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Unveiling the cost competitiveness of sector coupling technologies - Policy impacts on levelised costs of heat pumps and battery electric vehicles in Germany

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ABSTRACT

Heat pumps and battery electric vehicles play a crucial role in achieving a climate-neutral economy and integrating the Energy Efficiency First Principle into the building and transport sectors, rendering the overall energy system more efficient. To achieve cost competitiveness of these new technologies compared to conventional ones, investments, operating costs and conversion efficiencies are important. We conducted micro-simulations of the development of levelised cost of heat and transport for these sector coupling technologies to assess the direct cost impact of these parameters. With a broad and in-depth analysis of economies of scale, we determine future bandwidths of investment development. Based on this data, we compared implications of two policy scenarios of taxes and levies on final energy prices using a German case study. The first scenario considers recently adjusted taxes and levies: the national emissions trading system in 2021 and the abolishment of the electricity levy to finance renewable energy support in 2022. A counterfactual scenario includes previous framework conditions. Our results show that rising carbon and lower electricity prices already economically favour heat pumps from 2020 onwards. In contrast, taxes and levies do not decisively impact the cost competitiveness of battery electric vehicles, but expected reductions in manufacturing cost do.

1. Introduction

Established technologies for building heat and transport depend on fossil fuels, contributing to climate change through its carbon dioxide emissions [1]. To mitigate global warming, directly electrified sector coupling technologies, such as heat pumps and battery electric vehicles (BEV), are assigned a key role in the energy transition [2]. First, due to their highly efficient use of renewable electricity [3], they advance the realisation of the Energy Efficiency First Principle in the building and transport sector [4,5]. Second, both technologies contribute to implement the Energy Efficiency First Principle on the energy supply side of the energy system. For the integration of fluctuating renewable energy sources, heat pumps and BEV allow certain degrees of load shifting [6] and thus provide system flexibility [7]. Given these characteristics, the two sector coupling technologies will play pivotal roles in future energy systems that not only rely on renewable energies but also intelligently integrate volatile supply [8]. Consequently, sector coupling does not only facilitate decarbonisation, but also increases the overall system efficiency of the power sector [9].

Investment decisions in these application technologies determine long-term consumption behaviour and thus the demand of the related final energy carriers during their time of use. While the political climate objectives have recently become much more ambitious, actual market development is lagging behind the diffusion of sector coupling

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technology foreseen in long-term decarbonisation scenarios.[1] There are diverse and sector-specific reasons for lagging investments in sector coupling technologies. The transition to renewables in the heat sector exhibits structural challenges in the local context [10], and electrified mobility faces infrastructure and practicability issues [11].

Though, both the heat and the mobility sector exhibit similar economic restrictions of higher upfront capital expenditure (Capex) than their established fossil alternatives [12,13]. However, economies of scale as well as intensified R&D imply that cost decreases for energy technologies can be expected, once sales take off [14].

That said, the operational expenditures (Opex) for consumers are not only determined by the market development, but also by state-induced price components (SIPC), in particular taxes and other levies such as fees and charges on retail prices for final energy carriers. Especially Germany comprises many SIPC for different final energy sources, which are governed by numerous laws and regulations, among them the Energy Tax Act (EnergieStG), Electricity Tax Act (StromStG) and Renewable Energies Act (EEG). The newly introduced national emission trading scheme[2] on CO_2 (nETS) has established a new SIPC on fossil fuels in 2021. The nETS encompasses fossil final energy utilised for heating and transport, which was yet not covered by the EU Emission Trading Scheme (EU ETS).[3]

Against this background, German SIPC on electricity are comparably extensive and result in higher consumer prices per kilowatt-hour compared to the prices for fossil final energy carriers [15]. The renewable levy on electricity used to finance the renewable support scheme as part of the Renewable Energy Sources Act (EEG) comprised up to one quarter of the retail price for households [16,17]. In order to reduce the burden on electricity prices, the German government recently abolished the renewable levy. Since July 2022, the EEG is financed completely through the national budget [18].

Scenario studies of climate-neutral energy systems showed that direct electrified sector coupling technologies play a key role for an energy- and cost-efficient decarbonisation of the German energy system until 2050 [19–23]. To ensure the widespread uptake of sector coupling technologies, they must represent the most cost-effective option for supplying the end-use energy service over the entire time of use, for example building heat or mobility. Cost parity with fossil-fuel based technologies over the technologies lifecycle is a decisive factor for attractiveness. Hence, the design of the SIPC policies should not hinder sector coupling and provide a level playing field for climate-friendly technologies.

This paper aims to analyse the cost competitiveness of the sector coupling technologies heat pump and BEV under future Capex developments and direct impacts of the recent political decisions about SIPC changes in Germany. This has yet not been investigated. We use micro simulations to calculate the levelised cost of useful energy for building heat and transport until 2050 in two scenarios: (1) the cost with the SIPC regime under stated policies and (2) the SIPC policies with the renewable levy on electricity and without the nETS. This comparison shows interactions of a carbon price and a lower SIPC for electricity on the cost competitiveness of heat pumps and BEV.

To reflect uncertainties, we consider ranges of future developments of relevant cost parameters. With calculating bandwidths of global cost development for heat pumps and BEV we extend the existing literature. For this, we apply experience curves on cost components of heat pumps and vehicles which we derive from an extensive market analysis. We further consider ranges in wholesale price projections from the literature and calculate grid charge developments.

The paper is structured as follows. In section 2, we explain our modelling approach to calculating levelised cost of useful energy for heating and transport followed by Capex development using the concept of experience curves. In section 3, we present the simulation results. We end with a discussion and conclusion in section 4.

2. Methods and data

This section first presents the mathematical approach for calculating the levelised cost of useful energy for building heat and private transport. To reflect uncertainties, bandwidths of cost developments are calculated with three parameter constellations for each technology: (1) sector coupling favourable, (2) medium and (3) fossil favourable. The considered ranges of the development of wholesale prices and grid fees are then presented, while further assumptions can be found in the Appendix. Next, the approach to estimate the development of Capex ranges for heat pumps and vehicles using component based experience curves based on literature values for global demand scenarios is presented. Lastly, the SIPC policy scenarios are outlined, including the assumed development of carbon prices and the hypothetical renewable levy.

2.1. Levelised cost of useful energy

To estimate the impact of prices developments and SIPC changes on the competitiveness of sector coupling technologies, we calculate ranges of the levelised cost of useful energy for each technology. For this, we extend the concept of levelised cost of energy from Ref. [24] by integrating conversion efficiencies of final energy utilisation normalised to the output of one unit of end-use, similar to Ref. [25]. Following recommendations of [26] we consider different development ranges of Capex, Opex and conversion efficiencies of each technology in the comparison. For heating technologies, we derive Eq. (1) to calculate the levelised cost of heat (LCOH) in Euro cent per kilowatt-hour of heat. For transport technologies we calculated the levelised cost of transport (LCOT) in Euro cent per driven kilometre as described by Eq. (2). The derivation of the LCOH and LCOT is presented in the Appendix. The parameters and indices for both approaches are presented in Table 1.

$$LCOH_{\varepsilon}(t) = \frac{\sum_{t}^{t+T}\left[\left(\frac{capex^{FE}_{heat}(t)+omr^{FE}_{heat}(t+\tau)-RV(T)}{FLH}\right) + \left(p_{\varepsilon}(t+\tau)\right)\right] df(t+\tau)}{\eta_{heat}(t)\ \sum_{t}^{t+T}\delta_{heat}(t+\tau)\ df(t+\tau)} \tag{1}$$

$$LCOT_{\varepsilon}(t) = \frac{\sum_{t}^{t+T}\left[\left(\frac{CAPEX_{mob}(t)+OMR_{mob}(t+\tau)-RV(T)}{annual\ mileage}\right) + \left(\frac{p_{\varepsilon}(t+\tau)}{\eta_{mob}(t)\ \delta_{mob}(t+\tau)}\right)\right] df(t+\tau)}{\sum_{t}^{t+T} df(t+\tau)} \tag{2}$$

When comparing technologies, it is crucial to ensure that the conditions influencing the energy end-use are consistent across all alternatives. For instance, in the context of building heat, the parameter

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[1] As an example of Germany: Following a decision by the Federal Constitutional Court, the German government renewed the 2019 National Climate Protection Law in 2021 [74]. In the official German long-term scenarios [59] analysing pathways to national climate neutrality within an integrated European energy system, the scenario "TN Strom" with the lowest system costs assumed a deployment of 0.40 million heat pumps per year on average, while the registered sales of heat pumps in 2020 were only 0.12 million [75]. According to the registration statistics of [76] at the beginning of 2021, the market stock of BEV in Germany amounted to 0.31 million vehicles, with 0.14 million new registrations of BEV in 2020 [59] considered a market stock of 7.3 million BEV in 2030, which requires an annual diffusion of 0.70 million BEV on average in the next decade.

[2] Or emission price scheme, as the price development for emissions per tonne CO_2 is predefined until 2025 and there are plans to further enhance this mechanism from 2026 [77].

[3] Although the EU ETS impacts electricity prices, as it requires emission allowances for fossil-fuelled power plants with a capacity exceeding 20 MW, our analysis does not directly consider this influence. Instead, we rely on studies on electricity price trends that factor in the development of the power plant mix and the associated costs for emissions certificates.

Table 1
Parameters of LCOH and LCOT.

Parameter/ indices	unit	description
$CAPEX_{mob}(t)$	€	Total capital expenditure for the technology for mobility in year t, start of operation in year $t+\tau$
$capex_{heat}^{FE}(t)$	$\frac{€}{kW_{FE}}$	Specific capital expenditure for a technology for heat production per capacity of final energy in year t, start of operation in year $t+\tau$
$OMR_{mob}(t+\tau)$	€	Total annual fixed operational expenditure for insurance, taxes, maintenance and calculatory wear-and-tear repairs in year $t+\tau$
$omr_{heat}\ (t+\tau)$	$\frac{€}{kW_{FE}}$	Specific annual fixed operational expenditure for maintenance and calculatory wear-and-tear repairs per capacity of final energy in year $t+\tau$
$RV\ (T)$	€	Residual value in year T
FLH	%	Full load hours per year
$p\ (t+\tau)$	$\frac{€}{kWh_{FE}}$	Final energy price, e.g. electricity or natural gas in year $t+\tau$
$\eta_{heat}\ (t)$	$\frac{kWh_{Heat}}{kWh_{FE}}$	The efficiency of the conversion rate of a technology for heat production from final energy input
$\eta_{mob}\ (t)$	$\frac{kWh_{FE}}{km}$	The efficiency of the conversion rate of a technology from final energy input to one driven kilometre
$\delta\ (t+\tau)$	%	Annual efficiency decrease in year $t+\tau$, 0.5 for all technologies
$df\ (t+\tau)$	-	The discount factor $(1+r)^{-(t+\tau)}$ with real interest r
T	$year$	Year at end of use
FE	-	Final energy, e.g. electricity and natural gas
τ	$year$	Year of operation

settings for each technology must be adjusted to match the same energetic conditions and heat demand of a standard building type. In our analysis, we focus on heating technologies for single-family houses. Single-family houses represent a common case necessitating the deployment of decentralised heat pumps, particularly as multi-family residences with higher energy demands are often situated in densely populated areas where connections to district heating networks may be feasible [27]. To account for different standards of building efficiency, we calculate bandwidths of LCOH. The medium parameter constellation takes into account the typical building efficiency as described in the TABULA building database [28], while the upper and lower bandwidths consider less and more efficient building characteristics respectively. Assumptions regarding the parameters are listed in the Appendix.

Similarly, for vehicles, it is essential to consider identical vehicle types in terms of size, comfort, and mileage to ensure comparability. Our analysis is based on vehicles within the compact class segment, which accounted with 23.7 % for the largest share of passenger car stock in Germany in 2023 according to official statistics [29].

Furthermore, it is crucial to ensure comparability by using the same useful life for both technologies to be considered. In cases where the lifetime of one technology is shorter, partial reinvestment must be considered in order to account for the remaining time in the cost comparison with another technology.

2.2. Assumptions on energy prices

We follow a bottom-up approach and calculate the specific final energy price $p_{\varepsilon}(t)$ in Euro cent per kilowatt-hour for each final energy carrier ε by adding up all price components for households. These consist of the effective SIPC[4] rates $p_{\varepsilon}^{s}(t)$, the market-based price component $p_{\varepsilon}^{m}(t)$, if applicable infrastructure-related levies respectively grid fees $p_{\varepsilon}^{g}(t)$ and the value added tax (19 %).

The market-based price component is determined by the wholesale market price and mark-ups for procurement, sales and a margin [17]. The wholesale market price developments are taken from different scenario studies as described in Fig. 1.

The calculation of the development of grid fees for electricity and natural gas follows the methodology from Ref. [30], with grid costs and final energy demand from Ref. [19]. We assume that there will be no structural adjustments in the calculation of grid fees by the regulatory authorities and all consumption independent price components are included in the volumetric grid fees. On average, households in Germany that use electricity for building heat receive reduced grid fees [17]. The results for the electricity grid are presented in Fig. 2 and for natural gas grid are presented in Fig. 3. Grid fees for electricity are expected to rise due to higher increase of grid cost than electricity demand. Grid fees for natural gas are anticipated to rise as a result of a stronger decrease in gas demand compared to the reduction in grid cost.

Further assumptions for the parameter variations for the calculation of the levelised cost of useful energy are presented in Table A 1, Table A 2, Table A 3, and Table A 4 in the Appendix.

2.3. Economies of scale for capex development

To estimate the Capex development for the calculation of LCOH and LCOT, we apply experience curves based on [31]. Since various components of each technology are assumed to have different cost reduction potentials depending on their level of technological maturity, experience rates are considered separately for each technology component similar to Ref. [13,30,32]. Experience rates for the components are derived from literature values. The annual cost correspond to the sum of the cost shares of the individual components.

At the beginning of year t, the year of purchase, the cost C_i in Euro are calculated with $C_{i,0}$ as theoretical cost of first unit of component i, and X_t^{-b} as cumulated production with $X_t > 1$ (Eq. (3)).

$$C_i(t) = C_{i,0}\, X^{-b_i}(t) \tag{3}$$

The calculation of the experience curve parameter b_i, which relies on the experience rate er_i, is performed as shown in Eq. (4).

$$er_i = 1 - 2^{-b} \tag{4}$$

Applying these formulas leads to a cost reduction corresponding to the experience rates for each component of the respective technology when cumulative production doubles. Given the component-based approach to estimating economies of scale, no historical data is available, so we rely exclusively on data from the 2020 survey year for the calibration.

In order to estimate the annual deployed technologies, which are used to estimate annual production, a logistic growth model according to Ref. [33] is used based on the development of the global demand of the respective technology. Data from literature is used to estimate the cumulative deployed technologies in 2020 and the cumulative installed capacity of heat pumps or number of BEV in 2050 respectively. The model follows Eq. (5)

$$X_t = X_{sat} \frac{1}{1 + \frac{(X_{sat} - X_0)}{X_0} e^{-rt}} \tag{5}$$

where X_t is the annual market growth in year t. X_0 is the initial annual market growth estimated from literature. Further, r (growth rate) and X_{sat} (maximum annual market capacity) are fitted parameters to the model so that the cumulative installed capacity until 2050 meets literature estimations for different developments of the global production.

2.3.1. Assumptions for heating technologies

The Capex per kW_{th} are derived from cost projections per heating unit. We apply experience curves to estimate future cost development of heat pumps. For this, data on total costs per heat pump in 2020 are

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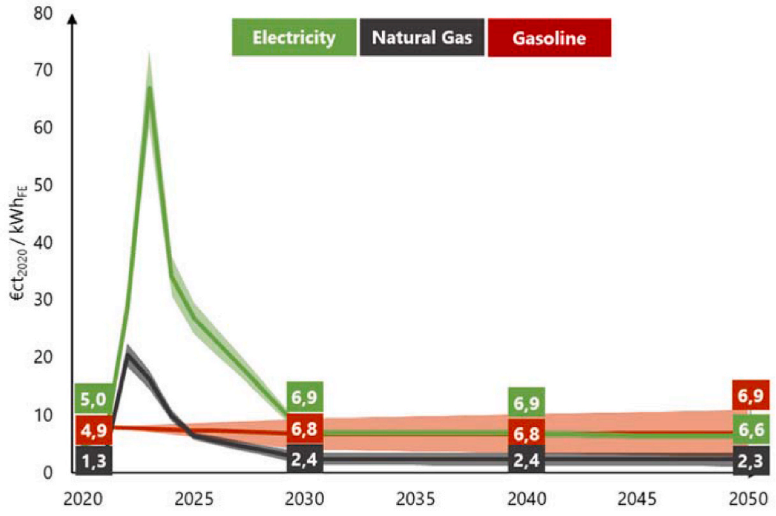
[4] The levies on electricity for the financing mechanisms of the KWKG, §19 NEV, §18 AbLaV and Offshore-Grid will not be considered for reasons of simplification and their low level [17]. Due to their regional character, we also exclude concession rights from the scope of SIPC.



Note: Solid line of each final energy carrier shows medium price range, bottom border depicts lower and higher border upper price range.

		2020	2030	2040	2050	Sources
Electricity	high	5.0	7.59	7.6	7.3	Historic prices for 2020 and 2021 from (BKartA and BNetzA 2021); medium prices: 2022 to 2025 EEX Phelix Futures Peak from 11th of August 2022, 2030 to 2050 shadow prices from the official German long-term scenario "TN Strom" (Fraunhofer ISI et al. 2022), linear interpolation in between; lower/upper electricity prices: ±10% of medium prices.
	medium	5.0	6.9	6.9	6.6	
	low	5.0	6.2	6.2	5.9	
Natural Gas	high	1.3	3.5	3.5	3.5	Historic prices for 2020 and 2021 from (BKartA and BNetzA 2021); medium prices: 2022 to 2025 TTF Future prices from 11th of August 2022, 2030 to 2050 average of upper and lower prices, linear interpolation in between; lower natural gas prices: 2022 to 2029 -10% of medium prices, 2030 to 2050 values from "Net zero" scenario of World Energy Outlook 2022 (IEA 2022); upper natural gas prices: 2022 to 2029 +10% of medium prices, 2030 to 2050 is set to €35/MWh.
	medium	1.3	2.4	2.4	2.3	
	low	1.3	2.3	1.3	1.1	
Gasoline	high	4.9	9.5	10.3	11.0	Historic prices for 2020 from (en2X 2022); medium prices: 2021 to 2050 mean value of upper and lower prices; upper prices: for 2021 to 2050 extrapolated historic price from 2020 with the change rate for crude oil prices from scenario "stated policies" from World Energy Outlook 2022 (IEA 2022); lower prices: for 2021 to 2050 extrapolated historic price from 2020 with the change rate for crude oil prices from scenario "net zero" from World Energy Outlook 2022 (IEA 2022).
	medium	4.9	6.8	6.8	6.9	
	low	4.9	4.1	3.4	2.8	

Fig. 1. Assumed development ranges of wholesale market prices for electricity, natural gas and gasoline [78,79].

required. Due to data constraints, assumptions for manufacturing cost of heat pumps respectively its components cost shares in 2020 are based on historical price data. We analysed 167 heat pump standard models for single- or two-family houses differing in thermal capacity, type of heat source and inverter technology from different producers (Fig. 4). We classify these heat pump models as small-scale, distinguishing them from the larger-scale heat pumps designed for deployment in district heating grids. Small-scale heat pumps are standardised products suitable to be deployed in single-family homes.

The graphic indicates that heat pump models can be categorised into four different groups based on their prices, depending on thermal capacities (<11 kW_{th}; 11–21 kW_{th}) and the presence or absence of an inverter technology.

Cost shares for each component were derived based on prices offered at the global wholesale trading platform *Alibaba* in January 2020 [37]. All considered offers for each components had to meet minimum standards, such as a one-year warranty. Final estimations on cost shares are based on prices for the highest available quantity of each offer. Consequently, the most cost intensive components - compressor, condenser, evaporator, expansion valve and inverter - were identified (Table 2). The remaining technology cost are summed up under the component “balance of systems".

Experience rates for each component are derived from Ref. [38], by considering the cost reduction potential for the influencing factors - learning effects, technological improvements, rationalisation, fixed-cost degression, economies of scale and economies of scope - from Ref. [39]. Since heat pump technology has been under research for decades, technological improvements are not considered to have significant impact on the cost reductions. Cost reductions are rather expected due to economies of scale and more efficient production processes. The assumed learning rates are presented in Table 2.

The development of the global production volume of small scale heat

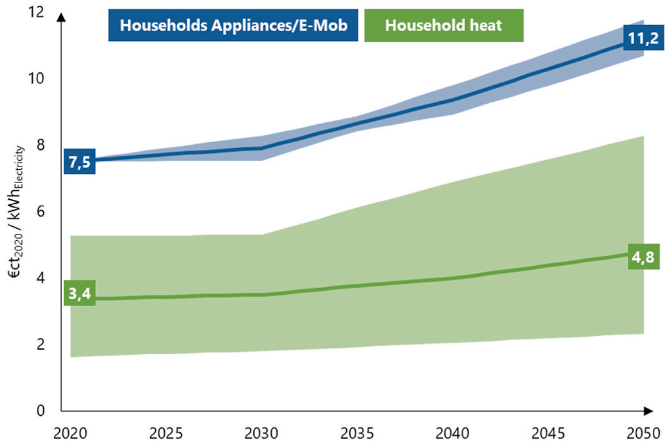


Fig. 2. Development of grid fees for electricity for households.
Source: [17,19], own calculations.

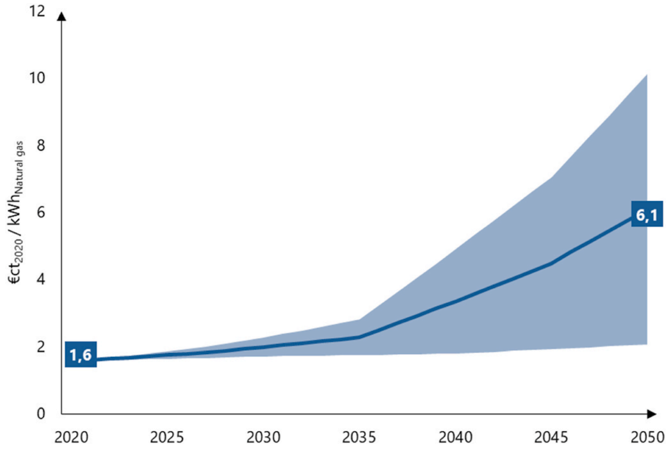


Fig. 3. Development of grid fees for natural gas for households.
Source: [17,19], own calculations.

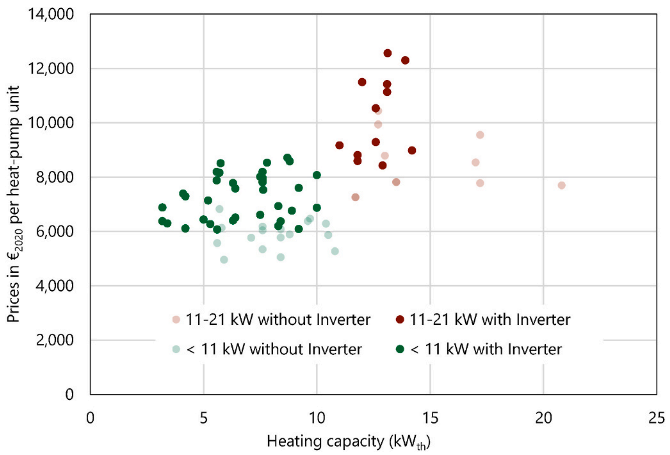


Fig. 4. Prices per heat pump unit in 2020 for 167 models in relation to their heating capacity.
Sources: [34,36,80]

pumps until 2050 is derived as follows. Based on IEA [40]; IRENA [41]; IRENA, IEA, REN21 [42]; DNV [43] regarding the cumulative global heating and cooling demand and the proportion of this demand covered by small heat pumps, we calculate the share of global heating demand covered by small heat pumps. With estimations on the average full load hours and COP of heat pumps, the cumulative installed thermal capacities are obtained. All relevant assumptions for the parameter constellations can be found in Table 3.

The resulting annual installed thermal capacity is used to derive the annual installed heat pump units with dividing it by the capacity of the categorised heat pump groups, assuming equal shares of the groups. The annual growth rate r is set to 0.4 for all scenarios.

As conventional alternative for heat pumps, we consider condensing boilers [44,45]. consider this a mature technology for which we do not assume further decreases of Capex in this study.

Installation costs for both heating technologies are factored in as a share of Capex, which we assume remains constant over time (see Table A 2 in the Appendix).

2.3.2. Assumptions for vehicles

We calculate the development of Capex in Euro per vehicle using experience curves with the cumulative number of vehicles for different vehicle technologies (BEV and ICEV petrol). Due to data constrains of manufacturing costs, we use average list prices from ten models of various brands [46] for different vehicle sizes. For this analysis, we use the data for the compact class vehicle size.

Standardised vehicle components are similar for both vehicle technologies. We differ in the components: drive train, chassis/vehicle body, equipment/others for both technologies. Their cost shares are taken from literature [47,48]. For BEV additional costs arise for power supply and energy storage system, i.e. battery cells, the battery management system and cooling. For compact class vehicles, an average battery size of 50 kW is assumed. Battery system costs are derived from Ref. [49–51]. The dominant technology for BEV are lithium-ion batteries. As additional component for ICEV the exhaust after treatment is considered. Tables 4 and 5 summarise the assumptions for cost shares and corresponding learning rates for BEV and ICEV are presented.

The largest cost share of the drive train of BEV corresponds to the mature components electric motor and inverter, for which we assume experience rates of 10 % with a variation of± 2 % based on [52]. The vehicle body and other equipment are assumed to experience only small cost effects due to learning effects since these components are used in conventional cars. Nevertheless, experience rates for these components are assumed slightly higher than for ICEV (internal combustion engine vehicle) due to minimal adjustments in the design of the vehicle. Highest learning rates of 16 % can be found for the battery system with variations of ±5 %. The variations are accounted for three parameter constellations - medium, high potential and low potential.

For ICEV the drive train accounts for 23 % of total cost for gasoline driven vehicles. According to Ref. [47,48,51] ICEV components belong to mature technologies and due to climate regulations and declining demand for ICEV, all learning rates are set in the low single-digit range based on own assumptions. Negative learning rates are assumed for exhaust after treatment in the future [51].

To estimate the annual predictions of the cumulative number of vehicles produced, data on the current vehicle stock as well as assumptions on the annual market growth and predictions on total vehicle numbers in 2050 is needed. For BEV, a total vehicle volume in 2020 of 10 m vehicles is assumed according to Ref. [53]. Prognosis until 2050 are taken from Ref. [54] and documented in Table 6. As stated before, three parameter constellations are considered. Based on the medium parameter constellation, ±20 % of total production volumes are assumed for the low and high potential deviations. For ICEV the same market prediction is used for diesel and gasoline driven cars.

2.4. Scenario description

For this analysis, two scenarios of SIPC policies are considered:

Scenario A (Stated Policies) follows current regulations. Regarding excise taxes on final energy, the current policy scheme is maintained.

Table 2
Total costs, component-based cost shares and learning rates for small heat pumps.

Component	Comprising unit	Cost share %				Learning rates[b]
		11 kW_{th}	11 kW_{th} inverter	21 kW_{th}	21 kW_{th} inverter	
Compressor	compressor, refrigerant collector	34 %	28 %	34 %	28 %	20 %
Evaporator	fin condenser, EC axial fan	18 %	14 %	18 %	14 %	15 %
Condenser	plate condenser	18 %	14 %	18 %	14 %	15 %
Expansion valve	expansion valve, switching valve	5 %	4 %	5 %	4 %	20 %
Balance of Systems	chassis, high pressure switch, low pressure switch, temperature sensor, insulation, control unit	25 %	20 %	25 %	20 %	25 %
Inverter	inverter technology	–	20 %	–	20 %	25 %
Total Costs in 2020[a]		6,000 €	7,500 €	9,000 €	10,500 €	

Sources: Values derived from a) 2020 market analysis of [34,36], b) [38]; cost shares derived based on market analysis of [37].

Table 3
Assumptions for derivation the cumulative global installed small heat pump capacity in 2050.

Assumptions	2020			2050		
	low	medium	max	low	medium	max
Global heating and cooling demand (TWh)	35,223	38,456	41,689	32,544	40,044	47,545
Share of small heat pumps (%) in global heating and cooling demand	2.8 %	3.2 %	3.6 %	4.4 %	8.3 %	21.0 %
Average FLH	1,490	1,665	2,015	1,490	1,665	2,015
Average COP	3.0	4.3	5.5	3.5	5.3	6.0
Cumulative installed capacity (GW_{th})	1,467	3,092	5,483	2,526	10,339	39,876

Sources: Data for the total heating and cooling demand, the heat pump share and the average COP are taken from Ref. [40–43]. Medium parameter values are derived as mean values from the high and low scenario if no other source was found. Other values are derived by calculation and own estimation. It is assumed that the COP will improve by 2050 due to technological improvements, greater building efficiency and lower heating requirements as a result of climate change.

Table 4
Cost shares and learning rates for BEV components.

Cost components BEV	Cost share in %	Experience rate		
		low	medium	high
Drive train	17 %	8 %	10 %	12 %
Chassis/vehicle body	18 %	3 %	5 %	7 %
Equipment/others	37 %	5 %	5 %	5 %
Battery cells	17 %	11 %	16 %	21 %
Battery management system	9 %	11 %	16 %	21 %
Cooling	3 %	3 %	5 %	7 %
Total cost 2020	43,382€			

Sources [46–51]: own assumptions.

From July 2022, renewable support is financed outside the energy system from the national budget and is no longer applied as a SIPC on electricity. With the introduction of the nETS, carbon prices are applicable on fossil final energy carriers with the beginning of 2021. In Table 7 the considered carbon price development is depicted.

To evaluate recent policy changes for alternative renewables financing and the introduction of the nETS, scenario B serves as a counterfactual for comparison. Carbon prices for CO_2 emissions on fossil final energy are not considered.

Table 5
Cost shares and learning rates for ICEV components.

Cost components ICEV	in % gasoline	Learning rates		
		low	medium	high
Drive train	23 %	0 %	2 %	4 %
Chassis/vehicle body	27 %	0 %	2 %	4 %
Equipment/others	40 %	0.1 %	0.1 %	0.1 %
Exhaust after	10 %	−5%	−2%	−1%
Total cost 2020	28,629€			

Sources: [46–48,51], own assumptions.

Table 6
Assumptions on cumulative global production volumes of BEV and ICEV for 2020 and 2050.

Vehicle technology	2020 (Mio. vehicles)	2050 (Mio. vehicles)		
		low	medium	high
BEV	10	670	837	1,004
ICEV gasoline	33	113	141	169

Sources [50,54,55]

However, the expected development of the renewable support levy on electricity are considered in scenario B. The development of the required financing volume for renewable support and the renewable levy until 2026 is derived from the Middle Term Prognosis of the German transmission grid operators [57]. The long-term development is derived from the calculation tool of [58] which foresees need for renewable support until 2040. With assumptions regarding the renewable diffusion according to the scenario “TN Strom" of the official German long term scenarios [19,59] the estimated financing volumes are presented in Table 8.

Table 9 summarises the SIPC settings for both scenarios. Regulatory measures that also affect the phase-out of fossil fuels, such as CO_2 limits for heating systems or bans on the registration of new ICEV, are not taken into account in the cost analysis.

3. Results

In the following, we present the results of our analysis. First, the Capex development for the considered heating technologies are presented, followed by vehicles of the compact class. As our analysis on Capex development is based on market values in 2020, effects such as the increase in commodity prices due to the recent Ukraine crisis are not reflected in the results. Next, the results for levelised cost of heat and transport as real values for 2020 are presented.

Table 7
Assumed carbon price development.

year	2020	2021	2022	2023	2024	2025	2030	2035	2040	2045	2050
€$_{2020}$/t$_{CO2}$	–	24.4	27.8	27.0	30.8	38.7	96.9	140.2	174.2	200.4	220.0

Source: Real values for 2019 from Ref. [56] with assumption of an inflation of 2 % between 2019 and 2020.

Table 8
Development of financing volume for renewable support.

	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2035	2040
Renewable support	€$_{2020}$ bn	24.23	33.03	16.21	22.75	22.58	22.50	20.36	18.22	16.08	13.94	11.80	4.39	–
Regular levy rate	€ct/kWh	6.76	6.50	3.70	5.87	5.77	5.26	4.84	4.27	3.84	3.36	2.77	0.99	–

Source: [57–59], own calculations.

Table 9
Overview of SIPC policy scenarios.

SIPC	Scenario A (Stated Policies)	Scenario B (Counterfactual)
Renewable levy on electricity	Removed from policy set (shift to state budget)	Still included in policy set (support evolving according to Table 8)
Carbon price on fossil final energy from nETS	Included in policy set (carbon price evolving according to Table 7)	Excluded from policy set
Excise taxes on final energy	Current policy scheme maintained	
Grid fees	Same assumptions for both scenarios	

Source: own assumptions.

3.1. *Capex development for heat pumps*

The results for Capex development for small heat pump are presented in Fig. 5.

It can be seen that the small-scale heat pump Capex is decreasing from €429/kW$_{th}$ in 2020 to €141/kW$_{th}$ in 2050 for the medium parameter constellation. The strongest decrease is expected between 2020 and 2030 resulting from a high expected increase in installed capacity. Within the study period (until 2050), heat pumps do not quite reach the Capex of conventional condensing boilers according to our calculations for the medium parameter constellation, but converge closely. Here, Capex of heat pumps are expected to remain above condensing boiler levels until 2050. Nevertheless, in a sector coupling favourable parameter constellations considering lowest cost range for heat pumps and highest costs for conventional technology (condensing boilers) the earliest break-even point of Capex is assumed in 2032. It should be noted that no Capex reductions for condensing boilers have been considered and values are based on literature data (compare section 2.3.1). Given the many assumptions, it can be anticipated that the Capex of the two technologies will approach a comparable level in the long term.

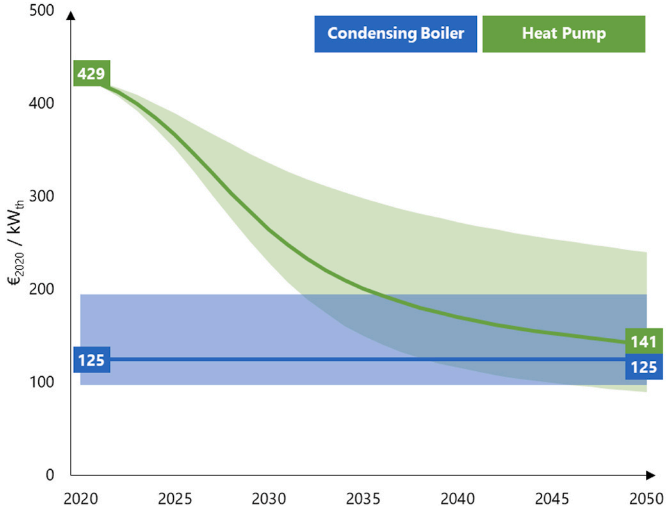


Fig. 5. Capex development of condensing boiler and small-scale heat pump until 2050.
Note: Solid line of each final energy carrier shows the results of the medium parameter constellation. Bottom border depicts lower and higher border upper result ranges. Sector coupling favourable parameter constellations are defined as lower border of heat pumps and upper border of condensing boiler. Fossil favourable parameter constellations are defined as upper border of heat pumps and lower border of condensing boiler. Sources: Condensing boiler: lower border from Ref. [44], upper border from Ref. [60], medium value from Ref. [45]. Heat pump: own calculation.

3.2. *Capex development for vehicles*

The results of Capex development for vehicles of the compact class are presented in Fig. 6.

It can be seen that Capex for BEV from the compact class size decrease from €43,382/vehicle in 2020 to €25,422/vehicle in 2050 according to our calculation. Capex for ICEV decrease as well but only slightly by 1.8 % for gasoline. Therefore, break-even points of BEV with gasoline driven vehicles are expected in 2035 for the medium parameter constellations, the year in which only climate-neutral cars are allowed to

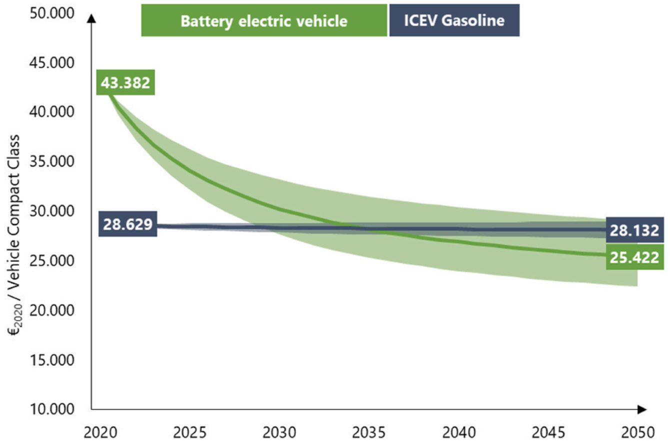


Fig. 6. Capex development of ICEV and BEV until 2050.
Note: Solid line of each final energy carrier shows the results of the medium parameter constellation. Bottom border depicts lower and higher border upper result ranges. Sector coupling favourable parameter constellations are defined as lower border of BEV and upper border of ICEV. Fossil favourable parameter constellations are defined as upper border of BEV and lower border of ICEV. Source: Own calculations.

be newly registered in the EU [61]. The earliest expected break-even point is expected in 2029, with the lowest Capex range for BEV and the highest cost range for ICEV gasoline.

3.3. Levelised cost of heat from small scale heat pumps

The results of levelised cost of heat of small scale heat pumps and condensing boilers for single family houses with varying building efficiency (compare section 2.1) for both SIPC policy scenarios are presented in Fig. 7.

Under stated policies, heat pumps are already cost competitive in 2020. The LCOH development for heat pumps in scenario A only shows slightly lower values than in scenario B due to the renewable support levy applied on electricity. With fossil favourable parameter constellations, scenario A (stated policies) clearly favours heat pumps after 2030, while the development of cost competitiveness in scenario B is not distinct. Especially the assumed increase of the carbon price significantly increases the LCOH of condensing boilers fired with natural gas (scenario A).

In 2020, the LCOH for heat pumps in scenario A are €ct17.6/kWh, €ct2.5/kWh lower than the fossil alternative in the medium parameter constellation. In the absence of nETS, scenario B shows a lower LCOH for the fossil alternative at €ct18.4/kWh, while heat pumps depict €ct0.4/kWh higher cost when applying the renewable levy. Here, due to

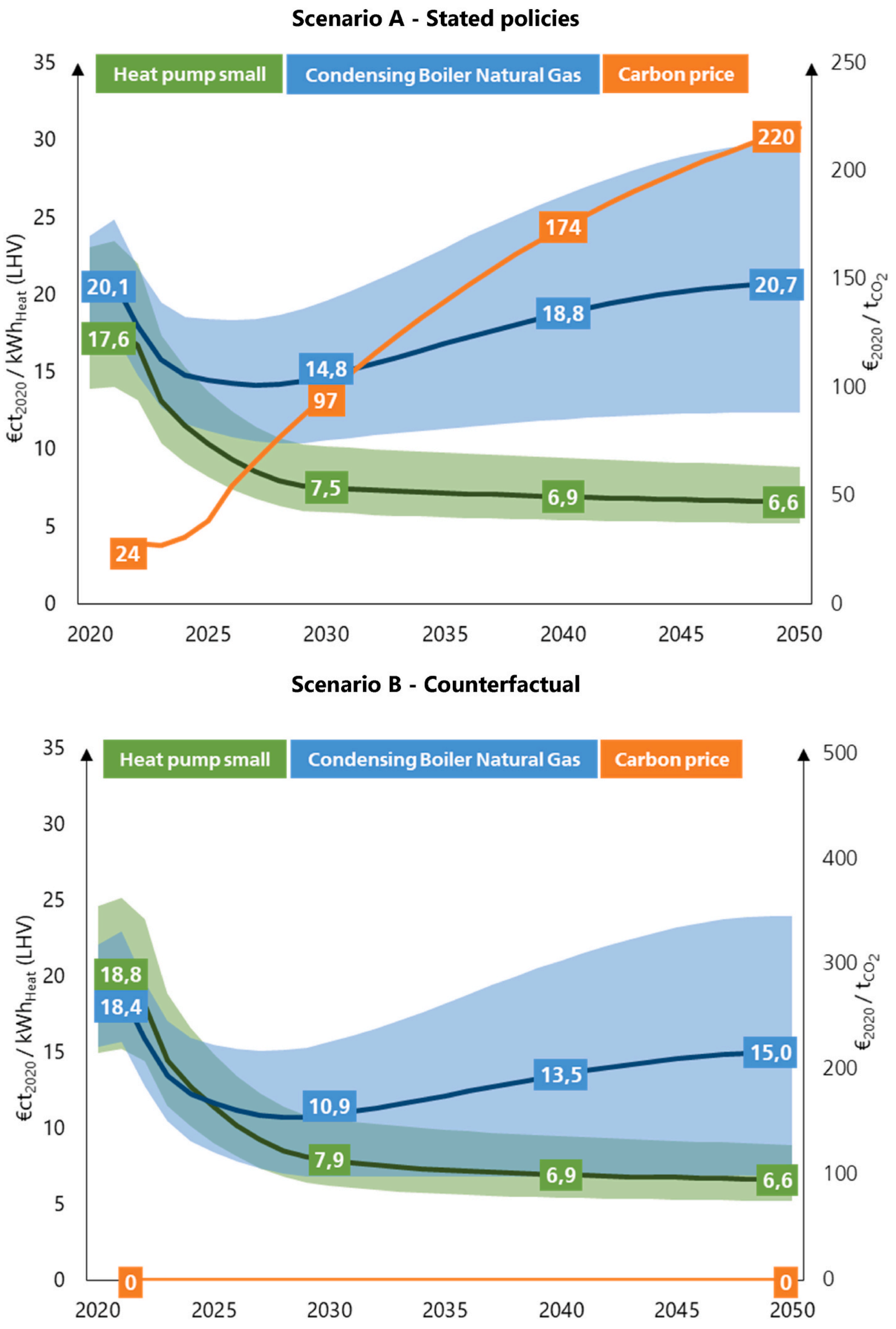


Fig. 7. Results of levelised cost of heat for households.
Note: Solid line of each final energy carrier shows the results of the medium parameter constellation. Bottom border depicts lower and higher border upper result ranges. Sector coupling favourable parameter constellations are defined as lower border of LCOH of heat pump and upper border of LCOH of condensing boiler. Fossil favourable parameter constellations are defined as upper border of LCOH of heat pump and lower border of LCOH of condensing boiler. Source: Own calculations.

decreasing renewable levy and rising grid fees for natural gas, cost parity is reached in 2025. In scenario B, depending among others on the grid fee for natural gas, the bandwidth of LCOH developments for the fossil technology remains in the range of heat pumps until 2050.

3.4. *Levelised cost of transport for vehicles of the compact class*

The results in Fig. 8 show the levelised cost per kilometre driven for a German household with an average annual mileage of 13,500 km [62] and high mileage of 27,000 km, corresponding to the average mileage of a family household with commuter [63], for both policy scenarios.

ICEV depict in both scenarios and mileage sensitivities lower LCOT than BEV in 2020. Considering average mileage, a cost advantage compared to BEV of €ct13.1/km in scenario A and €ct14.2/km in scenario B is given in 2020. With higher mileage, the LCOT of BEV are €ct6.2/km higher in scenario A and €ct7.3/km higher in scenario B compared to the fossil alternative in 2020. In this year, the LCOT for BEV in scenario A are €ct77.3/km, only €ct0.6/km higher than in scenario B.

The comparison of both scenario results reveals that the recent changes of SIPC policies did not influence the LCOT decisively in the short term. The reduction of the renewable support levy in scenario A does not lead to significantly different costs compared to the counterfactual scenario B, which still features the levy on electricity. This shows that the Capex has a stronger impact on the overall cost for final energy than the Opex. Hence, the expected reductions for the Capex of BEV lead to LCOT reductions in the long term in both scenarios.

The strong cost impact of Capex is also evident when looking at the break-even point for the compared technologies and comparing the level of LCOT across different mileages. When considering the average annual mileage of households, cost parity is reached in 2026 for scenario A, one year ahead of scenario B. In the case of high mileage, the break-even point of BEV is reached for scenario A and scenario B in 2024. In summary, the findings indicate that mileage significantly influences LCOT levels, albeit without notable effects on cost-competitiveness.

In 2050, transport costs of around €ct48.8/km with average mileage and €ct26.2/km with high mileage are expected for BEV in both SIPC policy scenarios. With the difference of €ct2.1/km for average mileage and €ct2.2/km for high mileage in both scenarios, the high carbon price does not decisively increase the LCOT for ICEV until 2050 even when strong increases are assumed. The decline in LCOT of ICEV until 2050, despite rising carbon prices, can be attributed to the presumed enhancement in conversion efficiency.

4. Discussion

To investigate cost-competitiveness of two important technologies for sector coupling in the decarbonisation of the energy system, as there are (small-scale) heat pumps and battery electric vehicles BEV, we

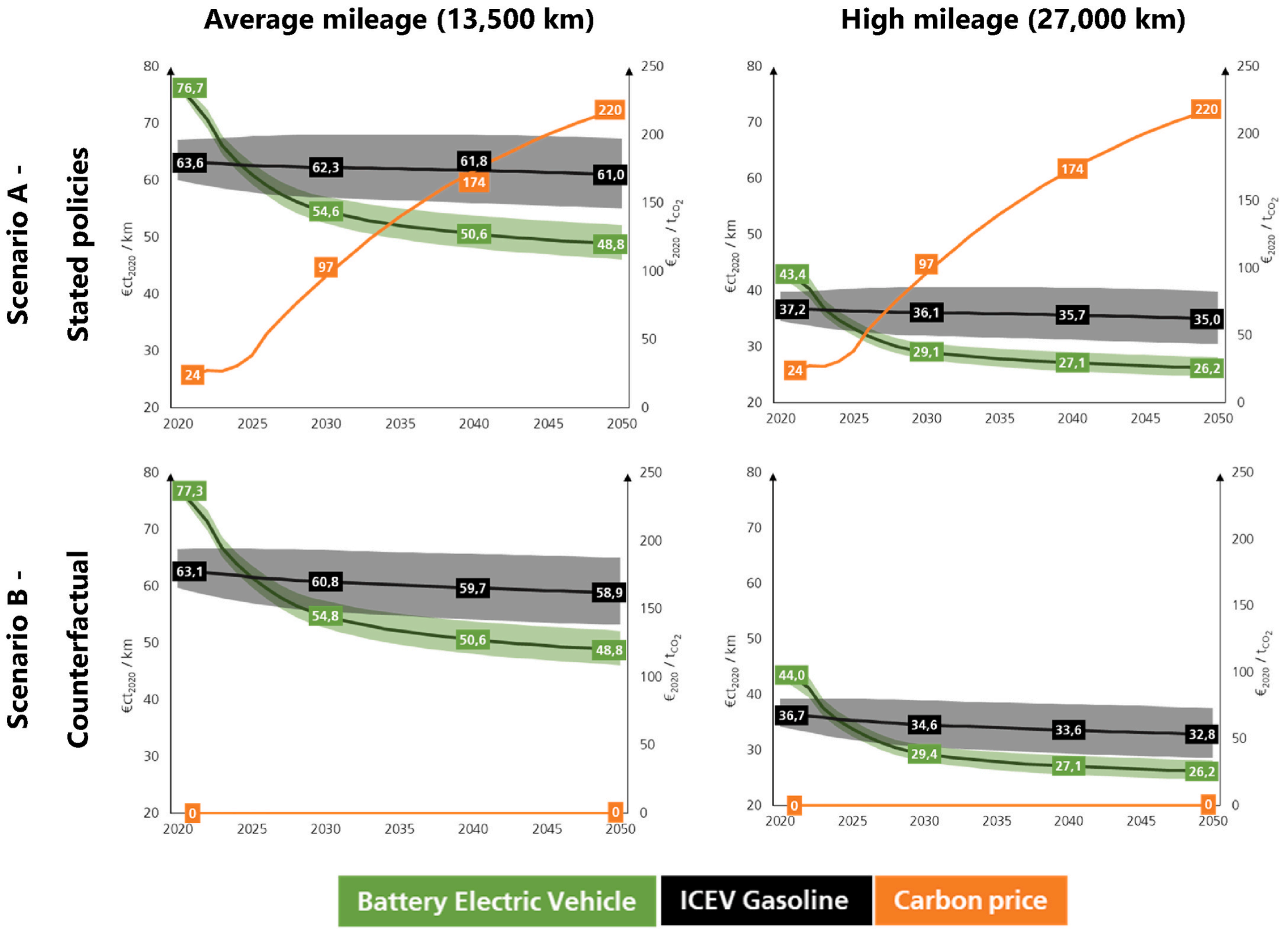


Fig. 8. Results of levelised cost of transport for households.
Note: Solid line of each final energy carrier shows the results of the medium parameter constellation. Bottom border depicts lower and higher border upper result ranges. Sector coupling favourable parameter constellations are defined as lower border of LCOT of BEV and upper border of LCOT of ICEV. Fossil favourable parameter constellations are defined as upper border of LCOT of BEV and lower border of LCOT of ICEV. Source: Own calculation.

investigate two important determinants of their cost. For both technologies, we conducted extensive analysis on market prices in 2020 and calculated ranges of Capex developments based on experience curves for respective technology components under future demand scenarios. We further investigated the impact of recent policy changes on levies and taxes on final energy prices within the context of the German energy transition from the perspective of households as end consumers.

Based on these results, we calculate developments of levelised cost of heat (LCOH) and of transport (LCOT) under sector coupling favourable, medium and fossil favourable parameter constellations until 2050 for two scenarios. Scenario A (stated policies) encompasses recently adapted state-induced price components (SIPC) policies, including state financed renewable support instead of a levy on electricity prices, and the introduction of the national emission trading system nETS. To assess the effects of the recent changes, we introduced scenario B (counterfactual), where the recent SIPC policies are excluded, i.e. where the renewable support levy on electricity remains in effect in absence of the nETS for heating and transport fuels.

Our results show that both determinants play an important role for providing favourable economic conditions for the market uptake of these sector-coupling technologies. The evolution of market prices for both technologies, based on experience curves established in this work, play an important role in enlarging the markets for both technologies while designing SIPC is important to remove economic barriers in the present uptake of those technologies. The picture differentiates nevertheless, between both technologies.

LCOH of heat pumps under stated policies are already lower than the fossil alternatives in 2020, in contrast to the counterfactual scenario B without nETS. Hence, recent SIPC policy changes had a positive effect on the cost-competitiveness of heat pumps, a technology which is assigned an important role in the energy transition due to its efficient conversion of electricity and its contribution to sector coupling. The LCOH are stronger influenced by the Opex than Capex development, as the lifetime for heating technologies is set to 15 years according to the depreciation table of [64]. Especially the assumed carbon price increase development derived from Ref. [56] determines the economic viability of heat pumps. Though, until 2050 Capex of heat pumps are expected to show considerable reductions to one third of 2020 values, but still remain above the level of condensing boilers in our medium parameter constellations. When interpreting the results, however, it is important to bear in mind that competitive effects in the energy transition can lead to rising commodity prices, which can decouple technological developments from cost degression. Additionally, it is important to note that we assumed installation costs decrease with Capex, but increasing demand and a shortage of skilled workers could lead to their rise instead.

Regarding individual transport of households, ICEV remain the cheaper technology in both scenarios in 2020, regardless of the carbon price. In the cost analysis of private transport vehicles of the compact class, the Capex influence costs stronger than Opex when considering the average annual mileage of households. This effect amplifies with larger vehicle classes, which entail higher investments. Consequently, with the consideration of six years of vehicle use [64], recent SIPC policy changes do not have a decisive impact on the cost-competitiveness of BEV. However, the calculated experience curves resulting from economies of scale show strong Capex decreases, which favour cost competitiveness of BEV in the short term. We find that cost-competitiveness of the sector coupling technology is reached in 2026 under stated policies in the medium parameter constellation. According to our results, Capex of BEV are expected to reach parity with ICEV in 2035. Accordingly, cost parity for LCOT will be reached about a decade earlier than expected for Capex, which emphasises the clear operating cost advantages of BEV.

Our analysis shows that the SIPC policy settings generate different impacts on the cost competitiveness of sector coupling technologies analysed. As the time of use of heat pumps is longer and cost shares of Capex in total cost smaller compared to vehicles, the carbon price increase on fossil fuels and electricity price reduction, are economically favourable for heat pumps. However, it is unclear whether the carbon price of the nETS will develop as assumed by Ref. [56] and be adequately anticipated by private or commercial investors. A reliable minimum carbon price or regulatory requirements can serve as policy instruments that combine the objectives of environmental compatibility and sector coupling. Our analysis shows that the impact of carbon pricing should be assessed in conjunction with electricity price levels and investment spending, as this policy instrument alone is not decisive, but rather its combined effect.

As heat pumps and BEV are relatively new technologies, their expected lifetime may vary compared to their conventional counterparts, on which the official depreciation tables are based. If the lifetime of the sector coupling technologies proves to differ, the proportionate reinvestment must be factored into future cost comparisons.

Regarding policy measures for BEV, our analysis shows that the impact of Capex is more important than Opex. Consequently, investment subsidies until cost parity is reached seem more adequate than changes of SIPC for final energy prices to foster cost competitiveness of BEV. Such support schemes could be grant schemes or tax reliefs for the vehicle purchase. Alternatively, annual taxes on the vehicle ownership, which could be partially or fully proportional to the technologies' emission intensity, could incentivise BEV investments. Our cost analysis indicates that the Capex for BEV are likely to decrease below those of ICEV in the medium term. This reduction in the initial investment alleviates the purchase barrier associated with BEV. It can therefore be expected that the cost trend in the transport sector will drive the transition towards BEV, which could potentially render regulatory measures redundant. However, “soft” obstacles might affect the decision to vehicle switch, such as insufficient charging points or lower driving ranges of BEV compared to ICEV.

Additionally, other economic barriers might also hinder investment decisions in heat pumps. As heat pumps require certain standards and conditions for efficient operation, the deployment of this sector coupling technology often requires additional investments [65]. This is especially relevant in the building stock, where besides investments in insulation, in particular replacing old windows and insulating ceilings and walls, additional measures like new radiators and exchanging the entire heating system might be required. However, these measures depend in turn on the individual characteristics of the heterogeneous building stock and are not reflected in our analysis. In particular, distributional effects for vulnerable households are expected from energy-related investments, e.g. in modernisation of buildings [66]. Therefore, tailored investment subsidies or enhanced loan possibilities, aligned with specific building types, could accelerate the technological transition. Nevertheless, if a substantial additional investment is required, this could discourage investments in heat pumps, which may necessitate regulatory policies to achieve renewable energy targets in the heating sector. This is particularly important given the long useful life of fossil fuel heating technologies.

Another cost consideration involves the simplified assumptions of market price trends for fossil fuels and electricity. The latter is influenced in particular by the expansion of variable renewable energy sources, which are expected to increase intertemporal price volatility in the electricity market [67,68]. The flexible operational nature of sector-coupling technologies suggests to take advantage from potential price deviations. In practice, lower weighted electricity prices can still impact the costs correspondingly. However, the extent of household benefit remains uncertain due to the additional costs associated with the necessary information and communication technology for flexible electricity market engagement [69]. Moreover, larger and more price-sensitive consumers, like large heat pumps, might offset market price disparities through their participation, reducing direct benefits to households [7].

Beyond the effects on energy prices, the recent crisis and resultant policy measures may influence the costs associated with the components of sector coupling technologies. Given the inherent unpredictability of crisis effects in general, and their specific uncertainty in relation to the energy transition in particular, this study could not encompass additional effects in the experience curve approach. Nevertheless, we anticipate that these effects will materialise in the short term, while our analysis also aims to shed light on the medium and long-term perspectives. Future research based on the component-based experience curve approach should compare our estimates of Capex developments with multi-year market data in order to calibrate the assumed experience curve parameters accordingly.

In summary, insufficient private investments could impede the diffusion of climate-friendly technologies needed for an efficient energy transition. Including additional investments for switching heating technology in the cost analysis are a subject for further research.

5. Conclusion

The direct electrified sector coupling technologies, heat pump and BEV, imply the Energy Efficiency First principle on the demand and supply side. Higher efficiencies in conversion of final energy into useful energy of these applications reduce the overall final energy demand in the heating and building sector. With offering demand flexibility, total system cost can be reduced when these technologies react to an increasingly volatile supply side. A rapid market uptake of heat pumps and BEV thus aids an expeditious energy transition as each additional investment decision in conventional technologies extends the future demand of fossil fuels over their time of use.

The economic attractiveness is a crucial factor to incentivise the switch from conventional to sector coupling technologies. We explore the development of the cost competitiveness of heat pumps and BEV until 2050. For this, two important determinants for the cost competitiveness of sector coupling technologies were considered.

(i) future market development which brings the technology cost down and
(ii) the impact of levies and taxes on final energy prices.

In summary, we find that recent adaptations to the SIPC in Germany, namely the introduction of a carbon price and the alternative financing of the renewable support, provide favourable conditions for the cost-competitiveness of heat pumps as early as 2020. With regard to BEV, economies of scale indicate to enable cost competitiveness of BEV prior to 2030, while the carbon prices on gasoline and lower electricity prices do not decisively favour the cost competitiveness. Based on the analysis of this paper, it can be concluded that a policy mix seems to be important for promoting sector coupling technologies and that relying on carbon prices alone might be insufficient. Furthermore, other financial and non-financial barriers should be taken into account by policy makers when designing instruments to foster market uptake of heat pumps and BEV.

CRediT authorship contribution statement

Jan Frederick George: Writing – original draft, Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Anne Held:** Writing – review & editing, Validation, Supervision, Project administration, Methodology. **Jenny Winkler:** Writing – review & editing, Supervision, Funding acquisition. **Wolfgang Eichhammer:** Writing – review & editing, Validation. **Mario Ragwitz:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Levelised cost of useful energy

We reformulate the LCOE according to Ref. [26] as discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of utilisation in real monetary value per energy unit, e.g. $€/kWh$. This indicator is obtained in calculating the net present value (NPV) of cost C over NPV of generated energy E:

$$LCOE = \frac{NPV_C}{NPV_E} = \frac{\sum_{t=0}^{T}\left[CAPEX(t) + OPEX_f(t) + OPEX_v(t)\right]\, df(t)}{\sum_{t=0}^{T}E(t)\, df(t)}$$

Deriving the formula of levelised cost of heat LCOH

For the levelised cost of heat (LCOH), the annual reference value of energy $E(t)$ pertains to generated heat, determined by the technology's input energy capacity (denoted as $capa^{in}$), e.g. final energy in kW, annual full load hours of operation FLH in hours, energy input to output conversion efficiency η_{heat} and an annually efficiency decrease $\delta_{heat}(t)$:

$$E(t) = capa^{in} * FLH * \eta_{heat} * \delta_{heat}(t)$$

The technology investment considers the specific capital expenditure $capex^{in}$ for the technology purchase including its expenditures for installation in $€/kW$ of input energy multiplied with the capacity of input energy installed:

$$CAPEX = capa^{in} * capex^{in}$$

Fixed operational expenditures consists of the technology's annual cost for operation, maintenance and calculative reinvestment omr^{in}, excluding financing costs:

$$OPEX_f = capa^{in} * omr^{in}$$

Variable operational expenditures are linked to input energy cost depending on the input energy price p_{ε}^{in}:

$$OPEX_v = capa^{in} * FLH * p_{\varepsilon}^{in}$$

Expressed as an equation:

$$LCOT = \frac{\sum_{t=0}^{T}\left[capa^{in} * capex^{in} + capa^{in} * omr(t) + capa^{in} * FLH * p_{\varepsilon}^{in}\right] * df(t)}{\sum_{t=0}^{T} capa^{in} * FLH * \eta_{heat} * \delta_{heat}(t) * \ df(t)}$$

Further simplification yields:

$$LCOH = \frac{\sum_{t=1}^{T}\left[\left(\frac{capex^{in} + omr^{in}(t)}{FLH}\right) + p_{\varepsilon}^{in}\right] * \ df(t)}{\eta_{heat} \sum_{t=0}^{T} \delta_{heat}(t) * \ df(t)} \quad in \ \frac{€}{kWh_{heat}}$$

Deriving the levelised cost of transport LCOT

The levelised cost of transport (LCOT) pertains to the annual reference value represented by the average mileage of a vehicle. To calculate the LCOT, we replace the energy quantity E(t) with the energy service of the mileage.

The technology investment is considered as the total capital expenditure *CAPEX* per vehicle class in €.

Assuming that fixed operational expenditures are solely associated with the total annual cost for operation, maintenance and calculative reinvestment *OMR* in €, excluding financing costs:

$$OPEX_f = OMR(t)$$

The residual value *RV* at the end of the vehicle's time of use *T*, denoted as *RV*, accounts for the capital expenditure reduced annually by a factor *l*:

$$RV = CAPEX * (1 - l)^{T}$$

Variable operational expenditures are related to input energy cost, depending on the annual mileage, the vehicles conversion efficiency η_{mob} in *km* per *kWh* and an annual efficiency decrease $\delta_{mob}(t)$:

$$OPEX_v = \frac{mileage}{\eta_{mob} * \delta_{mob}(t)} * p_{\varepsilon}^{in}$$

The resulting equation for LCOT is expressed as:

$$LCOT = \frac{\sum_{t=0}^{T}\left[CAPEX + OMR - RV(T) + \frac{mileage}{\eta_{mob} * \delta_{mob}(t)} * p_{\varepsilon}^{in}\right] * df(t)}{\sum_{t=0}^{T} mileage * \ df(t)}$$

when divided by mileage, the equation becomes:

$$LCOT_{\varepsilon}(t) = \frac{\sum\limits_{t=1}^{T}\left[\left(\frac{CAPEX + OMR(t) - RV(T)}{mileage}\right) + \left(\frac{p_{\varepsilon}(t)}{\eta_{mob} * \delta_{mob}(t)}\right)\right] * \ df(t)}{\sum\limits_{t=1}^{T} \ df(t)}$$

Parameter assumptions for the calculation

Table A1 to Table A4 contain details of the parameters assumed in our calculations. We utilise the asset depreciation period as the parameter for time of use in calculating the levelised cost of useful energy. Despite the potential for these technologies to operate for longer durations, the official expected useful life serves as an industry standard to which tax incentives, financing terms, and guarantee conditions are typically aligned.

Table A 1
General parameter for the calculation of LCOH

Parameter	Value
Interest rate	7 %
Useful life[a]	15 years
Annual full load hours[b]	1,752 h
Mark-up on wholesale price for final energy[c]	50 %
Residual value = dismantling costs	0€

Sources: a) [64]; b) [70]; c) [17]; own assumptions.

Table A 2
Ranges of parameter for low, medium and high values of LCOH

Parameter	Unit	Heat pump			Condensing Boiler		
		low	medium	high	low	medium	high
Installation cost	*% of CAPEX*	50	50	50	50	50	50
Annual O&M cost	*% of CAPEX*	2.5	2.5	2.5	3	3	3
Efficiency in 2020	*COP* / %	2.5	3.0	3.5	93	95	98
Efficiency in 2050	*COP* / %	3.0	3.5	4.0	93	95	98

Sources: Installation cost derived from Ref. [71]; O&M cost and efficiency of medium parameter constellation in 2020 derived from Ref. [72], ±10% deviation for low and high parameter constellation; own assumptions.

Table A 3
General parameter for LCOT

Parameter	**Value**
Interest rate:	7 %
Useful lifea	6 years
Annual mileageb	13,500 km
Mark-up on wholesale price for final energy sourcec	50 %
Loss of value per yeard	10 % (residual value after useful life taken into account as investment reduction)

Sources: a) [64]; b) [62]; c) [17]; d) estimations derived from Ref. [29]; own assumptions.

Table A 4
Parameter for LCOT of BEV and ICEV of compact class

Parameter	Unit	BEV			ICEV Gasoline		
		low	basis	high	low	basis	high
O&M cost	*€/a*	1,800	2,000	2,200	1,800	2,000	2,200
Specific consumption 2020	*kWh/km* *l/100km*	0.127	0.141	0.155	4.68	5.20	5.72
Efficiency in 2020	*km/kWh*	6.45	7.09	7.88	1.97	2.16	2.40
Specific consumption in 2050	*kWh/km* *l/100km*	0.105	0.117	0.129	3.28	3.64	4.00
Efficiency in 2050	*km/kWh*	7.77	8.54	9.49	2.81	3.09	3.43

Sources: O&M cost and efficiency of medium parameter constellation in 2020 derived from Ref. [46]; ±10% deviation for low and high parameter constellation; own assumptions.

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