The registry reports power for 2020 and 2021 mostly on a 30-minute basis, about half of peak power, which makes power a poor guide to the variant in those years. In addition, the drag coefficients were collected for the variants chosen by the main matching, so a matching that assigns registrations to other variants loses them from the decomposition sample, which requires a drag coefficient. With mass and power, the 2019 decomposition sample falls from 166,000 to 117,000 registrations, and the 2019 vehicles that remain have smaller batteries. Even so, larger batteries account for more of the increase in range than the efficiency frontier, 33 log points against 16. The matching on implied capacity therefore does not drive the results.

The last check concerns sampling uncertainty. The decompositions combine estimates from three frontiers, and their shares are ratios of estimated quantities, so they have no analytic standard error. Extended Data Table 6 reports a cluster bootstrap by make-model. Each draw resamples the 1,455 make-models of the drag-coefficient sample with replacement, keeping all of a model's registrations in every year. It then re-estimates the preferred efficiency frontier with and without price, the mass frontier with and without price, and the battery frontier, and recomputes every decomposition on the observed fleet. Holding the fleet fixed is the right choice for the question asked, because the fleet

means are the population of registrations, not a sample of it. The intervals therefore measure the uncertainty in the frontiers. The effects in Wh/km are estimated more precisely than the shares. The technology effect has an interval of 19 to 31 Wh/km and the mass effect of 9 to 18, so the share of progress absorbed by mass, their ratio, has an interval of 33 to 85 percent. The share absorbed by the mass of larger batteries has an interval of 14 to 44 percent, and the share absorbed by all attributes 30 to 67 percent. The range components are more precise: larger batteries account for 23 to 28 log points and the efficiency frontier for 12 to 19, and at constant price the battery frontier accounts for 14 to 31 and the efficiency frontier for 8 to 17. If the fleet means are also resampled, the intervals are wider: 19 to 88 percent for the share absorbed by mass, 10 to 46 percent for the mass of larger batteries, and 8 to 79 percent for all attributes. With either choice, the 95 percent interval for the technology effect is about 19 to 32 Wh/km. With the fleet held fixed, the share of progress absorbed by attributes is positive in every draw, and larger batteries contribute more to the increase in range than the efficiency frontier in every draw. With the fleet resampled as well, these hold in 99 and 88 percent of draws.

Supplementary Table 5 also reports the heat pump checks. Added to the preferred specification, a standard heat pump enters at 9 Wh/km, statistically significant at the 1 percent level. Within make-model-year, comparing trims of the same model in the same year, the coefficient is -2.3 Wh/km. Across models, the heat pump marks brands whose vehicles use more energy for other reasons, so I leave it out of the preferred load function. With brand fixed effects in the technology factor, in column (4), the drag-area coefficient falls to 50 Wh/km per square meter and the frontal-area term goes to zero. The mass coefficient, 0.052, the all-wheel-drive coefficient, 10.9, and the technology factor, 0.860, are about unchanged. The drag-area coefficient is therefore identified mostly across brands. The torque coefficient is also unchanged with brand fixed effects.

Supplementary Note 2: Neutral and factor-augmenting technical change

The year effects in equation (2) of the Methods represent Hicks-neutral technological progress: one factor multiplies the entire load function. The physics suggests that factor-augmenting progress may be present in two of the terms. The mass term could fall over time as tires and regenerative brakes improve. The term representing auxiliary systems might fall through such technologies as heat pumps. The physics also implies that the drag term should remain constant. This appendix investigates whether the data can identify these more specific sources of technological progress by letting the coefficients of the load function vary by year. Supplementary Table 9 reports two versions, and Supplementary Fig. 1 plots the mass coefficient from each.

Panel A estimates the load function separately in each year, so that every coefficient carries a year subscript and no neutral factor is imposed. This is the least restrictive specification and the least informative one: the neutral factor and the factor-specific changes cannot be separated, since a proportional fall in every coefficient is neutral progress, and anything else is not, and the

Supplementary Table 4. Decomposition of the change in consumption and range, 2019 to 2025, physics form

	Mass	Mass, size
Panel A: consumption, Wh/km		
Fleet mean, 2019	175.2	175.2
Fleet mean, 2025	162.9	162.8
Technology factor, $e^{a_{2025}}$	0.865	0.850
Technology effect at 2019 attributes	-23.6	-26.4
Counterfactual 2025 at 2019 attributes	151.7	149.2
Attribute effect of mass, at 2025 technology	11.1	14.6
Attribute effect of frontal area		3.1
Attribute effect of length		-4.2
Panel B: range, log points		
Change in mean ln range	39.4	39.3
Larger batteries, net of their mass penalty	24.1	25.3
Efficiency frontier shift	14.5	16.3
Mass frontier shift (lighter at given battery, power, and size)	0.3	-0.2
Other (power and size entering mass and consumption directly, residuals)	0.5	-2.0
Change in mean ln usable capacity	32.2	32.1
Memo: kilograms per usable kWh, κ	16.8	10.4
Memo: pass-through of capacity to range	0.75	0.79

Notes: Panel A uses the physics-form efficiency frontier with mass alone and with mass, frontal area, and length, estimated on all 7.9 million WLTP registrations with dimensions. The technology effect is $(e^{a_{2025}} - 1)$ times the 2019 load function at 2019 mean attributes; each attribute effect is $e^{a_{2025}} b$ times the change in the attribute's registration-weighted mean. Panel B applies the sequential counterfactuals described in the text to every 2019 specification: capacity is raised by the change in mean log capacity with mass following at κ kilograms per kWh and consumption at b_m Wh/km per kilogram, then the 2025 technology factor replaces the 2019 factor, then the 2025 intercept of the levels mass frontier replaces the 2019 intercept; the remainder is the other row. Samples: 7.9 million registrations in both columns. Supplementary Table 15 reports the log-linear decomposition.

Supplementary Table 5. The heat pump indicator in the efficiency frontier

	(1) Physics form, preferred + HP	(2) Linear, year effects	(3) Linear, within make-model-year	(4) Physics form, brand effects
b_m, mass (kg)	0.066^{***}	0.060^{***}	0.046^{***}	0.052^{***}
	(0.008)	(0.007)	(0.011)	(0.007)
b_{C_dA}, drag area (m^2)	109.4^{***}	95.8^{***}	113.2^{**}	49.8^{**}
	(15.5)	(13.7)	(46.3)	(24.8)
b_A, frontal area (m^2)	-24.3^{***}	-21.7^{***}	-39.2	4.2
	(6.9)	(6.2)	(24.0)	(8.7)
b_L, length (m)	-12.9^{*}	-12.2^{*}	42.0^{**}	-9.3
	(7.3)	(6.6)	(17.6)	(5.7)
b_{AWD}, all-wheel drive (0/1)	9.2^{***}	8.0^{***}	4.9^{***}	10.9^{***}
	(1.8)	(1.6)	(1.5)	(1.4)
b_{HP}, heat pump standard (0/1)	9.1^{***}	8.2^{***}	-2.3^{**}	1.3
	(2.1)	(1.8)	(1.1)	(1.6)
a_{2025}	-0.167^{***}			-0.151^{***}
	(0.017)			(0.015)
Technology factor, $e^{a_{2025}}$	0.847			0.860
Registrations (millions)	6.71	6.71	1.18	6.71
Make-models	1455	1455	72	1455

Notes: Column (1) adds an indicator for a standard heat pump to the preferred specification, column (5) of Extended Data Table 2, by nonlinear least squares. Column (2) is the linear specification Wh/km $= \alpha_t + b'x$ on the same sample, and column (3) the same with make-model-year fixed effects, estimated on the registrations of model-years sold both with and without a standard heat pump, so that the heat pump coefficient compares trims of the same model in the same year. Column (4) is the physics form of column (1) with brand fixed effects in the technology factor, Wh/km $= e^{a_t + f_b}(b_0 + b'x)$, so that every coefficient is identified within brand. In the linear specifications the coefficients are not divided by the technology factor, so they are smaller than the physics-form coefficients by the registration-weighted mean of e^{a_t}, about 0.9. Weights are registrations; standard errors clustered by make-model in parentheses. *, **, ***: significant at 10, 5, and 1 percent.

Supplementary Table 6. The preferred frontier and decomposition with WLTP and real-world consumption, on the registrations with a real-world figure

	WLTP rating	Real-world (EV Database)
Panel A: efficiency frontier, column (5) of Extended Data Table 2		
b_m, mass (kg)	0.039^{***}	0.051^{***}
	(0.014)	(0.018)
b_{C_dA}, drag area (m^2)	161.7^{***}	183.6^{***}
	(28.3)	(38.1)
b_{AWD}, all-wheel drive (0/1)	15.2^{***}	10.9
	(3.5)	(8.0)
a_{2025}	-0.135^{***}	-0.156^{***}
	(0.025)	(0.027)
Technology factor, $e^{a_{2025}}$	0.874	0.855
Panel B: consumption decomposition, 2019 to 2025 (Wh/km)		
Mean consumption, 2019	171.8	167.7
Mean consumption, 2025	159.1	148.2
Technology, at 2019 attributes	−21.7	−24.3
Mass, at 2025 technology	8.6	10.9
of which larger batteries	5.3	6.7
Attributes, total	8.6	4.5
Share of the technology effect absorbed by mass	0.40	0.45
by the mass of larger batteries	0.24	0.27
by all attributes	0.40	0.18
Panel C: range decomposition, 2019 to 2025 (log points)		
Change in mean log range	0.384	0.445
Larger batteries, net of their mass penalty	0.275	0.262
Efficiency frontier shift	0.135	0.156
Change with 2019 batteries	0.123	0.184
Registrations (millions)	2.95	2.95
EV Database variants	82	82
R^2	0.630	0.447

Notes: Both columns use the registrations of the decomposition sample whose matched EV Database variant reports a real-world consumption figure. The first column uses the WLTP rating from the registry, measured at the charging point; the second replaces it with EV Database's real-world figure, which is consumption from the battery modeled for mild weather and mixed driving, and so excludes charging losses. The real-world figure is one value per variant and does not vary across registration years. The mass frontier is column (3) of Extended Data Table 5. Standard errors clustered by make-model in parentheses. *, **, ***: significant at 10, 5, and 1 percent.

Supplementary Table 7. Implied and reported WLTP range on the decomposition sample

Year	Share with reported range	Mean log implied range	Mean log reported range	Mean log ratio	Median ratio	Within-variant log ratio
2020	0.66	5.731	5.920	0.189	1.167	0.000
2021	0.78	5.758	5.933	0.175	1.153	−0.002
2022	0.80	5.860	6.021	0.161	1.148	−0.008
2023	1.00	5.940	6.099	0.158	1.149	−0.008
2024	1.00	6.014	6.169	0.155	1.148	−0.009
2025	0.98	6.064	6.212	0.148	1.144	−0.008
Change, 2020 to 2025		0.334	0.293	−0.041		−0.008

Notes: Implied range is $1000\,K/E$, with K the usable battery capacity of the matched variant and E the WLTP consumption at the charging point from the registry; it is the range the decompositions use. Reported range, available from 2020, is the WLTP electric range in the registry. The ratio is reported over implied range; it exceeds one mainly because E includes charging losses. The within-variant log ratio is the year effect, relative to 2020, from a regression of the log ratio on variant and year effects. The sample is the decomposition sample of Extended Data Table 4, restricted to registrations with a reported range; means are weighted by registrations.

Supplementary Table 8. Decompositions under alternative matching of registrations to EV Database variants

	Main: mass and implied capacity	Mass only	Mass and power
Registrations matched (share)	0.99	0.99	0.99
Decomposition sample (million registrations)	6.65	6.30	5.99
of which 2019 (thousands)	166	166	117
Change in mean usable capacity (kWh)	16.5	16.9	21.6
Kilograms per usable kWh, κ	8.9	9.0	9.0
Technology factor	0.857	0.857	0.851
Technology effect (Wh/km)	24.9	25.0	25.7
Mass effect (Wh/km)	13.3	13.1	16.2
of which larger batteries	7.3	7.4	9.7
Share of progress offset by mass	0.53	0.52	0.63
by the mass of larger batteries	0.29	0.30	0.38
by all attributes	0.47	0.47	0.56
Change in mean log range	0.375	0.379	0.462
larger batteries, net of mass	0.252	0.255	0.333
efficiency frontier	0.154	0.155	0.161
battery frontier, at constant price	0.221	0.235	0.279
efficiency frontier, at constant price	0.126	0.122	0.125

Notes: Each column matches the registry to EV Database variants by make and model name and then chooses the nearest variant on the criteria in the heading, rebuilds the analysis file, and re-estimates the preferred specification, column (5) of Extended Data Table 2, with its mass and battery frontiers. The main matching uses mass and the usable capacity implied by the registry's range and consumption (range × Wh/km × 0.85). Mass and power uses the registry's power where it is reported; in 2020 and 2021 the registry reports most power on a 30-minute basis, about half of peak power. The drag coefficients were collected for the variants of the main matching, so an alternative matching that assigns registrations to other variants loses them from the decomposition sample, which requires a drag coefficient. Consumption decomposition as in Extended Data Table 4, range decomposition as in Extended Data Table 7, both 2019 to 2025.

year-by-year cross-sections are small early in the period, with 103 make-models in 2019. Panel B imposes the structure the physics suggests. It keeps the neutral factor e^{a_t} and lets only the mass coefficient vary by year:

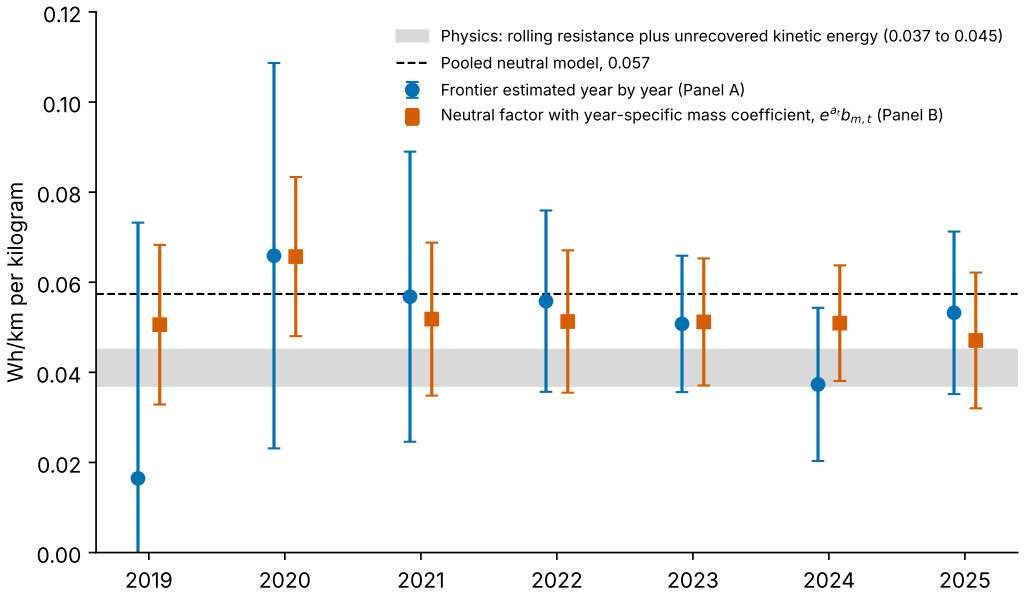
$$E_{it} = e^{a_t}\left(b_0 + b_{m,t}\, m_{it} + b_{C_dA}\, C_d A_{it} + b_A\, A_{it} + b_L\, L_{it} + b_{AWD}\, AWD_{it}\right) + \varepsilon_{it}. \tag{S1}$$

The drag, size, and drive terms are the numeraire: a_t is identified from them, and $b_{m,t}$ is the mass coefficient relative to them, so that $b_{m,t}/b_{m,2019}$ is the mass-augmenting factor and e^{a_t} the Hicks-neutral factor. The product $e^{a_t}b_{m,t}$ is the energy cost of a kilogram in year t in Wh/km, and it is the quantity the decomposition uses. Neutrality is the restriction that $b_{m,t}$ is the same in every year.

Supplementary Fig. 1 shows both series against the pooled coefficient of 0.057 and against the band that the physics implies for rolling resistance plus unrecovered kinetic energy, 0.037 to 0.045 Wh/km per kilogram. The results suggest that the mass coefficient may be getting slightly smaller over time, but the results are not statistically distinguishable from no change. In Panel B, $e^{a_t}b_{m,t}$ is 0.051 Wh/km per kilogram in 2019, between 0.051 and 0.066 from 2020 to 2024, and 0.047 in 2025, with standard errors of 0.007 to 0.009. The Wald test that the seven mass coefficients are equal has a p-value of 0.79, and the fit improves only from an R^2 of 0.619 to 0.622. The year-by-year estimates of Panel A tell the same story with wider bands: 0.051 to 0.066 from 2020 to 2023, and 0.037 and 0.053 in 2024 and 2025.

Two things keep me from reading the drift as mass-augmenting progress. The first is identification. Once the mass coefficient is free to move, the neutral factor is identified only from the drag, size, and drive terms, and it is poorly identified: the standard errors on a_t in Panel B are 0.14 to 0.25, eight to fourteen times those of the neutral model, and the point estimates wander from 0.63 in 2020 to 0.79 in 2025. Read literally, Panel B says that consumption at fixed attributes fell 21 percent through the drag term while the mass coefficient rose 18 percent, a split that the data cannot pin down. The intercept and the mass slope trade off against each other in a cross-section where mass varies over a narrow range relative to its mean, and a model that lets the mass slope move cannot tell a flatter slope from a higher intercept. The second is composition. The year-specific slopes are the cross-sectional gradients of fleets whose composition changed. In 2024 and 2025 the heavy vehicles are the efficient premium models and the light vehicles are the inexpensive models with the least efficient drivetrains, and that gradient flattens as the inexpensive segment grows, whatever happened to tires. A coefficient at the rolling-resistance floor in 2024 is consistent with better tires and regeneration, and equally with a fleet in which mass and drivetrain quality have become positively correlated.

What survives is the conclusion that matters for the decomposition. The shift of the frontier evaluated at 2019 attributes is 25 Wh/km in the neutral model and 24 Wh/km in equation (S1), the difference being that the latter attributes part of the change to a flattening of the mass gradient that composition can produce as well as technology. Progress in the drivetrain and the charger, which is neutral, is where the data and the physics agree that the progress came from. Tires and



Supplementary Fig. 1. The energy cost of a kilogram by year. Circles: the mass coefficient from the load function estimated separately in each year (Supplementary Table 9, Panel A). Squares: $e^{a_t}b_{m,t}$ from the model with a neutral factor and a year-specific mass coefficient (Panel B). Bars are 95 percent confidence intervals from standard errors clustered by make-model. The dashed line is the pooled coefficient of the neutral model, and the shaded band is the range that the physics of the Methods implies for rolling resistance plus unrecovered kinetic energy at the plug.

regeneration may have contributed, and the sign of the drift says they did, but the cross-section cannot measure how much, and a panel of models re-tested on new tires would be needed to do so. I therefore keep the neutral model as the preferred specification and report the decomposition with the year-specific mass coefficient as a robustness check in Supplementary Note 1.

Supplementary Note 3: The log-linear frontier and system

For comparison with Knittel [1], I estimate the log-linear specification of that paper:

$$\ln \text{eff}_{it} = a_t + \beta_m \ln m_{it} + \beta_p \ln p_{it} + \beta_s' \ln s_{it} + \varepsilon_{it}, \tag{S2}$$

where eff_{it} is km per kWh, p is motor power, and s collects frontal area and length, and the log form of the mass frontier:

$$\ln m_{it} = c_t + \gamma_k \ln K_{it} + \gamma_p \ln p_{it} + \gamma_s' \ln s_{it} + u_{it}. \tag{S3}$$

The physics form is the preferred specification; the log-linear form imposes a constant mass elasticity, which the physics and the translog estimates reject. Supplementary Table 10 reports the log-linear efficiency frontier on the full sample, with frontal area and length as the size controls,

Supplementary Table 9. Year-specific coefficients of the efficiency frontier: neutral and factor-augmenting technical change

	2019	2020	2021	2022	2023	2024	2025
Panel A: the load function estimated separately in each year							
$b_{0,t}$, fixed load (Wh/km)	−130.8	33.6	62.0	88.6***	89.2***	70.4***	122.1***
	(109.9)	(47.1)	(41.4)	(26.5)	(23.5)	(26.4)	(25.9)
$b_{m,t}$, mass (kg)	0.016	0.066***	0.057***	0.056***	0.051***	0.037***	0.053***
	(0.029)	(0.022)	(0.016)	(0.010)	(0.008)	(0.009)	(0.009)
$b_{C_dA,t}$, drag area (m^2)	425.0***	160.8***	178.5***	122.4***	88.9***	74.7***	67.9***
	(138.3)	(60.4)	(33.7)	(17.7)	(16.1)	(17.3)	(17.9)
$b_{A,t}$, frontal area (m^2)	−140.2***	−48.6	−59.0***	−38.7***	−19.1***	−2.2	−14.1**
	(53.7)	(49.2)	(22.2)	(9.7)	(7.2)	(7.1)	(5.7)
$b_{L,t}$, length (m)	77.4**	6.8	6.1	−3.1	−8.3	−7.6	−18.0**
	(37.3)	(20.6)	(9.6)	(7.9)	(7.1)	(8.6)	(8.4)
$b_{AWD,t}$, all-wheel drive (0/1)	16.4	14.4	13.5**	12.4***	9.7***	9.4***	7.6***
	(10.8)	(12.2)	(5.4)	(2.3)	(1.6)	(1.9)	(1.5)
Make-models	103	206	282	358	451	577	669
Registrations (millions)	0.18	0.52	0.76	1.03	1.38	1.33	1.51
R^2	0.690	0.577	0.597	0.701	0.670	0.621	0.628
Panel B: neutral factor with a year-specific mass coefficient, equation (S1)							
$b_{m,t}$, mass (kg)	0.051***	0.104***	0.062***	0.062***	0.065***	0.068***	0.060***
	(0.009)	(0.038)	(0.017)	(0.016)	(0.015)	(0.016)	(0.016)
a_t, neutral factor (log points, 2019 = 0)	0	−0.460*	−0.176	−0.193	−0.236*	−0.292**	−0.237
		(0.246)	(0.148)	(0.136)	(0.136)	(0.147)	(0.152)
$e^{a_t}b_{m,t}$, Wh/km per kilogram in year t	0.051***	0.066***	0.052***	0.051***	0.051***	0.051***	0.047***
	(0.009)	(0.009)	(0.009)	(0.008)	(0.007)	(0.007)	(0.008)
e^{a_t}, neutral factor	1.00	0.63	0.84	0.82	0.79	0.75	0.79
$b_{m,t}/b_{m,2019}$, mass-augmenting factor	1.00	2.06	1.22	1.23	1.28	1.35	1.18
Constant coefficients: b_0 = 97.1 (29.1), b_{C_dA} = 128.1 (27.7), b_A = −29.3 (10.4), b_L = −6.7 (8.5), b_{AWD} = 12.4 (2.3)							
Wald test that $b_{m,t}$ is equal across years: $\chi^2(6) = 3.1$, $p = 0.790$. $R^2 = 0.622$, against 0.619 in the pooled neutral model, where b_m = 0.057 (0.008).							

Notes: Panel A estimates the load function of the preferred specification by weighted least squares separately in each year, so every coefficient may change from year to year and no neutral factor is imposed; a neutral factor is not separately identified in this panel. Panel B estimates the physics form on 2019 to 2025 by nonlinear least squares with a neutral factor e^{a_t} and a mass coefficient that varies by year, with the other coefficients constant; a_t is then identified from the drag, size, and drive terms, and $b_{m,t}$ is the mass coefficient relative to them. The row $e^{a_t}b_{m,t}$ is the energy cost of a kilogram in year t in Wh/km, with delta-method standard errors, and is the quantity that the decomposition uses. Weights are registrations; standard errors clustered by make-model in parentheses. Sample: the drag-coefficient sample, 6.73 million registrations. *, **, ***: significant at 10, 5, and 1 percent.

since the drag coefficient is a level quantity that enters the physics form and not a log-linear one. Column (1) includes mass and power; this is the specification closest to the original paper. Column (2) adds the log of real price, column (3) adds frontal area and length, column (4) adds both, column (5) estimates within make-model, and column (6) estimates on the NEDC-era data for 2013 to 2017. Supplementary Table 11 reports the specification with mass alone and the one with acceleration time in place of power.

The mass elasticity is −0.52 in column (1) and −0.54 in column (3), both significant at 1 percent. Both are at the upper end of the range the physics predicts for a vehicle with effective regenerative braking, and both are close to the weight elasticity of fuel economy in the internal combustion fleet, which was about −0.4 to −0.5 in Knittel[1]. The within-model estimate in column (5) is larger at −0.85. Within a model, mass varies with battery size and with the addition of a second motor, and these come with larger wheels, wider tires, and performance trims that raise rolling resistance and drag, so the within-model estimate combines the physical mass effect with the effect of what tends to accompany mass. The NEDC-era elasticity in column (6) is −0.55.

Power does not raise consumption in any column. The point estimate is 0.070 in column (1), significant at 5 percent, 0.037 in column (3), not significant, −0.006 within model, and −0.016 in the NEDC era. Since the dependent variable is km per kWh, the positive estimate in column (1) means that more powerful vehicles are, if anything, more efficient at a given mass. It falls by about half and loses significance once frontal area and length are added, so it likely reflects the body shapes of the more powerful models rather than the motor. Acceleration time in Supplementary Table 11 gives the same answer from a different measure: the coefficient on log seconds to 100 km/h is −0.07 and not statistically significant, so quicker vehicles are, if anything, slightly more efficient conditional on mass. This is the prediction of the Methods, and it is the central difference from the internal combustion frontier, in which horsepower carried an elasticity of about −0.3 and torque a further −0.1.

The size controls in column (3) have the predicted signs. Frontal area enters at −0.36, significant at 5 percent and somewhat above the range the aerodynamic share of energy implies. Length enters positively at 0.46, significant at 5 percent: conditional on mass and frontal area, a longer vehicle is a lower and more streamlined one, and the coefficient is picking up the drag coefficient that the data do not record. Supplementary Table 13 shows that the mass elasticity rises with mass, from −0.37 in the lightest tercile of the 2020 fleet to −1.04 in the heaviest. The translog specification gives the same picture, with an elasticity of about zero at 1,200 kg, −0.25 at 1,500 kg, −0.50 at 1,800 kg and −0.90 at 2,400 kg, and year effects nearly identical to the Cobb-Douglas. An elasticity that rises with mass is what equation (2) of the Methods implies, and it is a reason to prefer the physics form.

The year effects in columns (1) and (3) rise from zero in 2019 to 0.13 and 0.14 in 2025, significant at 1 percent, with most of the increase in 2020 and 2021 and again in 2024. With price, in columns (2) and (4), they reach 0.07; the log-linear form attributes more of the shift to price than the physics form does, because its mass elasticity falls by 40 to 60 percent when price is added. The within-

Supplementary Table 10. The efficiency frontier: ln(km per kWh) on vehicle attributes and year effects

	(1)	(2)	(3)	(4)	(5)	(6)
	Mass power	Mass power price	Mass power size	Mass power size price	Within model	NEDC 2013–17
ln mass	−0.522***	−0.296***	−0.537***	−0.222*	−0.850***	−0.547***
	(0.075)	(0.076)	(0.128)	(0.125)	(0.164)	(0.118)
ln power	0.070**	0.101***	0.037	0.066***	−0.006	−0.016
	(0.033)	(0.033)	(0.023)	(0.022)	(0.012)	(0.041)
ln frontal area (width × height)			−0.359**	−0.479***		
			(0.169)	(0.162)		
ln length			0.464**	0.510***		
			(0.189)	(0.156)		
ln real price		−0.182***		−0.227***		
		(0.033)		(0.036)		
2020	0.040*	0.018	0.037*	0.008	0.026*	
	(0.024)	(0.025)	(0.021)	(0.024)	(0.014)	
2021	0.060***	0.038*	0.065***	0.037	0.030	
	(0.022)	(0.023)	(0.021)	(0.023)	(0.019)	
2022	0.063***	0.033	0.069***	0.033	0.048**	
	(0.021)	(0.022)	(0.021)	(0.022)	(0.019)	
2023	0.084***	0.049**	0.092***	0.049**	0.058***	
	(0.021)	(0.022)	(0.021)	(0.023)	(0.020)	
2024	0.113***	0.067***	0.121***	0.064***	0.083***	
	(0.021)	(0.022)	(0.021)	(0.023)	(0.021)	
2025	0.130***	0.074***	0.141***	0.073***	0.099***	
	(0.022)	(0.024)	(0.022)	(0.025)	(0.022)	
2014						0.043**
						(0.020)
2015						0.040
						(0.036)
2016						0.063*
						(0.036)
2017						0.112***
						(0.025)
Specification-years	570,310	570,310	568,634	568,634	570,310	1,679
Registrations	7,881,553	7,881,553	7,869,627	7,869,627	7,881,553	192,814
R^2	0.368	0.404	0.412	0.465	0.251	0.353
Years	2019-2025	2019-2025	2019-2025	2019-2025	2019-2025	2013-2017

Notes: Weighted least squares with registrations as weights; standard errors clustered by make-model in parentheses. Frontal area (width × height) and length are from EV Database and open-ev-data variants matched to each registered specification. Columns (2) and (4) add the log of the real list price of the matched variant, deflated by the euro-area HICP to 2019 prices. Column (5) demeans within make-model. Column (6) uses the NEDC-era data; its year effects are relative to 2013. Supplementary Table 11 reports the specifications with mass alone and with acceleration time in place of power. *, **, ***: significant at 10, 5, and 1 percent.

Supplementary Table 11. The log-linear efficiency frontier with mass alone and with acceleration time

	(1) Mass	(2) Mass 0–100 time
ln mass	−0.380***	−0.462***
	(0.041)	(0.062)
ln 0–100 km/h time		−0.074
		(0.047)
2020	0.025	0.038*
	(0.020)	(0.021)
2021	0.046**	0.055***
	(0.019)	(0.020)
2022	0.055***	0.062***
	(0.021)	(0.020)
2023	0.078***	0.085***
	(0.022)	(0.020)
2024	0.107***	0.112***
	(0.021)	(0.020)
2025	0.123***	0.129***
	(0.024)	(0.022)
Specification-years	583,006	572,989
Registrations	8,050,790	7,946,463
R^2	0.333	0.357
Years	2019-2025	2019-2025

Notes: Weighted least squares with registrations as weights; standard errors clustered by make-model in parentheses. WLTP sample, 2019–2025. *, **, ***: significant at 10, 5, and 1 percent.

model year effects in column (5) reach 0.10. The frontier moved out by 13 to 14 log points over six years, or about 2 percent per year. The NEDC-era frontier moved out by 11 log points between 2013 and 2017, or about 2.8 percent per year, but the estimate is imprecise, with a standard error of 2.5 log points, and the NEDC fleet is small.

The log-form results in Supplementary Table 14 are similar to these results. A 10 percent increase in usable battery capacity raises mass by 4.4 percent in the cross-section and by 2.7 percent holding frontal area and length fixed, both significant at 1 percent. Power adds little mass; the elasticity is 0.06 with size controls, and a second motor is light relative to the battery that feeds it. The year effects are small and not statistically significant: a vehicle of given battery capacity and power was 1.3 log points lighter in 2025 than in 2019 without size controls, 0.2 points lighter with them, and 0.8 points lighter within model.

Substituting the log-linear mass frontier (S3) into the log-linear efficiency frontier (S2) and taking registration-weighted means gives:

$$\Delta\overline{\ln \text{eff}} = \underbrace{\Delta a + \beta_m \Delta c}_{\text{technology}} + \underbrace{\beta_m \gamma_k \, \Delta\overline{\ln K}}_{\text{larger batteries}} + \underbrace{(\beta_p + \beta_m \gamma_p) \, \Delta\overline{\ln p}}_{\text{more power}} + \underbrace{(\beta_s + \beta_m \gamma_s)' \, \Delta\overline{\ln s}}_{\text{size}}, \tag{S4}$$

Supplementary Table 12. Attributes that should not shift the efficiency frontier conditional on mass and size, log-linear form

	(1) Battery kWh	(2) Battery kWh	(3) Torque	(4) LFP chemistry
ln mass	−0.700***	−0.662***	−0.407***	−0.543***
	(0.097)	(0.138)	(0.154)	(0.112)
ln power	0.054	0.027	0.030	0.040*
	(0.034)	(0.025)	(0.041)	(0.023)
ln frontal area		−0.333*	−0.438***	−0.333*
		(0.176)	(0.153)	(0.194)
ln length		0.422**	0.306	0.490*
		(0.195)	(0.366)	(0.270)
ln usable battery kWh	0.129**	0.094*		
	(0.056)	(0.051)		
ln torque			−0.013	
			(0.044)	
LFP cathode (0/1)				−0.013
				(0.033)
2025 year effect	0.119***	0.132***	0.132***	0.153***
	(0.021)	(0.021)	(0.024)	(0.024)
Specification-years	570,310	568,634	440,388	458,965
Registrations	7,881,553	7,869,627	5,554,071	6,145,418
R^2	0.386	0.421	0.416	0.421

Notes: Dependent variable is ln(km per kWh); WLTP sample, 2019–2025; year effects included; weighted least squares with registrations as weights; standard errors clustered by make-model. Usable battery capacity, torque and cathode chemistry are from EV Database and open-ev-data variants matched to each registered specification.

Supplementary Table 13. The efficiency frontier by mass segment

	(1) Light (<1,577 kg)	(2) Middle	(3) Heavy (>1,794 kg)
ln mass	−0.374**	0.239	−1.037***
	(0.176)	(0.224)	(0.112)
ln power	0.041	−0.029	0.014
	(0.044)	(0.020)	(0.013)
2025 year effect	0.083	0.093*	0.126***
	(0.062)	(0.048)	(0.032)
Specification-years	22,123	20,735	515,057
Registrations	1,533,335	1,259,715	4,790,715
R^2	0.272	0.057	0.542

Notes: Segments are terciles of the 2020 registration-weighted mass distribution. WLTP sample, 2019–2025; weighted least squares; standard errors clustered by make-model.

Supplementary Table 14. The mass frontier: ln(mass) on battery capacity, performance, size and year effects

	(1)	(2)	(3)	(4)	(5)
	kWh power	kWh 0–100 time	kWh power size	kWh power size LFP	Within model
ln usable battery kWh	0.443***	0.468***	0.269***	0.275***	0.154***
	(0.036)	(0.026)	(0.041)	(0.057)	(0.014)
ln power	0.061**		0.058**	0.041	0.018***
	(0.026)		(0.024)	(0.030)	(0.005)
ln 0–100 km/h time		−0.074**			
		(0.034)			
ln frontal area			0.595***	0.473***	
			(0.139)	(0.134)	
ln length			0.395***	0.677***	
			(0.138)	(0.100)	
LFP cathode (0/1)				−0.042*	
				(0.022)	
2020	−0.019	−0.015	−0.001	0.023	−0.007*
	(0.021)	(0.019)	(0.022)	(0.017)	(0.004)
2021	−0.007	−0.009	0.006	0.023	−0.007
	(0.021)	(0.019)	(0.020)	(0.019)	(0.005)
2022	−0.007	−0.004	0.004	0.028	−0.009*
	(0.023)	(0.020)	(0.022)	(0.021)	(0.005)
2023	−0.006	−0.002	−0.001	0.028	−0.009*
	(0.024)	(0.021)	(0.023)	(0.021)	(0.005)
2024	−0.007	−0.005	0.001	0.027	−0.008
	(0.023)	(0.021)	(0.022)	(0.021)	(0.005)
2025	−0.013	−0.011	−0.002	0.026	−0.008
	(0.023)	(0.021)	(0.022)	(0.021)	(0.005)
Specification-years	570,310	572,989	568,634	458,965	570,310
Registrations	7,881,553	7,946,463	7,869,627	6,145,418	7,881,553
R^2	0.857	0.855	0.913	0.923	0.552

Notes: WLTP sample, 2019–2025; weighted least squares with registrations as weights; standard errors clustered by make-model. Column (5) demeans within make-model.

Supplementary Table 15. Decomposition of the change in fleet-average efficiency and range, 2019–2025 (log points × 100)

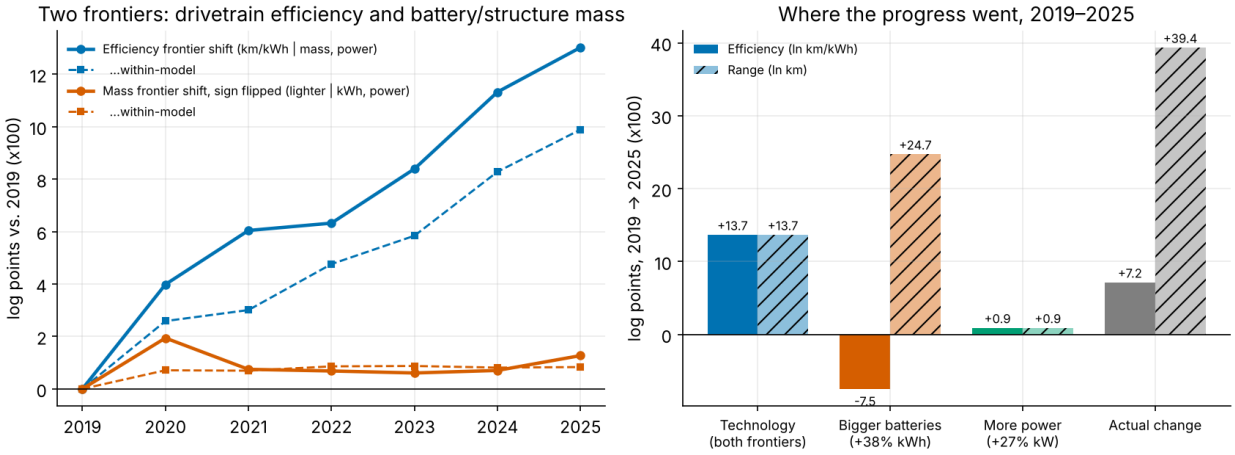
	Mass and power		Mass, power, and size	
	Efficiency	Range	Efficiency	Range
Technology: efficiency frontier shift, a_t	+13.0	+13.0		
Technology: lighter construction, $\beta_m c_t$	+0.7	+0.7		
Technology: total	+13.7	+13.7	+14.2	+14.2
Larger batteries	-7.5	+24.7	-4.6	+27.5
More power	+0.9	+0.9	+0.1	+0.1
Larger frontal area and length			-2.5	-2.5
Actual change	+7.2	+39.4	+7.2	+39.3
Change in usable kWh (percent)	38		38	
Change in power (percent)	27		27	
Change in frontal area (percent)	–		5.4	
Change in length (percent)	–		4.1	
Registrations covered	7.9 million		7.9 million	

Notes: Each column decomposes the change between 2019 and 2025 in the registration-weighted mean of ln(km per kWh) or ln(range) using the elasticities from Supplementary Tables 10 and 14: column (1) of each table for the first pair and column (3) of each, which adds frontal area and length, for the second. The efficiency decomposition is exact. The range decomposition uses the identity ln range = ln kWh + ln(km per kWh) + constant.

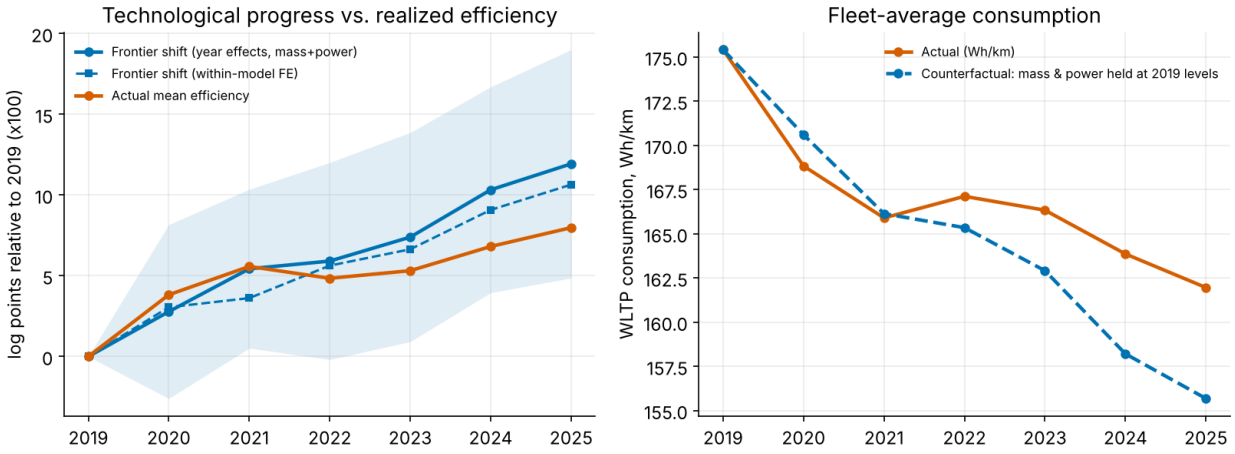
and, through the identity, the corresponding decomposition of range, in which the battery term becomes $(1+\beta_m\gamma_k)\Delta\overline{\ln K}$. Supplementary Table 15 reports it for 2019 to 2025 using column (1) of Supplementary Table 10 and column (1) of Supplementary Table 14, and the size-controlled columns of each, and Supplementary Fig. 2 shows the year effects of the two frontiers and the decomposition. In the mass-and-power specification, technology moved the efficiency frontier out by 13.0 log points and lighter construction added 0.7 points, for 13.7 points of technological progress. The fleet realized 7.2 points, because the mass of batteries 38 percent larger cost 7.5 points, while more power added 0.9. With size controls the technology term is 14.2 points, larger batteries cost 4.6, and size 2.5. Range rose 39.4 log points, of which 24.7 came from larger batteries and 13.7 from technology.

With the efficiency and mass frontiers in the log-linear form of equations (S2) and (S3), each with $\ln P$ added, and the battery frontier of equation (5) of the Methods, substituting the battery frontier into the mass frontier, the mass frontier into the efficiency frontier, and both into the identity $\ln R = \ln K + \ln \text{eff} + \text{constant}$, and taking registration-weighted means, gives:

$$\begin{aligned}\Delta\overline{\ln R} = {} & \underbrace{(1+\beta_m\gamma_k)\,\Delta d}_{\text{battery frontier}} + \underbrace{(1+\beta_m\gamma_k)\,\delta_p\,\Delta\overline{\ln p}}_{\text{battery bundled with power}} + \underbrace{(1+\beta_m\gamma_k)\,\delta_P\,\Delta\overline{\ln P}}_{\text{battery from spending}} \\ & + \underbrace{\Delta a}_{\text{efficiency frontier}} + \underbrace{\beta_m \Delta c}_{\text{mass frontier}} \\ & + \underbrace{(\beta_p+\beta_m\gamma_p)\,\Delta\overline{\ln p} + (\theta+\beta_m\gamma_P)\,\Delta\overline{\ln P} + \left(\beta_s+\beta_m\gamma_s+(1+\beta_m\gamma_k)\,\delta_s\right)'\Delta\overline{\ln s}}_{\text{other}},\end{aligned} \tag{S5}$$



Supplementary Fig. 2. Left: year effects of the efficiency frontier (Supplementary Table 10, columns 1 and 5) and of the mass frontier with the sign reversed (Supplementary Table 14, columns 1 and 5). Right: decomposition of the 2019–2025 change in mean log efficiency and mean log range from the first pair of columns of Supplementary Table 15.



Supplementary Fig. 3. Left: the log-linear efficiency frontier shift (year effects of Supplementary Table 10, columns 1 and 5, with the 95 percent confidence band for column 1) against the actual change in registration-weighted mean log efficiency. Right: actual fleet-average consumption and the counterfactual with mass and power held at 2019 levels, from the log-linear frontier.

where γ_P and θ are the price coefficients of the mass and efficiency frontiers. The factor $1+\beta_m\gamma_k$ is the log-linear counterpart of equation (8) of the Methods and is 0.91 to 0.96 in the estimates with price. The residual is zero by construction because each frontier is estimated by least squares on the same sample. Supplementary Table 17 reports the decomposition. It differs from the physics-system decomposition in Supplementary Table 21 mainly in the efficiency-frontier term, which is about 7 log points in the log-linear system against 12 in the physics form, because the log-linear year effects conditional on price are smaller, and in the mass elasticity, which with price is -0.30 without size controls and -0.22 with them, against the physics-form mass coefficient that the calibration supports.

Supplementary Note 4: The system without the drag coefficient on the full sample

The tables in this appendix report the specifications without the drag coefficient, with frontal area and length in the load function in its place, estimated on all registrations with a matched price, usable capacity, and power. Supplementary Table 18 is the physics-form efficiency frontier with and without price, Supplementary Table 19 the kilograms per usable kWh by year, Supplementary Table 20 the three frontiers conditional on price, Supplementary Tables 21 and 22 the constant-price decompositions of range and consumption, Supplementary Table 4 the unconditional decomposition on all 7.9 million registrations, and Supplementary Table 16 the three frontiers in the log-linear form. Supplementary Note 1 compares them with the preferred estimates.

Supplementary Note 5: Body type and the coverage of the size data

The dimensions reported by the two specification sources cover 85 percent of registrations, and the vehicles without dimensions are not a random sample. They include the Opel Corsa-e and Mokka-e, the Volkswagen e-Up! and its Seat twin, the smart fortwo, the Jeep Avenger, and several vans. Most are small, light, and inexpensive. I extended the coverage in two steps. I collected length, width, and height from manufacturer specifications and the ADAC catalogue for 48 further make-models, which account for 10 percent of registrations, and I assigned the within-make-model median to the remaining variants of models with at least one measured variant, which account for 5 percent. The three sources together cover 99.8 percent of registrations, and all of the size-controlled estimates in this paper use the extended data. The same sources give a body type for 99.9 percent of registrations, which I classify as hatchback, SUV, sedan, estate, van, or cabriolet. The composition of the fleet by body type changed sharply over the period. SUVs were 22 percent of registrations in 2019 and 62 percent in 2025, and hatchbacks fell from 54 to 19 percent.

Body type can matter for consumption beyond frontal area, because the drag coefficient differs across body styles, and because width times height overstates the true frontal area by more for

Supplementary Table 16. The three frontiers in the log-linear form, with and without real price, 2019 to 2025

	(1) Mass, power	(2) + price	(3) + size	(4) + size + price
Panel A. Efficiency frontier: dependent variable ln(km per kWh)				
ln mass	-0.522*** (0.075)	-0.296*** (0.076)	-0.537*** (0.128)	-0.222* (0.125)
ln power	0.070** (0.033)	0.100*** (0.033)	0.037 (0.023)	0.066*** (0.022)
ln frontal area			-0.359** (0.169)	-0.479*** (0.162)
ln length			0.464** (0.189)	0.510*** (0.156)
ln real price		-0.183*** (0.033)		-0.227*** (0.036)
2021	0.060*** (0.022)	0.038* (0.023)	0.065*** (0.021)	0.037 (0.023)
2022	0.063*** (0.021)	0.033 (0.022)	0.069*** (0.021)	0.033 (0.022)
2023	0.084*** (0.021)	0.049** (0.022)	0.092*** (0.021)	0.049** (0.023)
2024	0.113*** (0.021)	0.067*** (0.022)	0.121*** (0.021)	0.064*** (0.023)
2025	0.130*** (0.022)	0.074*** (0.024)	0.141*** (0.022)	0.073*** (0.025)
Specification cells	570,310	570,310	568,634	568,634
Registrations	7,881,553	7,881,553	7,869,627	7,869,627
R^2	0.368	0.404	0.412	0.465
Panel B. Mass frontier: dependent variable ln(mass)				
ln usable kWh	0.443*** (0.036)	0.300*** (0.030)	0.269*** (0.041)	0.202*** (0.029)
ln power	0.061** (0.026)	-0.006 (0.019)	0.058** (0.024)	0.011 (0.016)
ln frontal area			0.595*** (0.139)	0.525*** (0.097)
ln length			0.395*** (0.138)	0.223** (0.089)
ln real price		0.269*** (0.019)		0.208*** (0.016)
2021	-0.007 (0.021)	0.028* (0.017)	0.006 (0.020)	0.030* (0.017)
2022	-0.007 (0.023)	0.039* (0.021)	0.004 (0.022)	0.035* (0.019)
2023	-0.006 (0.024)	0.048** (0.022)	-0.001 (0.023)	0.038* (0.021)
2024	-0.007 (0.023)	0.063*** (0.022)	0.001 (0.022)	0.051** (0.020)
2025	-0.013 (0.023)	0.073*** (0.022)	-0.002 (0.022)	0.059*** (0.020)
Specification cells	570,310	570,310	568,634	568,634
Registrations	7,881,553	7,881,553	7,869,627	7,869,627
R^2	0.857	0.907	0.913	0.940
Panel C. Battery frontier: dependent variable ln(usable kWh)				
ln power	0.544*** (0.057)	0.221*** (0.045)	0.273*** (0.042)	0.175*** (0.048)
ln frontal area			0.803*** (0.298)	0.616** (0.258)
ln length			1.533*** (0.212)	1.119*** (0.292)
ln real price		0.599*** (0.049)		0.313*** (0.078)
2021	0.101 (0.062)	0.148*** (0.037)	0.097** (0.046)	0.122*** (0.039)
2022	0.107 (0.072)	0.174*** (0.044)	0.096* (0.051)	0.134*** (0.044)
2023	0.119 (0.075)	0.201*** (0.046)	0.095* (0.054)	0.143*** (0.046)
2024	0.156** (0.073)	0.262*** (0.046)	0.121** (0.053)	0.185*** (0.047)
2025	0.190** (0.074)	0.320*** (0.046)	0.152*** (0.053)	0.229*** (0.049)
Specification cells	570,310	570,310	568,634	568,634
Registrations	7,881,553	7,881,553	7,869,627	7,869,627
R^2	0.645	0.758	0.793	0.814

Notes: Weighted least squares with registrations as weights; standard errors clustered by make-model in parentheses. Year effects are relative to 2019. Real price is the EV Database list price of the matched variant deflated by the euro-area HICP to 2019 prices. Columns (1) and (2) use the sample with price and usable capacity, 7.9 million registrations; columns (3) and (4) add frontal area and length, on the same registrations. In Panel A the mass elasticity falls when price is added because price and mass are collinear across models; the physics-form estimates in Panel A of Supplementary Table 20 do not have this problem. *, **, ***: significant at 10, 5, and 1 percent.

Supplementary Table 17. Decomposition of the change in range, battery capacity, and efficiency, 2019 to 2025, in the log-linear system

	Iso-cost		Unconditional	
Log points	Mass, power	+ size	Mass, power	+ size
Change in mean ln range	39.4	39.3	39.4	39.3
Larger battery from the battery frontier shift (more kWh per euro), net of its mass penalty	29.1	21.9	14.6	13.0
Larger battery bundled with higher power, net of its mass penalty	4.9	4.0	10.2	5.6
Larger battery from change in real spending, net of its mass penalty	-4.7	-2.6	-0.0	-0.0
Efficiency frontier shift	7.4	7.3	13.0	14.1
Mass frontier shift (heavier at given battery, power, and price)	-2.2	-1.3	0.7	0.1
Other (power and price entering efficiency directly, size, residuals)	4.7	9.9	0.9	6.4
Change in mean ln usable capacity	32.2	32.1	32.2	32.1
Battery frontier shift (more kWh per euro)	32.0	22.9	19.0	15.2
Bundled with power	5.4	4.2	13.2	6.6
Change in real spending	-5.1	-2.7	-0.0	-0.0
Size and residual	0.0	7.7	-0.0	10.3
Change in mean ln efficiency	7.2	7.2	7.2	7.2
Efficiency frontier shift	7.4	7.3	13.0	14.1
Mass, total	-4.3	-3.2	-7.6	-7.8
of which battery from the battery frontier shift	-2.8	-1.0	-4.4	-2.2
of which battery bundled with power	-0.5	-0.2	-3.1	-1.0
of which battery from change in real spending	0.5	0.1	0.0	0.0
of which mass frontier shift	-2.2	-1.3	0.7	0.1
Power, direct	2.4	1.6	1.7	0.9
Price, direct	1.6	2.0	-0.0	-0.0
Memo: change in mean ln real price	-8.6	-8.6	-8.6	-8.6
Memo: pass-through of capacity to range, $1 + \beta_m \gamma_k$	0.91	0.96	0.77	0.86

Notes: Changes in registration-weighted means between 2019 and 2025 in the sample with price and usable capacity (7.9 million registrations), decomposed with the log-linear frontiers of Supplementary Table 16, for comparison with Knittel [1] and with the physics-system decomposition in Supplementary Table 21. The iso-cost columns use the frontiers conditional on real price, so that each year effect is the shift at constant cost and the price terms give the movement attributable to changes in real spending. The range rows chain the three frontiers through the identity $\ln R = \ln K + \ln \text{eff}$; each battery row is net of the efficiency that the battery's mass costs. Rows sum to the totals up to rounding.

Supplementary Table 18. The efficiency frontier in the physics form, estimated by nonlinear least squares, 2019 to 2025

	(1)	(2)	(3)	(4)	(5)
	Mass	Mass, price	Mass, size	Mass, size, price	Mass, size, additive
b_m, mass (kg)	0.0459^{***}	0.0336^{***}	0.0615^{***}	0.0351^{**}	0.0549^{***}
	(0.00427)	(0.00857)	(0.0107)	(0.0141)	(0.00946)
b_A, frontal area (m^2)			24.8^{**}	31.9^{***}	21.6^{**}
			(11.2)	(11.2)	(10.0)
b_L, length (m)			-27.5^{***}	-31.9^{***}	-24.6^{***}
			(8.9)	(8.8)	(8.1)
θ, ln real price		0.0777^{*}		0.164^{***}	
		(0.0447)		(0.0371)	
a_{2020}	-0.0329	-0.0218	-0.0367^{*}	-0.0124	-6.423^{*}
	(0.0219)	(0.0198)	(0.0206)	(0.0216)	(3.620)
a_{2021}	-0.059^{***}	-0.0457^{**}	-0.0738^{***}	-0.0472^{**}	-12.2^{***}
	(0.0198)	(0.0192)	(0.0197)	(0.0216)	(3.5)
a_{2022}	-0.0733^{***}	-0.058^{***}	-0.0882^{***}	-0.0575^{**}	-14.3^{***}
	(0.0227)	(0.0215)	(0.0198)	(0.023)	(3.6)
a_{2023}	-0.0984^{***}	-0.081^{***}	-0.115^{***}	-0.0805^{***}	-18.6^{***}
	(0.0234)	(0.0226)	(0.0203)	(0.0243)	(3.7)
a_{2024}	-0.129^{***}	-0.107^{***}	-0.144^{***}	-0.101^{***}	-23.6^{***}
	(0.0225)	(0.0225)	(0.0197)	(0.0244)	(3.6)
a_{2025}	-0.146^{***}	-0.121^{***}	-0.167^{***}	-0.116^{***}	-27.3^{***}
	(0.026)	(0.0245)	(0.021)	(0.0268)	(3.8)
Technology factor, $e^{a_{2025}}$	0.864	0.886	0.847	0.891	–
Attribute cells	11,010	12,532	10,793	11,981	10,793
Registrations	7,881,553	7,881,553	7,869,627	7,869,627	7,869,627
R^2	0.398	0.404	0.463	0.491	0.458

Notes: Dependent variable is Wh/km at the charging point. Columns (1) to (4) estimate $\text{Wh/km}_{it} = \exp(a_t + \theta \ln P_{it})(b_0 + b_m m_{it} + b_A A_{it} + b_L L_{it})$, so the coefficients inside the load function are in Wh/km per unit of the attribute in parentheses; column (5) estimates $\text{Wh/km}_{it} = a_t + b_0 + b_m m_{it} + b_A A_{it} + b_L L_{it}$, with year effects in Wh/km. The sample is the WLTP registrations from 2019 to 2025 with a matched list price, usable capacity, and power. Real price is the list price deflated by the euro-area HICP to 2019 euros and centered at 45,000 euros. The technology factor is the proportional change in consumption at fixed attributes between 2019 and 2025, at constant real price in columns (2) and (4). The intercept b_0 is not reported. Weights are registrations; standard errors clustered by make-model in parentheses. *, **, ***: significant at 10, 5, and 1 percent.

Supplementary Table 19. The mass frontier in levels: kilograms of vehicle mass per usable kWh of battery, by year

	Conditional on power		Conditional on power, frontal area, length	
Year	kg per kWh	(s.e.)	kg per kWh	(s.e.)
2019	13.9	(1.4)	9.3	(1.6)
2020	15.5	(1.6)	10.8	(1.7)
2021	16.9	(0.9)	10.1	(1.2)
2022	17.5	(1.1)	10.7	(1.0)
2023	17.2	(1.2)	10.6	(1.0)
2024	16.2	(1.0)	10.2	(1.0)
2025	16.4	(1.2)	10.4	(1.1)

Notes: Each column reports the year-specific coefficients δ_t from $m_{it} = \alpha_t + \delta_t K_{it} + \gamma_p p_{it} + \gamma_A A_{it} + \gamma_L L_{it} + u_{it}$, where K is usable battery capacity in kWh. In the second specification the other coefficients are 0.17 kg per kW of power (not significant), 306 kg per m^2 of frontal area and 218 kg per meter of length (both significant at 1 percent). Weighted least squares with registrations as weights; standard errors clustered by make-model. WLTP sample, 2019–2025.

some shapes than for others. The drag coefficient in the preferred specification addresses the first directly. Body type is the check that is available without it, and Supplementary Tables 23 and 24 report it: they re-estimate the physics form with frontal area and length on the extended sample, add body-type dummies, and then add interactions of the dummies with frontal area, without and with price. I find that the body-type dummies improve the fit and that they do not change the unconditional estimates of technological progress. The extension of the coverage itself raises the 2019 to 2025 technology effect from 23 to 26 Wh/km, and the body-type dummies and their interactions with frontal area leave it there. The mass coefficient is 0.062 Wh/km per kilogram without body-type controls and 0.074 with them, and it is 0.074 on the original sample with them. The frontal-area coefficient, 24 Wh/km per square meter without the dummies, falls to −11 and loses significance with them. Body type is largely a statement about height, so the dummies and frontal area are collinear, and the dummies take over the aerodynamic variation. The two cannot both be identified without the drag coefficient. Conditional on mass, frontal area, and length, a sedan uses 14 Wh/km less than a hatchback, significant at the 5 percent level, and a van uses 59 to 64 Wh/km more, significant at the 1 percent level. An SUV uses the same as a hatchback. The SUV's consumption penalty therefore operates entirely through its mass and frontal area. The dummies raise the R^2 from 0.46 to 0.55. The interactions with frontal area add little. Only the van interaction is significant, and the year effects are unchanged.

Conditional on price, body type changes little. Extending the coverage moves the 2019 to 2025 technology factor from 0.909 to 0.891. Adding the body-type dummies moves it to 0.892, and adding the interactions to 0.894. The constant-price shift of the efficiency frontier in that specification is therefore about 11 percent with or without body-type controls. The body-type dummies are not in the preferred specification, because the drag area carries the aerodynamic variation and because the classification of crossovers between hatchback and SUV is a judgment call.

Supplementary Table 20. The three frontiers at constant real price, 2019 to 2025

	(1) Without size controls	(2) With size controls
Panel A: efficiency frontier, physics form, Wh/km		
b_m, mass (kg)	0.0336*** (0.00857)	0.0351** (0.0141)
b_A, frontal area (m^2)		31.9*** (11.2)
b_L, length (m)		−31.9*** (8.8)
θ, ln real price	0.0777* (0.0447)	0.164*** (0.0371)
2020	−0.0218 (0.0198)	−0.0124 (0.0216)
2021	−0.0457** (0.0192)	−0.0472** (0.0216)
2022	−0.058*** (0.0215)	−0.0575** (0.023)
2023	−0.081*** (0.0226)	−0.0805*** (0.0243)
2024	−0.107*** (0.0225)	−0.101*** (0.0244)
2025	−0.121*** (0.0245)	−0.116*** (0.0268)
Technology factor, $e^{a_{2025}}$	0.886	0.891
R^2	0.404	0.491
Panel B: mass frontier, levels, kg		
κ, usable battery (kWh)	9.382*** (0.851)	6.483*** (0.656)
Power (kW)	−0.424*** (0.157)	−0.213* (0.122)
Frontal area (m^2)		287.3*** (46.8)
Length (m)		111.8*** (23.3)
ln real price	570.2*** (44.0)	439.8*** (37.1)
2020	50.3** (25.2)	54.8** (26.5)
2021	63.4** (24.7)	64.5*** (23.8)
2022	90.1*** (28.3)	82.2*** (25.0)
2023	106.7*** (31.0)	87.2*** (26.2)
2024	135.4*** (30.1)	111.0*** (25.5)
2025	160.3*** (29.2)	131.8*** (24.4)
R^2	0.909	0.941
Panel C: battery frontier, logs, ln usable kWh		
ln power	0.221*** (0.045)	0.175*** (0.048)
ln frontal area		0.616** (0.258)
ln length		1.119*** (0.292)
ln real price	0.599*** (0.049)	0.313*** (0.078)
2020	0.154*** (0.026)	0.126*** (0.026)
2021	0.148*** (0.037)	0.122*** (0.039)
2022	0.174*** (0.044)	0.134*** (0.044)
2023	0.201*** (0.046)	0.143*** (0.046)
2024	0.262*** (0.046)	0.185*** (0.047)
2025	0.32*** (0.046)	0.229*** (0.049)
R^2	0.758	0.814
Registrations	7,881,553	7,869,627

Notes: Each panel is one equation of the iso-cost system, estimated on the registrations with a matched list price, usable capacity, and power from 2019 to 2025, with real price deflated by the euro-area HICP to 2019 euros. Panel A is the physics form by nonlinear least squares, with price entering the technology factor and coefficients in Wh/km per unit of the attribute; year effects are log changes in the technology factor relative to 2019, and the technology factor is $e^{a_{2025}}$. Panel B is the mass frontier in levels by weighted least squares, with coefficients in kilograms per unit; year effects are kilograms relative to 2019 at given battery, power, size, and price. Panel C is the battery frontier in logs; year effects are log changes in the usable capacity that a given price buys. Weights are registrations; standard errors clustered by make-model in parentheses. Supplementary Table 16 reports all three frontiers in the log-linear form, with and without price. *, **, ***: significant at 10, 5, and 1 percent.

Supplementary Table 21. Decomposition of the change in range, 2019 to 2025, at constant real price and unconditional

	Iso-cost		Unconditional	
Log points	Mass, power	+ size	Mass, power	+ size
Change in mean ln range	39.4	39.3	39.4	39.3
Larger battery from the battery frontier shift (more kWh per euro), net of its mass penalty	28.6	21.2	14.4	12.2
Larger battery bundled with higher power, net of its mass penalty	4.7	3.9	9.7	5.2
Larger battery from change in real spending, net of its mass penalty	-4.5	-2.5	0.0	0.0
Efficiency frontier shift	12.1	11.6	14.6	16.7
Mass frontier shift (heavier at given battery, power, and price)	-2.9	-2.5	0.3	-0.2
Other (power, price, and size entering mass and efficiency directly, residuals)	1.4	7.6	0.3	5.5
Change in mean ln usable capacity	32.2	32.1	32.2	32.1
Battery frontier shift (more kWh per euro)	32.0	22.9	19.0	15.2
Bundled with power	5.4	4.2	13.2	6.6
Change in real spending	-5.1	-2.7	-0.0	-0.0
Size and residual	0.0	7.7	-0.0	10.3
Memo: technology factor of the efficiency frontier, $e^{a_{2025}}$	0.886	0.891	0.864	0.847
Memo: kilograms per usable kWh, κ	9.4	6.5	16.8	10.4
Memo: mass coefficient b_m	0.034	0.035	0.046	0.061
Memo: pass-through of capacity to range	0.89	0.93	0.76	0.80
Memo: change in mean ln real price	-0.086	-0.086	-0.086	-0.086

Notes: Changes in registration-weighted means between 2019 and 2025 in the sample with price and usable capacity (7.9 million registrations), decomposed through the physics system: the three frontiers of Supplementary Table 20. The iso-cost columns use the frontiers conditional on real price. Each component is a counterfactual applied to every 2019 specification in turn, battery frontier, capacity bundled with power, capacity from spending, efficiency frontier, and mass frontier, with range recomputed as $1000K$/Wh/km at each step and averaged with registration weights; the remainder is the other row. Each battery row is net of the efficiency that the battery's mass costs; the pass-through is the share of a capacity increase that reaches range, $1 - b_m \kappa K e^a$/Wh/km at the 2020 means. Rows sum to the totals up to rounding. Supplementary Table 17 reports the same decomposition in the log-linear system.

Supplementary Table 22. Technology and attribute effects in Wh/km at constant real price, 2019 to 2025, physics form

	Iso-cost		Unconditional	
Wh/km	Mass	Mass, FA, L	Mass	Mass, FA, L
Fleet mean, 2019	176.7	176.6	176.7	176.6
Fleet mean, 2025	162.9	162.8	162.9	162.8
Technology factor at constant price	0.886	0.891	0.864	0.847
Technology effect at 2019 attributes and price	-20.1	-19.2	-24.1	-27.2
Counterfactual 2025 at 2019 attributes and price	155.9	156.7	152.6	149.9
Attribute effect of mass	7.6	7.8	10.2	13.4
Attribute effect of frontal area		4.2		3.2
Attribute effect of length		-4.4		-3.7
Effect of the change in real price	-1.1	-2.3	0.0	0.0

Notes: From the physics-form estimates in Panel A of Supplementary Table 20. The technology effect is $(e^{a_{2025}} - 1)$ times the 2019 load at the 2019 real price; attribute effects are evaluated at 2025 technology and price. In the unconditional columns the price effect is zero by construction.

Supplementary Table 23. Efficiency frontier with extended dimension coverage and body-type controls, 2019 to 2025

	(1)	(2)	(3)	(4)
Dimension coverage	Original	Extended	Extended	Extended
Body-type dummies	No	No	Yes	Yes
Body × frontal area	No	No	No	Yes
Physics form, unconditional on price				
Mass (kg)	0.068***	0.062***	0.074***	0.075***
	(0.011)	(0.010)	(0.009)	(0.008)
Frontal area (m^2)	14.339	24.428**	-11.068	-1.307
	(11.008)	(11.047)	(11.417)	(21.240)
Length (m)	-28.018**	-27.409***	-18.806**	-17.319*
	(11.824)	(8.829)	(8.532)	(9.152)
SUV			-3.600	44.907
			(4.680)	(57.560)
Sedan			-14.009**	-81.191
			(6.090)	(84.232)
Estate			24.867***	205.360
			(7.592)	(135.818)
Van			63.784***	313.124**
			(12.752)	(136.476)
Cabriolet			19.994**	-529.679
			(9.416)	(809.996)
SUV × frontal area				-17.633
				(21.325)
Sedan × frontal area				23.218
				(29.782)
Estate × frontal area				-65.243
				(47.841)
Van × frontal area				-71.574*
				(40.296)
Cabriolet × frontal area				214.138
				(317.722)
Year 2025 effect a_{2025}	-0.143***	-0.163***	-0.161***	-0.163***
	(0.024)	(0.021)	(0.019)	(0.019)
Technology factor, 2025	0.866	0.850	0.851	0.849
Technology effect (Wh/km)	-23.0	-26.4	-26.2	-26.5
Mass effect (Wh/km)	12.4	14.6	17.6	17.7
Registrations (millions)	6.77	7.93	7.93	7.93
Cells	9,049	10,902	10,926	10,926
R^2	0.480	0.463	0.554	0.563

Notes: Nonlinear least squares estimates of the physics form, $\mathrm{Wh/km}_{it} = \exp(a_t + \theta \ln p_{it})(b_0 + b_m m_{it} + b_A A_{it} + b_L L_{it} + \sum_b c_b D_{b,it} + \sum_b d_b D_{b,it} A_{it})$, weighted by registrations, where D_b are body-type dummies and hatchback is the omitted type. Column (1) uses the dimensions reported by the EV Database and Open EV Data (85 percent of registrations). Columns (2) to (4) add dimensions from manufacturer specifications and the ADAC catalogue for 48 further make-models and fill the remaining variants of measured models with the make-model median (99.8 percent of registrations). The technology factor is $\exp(a_{2025})$. The technology effect is $(\exp(a_{2025}) - 1)$ times the predicted load at first-year mean attributes, and the mass effect is $\exp(a_{2025}) b_m$ times the change in mean mass between the first and last year. Standard errors clustered by make-model are in parentheses. *, **, and *** denote significance at the 10, 5, and 1 percent levels.

Supplementary Table 24. Efficiency frontier with body-type controls, conditional on real price, 2019 to 2025

	(1)	(2)	(3)	(4)
Dimension coverage	Original	Extended	Extended	Extended
Body-type dummies	No	No	Yes	Yes
Body × frontal area	No	No	No	Yes
Physics form with ln real price in the technology factor				
Mass (kg)	0.044***	0.035**	0.048***	0.047***
	(0.013)	(0.014)	(0.011)	(0.010)
Frontal area (m^2)	22.326**	31.931***	-4.473	13.426
	(10.469)	(11.207)	(11.462)	(22.942)
Length (m)	-34.689***	-31.860***	-21.382***	-20.667**
	(11.247)	(8.836)	(7.983)	(8.121)
ln real price	0.157***	0.164***	0.161***	0.172***
	(0.038)	(0.037)	(0.032)	(0.031)
SUV			-4.529	67.937
			(4.547)	(58.270)
Sedan			-16.210***	-53.982
			(5.734)	(77.896)
Estate			19.909**	112.903
			(8.751)	(156.322)
Van			58.580***	384.862***
			(12.289)	(125.691)
Cabriolet			13.937	-538.963
			(8.686)	(688.064)
SUV × frontal area				-26.434
				(21.865)
Sedan × frontal area				12.307
				(27.933)
Estate × frontal area				-34.519
				(55.937)
Van × frontal area				-94.586**
				(37.688)
Cabriolet × frontal area				215.346
				(269.966)
Year 2025 effect a_{2025}	-0.096***	-0.116***	-0.115***	-0.113***
	(0.030)	(0.027)	(0.023)	(0.022)
Technology factor, 2025	0.909	0.891	0.892	0.894
Technology effect (Wh/km)	-15.7	-19.6	-19.4	-19.1
Mass effect (Wh/km)	8.3	8.0	10.9	10.8
Registrations (millions)	6.76	7.87	7.87	7.87
Cells	10,032	11,981	11,984	11,984
R^2	0.506	0.491	0.580	0.592

Notes: Nonlinear least squares estimates of the physics form, $\mathrm{Wh/km}_{it} = \exp(a_t + \theta \ln p_{it})(b_0 + b_m m_{it} + b_A A_{it} + b_L L_{it} + \sum_b c_b D_{b,it} + \sum_b d_b D_{b,it} A_{it})$, weighted by registrations, where D_b are body-type dummies and hatchback is the omitted type. Column (1) uses the dimensions reported by the EV Database and Open EV Data (85 percent of registrations). Columns (2) to (4) add dimensions from manufacturer specifications and the ADAC catalogue for 48 further make-models and fill the remaining variants of measured models with the make-model median (99.8 percent of registrations). The technology factor is $\exp(a_{2025})$. The technology effect is $(\exp(a_{2025}) - 1)$ times the predicted load at first-year mean attributes, and the mass effect is $\exp(a_{2025}) b_m$ times the change in mean mass between the first and last year. Standard errors clustered by make-model are in parentheses. *, **, and *** denote significance at the 10, 5, and 1 percent levels.

Supplementary Note 6: The best-selling models

Supplementary Fig. 4 plots the change in mass, consumption, and range for the twelve best-selling models that were sold in 2025 and in either 2019 or 2020. Each model is an arrow from its registration-weighted mean mass and consumption in its first year to the same in 2025, and the color of the arrow is the percentage change in the model's range over the period. Within a model, consumption tended to fall, by 5 to 28 Wh/km for the Model 3, the Spring, the 500e, the e-2008, and the Corsa-e, but mass did not change, apart from the Mini. At the same time, however, the fleet's mass rose by 280 kilograms between 2019 and 2025. Supplementary Table 26 reports the attributes of each of these models in each year. In ten of the twelve models, range rose. Across all twelve models, the average increase was 16 percent. Not all of this increase is due to larger batteries. For the Model 3, the Spring, and the Corsa-e, their batteries are within 4 kWh of their first-year size, but range rose by 11, 13, and 13 percent, respectively. In contrast, the Mini, whose battery grew from 29 to 49 kWh on a new platform, had a range increase of 83 percent. These models did not gain performance over this time period. Their 0 to 100 km/h times in the specification data changed by less than a second, apart from the Spring, whose time fell from 19 to 14 seconds, and the Model 3 and the e-2008 became slightly slower.[1]

Supplementary Table 25 reports the same decomposition for eight attributes, including the three above. Real list prices fell 4,308 euros. Within continuing models they fell 5,657 euros, reallocation among continuing models lowered the fleet mean price by a further 2,574 euros, and entry and exit raised it by 3,923 euros. Acceleration time fell 0.99 seconds, with similar contributions from all three components. Drag area rose 0.023 square meters, and within continuing models it was slightly lower, so all of the increase came from which models were sold. Range rose 127 km on the identity measure, of which 48 km happened within continuing models, 58 km through reallocation, and 21 km through entry and exit. Within models, consumption fell and battery capacity rose, and both raise range. Mass, battery capacity, and drag area changed mainly across models. Consumption and price changed mainly within them, and acceleration time changed about equally within models, through reallocation, and through entry and exit.

Supplementary Table 26. The twelve best-selling models sold in 2025 and in either 2019 or 2020, by year

Year	Registrations	Mass (kg)	Consumption (Wh/km)	Usable battery (kWh)	Range (km)	Price (euros)	0 to 100 km/h (s)	Torque (Nm)
Tesla Model 3								
2019	26,372	1899	159.6	70.7	443	55,257	4.7	485
2020	42,536	1861	154.0	66.2	430	50,748	4.9	476
2021	80,155	1866	147.2	64.9	441	47,799	5.0	464
2022	64,474	1874	147.9	65.5	443	42,793	5.3	454

Continued on the next page

[1]The registry's power field tells a different story for the same models, rising by 65 to 97 percent for the Zoe, the e-208, the e-Niro, and the e-2008 between their first year and 2025 while their acceleration times did not move. Member states changed from reporting 30-minute rated power to peak power over the period, which is the inconsistency noted in the Methods and the reason the registry's power is not used as a performance measure for these comparisons.

Supplementary Table 26, continued

Year	Registrations	Mass (kg)	Consumption (Wh/km)	Usable battery (kWh)	Range (km)	Price (euros)	0 to 100 km/h (s)	Torque (Nm)
2023	75,821	1858	140.8	64.4	457	40,440	5.5	451
2024	90,185	1860	136.4	64.0	469	38,081	5.4	464
2025	57,193	1849	136.7	67.2	491	37,796	5.4	465
Renault Zoe								
2019	34,670	1563	175.1	42.9	245	32,515	12.2	225
2020	98,789	1577	178.8	51.4	287	29,169	11.4	225
2021	66,909	1577	180.8	51.8	286	29,078	11.4	225
2022	31,265	1577	181.8	51.9	285	29,097	11.4	225
2023	14,200	1577	179.9	51.9	289	29,106	11.4	225
2024	4,355	1577	172.6	52.0	301	29,123	11.4	225
2025	60	1582	171.8	52.0	303	29,123	11.4	225
Peugeot 208								
2019	107	1530	176.0	46.3	263	31,311	8.1	260
2020	27,729	1530	164.3	46.3	282	31,311	8.1	260
2021	38,296	1530	164.0	47.1	287	32,794	8.1	260
2022	41,648	1530	157.0	48.0	306	31,797	8.2	260
2023	45,111	1530	155.5	48.1	309	31,815	8.2	260
2024	35,341	1530	152.4	48.1	316	31,815	8.2	260
2025	23,126	1530	151.3	48.5	320	31,263	8.2	260
Fiat 500								
2020	3,744	1379	144.3	37.3	259	22,815	9.0	220
2021	38,733	1370	142.1	36.0	254	22,653	9.0	220
2022	58,782	1360	140.9	35.0	249	22,183	9.0	220
2023	57,488	1350	138.7	33.7	243	21,853	9.0	220
2024	26,748	1324	135.9	30.1	222	21,130	9.0	220
2025	16,251	1349	139.0	33.0	237	22,262	9.0	220
Dacia Spring								
2020	1,722	1020	152.0	25.0	164	18,649	19.1	150
2021	27,604	1014	142.5	25.0	175	18,465	19.1	150
2022	48,267	1012	139.2	25.0	180	18,401	19.1	150
2023	59,473	1020	141.1	25.0	177	18,931	17.2	150
2024	20,200	1035	138.9	25.0	180	19,179	14.7	150
2025	24,724	1042	134.1	25.0	186	18,597	14.3	150
Kia Niro								
2019	4,252	1810	167.9	63.6	379	36,437	7.8	395
2020	20,208	1810	158.9	63.7	401	36,444	7.8	395
2021	33,696	1807	158.8	63.1	398	36,375	7.9	395
2022	26,141	1786	160.2	64.0	399	35,632	7.8	334
2023	27,641	1757	162.0	64.8	400	34,604	7.8	255
2024	18,770	1757	162.0	64.8	400	34,600	7.8	255
2025	3,385	1759	162.0	64.8	400	34,600	7.8	255
Opel Corsa								
2020	13,191	1530	165.1	46.3	281	31,863	8.1	–
2021	19,897	1530	164.9	46.3	281	31,863	8.1	–
2022	22,637	1530	158.1	47.0	297	31,226	8.1	–
2023	26,092	1533	157.3	47.5	302	30,721	8.1	–
2024	13,144	1543	154.8	48.0	310	30,189	8.1	–
2025	10,922	1544	152.9	48.6	318	29,166	8.1	–
Peugeot 2008								
2019	1	1623	183.0	46.3	253	36,190	8.5	260

Continued on the next page

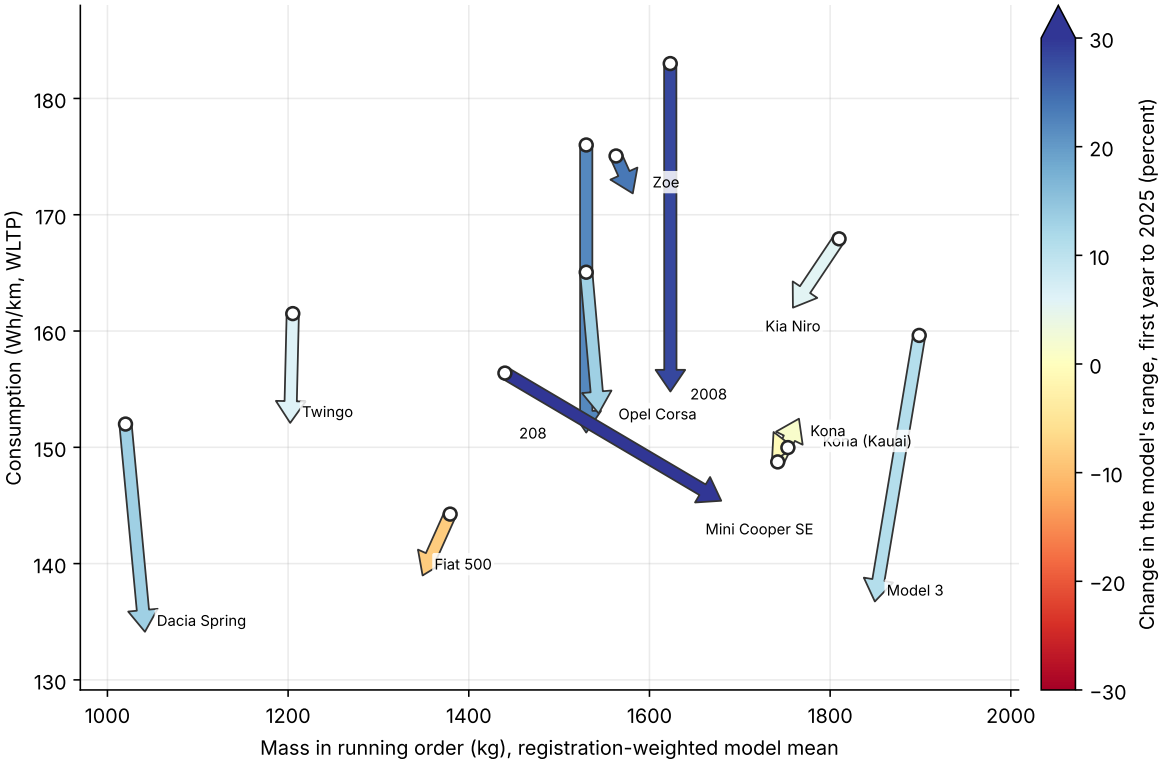
Supplementary Table 26, continued

Year	Registrations	Mass (kg)	Consumption (Wh/km)	Usable battery (kWh)	Range (km)	Price (euros)	0 to 100 km/h (s)	Torque (Nm)
2020	9,283	1623	176.0	46.3	263	33,558	8.5	260
2021	21,361	1623	175.7	46.3	264	33,558	8.5	260
2022	22,362	1623	160.9	46.3	288	33,558	8.5	260
2023	17,582	1623	158.1	47.0	298	33,084	8.6	260
2024	15,882	1623	155.9	48.4	310	32,226	8.8	260
2025	14,798	1623	154.8	50.2	324	30,783	9.2	260
Mini Cooper SE								
2019	427	1440	156.4	28.9	185	31,271	7.3	270
2020	3	1440	150.3	28.9	192	30,958	7.3	270
2021	22,781	1440	155.8	28.9	186	30,958	7.3	270
2022	26,948	1440	155.5	28.9	186	30,958	7.3	270
2023	28,448	1443	156.1	28.9	185	31,460	7.3	270
2024	11,276	1644	147.0	46.1	313	27,166	6.8	321
2025	8,851	1679	145.4	49.1	338	26,414	6.7	330
Renault Twingo								
2020	5,055	1205	161.5	21.3	132	21,674	12.6	–
2021	25,224	1204	161.3	21.3	132	21,674	12.6	–
2022	26,709	1203	161.2	21.3	132	21,674	12.6	–
2023	17,655	1204	157.3	21.3	135	21,674	12.6	–
2024	14,206	1201	152.1	21.4	141	21,608	12.6	175
2025	187	1202	152.1	21.3	140	21,674	12.6	–
Hyundai Kona (Kauai)								
2019	4,102	1742	148.7	61.0	410	40,775	8.1	395
2020	15,829	1719	147.7	57.1	387	34,871	8.5	395
2022	2,008	1705	145.5	54.9	377	34,374	8.6	395
2023	29,617	1708	146.5	55.2	376	33,882	8.6	376
2024	25,080	1754	150.3	61.3	408	32,657	8.2	393
2025	180	1765	152.5	63.3	415	32,234	8.2	–
Hyundai Kona								
2019	5,096	1753	150.0	62.5	417	41,205	8.0	395
2020	25,089	1745	149.6	61.5	411	35,824	8.1	395
2021	14,361	1731	146.6	59.3	404	35,333	8.3	395
2022	13,663	1697	145.4	53.7	369	34,110	8.7	395
2023	4	1762	146.0	57.8	396	35,015	8.4	395
2025	13,367	1760	149.9	62.0	414	32,239	8.2	255

Notes: Registration-weighted means within model and year. Range is 1000 times usable battery capacity divided by consumption, which is the identity used in the paper and is available in 2019, when the registry does not record range. Price is the real list price in 2019 euros. Acceleration and usable capacity are from the matched specification data, and torque is missing where the matched variant does not report it. The Mini Cooper SE changed to a new platform and a larger battery in 2024, and the registry records the Kona under two commercial names.

References

[1] Christopher R. Knittel. Automobiles on steroids: Product attribute trade-offs and technological progress in the automobile sector. *American Economic Review*, 101(7):3368–3399, 2011.

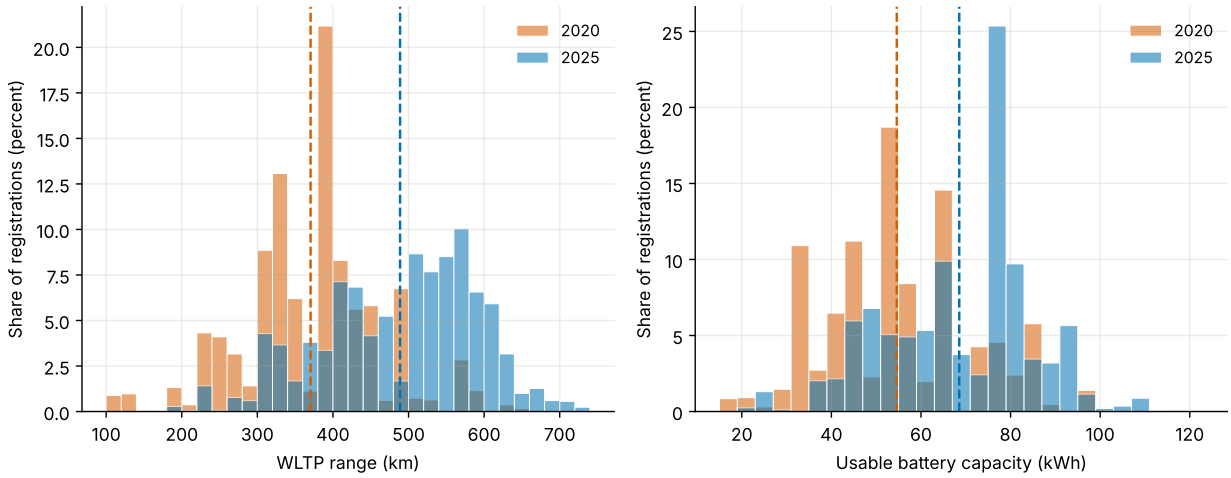


Supplementary Fig. 4. The twelve best-selling models sold in 2025 and in either 2019 or 2020. Each arrow runs from the model's registration-weighted mean mass and consumption in its first year on sale (open circle) to the same in 2025 (arrowhead). The color of the arrow is the percentage change in the model's range between the two years, where range is 1000 times usable battery capacity divided by consumption. The color scale is capped at 30 percent, and the Mini Cooper SE, whose range rose by 83 percent, is at the cap. The Opel Corsa and the Peugeot 208 share the same registry mass, so their arrows overlap at the start. The Kona appears twice because the registry records it under two commercial names.

Supplementary Table 25. Chained decomposition of the change in fleet means, 2019 to 2025

	2019	2025	Change	Within continuing models	Reallocation among continuing models	Entry and exit
Mass (kg)	1695	1975	280	11	133	136
Consumption (Wh/km)	175.2	162.9	−12.3	−12.9	−5.8	6.4
Usable battery capacity (kWh)	51.3	68.5	17.3	3.8	8.2	5.3
Range (km)	294	421	127	48	58	21
0 to 100 km/h (s)	8.19	7.20	−0.99	−0.35	−0.30	−0.34
Real list price (euros)	43,977	39,669	−4,308	−5,657	−2,574	3,923
Drag area (m^2)	0.760	0.783	0.023	−0.005	0.016	0.012
Torque (Nm)	405	387	−18	−7	−30	20

Notes: Registration-weighted fleet means over all WLTP registrations. For each pair of adjacent years, the models sold in both years are the continuing models, which are 71 to 90 percent of the later year's registrations (66 to 89 percent for drag area). The within-model component is the change in each continuing model's mean at the earlier year's registration shares, the reallocation component is the change in shares among continuing models at the later year's means, and entry and exit is the remainder of the change in the fleet mean. The links are summed over 2019 to 2025, and the three components add to the change. Range is 1000 times usable battery capacity divided by consumption, and is 16 to 22 percent below the registry's range field in 2020 to 2025. Drag area and torque are available for part of the sample.



Supplementary Fig. 5. The distribution of WLTP range and of usable battery capacity across registrations, 2020 and 2025. Bars are shares of the year's registrations; dashed lines are registration-weighted means. Range is recorded in the registry from 2020. Usable capacity is from the matched EV Database variant.