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Net emission reductions from electric cars and heat pumps in 59 world regions over time

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The electrification of passenger road transport and household heating features prominently in current and planned policy frameworks to achieve greenhouse gas emissions reduction targets. However, since electricity generation involves using fossil fuels, it is not established where and when the replacement of fossil-fuel-based technologies by electric cars and heat pumps can effectively reduce overall emissions. Could electrification policies backfire by promoting their diffusion before electricity is decarbonized? Here we analyse current and future emissions trade-offs in 59 world regions with heterogeneous households, by combining forward-looking integrated assessment model simulations with bottom-up life-cycle assessments. We show that already under current carbon intensities of electricity generation, electric cars and heat pumps are less emission intensive than fossil-fuel-based alternatives in 53 world regions, representing 95% of the global transport and heating demand. Even if future end-use electrification is not matched by rapid power-sector decarbonization, it will probably reduce emissions in almost all world regions.

Policymakers widely consider electrification a key measure for decarbonizing road transport and household heating. Combined, these sectors generate 24% of global fuel-combustion emissions and are the two major sources of direct carbon emissions by households[1–5]. For passenger road transport, plug-in battery electric vehicles (EVs) are expected to gradually replace petrol and diesel vehicles (petrol cars). For heating, heat pumps (HPs) are an alternative to gas, oil and coal heating systems (fossil boilers). Recent policy examples aimed at such end-use electrification include announced bans of petrol car sales, financial incentives for EV and HP purchases, planned phase-outs of gas heating and the inclusion of HPs into the European Union's renewable heating targets[1,2,6–8].

The use of EVs and HPs eliminates fossil fuel use and tail-pipe/on-site greenhouse gas (GHG) emissions (hereafter referred to as emissions), but causes emissions from electricity generation. Emission intensities in the power sector differ widely across the globe and will change over time[3]. Additionally, producing and recycling EVs and HPs involve higher emissions than producing petrol cars and fossil boilers, owing to battery production for EVs and refrigerant liquid use for HPs[9,10]. The question thus arises as to where and when the electrification of energy end-use could, under a failure to decarbonize electricity generation, increase overall emissions[11,12].

Multisectoral mitigation scenarios (such as those reviewed by the Intergovernmental Panel on Climate Change (IPCC)) have identified electrification as a robust policy strategy, but they typically focus on a context of rapid power-sector decarbonization[3,5]. However, sector-specific policies and self-reinforcing social and industrial dynamics could also lead to real-world trajectories in which end-use electrification and power-sector decarbonization take place at completely different rates[13]. In such a context, could end-use electrification turn into a counterproductive policy strategy for reducing emissions?

The answer requires a comprehensive and dynamic life-cycle assessment of all relevant production and use-phase emissions in different world regions, of current technology in its full heterogeneity, now and in the future. Time- and location-specific differences stem not only from the power-sector fuel mix but also from individual preferences and decision-making by millions of people. Which types of fossil fuel technology are likely to be replaced by which types of EV or HP? This requires a comparison not only of generic (representative) technology types but also of technology ranges (market segments), on the basis of empirically observed sales in each region.

This is different from existing life-cycle studies of EVs and HPs, which are limited to the present situation and mostly focus on a few regions or global averages (see refs. [14–22] for studies on EVs and refs. [10,23,24] on HPs). For the case of EVs, only two studies extend the analysis into the future[9,25]. However, they do not consider regional differences around the globe, heterogeneous technology choices by consumers or the electrification of heating, and thus cannot adequately and comprehensively inform policymaking processes at the national level.

Our study consistently investigates the full life-cycle emission trade-offs from EVs and HPs over time in a regionally highly disaggregated way, on the basis of forward-looking simulations of heterogeneous consumer choices, while explicitly investigating possible temporal mismatches between end-use electrification and power-sector decarbonization.

Scenarios of technology diffusion

We simulate future technology diffusion and the resulting emissions in power generation, passenger road transport and household heating for 59 regions covering the world (Supplementary Table 1), using the integrated assessment model E3ME-FTT-GENIE[26,27]. This model's representation of technology uptake in transport and heating is strongly empirical, on the basis of detailed regional

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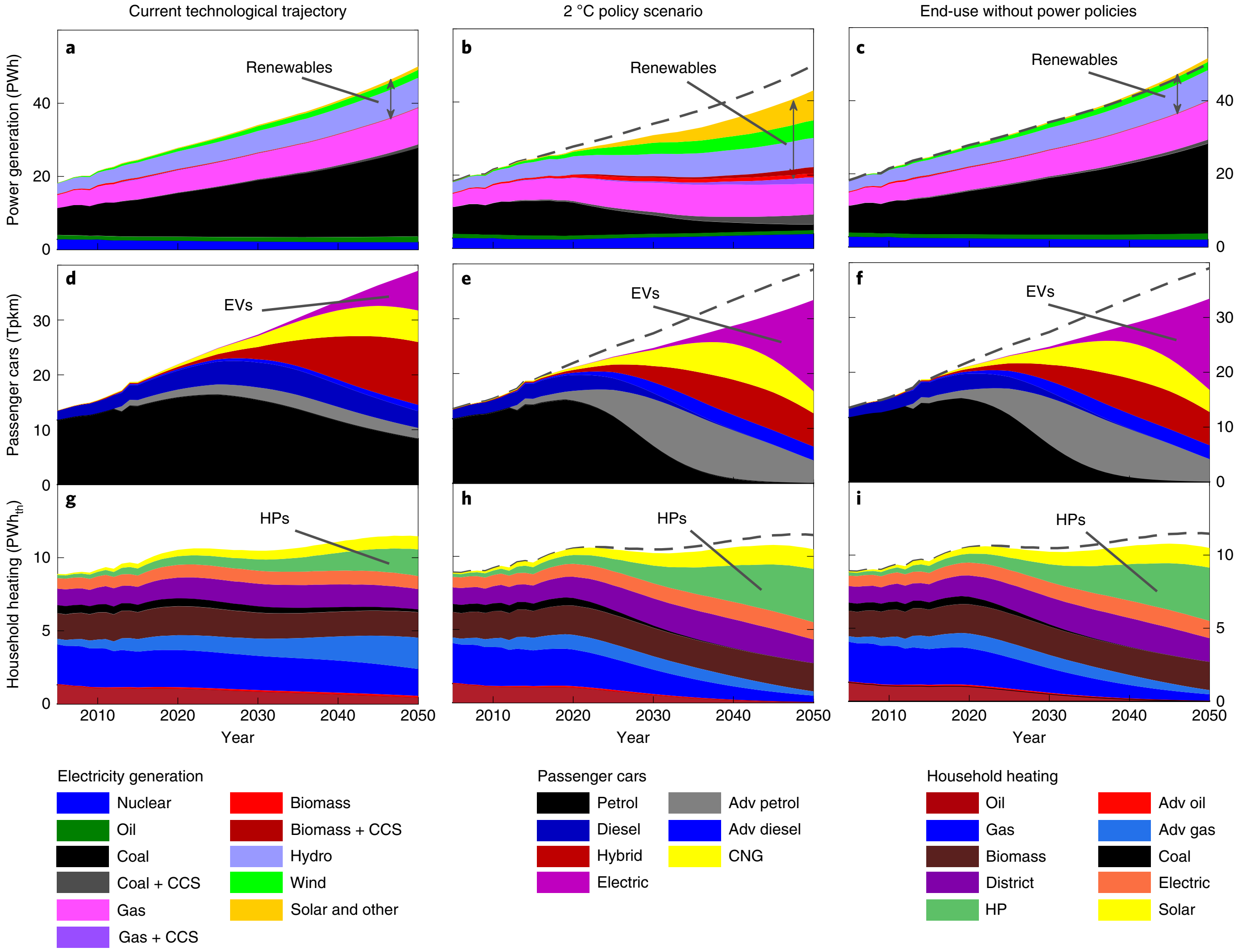

Fig. 1 | Projections of global future technology diffusion in power generation, passenger road transport and household heating. a–c, Global technology mix in power generation. **d–f**, Global technology mix in road transport by passenger cars (Tpkm, trillion person-kilometres). **g–i**, Global technology mix in residential space and water heating (PWh$_{th}$, PWh thermal). Projections under the current technological trajectory (**a**, **d** and **g**), the 2 °C policy scenario (**b**, **e** and **h**) and the end-use without power policies scenario (**c**, **f** and **i**) are shown. Dashed lines show the total demand in the current technological trajectory (**a**, **d** and **g**) for comparison. Relative to this trajectory, global electricity demand in 2050 is around 3% larger in **c**. CCS, carbon capture and storage; CNG, compressed natural gas; Adv, advanced.

datasets on consumer markets, and simulates technology diffusion profiles consistent with historical observations (Methods)[28–30]. We combine scenario projections with bottom-up estimates of life-cycle emissions from producing different technologies and their fuels[9,10], to analyse emissions trade-offs and net changes from end-use electrification under three scenarios:

(1) A scenario projecting existing observed technological trajectories into the future (current technological trajectory)
(2) A scenario of detailed sectoral climate policies with a 75% probability of achieving the 2 °C climate target (2 °C policy scenario)
(3) A scenario of mismatched policies, in which climate policies are applied only to transport and heating (end-use without power policies)

Figure 1 shows the simulated future diffusion of electricity-generation technologies in the power sector, passenger cars in the road transport sector and heating technologies in the household sector, building on previous detailed modelling studies[26,27,29–31].

Under the current technological trajectory, the future technology uptake is assumed to follow current technological diffusion trajectories in each sector, as can be observed in the market data (such as the diffusion of renewables, a shift towards more efficient petrol cars and an increasing uptake of EVs and HPs). We model the underlying decision-making by investors and consumers until 2050, using a simulation-based algorithm (Methods). The scenario includes existing policies (such as the European Union Emissions Trading System (EU ETS)), but excludes policies that are not yet implemented (such as announced phase-outs of petrol cars). The model does not optimize the technological configuration, and therefore does not prevent end-use electrification where it would lead to emission increases or higher overall system costs.

In the 2 °C policy scenario, we impose bundles of additional policies on all three sectors from 2020 onwards[26,27,29–31] (Methods). The policies were chosen on the basis of what has already been implemented in at least some countries, and could therefore also be politically feasible in other countries. These policies include carbon pricing and feed-in tariffs for power generation, along with fuel taxes and technology-specific subsidies for transport and heating. The policy mixes induce demand reductions and a more rapid uptake of low-carbon technologies compared with the current

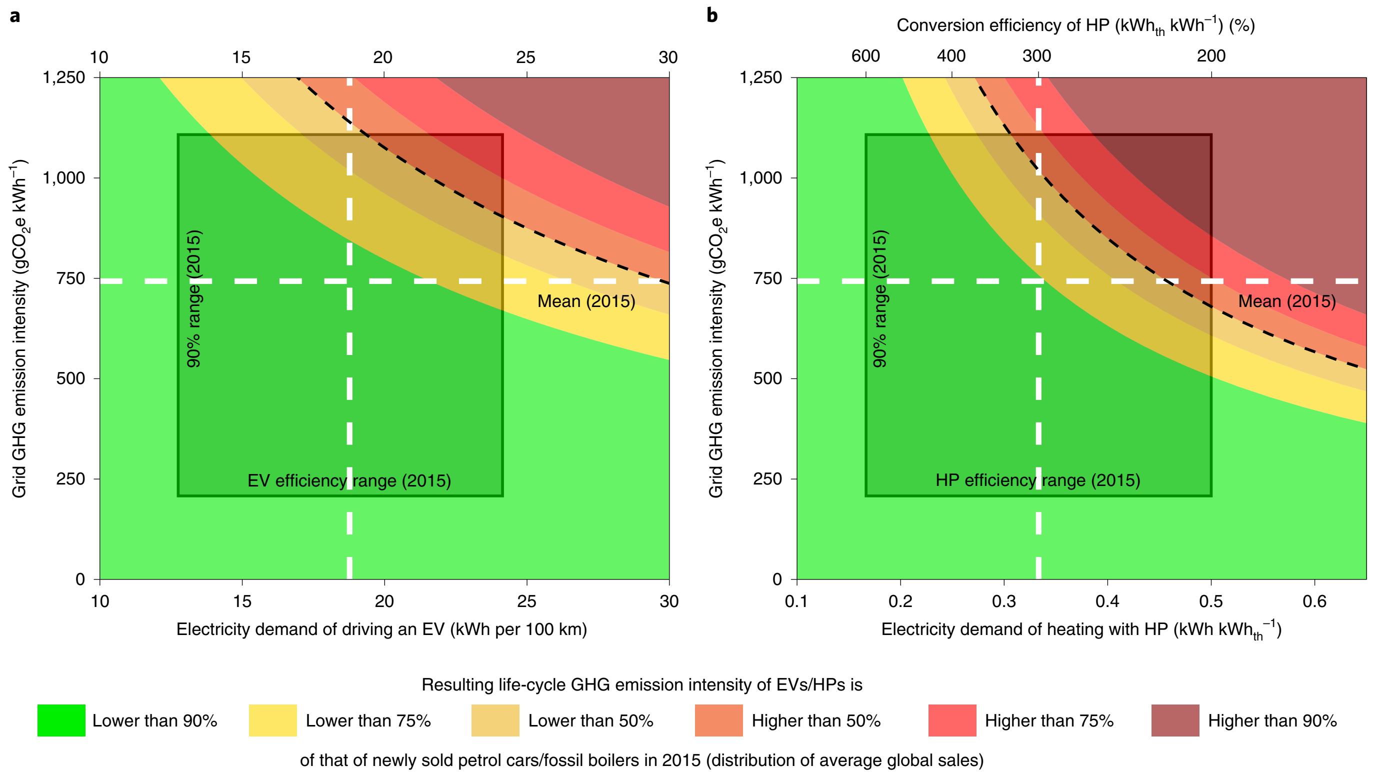

Fig. 2 | Boundary conditions for the use of EVs and HPs. a,b, Conditions under which the life-cycle GHG emission intensities from driving EVs (**a**) and heating with HPs (**b**) are currently lower than those from new petrol cars and fossil boilers being sold in the market, given different combinations of use-phase electricity demand and the electricity grid's GHG emission intensity. Horizontal dashed lines indicate the average emission intensity of global electricity generation (in 2015); vertical dashed lines indicate the estimates of average EV and HP use-phase efficiencies (in 2015). Boxes indicate the 90% range of EV use-phase efficiencies and the range of HP use-phase efficiencies (in 2015). (See Supplementary Figs. 2 and 3 for boundary conditions in 2030 and 2050 under different scenarios.)

technological trajectory—not only of EVs and HPs but also of higher-efficiency petrol cars and heating systems.

In the end-use without power policies scenario, we apply the full set of climate policies from the 2 °C policy scenario to transport and heating, but not to the power and other sectors, which are assumed to follow the current technological trajectory scenario. While such a combination of policies is perhaps unlikely in reality, the scenario's purpose is a worst-case analysis: what impact would an increased uptake of EVs and HPs have on overall emissions, if the carbon intensity of electricity generation worldwide followed its current trajectory?

Under the current technological trajectory, the global mean emission intensity of electricity generation (direct plus indirect emissions per kWh) is projected to decrease 10% by 2030 and 16% by 2050 (relative to a 2015 average of 740 g CO_2-equivalent (CO_2e) per kWh), with considerable variation between countries (Supplementary Table 2). EVs are projected in the current trajectory to account for 19% of global passenger road transport in 2050 (1% in 2030), and HPs for 16% of the global residential heat demand (7% in 2030)[27], also with considerable variation between regions (Supplementary Tables 3 and 4). In the 2 °C policy scenario, the power sector's carbon intensity decreases 44% by 2030, and 74% by 2050 (relative to 2015). The policies will take some time to change the technology mix in transport and heating, but they eventually increase the market share of EVs to 50% by 2050 (1% in 2030), and of HPs to 35% by 2050 (12% in 2030).

Current emission intensities in transport and heating

Figure 2 presents the global conditions under which life-cycle emission intensities from driving EVs and heating with HPs are lower than those from new petrol cars and fossil boilers. Figures 3 and 4 illustrate this comparison in more detail for the ten countries with the largest passenger road transport and residential heating demand, for all three scenarios, both under current conditions and in the future. Figure 5 gives a global overview of where and when electrification would reduce emissions. All estimates include production and end-of-life emissions (of cars, batteries and heating systems), upstream emissions from the extraction and processing of fossil fuels, and the equivalent indirect emissions from electricity generation (Methods).

For EVs, the range of emission intensities reflects higher and lower energy use of different EV models and sizes that are currently available in the market. The central estimates in different regions refer to an average efficiency model with an energy use of 19 kWh per 100 vehicle-kilometres in 2015, subject to future improvements (17 kWh per 100 km in 2030 and 14 kWh per 100 km in 2050)[9] (Methods). For petrol cars, the distribution of intensities refers to empirically measured and projected sales of all petrol and diesel cars (including non-plug-in hybrids) in the respective year and country, according to market data and projections by E3ME-FTT[28,29] (Methods). For HPs, the range of emission intensities reflects higher and lower conversion efficiencies (ratio of heat output to electricity input) of different HP models and under different operating conditions. The central estimates in each region correspond to an average efficiency system with a realized conversion efficiency of 300% in 2015 (390% in 2030 and 420% in 2050)[32]. For fossil boilers, distributions indicate the intensities of newly sold heating systems in a given year and region (oil, gas and coal), also on the basis of empirical data and model projections[30].

From a global perspective, given current conversion efficiencies and production processes, we find that in 2015 driving an average

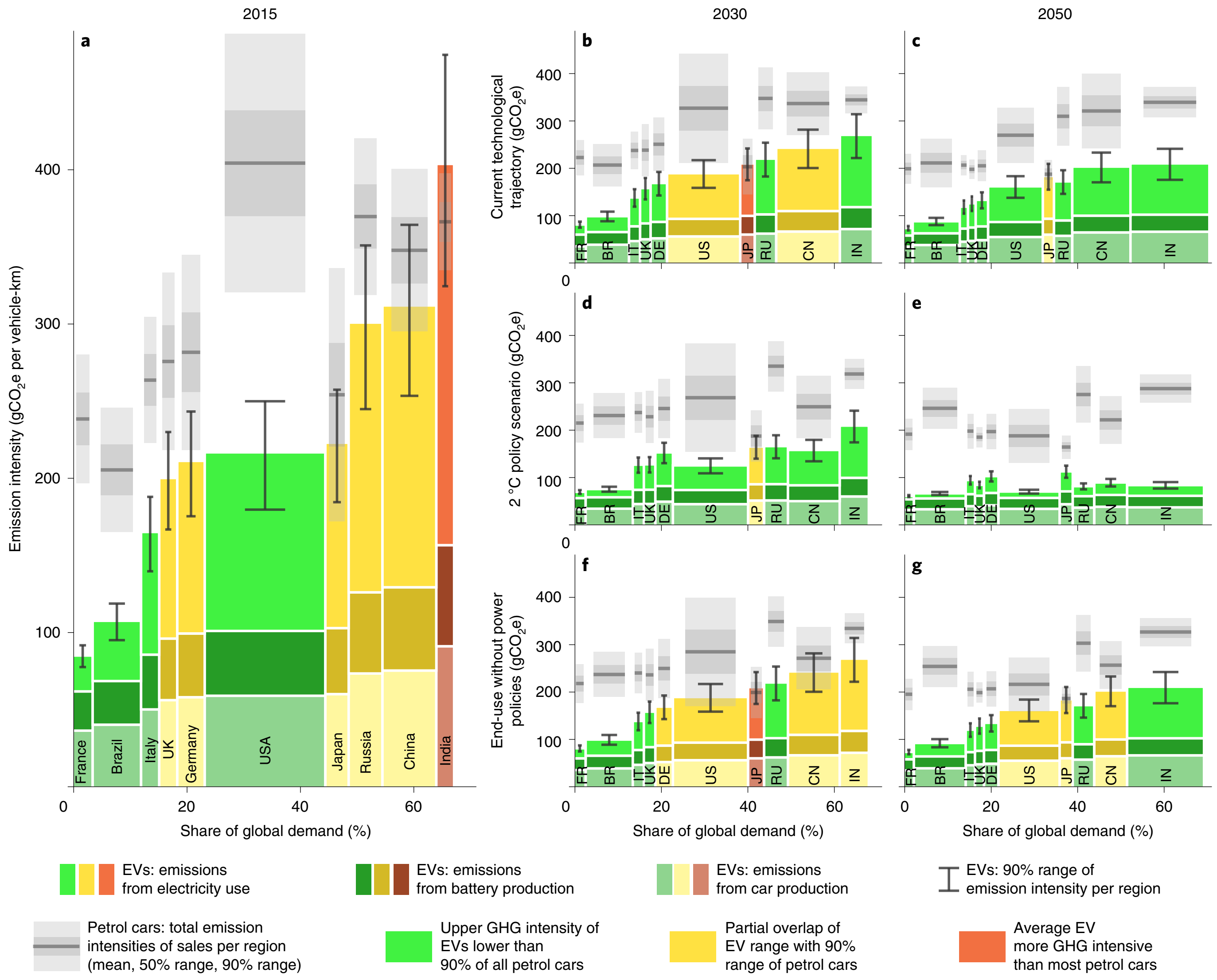

Fig. 3 | GHG emission intensities of passenger cars. a–g, Current (**a**) and projected (**b–g**) GHG emission intensities from driving EVs, for the ten countries with the highest passenger car transport demand in 2015 (the shares in global demand are equivalent to the widths of the bars). Projections under the current technological trajectory (**b**,**c**), the 2 °C policy scenario (**d**,**e**) and the end-use without power policies scenario (**f**,**g**) are shown. The heights of the vertical bars show an average EV's estimated GHG emission intensity, given the power sector's emission intensity in each country (results from this study). The range of the GHG emission intensities reflects higher and lower use-phase energy requirements of different available EV models and sizes. For comparison, the grey box plots show the distributions of GHG emission intensities of newly sold fossil fuel cars in each country (mean, 50% and 90% ranges)[28,29].

EV had a lower life-cycle emission intensity than driving an average new petrol car if the electricity grid's emission intensity was below 1,100 $\mathrm{gCO_2e\,kWh^{-1}}$ (weighted by regional service demand) (Fig. 2a). For heating, average HPs had a lower life-cycle emission intensity than average new fossil boilers if the grid's emission intensity did not exceed 1,000 $\mathrm{gCO_2e\,kWh^{-1}}$ (Fig. 2b). This roughly corresponds to the emission intensity of older coal power plants[33] and is higher than the estimated life-cycle emission intensity of more than 90% of the global electricity generation in 2015 (Supplementary Table 2).

On global average, even very inefficient EVs and HPs would be less emission intensive than very efficient new petrol cars and fossil boilers if the grid's emission intensity was below 700 $\mathrm{gCO_2e\,kWh^{-1}}$ (in the case of EVs) and 500 $\mathrm{gCO_2e\,kWh^{-1}}$ (in the case of HPs), respectively (Fig. 2). These thresholds roughly correspond to the emission intensity of gas power plants[33] and are lower than the average emission intensity of the global electricity generation in 2015 (around 740 $\mathrm{gCO_2e\,kWh^{-1}}$; see Supplementary Table 2). The general finding that EVs and HPs have lower life-cycle emissions than most petrol cars and fossil boilers is robust against variations in uncertain production emissions, such as uncertain embodied emissions from producing batteries of EVs[9,34] and higher-than-expected leakage of refrigerant liquids during all life-cycle phases of HPs[10] (Supplementary Figs. 5 and 6).

Importantly for policymaking on the national level, region-specific threshold emission intensities can be lower or higher than the global averages, depending on the region-specific mix of new petrol cars and fossil boilers that would be replaced. For road transport, the current thresholds below which average-efficiency EVs would result in lower net emissions than average new petrol cars are between 700 $\mathrm{gCO_2e\,kWh^{-1}}$ (in Brazil) and 1,500 $\mathrm{gCO_2e\,kWh^{-1}}$ (in the United States and Canada) (Fig. 3), depending on the region-specific mix of new petrol cars. Very inefficient EVs would still be less emission intensive than very efficient new petrol cars ('green' cases), if the electricity grid's emission intensity was below between 300 $\mathrm{gCO_2e\,kWh^{-1}}$ (in Japan) and 1,000 $\mathrm{gCO_2e\,kWh^{-1}}$ (in Canada). For heating, the current threshold emission intensity for average

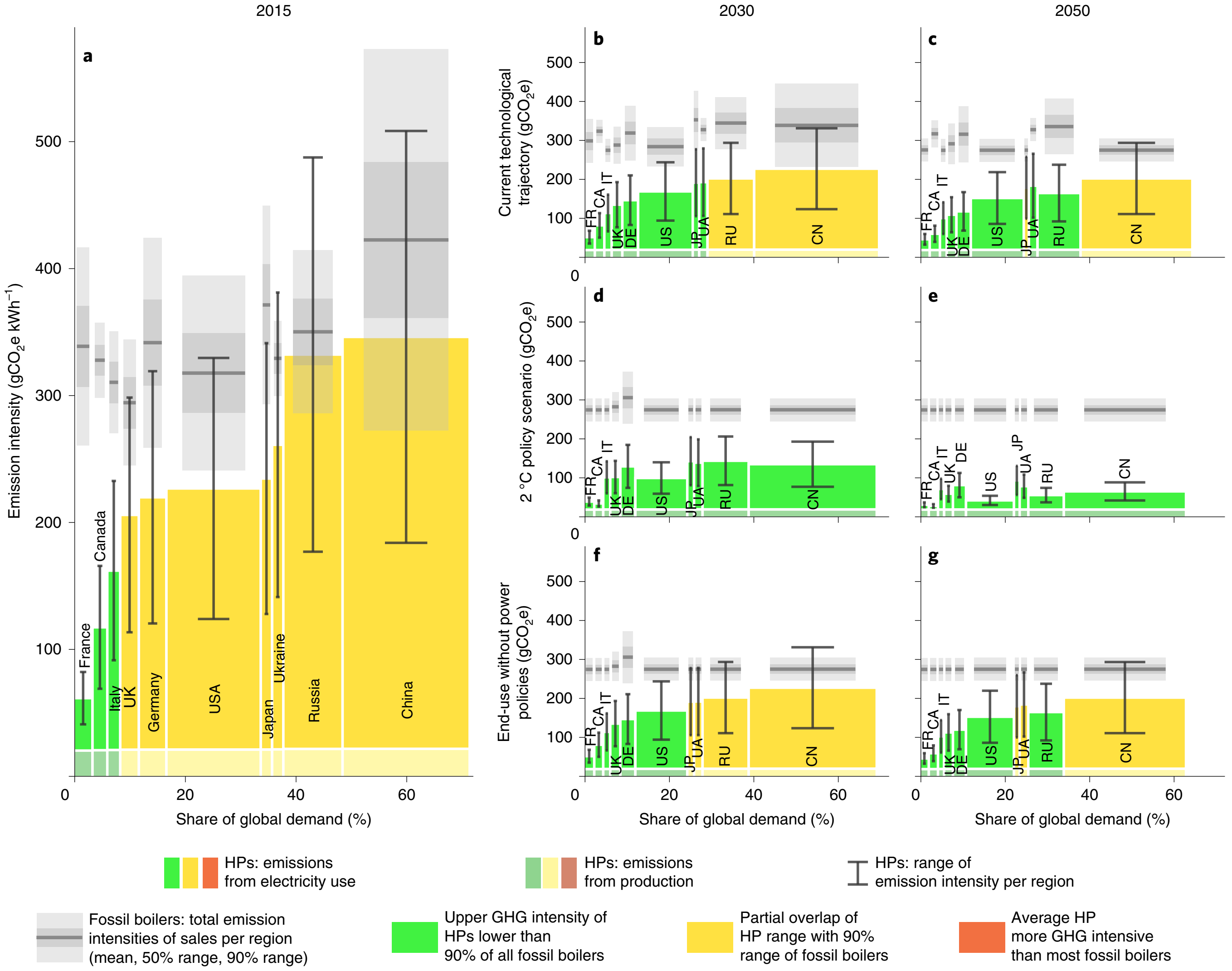

Fig. 4 | GHG emission intensities in household heating. a–f, Current (**a**) and projected (**b**–**g**) GHG emission intensities from heating with HPs, for the ten countries with the highest residential heat demand in 2015 (the shares in global demand are equivalent to the widths of the bars). Projections under the current technological trajectory (**b**,**c**), the 2 °C policy scenario (**d**,**e**) and the end-use without power policies scenario (**f**,**g**) are shown. The heights of the vertical bars show an average HP's estimated GHG emission intensity, given the power sector's emission intensity in each country. The range of the GHG emission intensities reflects higher and lower conversion efficiencies of different HP models and operating conditions. For comparison, the grey box plots show the distributions of GHG emission intensities of newly sold fossil-fuel-based heating systems in each country (mean, 50% and 90% ranges).

HPs is between 800 $gCO_2e\,kWh^{-1}$ (in Sweden and the Netherlands) and 1,400 $gCO_2e\,kWh^{-1}$ (in Poland and South Africa), depending on the region-specific mix of fossil boilers that HPs could replace (Fig. 4). Very inefficient HPs would still have lower emission intensities than very efficient fossil boilers when the grid's carbon intensity was below around 450 $gCO_2e\,kWh^{-1}$.

Accordingly, we find that current models of EVs and HPs have lower life-cycle emission intensities than current new petrol cars and fossil boilers in 53 of 59 world regions, accounting for 95% of the global road transport demand and 96% of the global heat demand in 2015 (Supplementary Fig. 1). Relative differences range from EVs being around 70% less emission intensive per vehicle-kilometre (in largely renewable- and nuclear-powered Iceland, Switzerland and Sweden) to being 40% more emission intensive (in oil-shale-dependent Estonia) (Supplementary Table 6). For HPs, relative differences in life-cycle emissions per kWh of useful heat are between −88% (Switzerland) and +120% (Estonia). On global average in 2015, EVs resulted in 31% lower emissions per vehicle-kilometre than petrol cars (each region weighted by its transport demand), and the emission intensity of HPs was on average 35% lower than that of fossil boilers (regions weighted by their heat demand) (Supplementary Table 6).

While EVs and HPs generally cause less emissions than fossil-fuel-based technologies in most of the world, this may not always be true when comparing specific pairs of technologies. Markets are highly diverse, owing to varying preferences, incomes, household characteristics and attraction to energy-intense luxury items[28]. In many regions, this empirical diversity results in substantial overlap between the observed emission-intensity distributions of petrol cars and fossil boilers on one side, and the likely emission-intensity ranges of available EVs and HPs on the other side. Efficient new petrol cars can cause less emissions than average EVs, and efficient new gas boilers can outperform average HPs (indicated in yellow in Figs. 3–5). In 2015, this happens in regions accounting for 43% of the global demand in road transport (23 regions) and 80% of the global demand in household heating (28 regions).

Region-wide emission increases are likely only where the average emission intensity of EVs or HPs is higher than for the majority

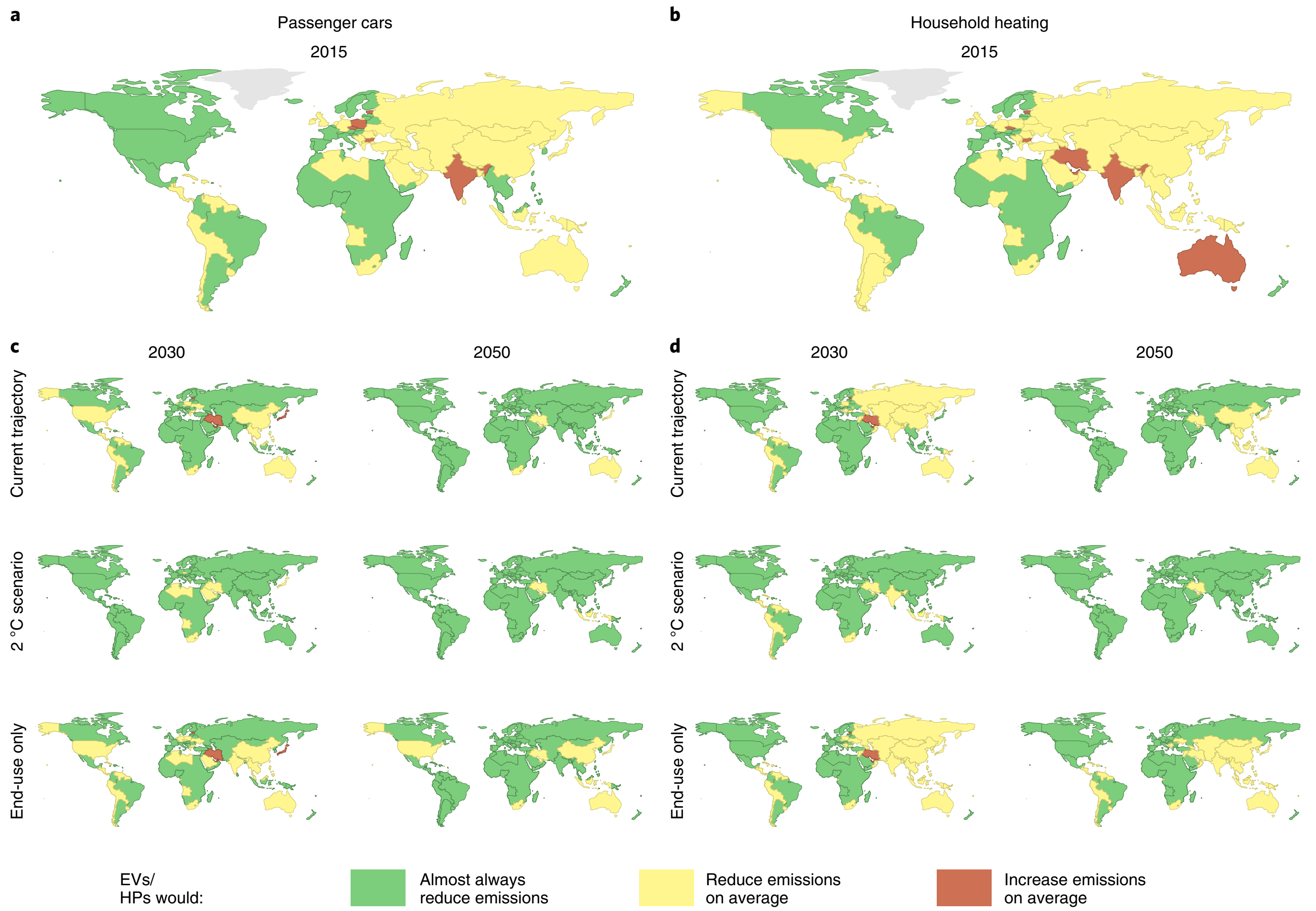

Fig. 5 | Relative GHG emission intensities of EVs and HPs around the world. a,**b**, World regions in which EVs (**a**) and HPs (**b**) have lower projected life-cycle GHG emissions than new petrol cars/fossil boilers in almost all cases (green) or on average (yellow), or are more GHG emission intensive on average (red). **c**,**d**, Projections for 2030 and 2050 for EVs (**c**) and HPs (**d**) under the current technological trajectory (current trajectory), the 2 °C policy scenario (2 °C scenario) and the end-use without power policies scenario (end-use only).

of new petrol cars or fossil boilers (indicated in red in Figs. 3–5). As of 2015, this applies to 5% of the global road transport demand (five regions) and 4% of the global heating demand (six regions) (Fig. 5). In the most favourable case (indicated in green), even very inefficient electrification (equivalent to the upper ends of their ranges) is less emission intensive than using the most efficient new petrol cars or fossil boilers instead (equivalent to the lower bounds of their respective distributions). EVs or HPs can thus reduce net emissions in almost all situations. This is the case in regions accounting for 52% of the global demand for passenger road transport (31 regions) and in regions with 16% of the global demand for household heating (25 regions).

Future emission intensities in transport and heating

Since technology continuously evolves in any policy regime, the emissions trade-offs change over time (Supplementary Figs. 2 and 3). Under the current technological trajectory, in many regions an ongoing reduction in the power sector's emission intensity gradually decreases the indirect emission intensities of using EVs and HPs (also the electricity-related emissions from producing them). In addition, technological progress gradually improves their energy efficiency (Methods). Owing to a combination of both effects, mean emission intensities of EVs are projected to be around 20% lower in 2030 (relative to 2015) and 30% lower in 2050 (weighted by transport demand in 2015). Mean intensities of HPs are projected to decrease 30% below their 2015 value by 2030 and 40% by 2050 (weighted by heat demand in 2015).

Meanwhile, in most regions more efficient variants of fossil-fuel-based technologies will increase their market shares, such as hybrid cars or condensing gas boilers, reducing the emission abatement potential from electrification (Supplementary Tables 4 and 5). Averaged over all regions, new petrol cars in 2050 will emit 20% less emissions per vehicle-kilometre than in 2015, and new fossil boilers will be 15% less emission intensive (weighted by service demand in 2015), with large variations between regions. The largest changes are projected for countries where petrol cars or boilers are currently still relatively inefficient. For example, on the basis of current trends, we project that the 2050 emission intensities of new petrol cars in the United States and new fossil boilers in China will be around 30% below their 2015 levels.

In 2030, under the current technological trajectory and the end-use without power policies scenario, the resulting average emission intensities of EVs and HPs do not exceed those of fossil-fuel-based alternatives in any of the ten countries with the highest transport and heating demands, even without additional decarbonization policies in the power sector (Figs. 3 and 4). The only exception is road transport in Japan: owing to the unique combination of very efficient petrol cars (with a growing share of hybrids) and a power sector that is not highly decarbonized, EVs could lead to marginally higher emissions (Supplementary Table 6). By 2045 and 2035, respectively, EVs and

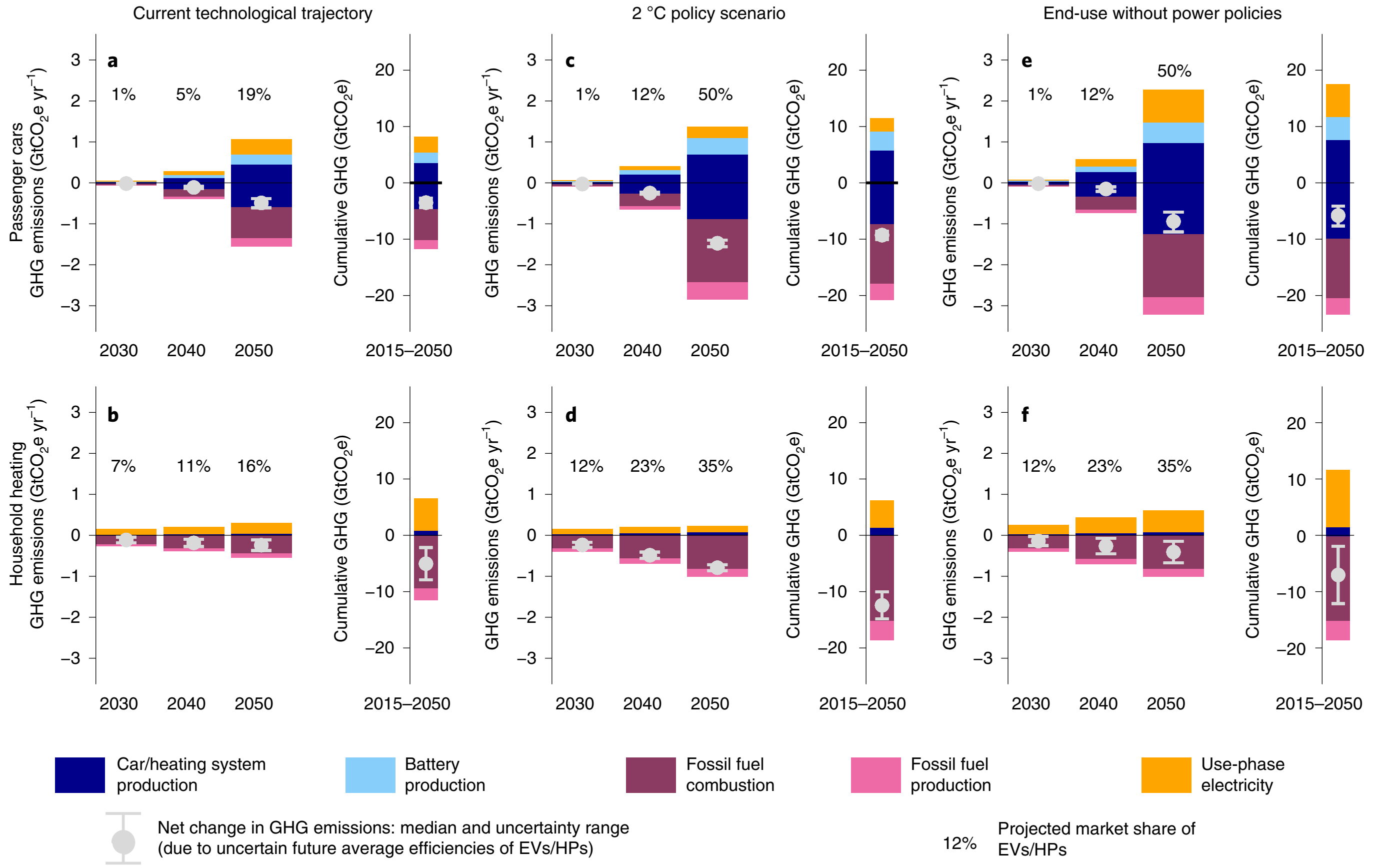

Fig. 6 | Changes in global GHG emissions from EVs and HPs. a–f, Indirect GHG emissions from use-phase electricity generation (orange), compared with avoided direct GHG emissions from fossil fuel combustion (dark purple) and indirect GHG emissions from fossil fuel production (light purple) that would result if the same demand were fulfilled with average new fossil-fuel-based cars (**a**, **c**, and **e**) and heating systems (**b**, **d** and **f**). The GHG emissions from producing cars and heating systems are shown in dark blue (battery production in light blue). Grey dots indicate the overall net change in global GHG emissions from using EVs and HPs. Ranges around the median estimate illustrate the possible range of net changes under lower and higher average use-phase efficiencies of EVs and HPs. Percentages show the global market share of EVs/HPs. Projections under the current technological trajectory (**a**,**b**), the 2 °C policy scenario (**c**,**d**), and the end-use without power policies scenario (**e**,**f**) are shown.

HPs in the current trajectory are on average less emission intensive than fossil alternatives in all world regions (Supplementary Fig. 1). This means that electrification will reduce region-wide emissions as a whole, which is most relevant for policymaking. Note, however, that the diversity of technology choices implies that in some regions (indicated in yellow in Figs. 3–5), some consumers may still buy EVs or HPs that cause higher emissions than efficient new petrol cars or gas boilers. Meanwhile, in the green regions, electrification will reduce emissions in almost any conceivable case.

Possible overlaps between technology categories are much rarer in the 2 °C policy scenario, with its much faster power sector decarbonization. In all world regions, EVs and HPs are on average less emission intensive than fossil fuel alternatives from around 2025 onwards (Fig. 5c,d). This is despite increased average efficiencies of new petrol cars and fossil boilers, relative to the current technological trajectory (Supplementary Table 7). By 2030, even inefficient EVs or HPs have lower emission intensities than very efficient new fossil-fuel-based alternatives in regions accounting for around 90% of the global transport and heat demands. This implies that in the medium term, in almost all cases the more effective policy strategy for reducing transport and heating emissions is to push EVs and HPs, instead of supporting the uptake of more efficient fossil-fuel-based technologies.

In the end-use without power policies scenario, future intensities follow the 2 °C policy scenario trend for petrol cars and fossil boilers, but remain identical to the current technological trajectory for EVs and HPs (Supplementary Table 8). Between 2020 and 2050, there is thus a relatively larger share of the global demand for which future emission intensities will partially overlap in both transport and heating (yellow regions), compared with the current technological trajectory. Although this reduces the potential magnitude of net emission reductions from electrification relative to the 2 °C policy scenario, the risk of region-wide emission increases (red regions) remains limited. The share of the transport and heat demands for which EVs and HPs would increase average emissions compared with the use of their fossil fuel counterparts never exceeds 6%.

Net changes in total emissions

Finally, we project how EVs and HPs could change future levels of economy-wide emissions over time, compared with fossil-fuel-based technologies. For each region, we estimate the emissions from using and producing EVs and HPs in each year, and subtract avoided emissions from the alternative use and production of new petrol cars and fossil boilers (Methods). We find that both EVs and HPs reduce global emissions in all scenarios and at all times (Fig. 6): EVs by up to $-1.5\,\text{GtCO}_2\,\text{yr}^{-1}$ (−29% of the total passenger road transport emissions without the use of EVs), and HPs by up to $-0.8\,\text{GtCO}_2\,\text{yr}^{-1}$ (−46% of the total residential heating emissions without the use of HPs).

As EVs and HPs replace fossil-fuel-based technologies over time, production emissions are projected to grow from around 25% of the total road transport emissions in 2015 to 35–38% in 2050, and from 1% of the total heating emissions in 2015 to 2–9% in 2050 (Supplementary Fig. 4). This is due to reduced use-phase emissions from electricity and increased production emissions, which are currently around 30% higher for EVs than for petrol cars (at the average global electricity mix) and 15 times higher for HPs than for fossil boilers (mainly from the leakage of refrigerant liquid). A full decarbonization of household energy use therefore remains infeasible without also reducing the embodied emissions from producing and recycling technologies and required materials (such as steel), beyond the decarbonization of the electricity input.

Owing to the delay between (relatively higher) production emissions and (relatively lower) use-phase emissions, a rapid technological transition towards EVs and HPs could temporarily increase emissions in individual regions, compared with the production and use of fossil-fuel-based technologies—even if EVs and HPs cause lower emissions over their whole life cycles[35]. However, we find that in all three scenarios, temporary emission increases from EV and HP production are limited to regions accounting for less than 7% of the global transport demand and 4% of the global heat demand (Supplementary Table 9). In almost all regions, such temporary increases are outweighed by emission reductions in subsequent years. Even in the end-use without power policies scenario, EVs and HPs would therefore reduce cumulative emissions from 2015 to 2050 in regions accounting for 96% of road transport and 97% of the heating demand.

Discussion

Overall, we find that current and future life-cycle emissions from EVs and HPs are on average lower than those of new petrol cars and fossil boilers—not just on the global aggregate but also in most individual countries. Over time, in increasingly more regions even the use of inefficient EVs or HPs is less emission intensive than the most efficient new petrol cars or fossil boilers.

Importantly for policymaking on the national level, given that the alignment of policymaking across departments is highly complex and not always successful[36–38], we showed that the risk of implementing incoherent decarbonization policies is low in the case of EVs and HPs. Even if future end-use electrification is not matched by rapid power-sector decarbonization, the use of EVs and HPs almost certainly reduces emissions in most world regions, compared with fossil-fuel-based alternatives.

Our analysis disaggregates global demand into 59 world regions, a spatial resolution that is considerably higher than in any previous forward-looking life-cycle study of EVs or HPs. Further research could focus on the remaining variation within larger simulated world regions (such as China[19] and the United States[16,20]). Such studies could also analyse the location-specific impacts of integrating EVs and HPs into the electricity grid[39–42], and how this translates into varying marginal emission intensities over time (compared with the average emission intensities used in this study)[42,43].

Finally, our findings imply (1) that support for high-efficiency fossil fuel technologies may be justified only in the short term, when the market uptake of EVs and HPs can still be constrained by limited production capacities and necessary infrastructure adjustments, and (2) that policymakers in most parts of the world can go ahead with ambitious end-use electrification policies, without the need to rely on further power sector decarbonization, while (3) achievable emission reductions in transport are partly constrained by the remaining production emissions.

Methods

GHG emission intensities. For estimating current and future emission intensities of electricity generation, passenger road transport and household heating, we combined estimates from the life-cycle assessment literature with model projections of future technology uptake and the resulting emission intensities[27,31], inspired by the work in refs. [44–48]. For both the use and the production of technologies, we explicitly included the projected emission changes that result from the changing mix of electricity generation technologies over time. For all technologies, we included all production and end-of-life emissions. These were equally distributed over the entire lifespan for the calculation of emission intensities (Figs. 2–5), and allocated to the respective years of production and disposal for the estimation of absolute emission levels over time (Fig. 6). Note that we evaluated the emission intensities of technologies rather than those of households (which in some cases may use a combination of technologies).

Electricity generation. We based all calculations on the region-wide average grid emission intensities of electricity generation (gCO$_2$e kWh^{-1}), which we calculated from the model-projected levels of total power-sector emissions and electricity demand in each region and year. As we divide the total GHG emissions by the total electricity demand (instead of generation), the resulting intensity values include transmission and distribution losses. Historic data (up to 2012) were calculated based on data from the International Energy Agency (IEA), while relative future changes of these historic values were projected by E3ME-FTT. We included indirect emissions from the extraction and processing of fossil fuels, the construction of power-generation technologies (including the necessary infrastructure and supply chain emissions) and methane emissions (all on the basis of the most likely estimates from the IPCC's Fifth Assessment Report[33]), as well as indirect emissions from biomass use[49]. The resulting life-cycle emission intensities per year and region are given in Supplementary Table 2.

EVs. For all cars, we subdivided GHG emissions into use-phase emissions (from driving the car), and production and end-of-life emissions. We calculated use-phase emissions as the product of the car's electricity use and the emission intensity of electricity generation in each region (as described above). Ranges of current and future electricity use per vehicle-kilometre were based on estimates by Cox et al.[50] for 2015 (median, 0.19 kWh km^{-1}; 5th–95th percentile range, 0.13–0.24 kWh km^{-1}) and 2040 (median, 0.15 kWh km^{-1}; 5th–95th percentile range, 0.10–0.19 kWh km^{-1}, on the basis of the 'most likely automation' scenario), including auxiliary power demand and charging losses. These values were based on a review of currently available EVs, and calibrated to match empirical energy use under real-world driving conditions. We linearly interpolated the efficiency ranges between 2015 and 2040, and linearly extrapolated this trend to 2050. Relative improvements compared with 2015 equal around −12% until 2030 and −24% until 2050.

Production and end-of-life emissions were further subdivided into emissions from electricity required for the production process, and non-electricity emissions. Electricity requirements (excluding the battery) were obtained from EcoInvent[51] (v.3.5), adding up the electricity inputs of the foreground process (the production of the car) and of all background processes (the production of parts and materials, transport, mining and so on) (Supplementary Methods 1). We determined the electricity emissions by multiplying the amount of required electricity by the projected GHG intensity of electricity generation in the country where the car is driven, thereby abstracting from the import and export of cars (and car parts). For the production of medium-sized EVs (curb weight of 1,500 kg), electricity requirements (excluding the battery) were estimated at 6,900 kWh (0.046 kWh km^{-1}, assuming an average lifetime of 150,000 km)[51]. Emissions from other sources in the car production (excluding the battery) were set at 4,700 kgCO$_2$e (31 gCO$_2$e km^{-1})[51]. For the battery production, non-electricity emissions were estimated at 3,200 kgCO$_2$e (21.3 gCO$_2$e km^{-1}), and battery cell electricity requirements at 5,000 kWh (0.034 kWh km^{-1})[50]. The latter was estimated to linearly decrease to 3,400 kWh (0.023 kWh km^{-1}) in 2040[50], and we further linearly extrapolated this trend to 2050. As electricity requirements and embodied emissions of the production processes can be subject to uncertainty, we included a sensitivity analysis for a range of life-cycle parameters (Supplementary Figs. 5 and 6).

Petrol cars. For use-phase emissions, we first calculated tank-to-wheel emissions of cars on the basis of the distributions of manufacturer-rated intensities (without any blend of biofuels) of all liquid-fuel cars (petrol and diesel, including non-plug-in hybrids) that are sold in a given region and year—on the basis of empirical data at the start of the simulation, and projected into the future by E3M3-FTT. Real-world fuel use and resulting use-phase CO$_2$ emissions of petrol cars are widely recognized to exceed official manufacturer ratings, by an average margin of 10–40% (on the basis of empirical studies in Europe, the United States and China)[52–56]. We therefore adjusted all manufacturer ratings by the central estimate of 25%, consistent with the adjustment calculations by the US Environmental Protection Agency[56]. For obtaining well-to-wheel emissions, we added upstream emissions from the extraction and processing of fuels (26% of tank-to-wheel emissions for petrol, and 28% for diesel)[57–59]. Emissions from car production and end-of-life were subdivided into emissions from electricity required for the production process (including background processes) and non-electricity emissions. The electricity requirements for producing a medium-sized car (curb weight 1,600 kg) were estimated at 9,200 kWh (0.061 kWh km^{-1}), and emissions from other sources at 5,900 kgCO$_2$e (40 gCO$_2$e km^{-1})[51].

HPs. We differentiated between use-phase emissions (from heating), and production and end-of-life emissions. We calculated use-phase emissions as the product of HP point-of-use conversion efficiencies (that is, the ratio of heat delivered to the electricity consumed over the season), and the region-specific intensities in electricity generation. The average efficiency was set to 300% in 2015 (range: 200–600%), on the basis of the IEA Energy Technology Systems Analysis Programme expert ranges given for the most common types of HPs (air-to-air, air-to-water and ground-source)[32]. The same literature source estimated that future efficiencies of HPs will improve by 30–50% until 2030 and 40–60% until 2050. As HPs are a relatively mature technology, we based our calculations on the lower-bound estimates (30% efficiency improvement until 2030, 40% until 2050). We linearly interpolated between 2015 and 2050, yielding average efficiencies of 390% in 2030 (range: 260–780%) and 420% in 2050 (range: 280–840%).

For the production and end-of-life stage of HPs, we estimated emissions from non-electricity sources at 830 kgCO$_2$e per kW of installed capacity[51]. Of these emissions, 750 kgCO$_2$e stem from the leakage of refrigerant liquids over the entire life cycle, all included here in the production emissions. We converted the impacts into the functional unit of gCO$_2$e kWh$_{\mathrm{th}}^{-1}$, assuming an average technical lifetime of 20 yr (ref. [60]) with 2,000 operating hours per year[61], yielding non-electricity emissions of 20.8 gCO$_2$e kWh$_{\mathrm{th}}^{-1}$ (including leakage). Electricity requirements for the production of HPs (including background processes) were set at 65 kWh per kW of installed capacity (0.002 kWh kWh$_{\mathrm{th}}^{-1}$)[51].

Fossil fuel heating systems. We based our calculation of use-phase emissions on the distribution of intensities of all decentral residential fossil-fuel-based heating systems (oil, gas and coal) being sold in a respective region and year, simulated until 2050 by E3ME-FTT ('Distributions of petrol cars and fossil boilers'). We assumed conversion efficiencies of 75% for oil and gas heating systems, 86% for advanced oil systems and 90% for advanced gas systems[62]. We combined these with IPCC emission factors to obtain emission intensities per technology. We added upstream emissions from the extraction and processing of heating oil (equivalent to 28% of direct emissions, on the basis of the estimate for diesel[57], which is chemically near-equivalent to heating oil), gas (23% of direct emissions[63]) and coal (6% of direct emissions[64]). For the production, we based our calculations on EcoInvent (v.3.5) estimates for gas and oil boilers[51], which constitute the large majority of global sales. The electricity requirements (including background processes) are 37 kWh per kW of installed capacity (0.001 kWh kWh$_{\mathrm{th}}^{-1}$, on the basis of the same lifetimes and operating hours as for HPs), and emissions of other sources are 30 kgCO$_2$e kW^{-1} (0.8 gCO$_2$e kWh$_{\mathrm{th}}^{-1}$)[51].

Distributions of petrol cars and fossil boilers. We estimated the ranges of emission intensities from empirically measured and projected sales in the respective year and country (Supplementary Tables 4 and 5). For cars, the distribution of current sales was derived from detailed market data on vehicle sales (years 2004–2012), which we compiled by matching sales data to manufacturer data for thousands of individual vehicle models currently on the market in 18 countries, and we extrapolated these values for countries where data is missing[28,29]. Distributions of future sales (2013–2050) were projected by E3ME-FTT (see 'Integrated assessment model'), on the basis of the market data and simulated future consumer choices. For some regions (mainly in Africa; see Supplementary Table 1), vehicle sales were assumed to equal global averages, owing to the unavailability of empirical data. For heating systems, current and future sales were simulated by E3ME-FTT (from 2015 to 2050), according to the available data on fuel use and technology stocks (years 1990–2014)[30,65]. Both for cars and for boilers, we then calculated the mean and standard deviation of emission intensities (including upstream emissions) of all sales in a respective region, for each year until 2050, according to our simulations (Supplementary Tables 6–8). The intensity of each technology type was thereby weighted by the number of model-projected sales in each world region. Emissions from the production of technologies were added as a constant. This way, future changes in the range of emission intensities are not an exogenous input, but are endogenously projected by the model, on the basis of a gradually changing technology composition in the context of different policy assumptions.

Net changes in GHG emissions. We estimated the net changes in overall emissions for each world region in each year. First, we calculated the emissions from EVs and HPs, on the basis of their model-projected region-specific market shares and average use-phase emission intensities ('Scenarios of technology uptake'). Emissions from the production phase were fully allocated to the year in which a car or heating system is produced, and end-of-life emissions to the year of its disposal (assuming average lifetimes of 10 yr for cars and 20 yr for heating systems) (see Supplementary Methods 2 for the relative shares). Second, we subtracted avoided emissions that otherwise would have been emitted by new petrol cars or fossil boilers, if they would have been used to fulfil the same service demand, also on the basis of the projected average intensities of sales in each region (without the blend of biofuels). The use of region-specific intensities results in relatively smaller net savings in regions where the average efficiency of new petrol cars or fossil boilers is relatively higher and relatively larger net savings in regions where the average efficiency is relatively lower. Results depend on the assumed reference point: while many combinations are possible, what matters for region-wide effects is the sum over all individual choices of cars and heating systems within one region in any given year. While the mean efficiencies in each region can change over time, we assumed that the structure of all sales remains distributed (that is, that people would not suddenly all buy economic small-engine cars). Cumulative net changes can then be approximated on the basis of the region-specific means of distributed intensities. Global changes in emissions equal the sum of all region-specific estimates.

Scenarios of technology uptake. We used E3ME-FTT model projections of future technology diffusion and fuel use in three scenarios: (1) current technological trajectory, (2) 2 °C policy scenario and (3) end-use without power policies. These scenarios were chosen so that they allowed us to simulate the emission trade-offs from electrification as realistically as possible, given (1) what is likely from a current perspective, (2) what would be likely in a hypothetical case of ambitious climate policies around the globe and (3) a worst-case scenario in which end-use electrification is not matched by power-sector decarbonization. The first two scenarios were based on recent modelling studies[26,27,31], and detailed descriptions of the underlying policy assumptions are available in ref. [27]. All policies included in the scenarios are designed to match as closely as possible real-world policy instruments (for example, energy taxes, vehicle taxes, feed-in tariffs, subsidies, direct regulation or efficiency standards).

Current technological trajectory. As a result of the path-dependent simulation nature of E3ME-FTT, the model projects a baseline trajectory in which technological change already takes place without the implementation of additional policies. To differentiate from baselines without any technological change, we refer to it as the current technological trajectory, in which several low-carbon technologies (such as solar photovoltaics, EVs or HPs) already diffuse to some extent, following the trajectory observed in historical data, while other technology types (such as low-efficiency petrol cars or coal and oil heating systems) are projected to decline in market shares, also observed in the data. The scenario implicitly includes current policies in the transport and heating sectors, given that they already had a measurable impact on empirically observed technology uptake in our historic datasets. For the heating sector, we further assumed that the average insulation efficiency of buildings gradually increases over time (Supplementary Methods 3). For the power sector, we explicitly included existing policy schemes, such as the EU ETS.

2 °C policy scenario. We imposed sets of sector-specific policies to achieve a projected trajectory of global emissions that is consistent with a 75% probability of not exceeding 2 °C of global warming by the end of the century. Policies are implemented in or after 2020. In electricity generation, transport and heating, they are defined so that they incentivize the uptake of low-carbon technologies (for example, subsidies or feed-in tariffs), disincentivize the use of fossil fuels (for example, carbon taxes) or regulate the use of fossil fuel technologies (for example, efficiency standards or a phase-out of coal power plants). In electricity generation, the main policies are carbon pricing, subsidies for renewables and nuclear, feed-in tariffs (for wind and solar), a ban on the construction of new coal power plants, and increased capacities for electricity storage. In passenger road transport, the main policies are fuel efficiency standards for newly sold petrol cars; a gradual phase-out of older, low-efficiency petrol cars; a gradually increasing fuel tax; a purchase tax for vehicles proportional to their rated emission intensity; procurement programmes for EVs where they are not available yet; and an increasing biofuel mandate (reaching up to 10–30% in 2050; region-specific mandates extrapolate IEA projections). In household heating, the main policies are a tax on the residential use of fossil fuels (oil, gas and coal); subsidies on the upfront purchase costs of renewable heating technologies (HPs, solar thermal and modern biomass), which start in 2020 and are linearly phased out after 2030; and more stringent building regulations, implying that a large fraction of houses are retrofitted to passive house properties. More details can be obtained from refs. [26,27].

End-use without power policies. We combined the power sector trajectory from scenario 1 with the road transport and heating trajectories from scenario 2, making the scenario assumption that policymakers would implement policies to push EVs and HPs while not pursuing any further decarbonization of electricity generation. No policies were imposed on any other sectors. Although such a combination of policies is unlikely in the real world, the scenario serves as a worst-case analysis.

Integrated assessment model. E3ME-FTT-GENIE is a simulation-based integrated assessment model that combines bottom-up representations of the power, transport and heating sectors with a macroeconometric representation of the global economy, for 59 regions covering the globe (Supplementary Table 1)[26].

Future technology transformation models. The future technology transformation (FTT) family of models project the uptake of energy technologies in the future until 2050, by extending the current trajectory of technological change with a diffusion algorithm, which is calibrated on datasets of technology uptake in recent history (up to 2012 for power and transport, 2014 for heating) (Supplementary Tables 4 and 5). Each FTT model is based on a bottom-up description of heterogeneous agents who own or operate technologies that produce certain societal services (such as electricity generation, road transport and household heating), and who consider replacing such technologies according to lifetimes and contexts. As such, it is both a model of choice and one of technology vintage (or technology fleets). Replacement, or technological change, takes place at rates determined by the survival in time of technology units and/or the financing schedule. We assume that agents make comparisons between technology options that they individually see as available in their respective national markets, which we structure by pairwise comparisons of distributed preferences. The model is a discrete choice model in which choice options are weighted by their own popularity, a method that generates endogenous S-shaped technology diffusion curves[66]. The technological trajectory is not based on economy-wide optimization, but endogenously evolves from the sum of individual choices of heterogeneous agents with bounded rationality. FTT models are characterized by strong path-dependence of projected technology diffusion (equivalent to strong autocorrelation in time), as it is typically found in technology transitions[67,68], and for that reason, these models provide a good representation of the inertia embedded in technological systems. They are thus well suited to analysing existing technological trajectories as observed in recent historical data. A description of how future demand for transport and heating is determined is given in Supplementary Methods 3. Further descriptions of the individual FTT models are in refs. [29,30,65,69–71].

E3ME model. The FTT models are part of E3ME (hard-coupled in the same computer code), which represents relationships between macroeconomic quantities in a top-down aggregate perspective through a chosen set of econometric relationships that are regressed on the past 45 yr of data and are projected 35 yr into the future (until 2050). The macroeconomics in the model determine the total demand and trade for manufactured products, services and energy carriers, output and employment for 43 economic sectors, 24 fuel users and 12 fuels. The model is path-dependent, such that different policy scenarios generate different techno-economic and environmental trajectories that diverge from each other over time. Using the what-if mode of impact assessment, policies are chosen, and the resulting outcomes can be projected. Meeting policy objectives (such as emissions targets) is not achieved by means of maximizing or minimizing some target function (such as welfare or costs). Instead, the model is run iteratively until the target would be met with a chosen set of policies. The model is regularly used in policy analyses and impact assessments for the European Commission and elsewhere[72,73]. See ref. [26] for a detailed description of the integrated model, and ref. [74] for the E3ME manual.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The main data that support the findings of this study are available as supplementary tables. Additional data are available from the corresponding authors upon request.

Code availability

The computer code used to generate the results that are reported in this study are available from the corresponding authors on reasonable request.

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Author contributions

F.K. designed the research and wrote the manuscript, with contributions from all authors. S.V.H. and F.K. performed the life-cycle analysis, with contributions from M.A.J.H. F.K., J.-F.M., U.C. and H.P. ran the model simulations. U.C. and H.P. managed E3ME. J.-F.M. and A.L. developed FTT:Transport. F.K. and J.-F.M. developed FTT:Heat. J.-F.M. and P.S. developed FTT:Power.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

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Policy information about availability of computer code

Data collection	The IAM scenario data is derived from the E3ME-FTT integrated assessment model.
Data analysis	The data was analysed with R (version 3.5.3).

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Study description	Combination of quantitative scenario modelling with quantitative LCA
Research sample	59 world regions covering the globe, as defined in the manual of the E3ME-FTT integrated assessment model
Sampling strategy	no sampling
Data collection	no data collection
Timing	NA
Data exclusions	no data was excluded
Non-participation	NA
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