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

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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 policy backfire by promoting their diffusion before electricity is decarbonised? 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 assessment. 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 global transport and heating demand. Even if future end-use electrification is not matched by rapid power sector decarbonisation, it likely avoids emissions in world regions representing 94% of global demand.

Policy-makers widely consider electrification a key measure for decarbonizing road transport and household heating. Combined, they 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 for 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 tailpipe/on-site greenhouse gas emissions ('emissions'), but causes emissions from electricity generation. Emission intensities in the power sector widely differ across the globe and will change over time[3]. Additionally, producing and recycling EVs and HPs involves higher emissions than producing petrol cars and fossil boilers, due 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 decarbonise electricity generation, increase overall emissions[11,12].

Multi-sectoral mitigation scenarios (such as those reviewed by the IPCC) have identified electrification as a robust policy strategy, but typically focus on a context of rapid power sector decarbonisation[3,13]. However, sector-specific policies and self-reinforcing social and industrial dynamics could as well lead to real-world trajectories in which end-use electrification and power sector decarbonisation take place at completely different rates[14]. In such a context, could end-use electrification turn into a counterproductive policy strategy for reducing emissions?

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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 type of fossil fuel technologies are likely to be replaced by which type of EV or HP? This requires a comparison not only of generic (representative) technology types, but of technology ranges (market segments), based on empirically observed sales in each region.

This is different to 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.[15–23] for studies on EVs, and refs.[10,24,25] on HPs). For the case of EVs, only two studies extend the analysis into the future[9,26]. 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 policy-making processes at the national level.

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

Scenarios of technology diffusion

We simulate future technology diffusion and 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[27,28]. This model's representation of technology uptake in transport and heating is strongly empirical, based on detailed regional datasets on consumer markets, and simulates technology diffusion profiles consistent with historical observations (see Methods)[29–31]. We combine scenario projections with bottom-up estimates of life-cycle emissions from producing different technologies and their fuels[9,10], in order to analyse emissions trade-offs and net changes from end-use electrification under three scenarios:

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

Fig. 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[27,28,30–32].

Under the 'current technology trajectory', future technology uptake is assumed to follow current technological diffusion trajectories in each sector, as can be observed in 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 EU-ETS), but excludes policies that are not implemented yet (such as announced phase-outs of petrol cars). The model does not optimise 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 scenario', we impose bundles of additional policies on all three sectors from 2020 onwards[27,28,30–32] (Methods). The policies were chosen based on what has already been implemented in at least some countries, and could therefore also be politically feasible in other countries. This includes 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 to the 'current 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 scenario' to transport and heating, but not to the power and other sectors, which are assumed to follow their 'current technological trajectory'. 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 follows 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 gCO_2eq/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 global residential heat demand (7% in 2030)[28], also with considerable variation between regions (Supplementary Tables 3 and 4). In the '2°C 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

Fig. 2 presents the global conditions under which life-cycle emission intensities from driving EVs and heating with HPs are lower than those of new petrol cars and fossil boilers. Fig. 3 and Fig. 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. Fig. 5 gives a global overview over 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 electric car models and sizes which are currently available in the market. The central estimates within different regions refer to an average efficiency model with an energy use of 19 kWh electricity per 100 vehicle-kilometre in 2015, subject to future improvements (17 kWh/100km in 2030, and 14 kWh/100km in 2050)[9] (Methods). For petrol cars, the distribution of intensities refers to empirically measured and projected sales of all petrol and diesel cars (incl. non-plug-in hybrids) in the respective year and country, according to market data and projections by E3ME-FTT[29,30] (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 respective region correspond to an average efficiency system with a realised conversion efficiency of 300% in 2015 (390% in 2030, and 420% in 2050)[33]. For fossil boilers, distributions indicate the intensities of newly sold heating systems within a given year and region (oil, gas and coal), also based on empirical data and model projections[31].

From a global perspective, given current conversion efficiencies and production processes, we find that in 2015 driving an average EV had a lower life-cycle emission intensity than average new petrol cars if the electricity grid's emission intensity was below 1100

gCO_2eq/kWh (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 1000 gCO_2eq/kWh (Fig. 2b). This roughly corresponds to the emission intensity of older coal power plants[34], and is higher than the estimated life-cycle emission intensity of more than 90% of 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 gCO_2eq/kWh (in case of EVs) and 500 gCO_2eq/kWh (in case of HPs), respectively (Fig. 2). These thresholds roughly correspond to the emission intensity of gas power plants[34], and are lower than the average emission intensity of global electricity generation in 2015 (around 740 gCO_2eq/kWh, 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[9,35] and higher-than-expected leakage of refrigerant liquids during all life-cycle phases of HPs[10] (Supplementary Figures 5 and 6).

Importantly for policy-making 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 gCO_2eq/kWh (in Brazil) and 1500 gCO_2eq/kWh (in the USA 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 gCO_2eq/kWh (in Japan) and 1000 gCO_2eq/kWh (in Canada). For heating, the current threshold emission intensity for average HPs is between 800 gCO_2eq/kWh (in Sweden and the Netherlands) and 1400 gCO_2eq/kWh (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_2eq/kWh.

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 global road transport demand and 96% of 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 result in 31% lower emissions per vehicle-kilometre compared to petrol cars (each region weighted by its transport demand), and the emission intensity of HPs is 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, due to varying preferences, incomes, household characteristics, and attraction to energy-intense luxury items[29]. In many regions, this empirical diversity results in significant 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 Fig. 3-5). In 2015, this happens in regions accounting for 43% of global demand in road transport (23 regions), and 80% in household heating (28 regions).

Region-wide emission increases are only likely where the average emission intensity of EVs or HPs is higher than for the majority of new petrol cars or fossil boilers (indicated in red in Fig. 3-5). As of 2015, this applies to 5% of global road transport demand (5 regions) and 4% of global heating demand (6 regions) (Fig. 5). In the most favourable case (indicated in green), even very inefficient electrification (equivalent to the upper end 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 then reduce net emissions in almost all situations. This is the case in regions accounting for 52% of global demand for passenger road transport (31 regions), and in regions with 16% of 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 Figures 2 and 3). Under the 'current technological trajectory', in many regions an ongoing reduction in the power sector's emissions intensity gradually decreases 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). Due 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 boiler will be 15% less emissions 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, based on current trends, we project that the 2050 emission intensities of new petrol cars in the USA 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' scenarios, 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 demand, even without additional decarbonisation policies in the power sector (Fig. 3 and Fig. 4). The only exception is road transport in Japan: Due to the unique combination of very efficient petrol cars (with a growing share of hybrids) and a power sector that is not highly decarbonised, EVs could lead to marginally higher emissions (Supplementary Table 6). By 2045 and 2035, respectively, EVs and HPs in the current trajectory are on average less emission intensive than fossil alternatives in all world regions (Supplementary Figure 1). This means that electrification will reduce region-wide emissions as a whole, which is most relevant for policy-making. Note, however, that the diversity of technology choices implies that in some regions (indicated in yellow in Fig. 3-5), some consumers may still buy EVs or HPs which 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 scenario', with its much faster power sector decarbonisation. In all world regions, EVs and HPs are on average less emission intensive than fossil-fuel alternatives from around 2025 onwards (Fig. 5 c-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-based alternatives in regions accounting for around 90% of global transport and heat demand, respectively. 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' trend for petrol cars and fossil boilers, but remain identical to the 'current trajectory' for EVs and HPs (Supplementary Table 8). Between 2020 and 2050, there is thus a relatively larger share of global demand for which future emission intensities will partially overlap in both transport and heating ('yellow regions'), compared to the 'current trajectory'. Although this reduces the potential magnitude of net emission reductions from electrification relative to the '2°C scenario', the risk of region-wide emission increases ('red regions') remains limited: The share of transport and heat demand for which EVs and HPs would increase average emissions compared to the use of their fossil 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 to 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 $GtCO_2$/y (-29% of total passenger road transport emissions without use of EVs), and HPs by up to -0.8 $GtCO_2$/y (-46% of total residential heating emissions without use of HPs).

As EVs and HPs replace fossil-based technologies over time, production emissions are projected to grow from around 25% of total road transport emissions in 2015 to 35-38% in 2050, and from 1% of total heating emissions in 2015 to 2-9% in 2050 (Supplementary Figure 4). This is due to (i) reduced use-phase emissions from electricity and (ii) increased production emissions, which are currently around 30% higher for EVs than for petrol cars (at the average global electricity mix), and fifteen times higher for HPs than for fossil boilers (mainly from the leakage of refrigerant liquid). A full decarbonisation 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 decarbonisation of the electricity input.

Due 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 emission in individual regions, compared to the production and use of fossil-fuel based technologies – even if EVs and HPs cause lower emission over their whole life-cycle[36]. 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 global transport and 4% of 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 2015-2050 in regions accounting for 96% of road transport and 97% of 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 more and 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 policy-making on the national level, given that the alignment of policy-making across departments is highly complex and not necessarily always successful[37–39], we showed that the risk of implementing incoherent decarbonisation policies is low in the case of EVs and HPs. Even if future end-use electrification is not matched by rapid power sector decarbonisation, the use of EVs and HPs almost certainly avoids emissions in most world regions, compared to fossil-fuel based alternatives.

Our analysis disaggregates global demand into 59 world regions, a spatial resolution which 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[20], the USA[17,21]). Such studies could also analyse the location-specific impacts of integrating EVs and HPs into the electricity grid[40–43], and how this translates into varying marginal emission intensities over time (compared to the average emission intensities used in this study)[43,44].

Finally, our findings imply (i) that support for high efficiency fossil-fuel technologies may only be justified 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 (ii) that policy-makers in most parts of the world can go ahead with ambitious end-use electrification policies, without the need to rely on further power sector decarbonisation, while (iii) achievable emission reductions in transport are partly constrained by remaining production emissions.

Methods

Greenhouse gas 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 resulting emission intensities[28,32], inspired by the work in Refs.[45–49]. For both the use and the production of technologies, we explicitly included the projected emission changes which 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 life-span for the calculation of emission intensities (Fig. 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 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_2eq/kWh), which we calculated from the model-projected levels of total power sector emissions and electricity demand in each region and year. As we divide total GHG emissions by total electricity demand (instead of generation), the resulting intensity values include transmission and distribution losses. Historic data (up to 2012) was based on 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 necessary infrastructure and supply chain emissions), and methane emissions (all based on the 'most likely estimates' from IPCC-AR5[34]), as well as indirect emissions from biomass use[50]. The resulting life-cycle emission intensities per year and region are given in Supplementary Table 2.

Electric cars (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.[51] for 2015 (median: 0.19 kWh/v-km; 5th-95th percentile range: 0.13-0.24 kWh/v-km) and 2040 (median: 0.15 kWh/v-km; 5th-95th percentile range: 0.10-0.19 kWh/v-km, based on 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 2015-2040, and linearly extrapolated this trend to 2050. Relative improvements compared to 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[52] (version 3.5), adding up the electricity inputs of the foreground process (production of the car) and of all background processes (production of parts and materials, transport, mining, etc.) (see Supplementary Section 4). We determined electricity emissions by multiplying the amount of required electricity with 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/v-km, assuming an average lifetime of 150,000 v-km)[52]. Emissions from other sources in the car production (excl. the battery) were set at 4,700 kgCO_2eq (31 gCO_2eq/v-km)[52]. For the battery production, non-electricity emissions were estimated at 3,200 kgCO_2eq (21.3 gCO_2eq/v-km), and battery cell electricity requirements at 5,000 kWh (0.034 kWh/v-km)[51]. The latter was estimated to linearly decrease to 3,400 kWh (0.023 kWh/v-km) in 2040[51], 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 Figures 5 and 6).

Petrol cars. For use-phase emissions, we first calculated 'tank-to-wheel' emissions of cars based on the distributions of manufacturer-rated intensities (without any blend of biofuels) of all liquid-fuel cars (petrol and diesel, including non-plug-in hybrids) which are sold in a given region and year – based on 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% (based on empirical studies in Europe, the USA and China)[53–57]. We therefore adjusted all manufacturer ratings by the central estimate of 25%, consistent with the adjustment calculations by the US Environmental Protection Agency[57]. 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)[58–60]. Emissions from car production and end-of-life were sub-divided into emissions from electricity required for the production process (including background processes), and non-electricity emissions. Electricity requirements for producing a medium-sized car (curb weight 1,600 kg) were estimated at 9,200 kWh (0.061 kWh/v-km), and emissions from other sources at 5,900 kgCO_2eq (40 gCO_2eq./v-km)[52].

Heat pumps (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 (i.e. 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%), based on the IEA-ETSAP expert ranges given for the most common types of HPs (air-to-air, air-to-water, ground-source)[33]. 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 2015-2050, 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 kg CO_2eq per kW of installed capacity[52]. 750 kg CO_2eq of these emissions 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_2eq/kWh_{th}, assuming an average technical lifetime of 20 years[61] with 2,000 operating hours per year[62], yielding non-electricity emissions of 20.8 gCO_2eq/kWh_{th} (incl. 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_{th})[52].

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 (see section '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[63]. 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, based on the estimate for diesel[58], which is chemically near-equivalent to heating oil), gas (23% of direct emissions[64]), and coal (6% of direct emissions[65]). For the production, we based our calculations on EcoInvent (v3.5) estimates for gas and oil boilers[52], which constitute the large majority of global sales. Electricity requirements (including background processes) are 37 kWh per kW of installed capacity (0.001 kWh/kWh_{th}, based on the same lifetimes and operating hours as for HPs), and emissions of other sources are 30 kg CO_2eq per kW (0.8 gCO_2eq/kWh_{th})[52].

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[29,30]. Distributions of future sales (2013-2050) were projected by E3ME-FTT (section 'Integrated assessment model'), based on the market data and simulated future consumer choices. For some regions (mainly in Africa, Supplementary Table 1), vehicle sales were assumed to equal global averages, due to the unavailability of empirical data. For heating systems, current and future sales were simulated by E3ME-FTT (from 2015-2050), according to available data on fuel use and technology stocks (years 1990-2014)[31,66]. Both for cars and boilers, we then calculated the mean and standard deviation of emission intensities (incl. 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 endogenously projected by the model, based on a gradually changing technology composition in the context of different policy assumptions.

Net changes in GHG emissions. We estimated net changes in overall emissions for each world region in each year. First, we calculated the emissions from EVs and HPs, based on their model-projected region-specific market shares and average use-phase emission intensities (section '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 years for cars and 20 years for heating systems) (see Supplementary Section 5 for the relative shares). Second, we subtracted avoided emissions which 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 based on the projected average intensities of sales in each region (without blend of biofuels). The use of region-specific intensities results in relatively smaller/larger net savings in regions where the average efficiency of new petrol cars/fossil boilers is relatively higher/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, i.e. that people would not suddenly all buy economic small engine cars. Cumulative net changes can then be approximated based on 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: (i) 'Current technological trajectory', (ii) '2°C policy scenario', (iii) 'end-use without power policies'. These scenarios were chosen so that they allowed to simulate the emission trade-offs from electrification as realistically as possible, given (i) what is likely from a current perspective, (ii) what would be likely in a (hypothetical) case of ambitious climate policies around the globe, and (iii) a worst-case scenario in which end-use electrification is not matched by power sector decarbonisation. The first two scenarios were based on recent modelling studies[27,28,32], and detailed descriptions of the underlying policy assumptions are available in ref.[28]. 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.

(i) '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, coal and oil heating systems) are projected to decline in market shares, also observed in 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 data sets. For the heating sector, we furthermore assumed that the average insulation efficiency of buildings gradually increases over time (see Supplementary Section 4). For the power sector, we explicitly included existing policy schemes, such as the EU-ETS.

(ii) '2°C policy scenario'. We imposed sets of sector-specific policies to achieve a projected trajectory of global emissions which is consistent with a 75% probability of not exceeding 2 °C 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 either incentivise the uptake of low-carbon technologies (e.g. subsidies or feed-in tariffs), disincentivise the use of fossil fuels (e.g. carbon taxes), or regulate the use of fossil fuel technologies (such as efficiency standards or a phase-out of coal power plants). In *electricity generation*, the main policies are (i) carbon pricing; (ii) subsidies for renewables and nuclear; (iii) feed-in tariffs (for wind and solar); (iv) a ban on the construction of new coal power plants; and (v) increased capacities for electricity storage. In *passenger road transport*, the main policies are (i) fuel efficiency standards for newly sold petrol cars; (ii) a gradual phase-out of older low-efficiency petrol cars; (iii) a gradually increasing fuel tax; (iv) a purchase tax for vehicles proportional to their rated emission intensity; (v) procurement programmes for EVs where they are not available yet; (vi) an increasing biofuel mandate (reaching up to 10%-30% in 2050, region-specific mandates extrapolate IEA projections). In *household heating*, the main policies are (i) a tax on the residential use of fossil fuels (oil, gas and coal); (ii) 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 (iii) more stringent building

regulations, implying that a large fraction of houses are retrofitted to passive house properties. More details can be obtained in Refs.[27,28].

(iii) 'End-use without power policies'. We combined the power sector trajectory from scenario (i) with the road transport and heating trajectories from (ii), making the scenario assumption that policy makers would implement policies to push EVs and HPs while not pursuing any further decarbonisation 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 which combines bottom-up representations of the power, transport and heating sectors with a macro-econometric representation of the global economy, for 59 regions covering the globe (Supplementary Table 1)[27].

FTT models. The FTT (Future Technology Transformation) 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 (electricity generation, road transport, 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 pair-wise 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[67]. The technological trajectory is not based on economy-wide optimisation, but endogenously evolves from the sum of individual choices of heterogeneous agents with bounded rationality. FTT models are characterised by strong path-dependence of projected technology diffusion (equivalent to strong autocorrelation in time), as it is typically found in technology transitions[68,69], and for that reason, provides a good representation of the inertia embedded in technological systems. It is thus well suited to analyse 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 Section 2. Further descriptions of the individual FTT models can be found in refs.[30,31,66,70–72].

E3ME model. The FTT models are part of E3ME (hard-coupled within the same computer code), which represents in a top-down aggregate perspective relationships between macroeconomic quantities through a chosen set of econometric relationships that are regressed on the past 45 years of data and are projected 35 years into the future (until 2050). The macroeconomics in the model determine 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 resulting outcomes can be projected. Meeting policy objectives (such as emissions targets) is not achieved by means of maximising or minimising 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[73,74]. See ref.[27] for a detailed description of the integrated model, and ref.[75] for the E3ME manual.

Supplementary information for this paper is available as a PDF file and an Excel file.

Data availability

The data that support the findings of this study are available from the corresponding authors on reasonable request.

Code availability

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

Author contributions

F.K. designed the research and wrote the manuscript, with contributions from all authors. S.H. performed the life-cycle analysis, with contributions from M.H. F.K., J.-F.M., U.C., and H.P. ran 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.

Acknowledgements

The authors acknowledge funding from the EPSRC (J.-F.M., fellowship no. EP/ K007254/1), the Newton Fund (J.-F.M. and P.S.; EPSRC grant no EP/N002504/1 and ES/N013174/1), the ERC (M.H. and S.H., 62002139 ERC – CoG SIZE 647224), Horizon 2020 (J.-F.M., F.K., H.P.; Sim4Nexus project no. 689150), and the European Commission (J.-F.M., H.P., F.K., U.C.; DG ENERGY contract no. ENER/ A4/2015-436/SER/S12.716128).

Competing interests

The authors declare no competing interests.

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Figures

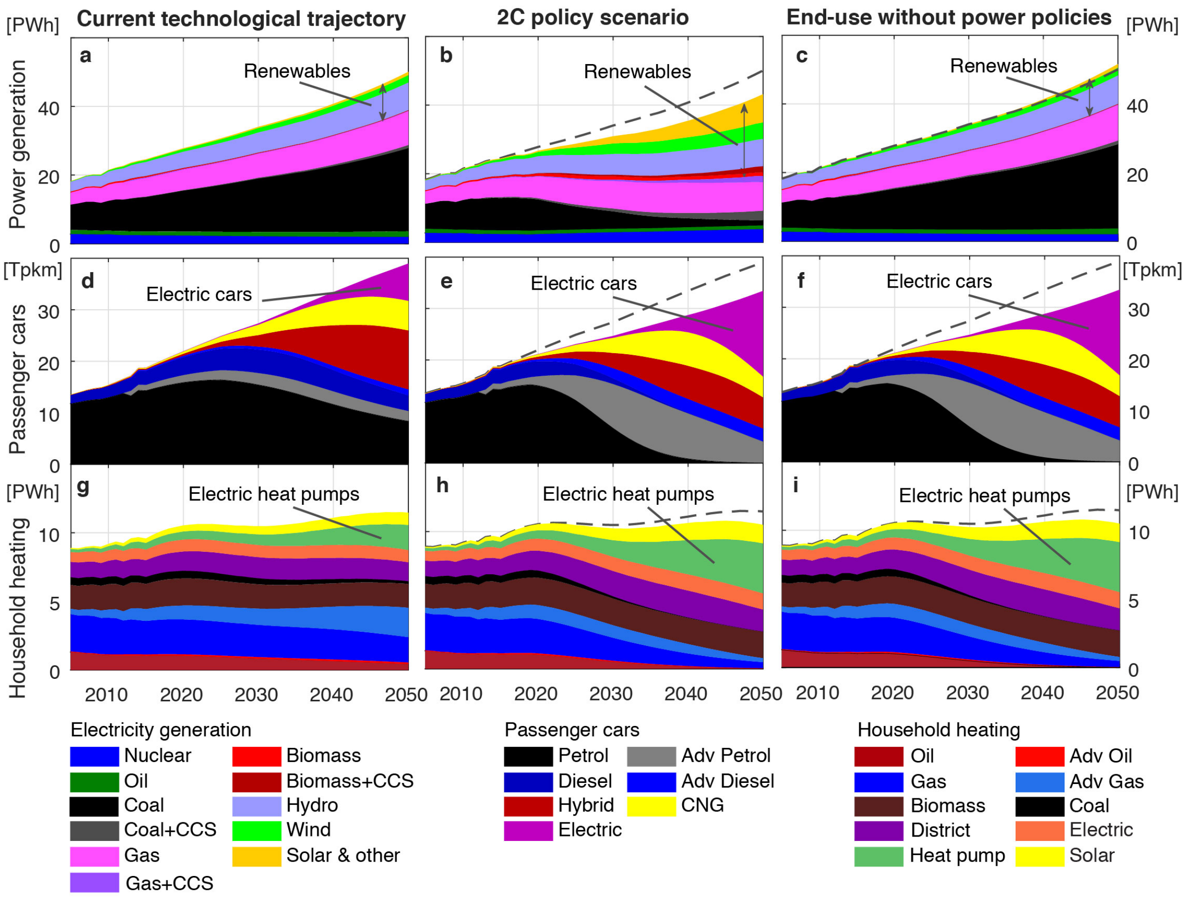

Fig. 1 Projections of global future technology diffusion in power generation, passenger road transport and household heating. Global technology mix in power generation (in PWh per year; **a-c**), road transport by passenger cars (in trillion person kilometre per year; **d-f**), and residential space and water heating (in PWh thermal per year; **g-i**). Projections under the 'current technological trajectory' (left), the '2°C policy scenario' (middle), and a scenario in which the 2°C policies are applied to transport and heating, but power generation follows its current trajectory ('End-use without power policies'; right). Dashed lines show the total demand in the 'current technological trajectory' (**a**), for comparison. Relative to this trajectory, global electricity demand in 2050 is around 3% larger in **c**.

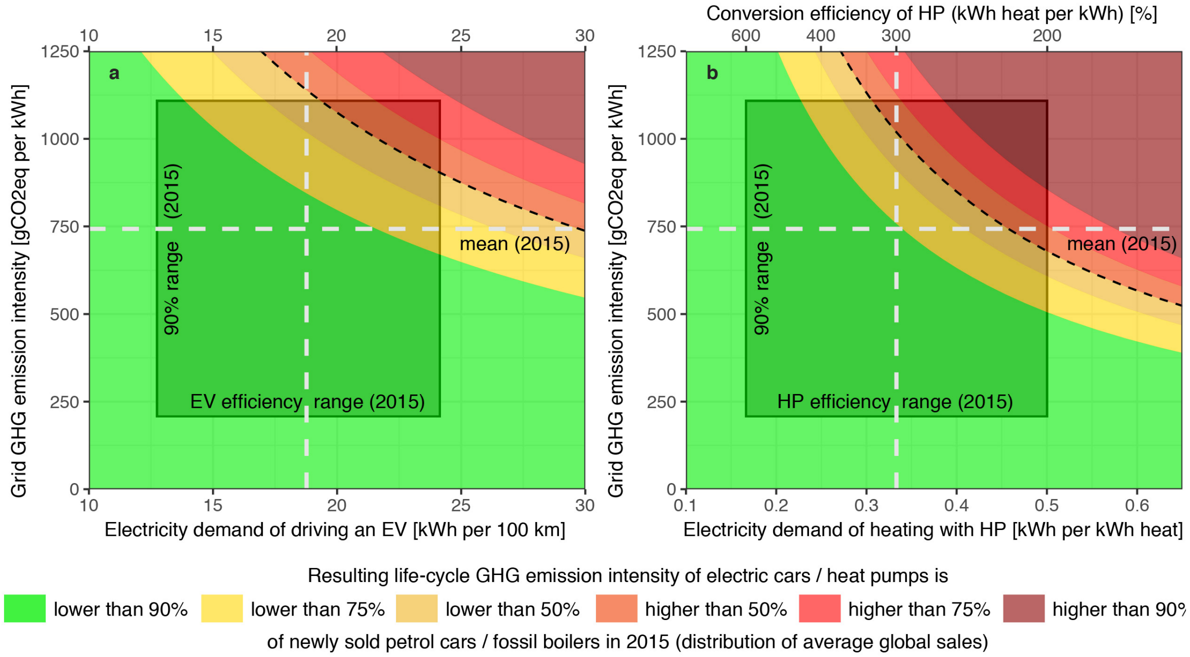

Fig. 2 Boundary conditions for the use of electric cars and heat pumps. Conditions under which the life-cycle GHG emission intensities from (**a**) driving electric cars (EV) and (**b**) heating with electric heat pumps (HP) is currently lower compared to new petrol cars and fossil boilers being sold in the market, given different combinations of use-phase electricity demand and the electricity grid's GHG emission intensity. Horizontal white lines indicate the average emission intensity of global electricity generation (in 2015), vertical dashed lines 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 Information Fig. 2 and 3 for boundary conditions in 2030 and 2050 under different scenarios.)

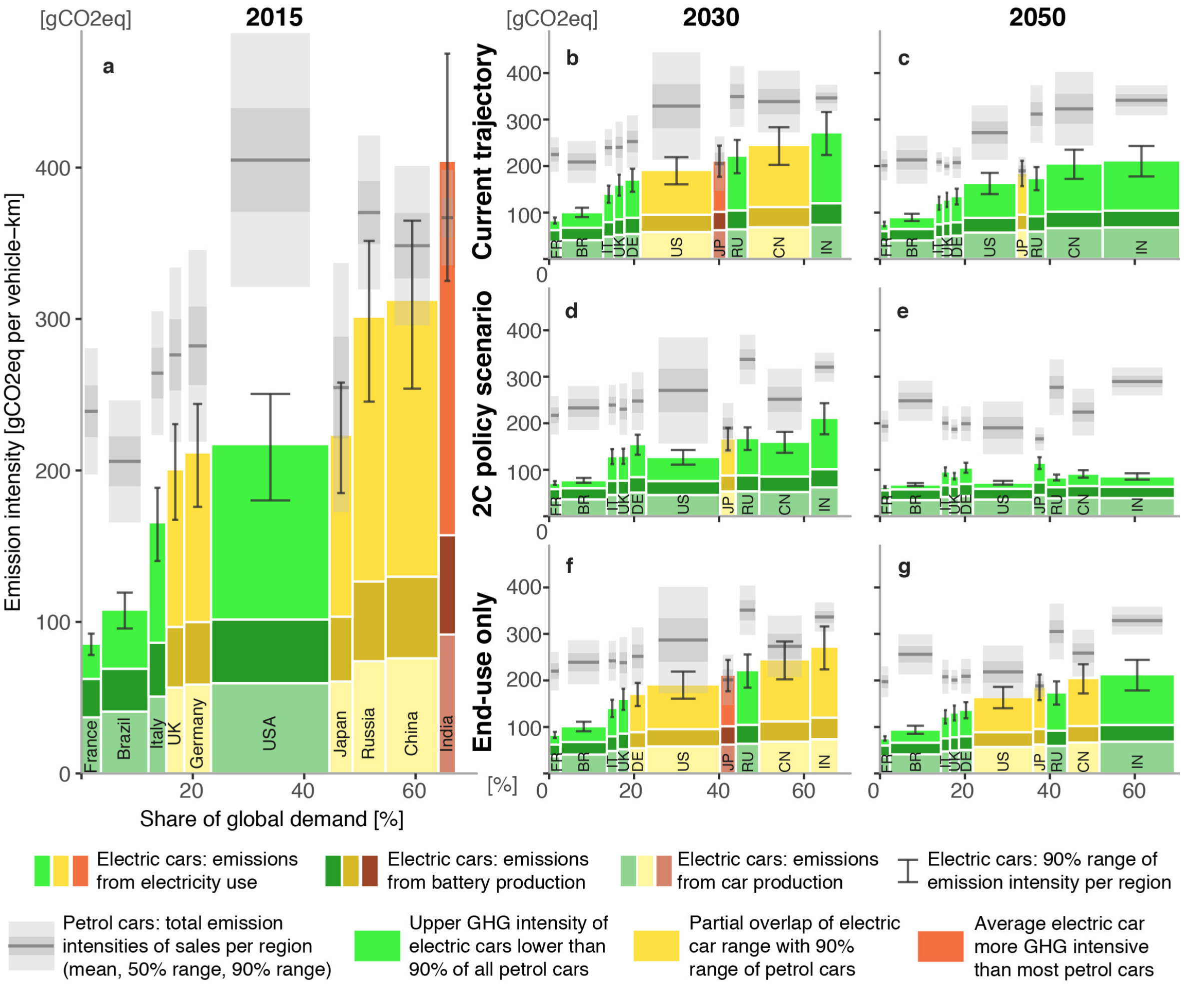

Fig. 3 GHG emission intensities of passenger cars. Current (in 2015; **a**) and projected (in 2030 and 2050; **b-e**) GHG emission intensities (in gCO_2eq per vehicle-kilometre) from driving battery electric cars, for the ten countries with the highest passenger car transport demand in 2015 (share in global demand equivalent to width of 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**). Height of vertical bars shows an average electric car'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 intensity reflects higher and lower use-phase energy requirements of different available electric car models and sizes. For comparison, grey boxplots show the distribution of GHG emission intensities of newly sold fossil fuel cars in each country (mean, 50% and 90% ranges)[29,30].

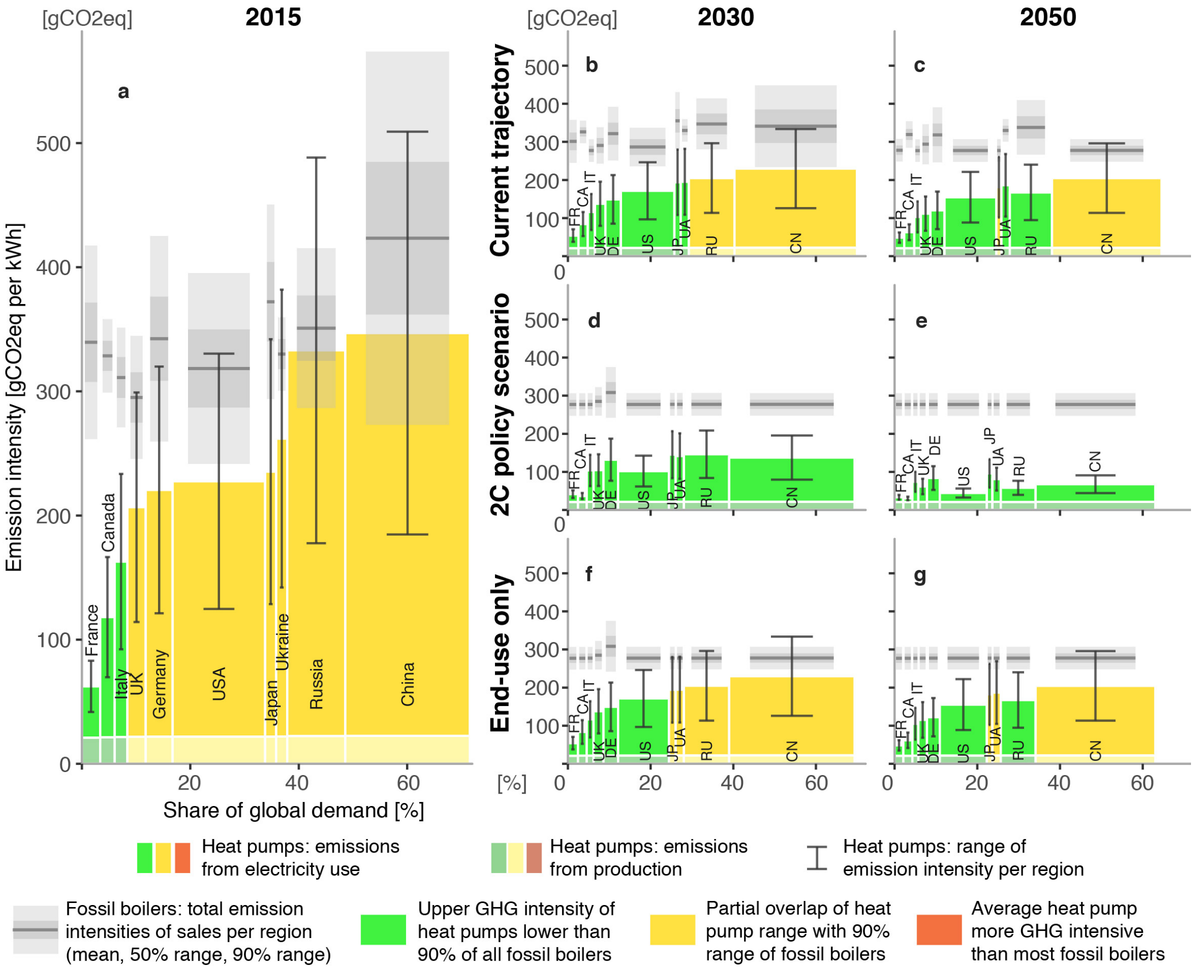

Fig. 4 GHG emission intensities in household heating. Current (in 2015; **a**) and projected (in 2030 and 2050; **b-e**) GHG emission intensities (in gCO_2eq per kWh of heat) from heating with heat pumps, for the ten countries with the highest residential heat demand in 2015 (share in global demand equivalent to width of 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**). Height of vertical bars shows an average heat pump's estimated GHG emission intensity, given the power sector's emission intensity in each country. The range of the GHG emission intensity reflects higher and lower conversion efficiencies of different heat pump models and operating conditions. For comparison, grey boxplots show the distribution of GHG emission intensities of newly sold fossil-based heating systems in each country (mean, 50% and 90% ranges).

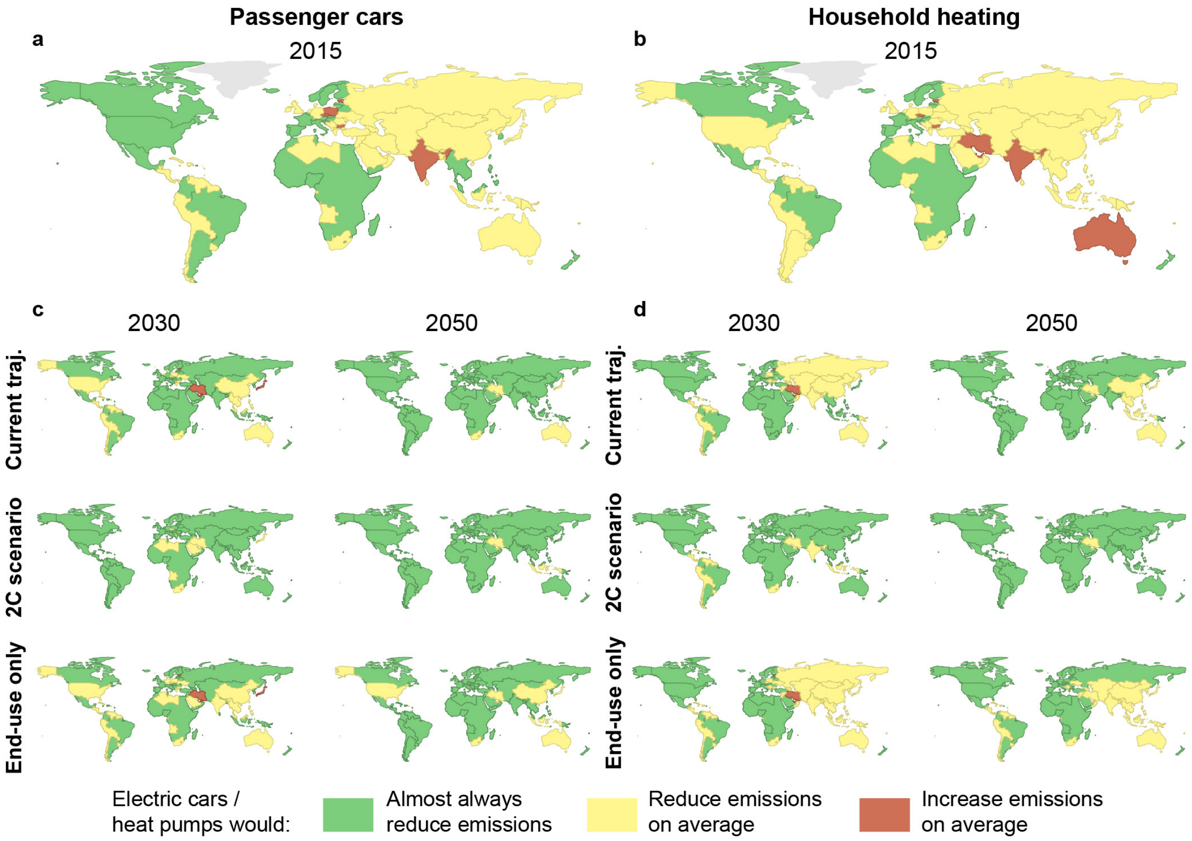

Fig. 5 Relative GHG emission intensities of electric cars and heat pumps around the world. World regions in which electric cars (**a**) / heat pumps (**b**) have lower projected life-cycle GHG emissions than new petrol cars / fossil boilers in almost all cases ('green') or on average ('yellow'), or are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

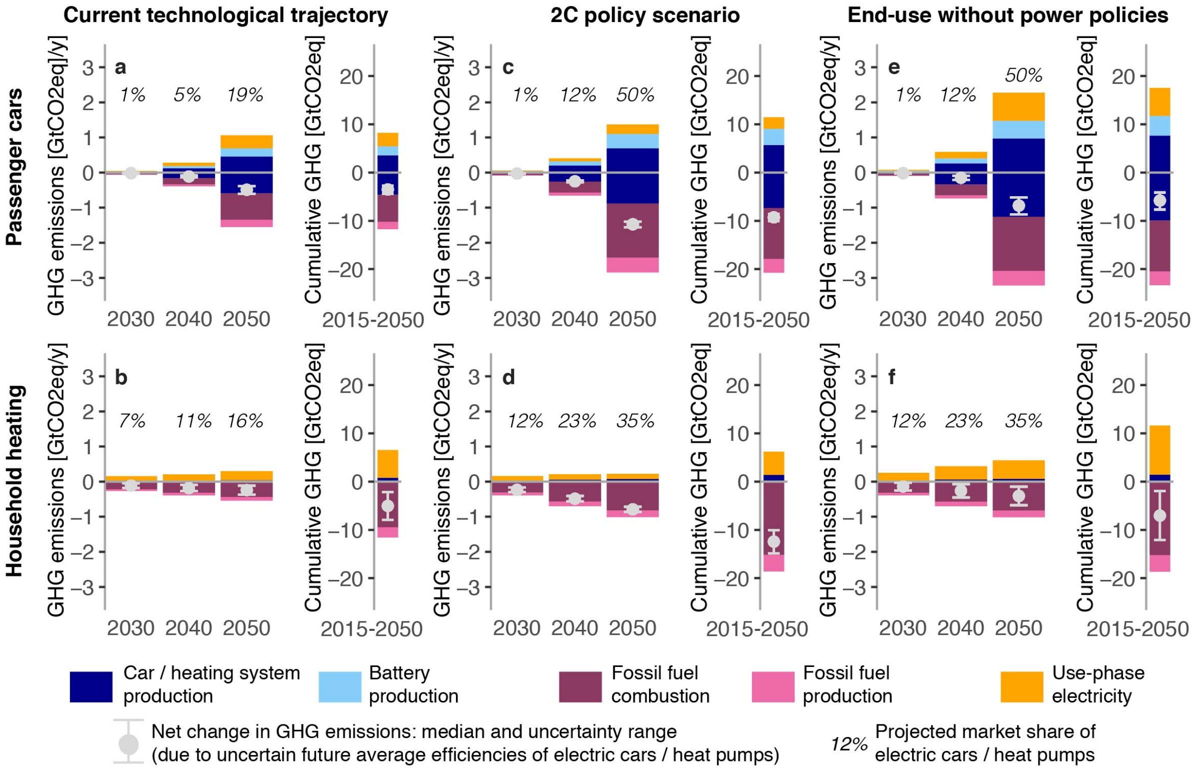

Fig. 6 Changes in global GHG emissions from electric cars and heat pumps. Indirect GHG emissions from use-phase electricity generation (orange); compared to avoided direct GHG emissions from fossil fuel combustion (dark purple) and indirect GHG emissions from fossil fuel production (light purple) that would result if the same demand would be fulfilled with average new fossil fuel-based cars and heating systems. 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 electric cars and heat pumps, respectively. Ranges around the median estimate illustrate the possible range of net changes under lower and higher average use-phase efficiencies of electric cars and heat pumps. Number in italics show the global market share of electric cars/heat pumps. Projections under the 'current technological trajectory' (**a-b**), the '2°C policy scenario' (**c-d**), and under a scenario in which the 2°C policies are applied to transport and heating, but power generation follows the 'current technological trajectory' ('end-use without power policies'; **e-f**).

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