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The role of shared autonomous electric vehicles in decarbonizing China's passenger transport sector

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HIGHLIGHTS

- China TIMES 2.0 is extended to evaluate the SAEV system-wide effects.
- SAEVs can meet passenger mobility demand with far fewer vehicles.
- CN60-High cuts the passenger-LDV fleet by 80.5% by 2060.
- CN60-High reduces final energy use by 26.5% by 2060.
- SAEVs sharply reduce battery-metal demand and upstream emissions.

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ABSTRACT

Electrification is central to decarbonizing passenger transport in China, but its system-level benefit is constrained if future mobility demand continues to be met by a large and underutilized private-vehicle fleet. This study uses the China TIMES 2.0 energy-system analysis model to assess shared autonomous electric vehicles (SAEVs) under two climate-policy pathways (NDC and CN60), with linked accounting for fleet turnover, material demand, recycling, and associated industrial emissions. Under CN60-High, the passenger light-duty vehicle (LDV) fleet is 80.5% smaller and final energy use is 26.5% lower than in CN60-No by 2060. Under NDC-High, direct passenger-LDV CO_2 emissions are 80.4% lower than in NDC-No by 2060. By 2050 under CN60-High, gross demand for the four tracked critical battery metals is 77.6% lower than in CN60-No, while annual vehicle-material-production emissions are 23.9 Mt lower. Monte Carlo and rebound analyses show that material-demand results and the broader total-CO_2 advantage become more robust once the transition advances, whereas final-energy outcomes are more sensitive to adverse SAEV operating assumptions and induced demand. The results indicate that the system-level benefit of SAEV deployment arises not only from cleaner vehicle operation, but also from meeting passenger mobility demand with fewer vehicles, lower battery deployment, and lower material throughput.

1. Introduction

1.1. General context and problem motivation

Addressing climate change in line with the Paris Agreement requires far-reaching transformation of energy systems worldwide. China has adopted ambitious national climate goals: peaking CO_2 emissions before 2030 and achieving carbon neutrality by 2060. Meeting these goals will require broad restructuring across the national energy system.

Within this transition, the transport sector is a major focus. It accounts for around one-tenth of China's CO_2 emissions and a substantial share of final energy demand [1,2], making it a major challenge for deep decarbonization. Both heavy-duty freight and passenger road mobility matter in this regard, but this study focuses on passenger light-duty vehicles (LDVs) because shared autonomous electric vehicle (SAEV) deployment directly targets passenger mobility services, where low average utilization, extensive idle time, and a large privately owned fleet create considerable scope for service consolidation through sharing. By contrast, heavy-duty freight vehicles typically operate at higher utilization, with longer annual mileage, payload-constrained logistics, and route-specific dispatch requirements. The passenger-style sharing mechanism examined here is therefore less directly transferable to heavy-duty freight.

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Table 1
Overview of representative SAEV-related studies.

Year	Study Focus	Scope	Methodology	Long Term	Integrated Modeling	Whole System	Material Circularity
2018	Transport-grid link	Japan	Modeling	×	✓	×	×
2018	VKT & trip duration impacts	Germany	Modeling	×	×	×	×
2019	Climate change mitigation	USA	Optimization	✓	✓	✓	×
2020	Services & impacts review	Global	Review	×	✓	✓	×
2021	AEV diffusion & urban impacts	China	Review	×	✓	✓	×
2021	Air quality & health impacts	USA	Modeling	✓	✓	×	×
2022	Emissions & air pollution	USA	Modeling	✓	✓	✓	×
2022	Fleet emission benefits	USA	Modeling	×	✓	✓	×
2022	Shared mobility study	China	Analysis	×	×	×	×
2022	Energy & GHG implications	Canada	Optimization	×	✓	×	×
2023	Environmental impacts	USA	Analysis	✓	×	×	✓
2023	Environmental impacts	China	Modeling	×	✓	✓	×
2023	AV adoption in mobility	USA	Optimization	×	✓	✓	×
2023	Mobility demand modeling	Global	Review	×	×	×	×
2024	Shared mobility	China	Analysis	✓	✓	×	×
2024	Power-transport nexus	Global	Review	×	✓	✓	×
2025	SAEV inter-city system	China	Optimization	×	✓	✓	×
2025	Vehicle-to-grid (V2G) integration	Asian	Optimization	×	✓	✓	×

Representative studies, in row order, correspond to Refs. [11,13,18,25,32–45].

Achieving deep emissions reductions in passenger transport is therefore important for meeting China's broader carbon-neutrality goals. The pace and scale of decarbonization in this area will influence the feasibility and trajectory of the national transition.

1.2. Existing research and remaining limitations

Vehicle electrification has emerged as the dominant strategy for reducing transport emissions, both globally and in China. Replacing conventional internal-combustion vehicles with electric drivetrains can reduce direct tailpipe emissions and dependence on petroleum, and China has consequently become a global leader in EV adoption. Recent pathway studies for China and other deep-decarbonization contexts nonetheless show that electrification is indispensable but not sufficient on its own unless it is coordinated with broader demand-side changes, infrastructure provision, and power-sector transition [1–4].

However, a simple one-for-one replacement of private internal combustion engine vehicles with private electric vehicles (PEVs) also has limitations. Achieving carbon-neutrality targets through this route alone could require large EV fleet expansion, potentially stretching infrastructure capacity and deployment rates. The climate benefit of electrification also depends heavily on the pace and depth of power-sector decarbonization; with a carbon-intensive grid, part of the emissions burden is shifted upstream rather than eliminated [5,6]. In addition, rapid EV scale-up raises concerns over the supply security, geopolitical concentration, and environmental footprint of critical battery materials such as lithium, cobalt, and nickel [7–9]. The conventional private-ownership model also leaves key structural inefficiencies largely unchanged, including low average vehicle utilization and extensive land requirements for parking.

These limitations suggest that technological substitution, while essential, should be complemented by strategies that improve transport-system efficiency and reshape mobility demand patterns [10,11]. Large-scale EV transitions not only depend on power-sector decarbonization, but also shift pressure upstream to vehicle manufacturing and material supply chains. Meeting mobility demand through large privately owned fleets requires not only critical battery minerals such as lithium, cobalt, nickel, and manganese, but also large volumes of vehicle materials including steel, aluminum, copper, and glass. It also increases battery-manufacturing emissions, whose magnitude depends on both electricity decarbonization and the chemistry mix adopted over time, since lithium-ion chemistries such as nickel-cobalt-manganese (NCM), nickel-cobalt-aluminum (NCA), and lithium iron phosphate (LFP) differ in material composition and manufacturing emission intensity [7,8,12]. The interaction between fleet scale and per-vehicle material requirements is therefore important but still insufficiently understood. This motivates examining shared-mobility configurations that can provide the same service with lower energy and material requirements. In this context, SAEVs combine automation, electrification, and shared use and may improve system efficiency by raising vehicle utilization and reducing fleet requirements.

In this context, SAEVs have received growing attention as a form of shared mobility (see Table 1 for a comparative summary). Existing studies and reviews have examined several relevant dimensions, including fleet-replacement effects, operating costs, charging coordination, and environmental performance [13,14]. Representative work has quantified multi-vehicle replacement effects under shared autonomous service and evaluated the environmental implications of automated and shared mobility [15–18]. More recent operational studies have also extended this discussion to the transport–power interface: Ji et al. examined urban-scale rooftop-photovoltaic charging of electric vehicles, while Tu et al. analyzed photovoltaic-aware scheduling for shared autonomous ride-hailing fleets in intelligent microgrids [19,20]. Other studies and reviews have further clarified enabling conditions such as fleet management, ride pooling, smart charging, and grid integration, but they remain primarily focused on subsystem-level or near-term operational questions [11,21–23].

The literature nevertheless remains fragmented: many studies still address isolated subsystems, prevailing methods are better suited to short-run or local analysis than to multi-decadal national pathways, detailed China-specific evidence remains limited, and few studies connect SAEV fleet turnover to long-run battery-metal demand, vehicle-material requirements, recycling, and power-sector decarbonization within one consistent national assessment [9,24–31].

1.3. Research gaps and study objective

The literature above leaves four interconnected gaps that impede a comprehensive understanding of SAEV deployment within national decarbonization strategies:

1. **Limited integrated system assessment**: Existing studies still rarely evaluate SAEVs within a single framework that links transport activity, energy supply, industrial production, and climate outcomes.
2. **Limited long-term pathway representation**: Prevailing micro-simulation and static assessment approaches cannot represent multi-decadal interactions between SAEV deployment,

energy-system evolution, and climate-policy constraints at the national scale.

3. **Insufficient China-specific analysis**: Most detailed SAEV assessments are grounded in North American or European settings and do not fully reflect China's mobility market, policy environment, and power-sector transition.
4. **Limited integration of materials and recycling**: Few prior studies systematically link SAEV fleet dynamics to critical battery metal demand, vehicle-material requirements, recycling, and induced-demand uncertainty within a national energy-system analysis.

To address these gaps, this study develops a China-specific assessment of SAEV deployment within the China TIMES 2.0 model. SAEVs are represented as passenger-LDV technology options with service-specific cost and operating assumptions, allowing the model to determine their implications for fleet size, energy use, and emissions within the 2020–2060 model horizon.

The analysis combines this transport representation with scenario-consistent material, recycling, and manufacturing-emission accounting, and evaluates three SAEV deployment cases—No-SAEV, Low-SAEV, and High-SAEV—under the NDC and CN60 climate-policy pathways. Monte Carlo analysis (MCA) is used to test uncertainty in key SAEV operating assumptions, while rebound effect stress testing is used to examine the induced-travel risk associated with SAEV deployment. Together, these elements allow us to assess how SAEV deployment reshapes transport energy use, vehicle stock requirements, industrial production needs, critical battery metal demand, and climate outcomes in China.

1.4. Study design

The remainder of this paper is structured as follows. Section 2 presents the research methodology, including model enhancements and scenario design. Section 3 presents the main research results across the assessed dimensions. Section 4 discusses the findings and their policy implications. Finally, Section 5 concludes the paper.

2. Methodology

Fig. 1 summarizes the linked analysis used in this study. SAEV representation, transport energy use, material requirements, recycling assumptions, and associated industrial-emission implications are evaluated under shared scenario assumptions. The input data include socioeconomic drivers, a detailed techno-economic database, resource potential assessments, and energy service demand forecasts. Scenario assumptions specify climate-policy targets, SAEV deployment pathways, and recycling conditions. The overall analysis additionally incorporates uncertainty quantification through LHS and Monte Carlo simulations.

2.1. The China TIMES 2.0 energy-system analysis model

The analytical foundation of this research is the China TIMES 2.0 model, built on The Integrated MARKAL-EFOM System (TIMES) framework [46] and extended in prior China-focused transition analysis [47]. The model solves for the least-cost evolution of technologies and commodity flows over 2020–2060 with a real discount rate of 5%. In this study, China TIMES 2.0 is solved with annual resolution through 2025 and at five-year intervals from 2030 onward. Within the transport sector, passenger-service demands are represented by service categories that can be met by multiple competing modes and technologies, allowing the model to capture both substitution across passenger modes and competition within the same mode. For example, private cars, buses, and rail-based passenger modes can compete to meet different travel demands under one consistent optimization framework. For this study, the model explicitly represents passenger and freight transport, multiple road-transport powertrains, electricity and hydrogen supply, and industrial material production, thereby providing the broader system context needed to evaluate SAEV deployment within the national transition.

2.2. SAEV representation in the transport sector

To assess the system-level implications of SAEV deployment, SAEVs are represented in the transport sector of the China TIMES 2.0 model as distinct passenger-LDV technologies competing for passenger-kilometer (pkm) demand. In the Low-SAEV and High-SAEV scenarios, passenger-LDV road-travel demand is further adjusted by a literature-informed rebound term linked to the scenario-specific SAEV service-share upper bound (Section 2.6); the No-SAEV scenarios retain the unadjusted base-demand trajectory.

Central to the methodology is the characterization of SAEVs using the parameters summarized in Table 2. Relative to PEVs, the SAEV assumptions reflect much greater annual mileage, shorter effective lifetime

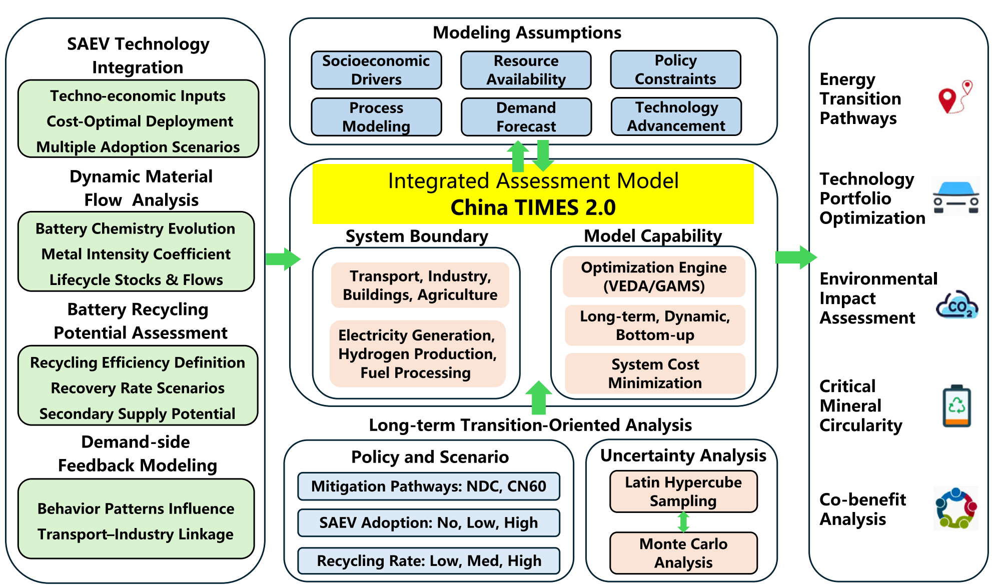

Fig. 1. Integrated analytical structure used in this study, linking SAEV representation, transport energy use, material-demand tracking, recycling, and industrial-emission implications within the China Times 2.0 model.

Table 2
Key operating parameters and reference cost levels for PEVs and SAEVs, with literature-informed ranges.

Parameter	Unit	PEV	SAEV	SAEV range	Source
Reference investment cost	kUSD/veh.	20.6	55.9	52.9–58.8	[17,48]
Annual mileage	km/yr	15k	110k	100k–150k	[49,50]
Operational lifetime	yr	9	5	4–5	[50]
Energy efficiency	kWh/100 km	15	15	12–18	[37,51]
Empty mileage rate	%	~0	45 → 20	35–50 → 15–25	[52,53]
Vehicle occupancy	pax/trip	1.4	2.2	1.6–2.6	[54,55]
Replacement ratio	—	—	1 : 9	1:8–10	[14,15]

under high utilization, non-zero empty mileage, and higher passenger occupancy. Table 2 also reports a reference SAEV investment-cost level, while the scenario-specific cost trajectories used to distinguish the Low-SAEV and High-SAEV pathways are reported in Table 3. The broader literature-informed ranges document empirical support and define the parameter ranges used in the MCA. Supporting details are summarized in the Supplementary Information.

Across the six deterministic scenarios, the operating and service parameters in Table 2 are held fixed. The Low-SAEV and High-SAEV scenarios are differentiated through the scenario-specific maximum SAEV passenger-kilometer shares reported in Table 3, the corresponding SAEV investment-cost trajectories, and the central rebound adjustment applied to passenger-LDV road-travel demand.

Available Chinese operating evidence provides empirical plausibility support for these parameter choices. Earlier Beijing-based evidence on shared transport provides a reference for whether the utilization and service assumptions employed here are broadly consistent with Chinese megacity conditions [27]. More recent official evidence from Wuhan reports about 732,000 autonomous-travel service orders, around 900,000 passenger trips, nearly 500 routinely operating autonomous vehicles, and more than 3378 km of open test roads [56], indicating that public robotaxi deployment in China has already moved beyond isolated testing while still remaining closer to an early-stage, relatively low-occupancy service model than to mature high-pooling operation. Early operator disclosures from Shenzhen likewise suggest vehicle activity levels materially above those of privately owned cars. Taken together, these observations provide empirical support for the utilization and occupancy ranges examined here, although they do not constitute direct validation of the modeled national pathways.

2.3. Material demand representation

To capture the upstream material implications of alternative fleet pathways, the analysis tracks vehicle additions, battery capacity requirements, and material intensities for four critical battery metals and four major vehicle materials. The critical battery metals are lithium (Li), cobalt (Co), nickel (Ni), and manganese (Mn), while the vehicle-material accounting covers steel, aluminum, copper, and glass. These requirements are evaluated consistently with the scenario outcomes generated by China TIMES 2.0 for each modeled period.

The annual primary demand for each critical metal m in year t is calculated as:

$$D_m(t) = \sum_{v \in V} N_{\mathrm{new},v}(t) \times C_v(t) \times \mathrm{MI}_{m,v}(t) \tag{1}$$

where $N_{\mathrm{new},v}(t)$ is the number of new vehicles of type v in year t, $C_v(t)$ is the average battery capacity per vehicle (in kWh), and $\mathrm{MI}_{m,v}(t)$ is the metal intensity coefficient (in kg/kWh) for metal m implied by the battery chemistry assigned to vehicle type v in year t.

The battery metal-intensity coefficients follow the battery chemistry and life-cycle literature summarized in the Supplementary Information [12,29]. These coefficients are fixed by battery chemistry; variation over time arises from the assumed battery-chemistry mix and battery-capacity trajectory. The representative battery-capacity trajectory and the supporting battery metal-content assumptions are reported in Tables S10 and S11 of the Supplementary Information.

For major vehicle materials—steel, aluminum, copper, and glass—the analysis similarly tracks annual material demand using time-varying per-vehicle material intensity factors (in tonnes/vehicle). These coefficients evolve by model year to reflect lightweighting and broader vehicle-design changes. The corresponding vehicle-material intensity assumptions are reported in Table S9 of the Supplementary Information.

The associated upstream industrial CO_2 implications are evaluated using the material-production requirements and industrial emission conditions represented under each scenario. The corresponding vehicle-material and battery requirements are linked to those pathway-specific conditions period by period. The resulting upstream industrial results therefore reflect both changes in physical production requirements and differences in industrial decarbonization across the alternative SAEV and climate-policy scenarios.

2.4. Battery recycling representation

To assess the extent to which end-of-life batteries can offset primary material requirements, the analysis tracks the temporal availability of retired batteries and the quantity of secondary metals recoverable under different recycling assumptions.

The net primary demand for metal m in year t is computed as:

$$D_{\mathrm{net},m}(t) = D_m(t) - \sum_{v \in V} N_{\mathrm{ret},v}(t) \times C_v(t_0) \times \mathrm{MI}_{m,v}(t_0) \times \mathrm{RR}_m \tag{2}$$

where $N_{\mathrm{ret},v}(t)$ is the number of retired vehicles of type v in year t, t_0 is the vehicle-addition year, and RR_m is the effective recovery parameter for metal m, reflecting the scenario-level battery-recycling rate together with the metal-specific recovery efficiency.

Three battery-recycling rates are examined: Low (30%), Medium (60%), and High (90%), representing the share of end-of-life batteries entering recycling. Conditional on recycling, metal-specific recovery efficiencies vary by metal and over time; the corresponding assumptions are reported in Table S13 of the Supplementary Information. For post-2030 five-year milestone periods, vehicle additions are annualized

Table 3
Scenario definitions for climate-policy pathways, SAEV deployment bounds, and representative SAEV cost trajectories.

Parameter	NDC-No	NDC-Low	NDC-High	CN60-No	CN60-Low	CN60-High
CO_2 constraint	Peak ~2030, decline to ~5.4 Gt by 2060			Net-zero by 2060		
Maximum SAEV pkm share (2030)	0%	5%	12%	0%	5%	12%
Maximum SAEV pkm share (2040)	0%	12%	30%	0%	12%	30%
Maximum SAEV pkm share (2050)	0%	18%	45%	0%	18%	45%
Maximum SAEV pkm share (2060)	0%	20%	50%	0%	20%	50%
Representative SAEV investment cost (2030, kUSD/veh.)	—	55.9	55.9	—	55.9	55.9
Representative SAEV investment cost (2040, kUSD/veh.)	—	55.4	45.3	—	55.4	45.3
Representative SAEV investment cost (2050, kUSD/veh.)	—	49.2	36.4	—	49.2	36.4
Representative SAEV investment cost (2060, kUSD/veh.)	—	41.1	27.4	—	41.1	27.4

across the represented interval when deriving retired-battery availability for the net-demand calculation.

The assumed battery chemistry composition evolves over the study horizon following a China-oriented pathway anchored in observed 2023 passenger-vehicle battery deployment and the S2-B1 chemistry-mix trajectory in the Automotive Material Tracker database, with LFP remaining dominant while higher-nickel chemistries continue to serve a smaller share of longer-range applications [57–59]. The detailed chemistry-share assumptions are reported in Table S12 of the Supplementary Information.

2.5. Scenario design

This study evaluates future SAEV pathways along two dimensions: climate-policy stringency and the pace of SAEV deployment, as summarized in Table 3.

The **NDC** pathway represents the current-policy transition pathway in this study, with national CO_2 emissions peaking around 2030 and declining thereafter to about 5.4 Gt by 2060. The **CN60** pathway represents a deeper decarbonization trajectory with a net-zero CO_2 limit by 2060 and a cumulative carbon budget constraint. Both pathways share the same base passenger-transport demand trajectory so that climate-policy stringency is compared against a common socio-economic basis. The realized passenger-LDV road-travel demand can differ in the SAEV Low and High pathways because a scenario-specific central rebound adjustment is applied to passenger-LDV road-travel demand, whereas No-SAEV retains the unadjusted demand series.

Within each climate-policy context, three SAEV deployment pathways are explored: **No-SAEV** (no SAEV deployment), **Low-SAEV** (gradual adoption), and **High-SAEV** (rapid, widespread uptake). By combining these two dimensions, six deterministic scenarios are constructed: NDC-No, NDC-Low, NDC-High, CN60-No, CN60-Low, and CN60-High.

These SAEV passenger-kilometer shares are implemented as scenario-specific upper bounds on the passenger-LDV service provided by SAEVs. The upper bounds represent differentiated deployment conditions under differing degrees of technology maturity, policy support, infrastructure readiness, and market acceptance. In parallel, the Low and High pathways use different SAEV investment-cost trajectories to represent slower versus faster capital-cost decline. Table 2 reports the corresponding reference cost level, whereas Table 3 reports the representative trajectory used to distinguish these pathways over time. Because SAEVs operate at much higher annual mileage and occupancy than privately owned vehicles, these service-share bounds do not imply the same share of the physical vehicle stock. Even when SAEVs provide a large share of passenger-LDV service, a substantial privately owned vehicle stock can still remain in coexistence.

2.6. Rebound scenario design

A potential consequence of the increased convenience and reduced per-trip cost associated with SAEV services is induced travel demand (the “rebound effect”), whereby individuals travel more frequently or over longer distances than they would under private vehicle ownership. Existing studies of automated and shared mobility indicate that this effect is directionally important but highly uncertain: published reviews generally find additional travel demand when generalized travel cost falls, although the magnitude varies widely with assumptions about sharing, pooling, service price, and access for currently underserved user groups [51,60,61]. In the deterministic SAEV Low and High pathways, we therefore include a literature-informed central rebound adjustment linked to the scenario-specific maximum SAEV passenger-kilometer share:

$$D_t^{\text{adj}} = D_t^{\text{base}} \times \left(1 + \alpha s_t\right), \tag{3}$$

where D_t^{base} is the base passenger-LDV road-travel demand, s_t is the scenario-specific maximum SAEV passenger-kilometer share in year t, and α is a proportional rebound coefficient. Following the empirical 10–20% moderate rebound band reported in the literature, we set $\alpha = 0.30$ so that the resulting demand uplift under the High pathway reaches approximately 15% by 2060, within that empirical range.

The rebound treatment has three layers: a deterministic baseline rebound embedded in the Low-SAEV and High-SAEV pathways, an additional rebound-uncertainty layer sampled in the MCA, and a separate deterministic stress-test envelope used to examine extreme induced-demand shocks. The additional rebound increment is sampled around the deterministic baseline case, and the stress-test increments are applied to that same baseline case. The main text focuses on CN60-High stress-test scenarios in which passenger-LDV road-travel demand is increased by an additional + 10% to + 200% relative to the corresponding deterministic SAEV case that already includes the central baseline rebound adjustment, with the stress-test increment applied multiplicatively to that adjusted demand path; these cases are denoted as RB10 to RB200 in the figures and discussion. Within this range, the higher rebound cases are used to identify when the SAEV energy advantage is exhausted and whether the corresponding operational and total CO_2 benefits are similarly reduced. Each rebound case is implemented as a modified passenger-LDV demand case and re-solved within the model. The CN60 rebound results are reported in the main text, while the corresponding NDC summary is reported in Figure S1 of the Supplementary Information. In this study, operational CO_2 includes direct tailpipe and power-side emissions, whereas total CO_2 further includes production-phase contributions from vehicle-material production and battery manufacturing.

The rebound adjustment is phased in from 2030 onward in line with the timing of meaningful SAEV deployment. Comparison against the corresponding CN60-No reference and CN60-High then shows how induced demand reduces the energy, operational CO_2, and total CO_2 benefits of SAEV deployment under a deep-decarbonization pathway.

2.7. Data and key assumptions

The analysis is based on sectoral energy-service demands and techno-economic inputs specified in China TIMES 2.0. In the transport sector, passenger- and freight-service demands are projected using established demand-forecasting methods driven by GDP, population, urbanization, and time-varying demand elasticities. For the transport-demand components most relevant to this study, the resulting pkm and tonne-kilometer assumptions were benchmarked against recent transport-demand and transport-decarbonization literature [62,63]. The detailed passenger-demand assumptions are reported in the Supplementary Information (Tables S3 and S4).

Techno-economic parameters for conventional energy-supply, conversion, and end-use technologies are specified in China TIMES 2.0 and calibrated against national energy statistics and sectoral activity data. The SAEV-specific parameters reported in Table 2 were compiled from recent academic literature and available SAEV deployment evidence, with the corresponding assumptions summarized in the Supplementary Information.

3. Results

This section presents the main results on passenger-LDV fleet transition, energy use, emissions, critical material demand, and broader climate implications.

3.1. National energy and emission pathways

Fig. 2 compares the evolution of China’s primary energy supply and the corresponding CO_2 emission pathways under the two climate-policy reference pathways (NDC and CN60). Under the NDC pathway, the energy system follows a gradual decarbonization transition. By 2060, the total share of non-fossil energy sources in the primary energy supply is projected to exceed 50%. Coal’s share declines from approximately 60.4% in 2020 to approximately 27.3% by 2060, while the combined share of renewable energy sources rises from approximately 9.7% to

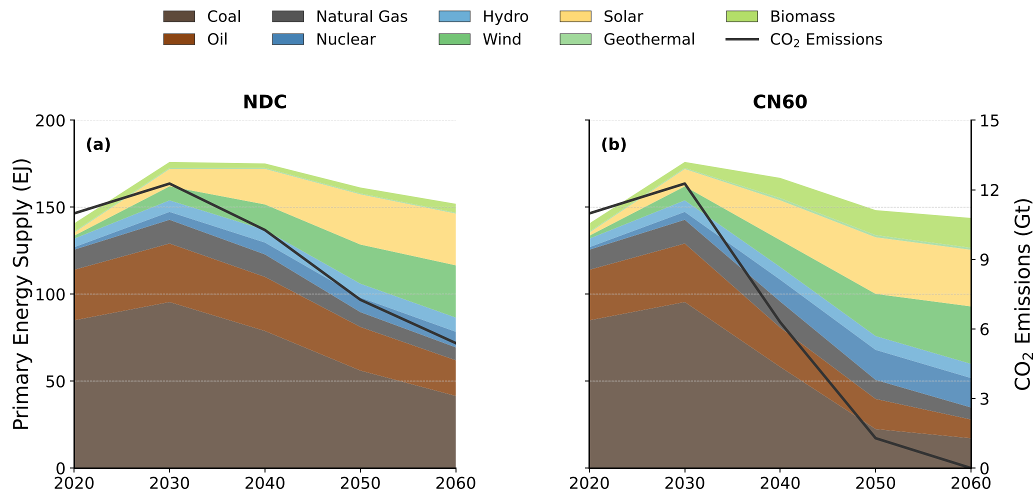

Fig. 2. Primary energy supply and CO_2 emission pathways under the NDC and CN60 climate-policy reference pathways (2020–2060).

approximately 48.4%. CO_2 emissions are projected to peak around 2030 and then decline to an estimated 5.4 Gt by 2060.

By contrast, the CN60 pathway represents a much deeper decarbonization transition. By 2060, coal accounts for about 11.9% of primary energy supply, while non-fossil energy sources rise to approximately 75.8%. Negative-emission technologies, especially bioenergy with carbon capture and storage (BECCS), become increasingly important in the later stages of the transition. Under CN60, emissions decline much more rapidly after 2030 and reach net-zero by 2060. Detailed data underlying the NDC and CN60 pathways are reported in Tables S5 and S6 of the Supplementary Information.

These contrasting system contexts shape the interpretation of the SAEV results reported below. The same SAEV deployment shift is evaluated against a less deeply decarbonized energy system under NDC and a more deeply decarbonized system under CN60, leading to different energy and emissions outcomes across the two pathways.

3.2. Fleet transition and operational outcomes

SAEV deployment changes not only the powertrain mix but also the scale of the passenger-LDV fleet. In the No-SAEV scenarios, rising incomes and continued mobility growth keep the fleet on an expansionary path through mid-century, while the powertrain mix shifts steadily away from liquid-fuel vehicles. Under High-SAEV deployment, the fleet contracts sharply despite the rebound-induced increase in passenger travel demand, because higher utilization reduces the number of vehicles needed to provide that mobility service. By 2060, total fleet stock falls from about 446.4 to 104.3 million vehicles in NDC-High and to 87.1 million in CN60-High, corresponding to reductions of about 76.6% and 80.5%, respectively, relative to the corresponding No-SAEV cases. No-SAEV decarbonization is therefore driven mainly by powertrain substitution, whereas High-SAEV combines powertrain change with a much smaller fleet.

These fleet changes are mirrored in final energy use, but not in electricity demand alone (Fig. 3b). By 2060, total LDV final energy consumption falls from 4464.3 to 2307.0 PJ in NDC and from 3108.0 to 2283.4 PJ in CN60 under High-SAEV deployment, equivalent to reductions of 48.3% and 26.5%, respectively. Electricity demand, however, first rises and then falls as the balance shifts from faster electrification to fleet contraction. In 2040, passenger-LDV electricity demand increases from 1207.9 to 1592.1 PJ in NDC and from 1371.2 to 1652.9 PJ in CN60 under High-SAEV, whereas by 2050–2060 CN60-High electricity demand is about 31% lower than CN60-No.

Operational emissions show a similarly differentiated pattern across pathways. Under NDC, direct passenger-LDV CO_2 emissions fall from 166.0 Mt in NDC-No to 32.6 Mt in NDC-High by 2060, a reduction of about 80.4%. Under CN60, the more informative contrast lies in operational CO_2 rather than tailpipe emissions alone. By 2040, CN60-High still lowers operational CO_2 substantially (247.2 vs. 383.8 Mt), but this gap narrows sharply by 2050 (46.4 vs. 49.6 Mt) and reverses slightly by 2060 (−3.8 vs. −19.6 Mt), as the power sector approaches very low or net-negative carbon intensity. Under deep decarbonization, operational metrics therefore become increasingly compressed and cannot by themselves capture the full system value of SAEV deployment.

3.3. Material demand and upstream industrial emissions

The large-scale electrification of passenger transport drives a large demand for critical battery metals (Fig. 4). In the No-SAEV scenarios, annual demand for lithium, cobalt, nickel, and manganese all rises strongly toward mid-century, illustrating the substantial material requirements of a passenger-LDV transition dominated by private EV replacement.

The deployment of SAEVs reduces this demand (Fig. 4a). Under the CN60 pathway, gross annual demand for the four tracked battery metals falls from about 1.13 Mt in CN60-No to about 0.25 Mt in CN60-High by 2050, a reduction of about 77.6%. Under the adopted chemistry pathway, the remaining gross demand is concentrated in lithium and nickel (about 98 and 110 kt in 2050), while cobalt and manganese fall to much smaller levels (about 23 and 22 kt). SAEV deployment therefore eases mid-century battery-metal pressure primarily through lower fleet and battery requirements, while the chemistry pathway shapes which metals remain most exposed.

When combined with battery recycling (Fig. 4b), these benefits are amplified, but the net-primary-demand pattern becomes more metal-specific. Under CN60-High with 90% recycling, net primary demand falls by 2050 to about 39 kt Li, 7 kt Co, 34 kt Ni, and 7 kt Mn, compared with about 109, 11, 53, and 11 kt under CN60-No. By 2060, lithium remains much lower under CN60-High (about 27 vs. 60 kt), whereas the differences for cobalt, nickel, and manganese narrow markedly or reverse because the larger No-SAEV battery stock also yields a larger retired-battery pool under high recycling. Gross demand therefore captures the fleet- and battery-reduction effect directly, whereas net demand additionally reflects the timing and scale of secondary material supply.

Upstream industrial CO_2 emissions from vehicle material production also decline (Fig. 5). Under CN60-High, emissions from steel, aluminum, copper, and glass production for the vehicle fleet are about 34.5 Mt CO_2 lower per year in 2040, 23.9 Mt lower in 2050, and 14.5 Mt lower in 2060 than in CN60-No. Aluminum contributes the

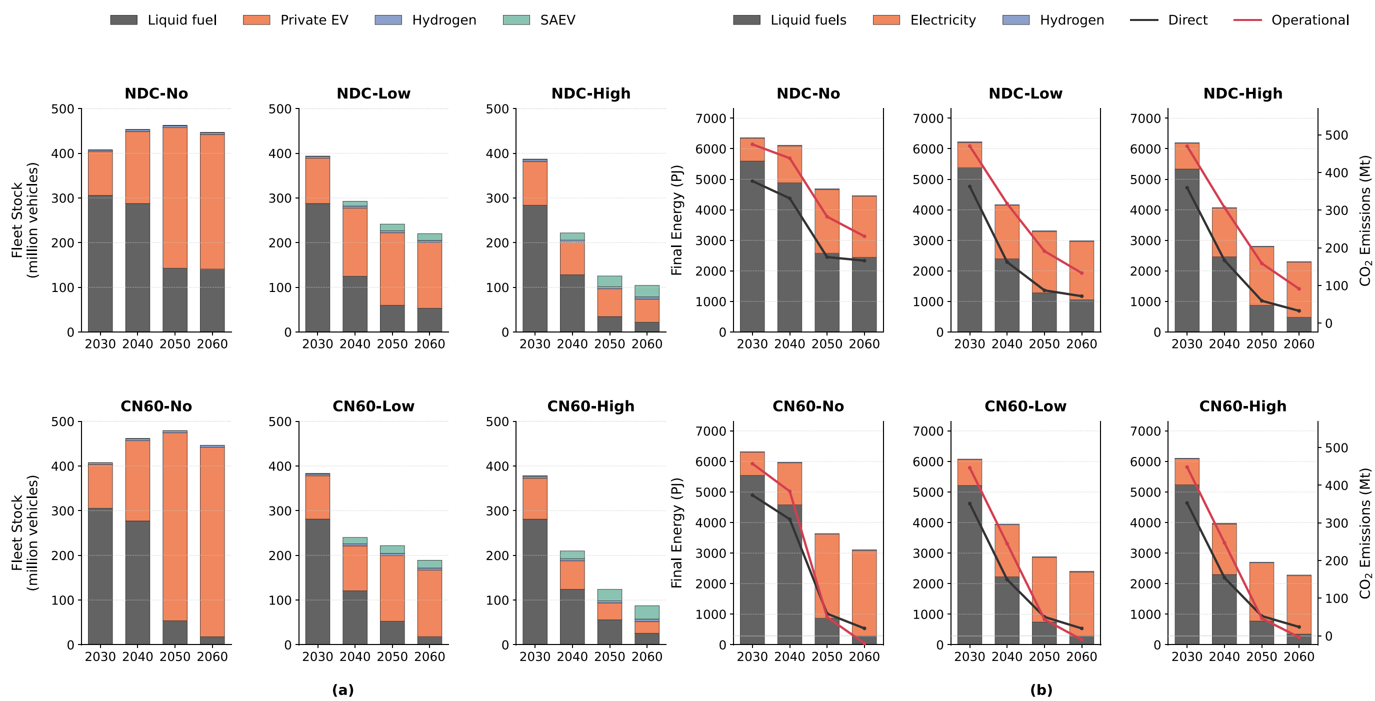

Fig. 3. Passenger-LDV fleet transformation, final energy use, and operational emissions across all six scenarios (2020–2060). (a) Passenger-LDV fleet stock by vehicle category, with SAEVs shown separately from privately owned battery-electric vehicles. (b) Passenger-LDV final energy consumption, direct CO_2 (black line), and operational CO_2 including power-side emissions (red line).

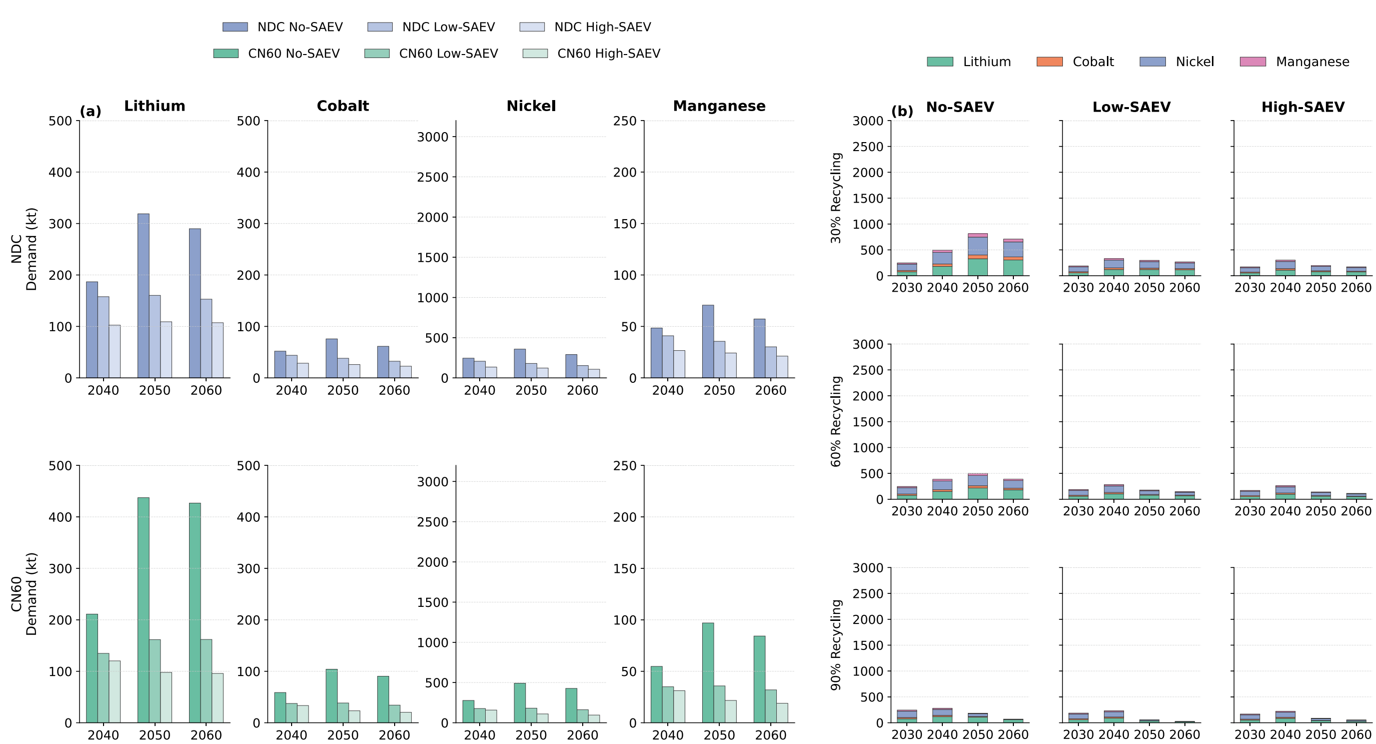

Fig. 4. Critical battery metal demand across scenarios. (a) Annual gross primary demand for Li, Co, Ni, and Mn across the six scenarios (2030–2060). (b) Net demand for critical battery metals under different battery-recycling rates (30%, 60%, 90%) and SAEV scenarios (CN60 pathway).

largest share throughout, followed by steel, reflecting both the material composition of vehicles and the relatively high carbon intensity of aluminum production. This material ranking is not driven by physical demand alone: aluminum combines relatively high per-vehicle use with by far the highest emission intensity among the four tracked materials, while steel remains the second-largest contributor and copper and glass contribute much smaller reductions throughout the horizon. Fig. 5(a) also shows that the cross-pathway gap in emission intensity is especially pronounced for aluminum and steel: by 2050, aluminum production intensity falls to 3.528 t CO_2/t under NDC and 1.128 t CO_2/t under

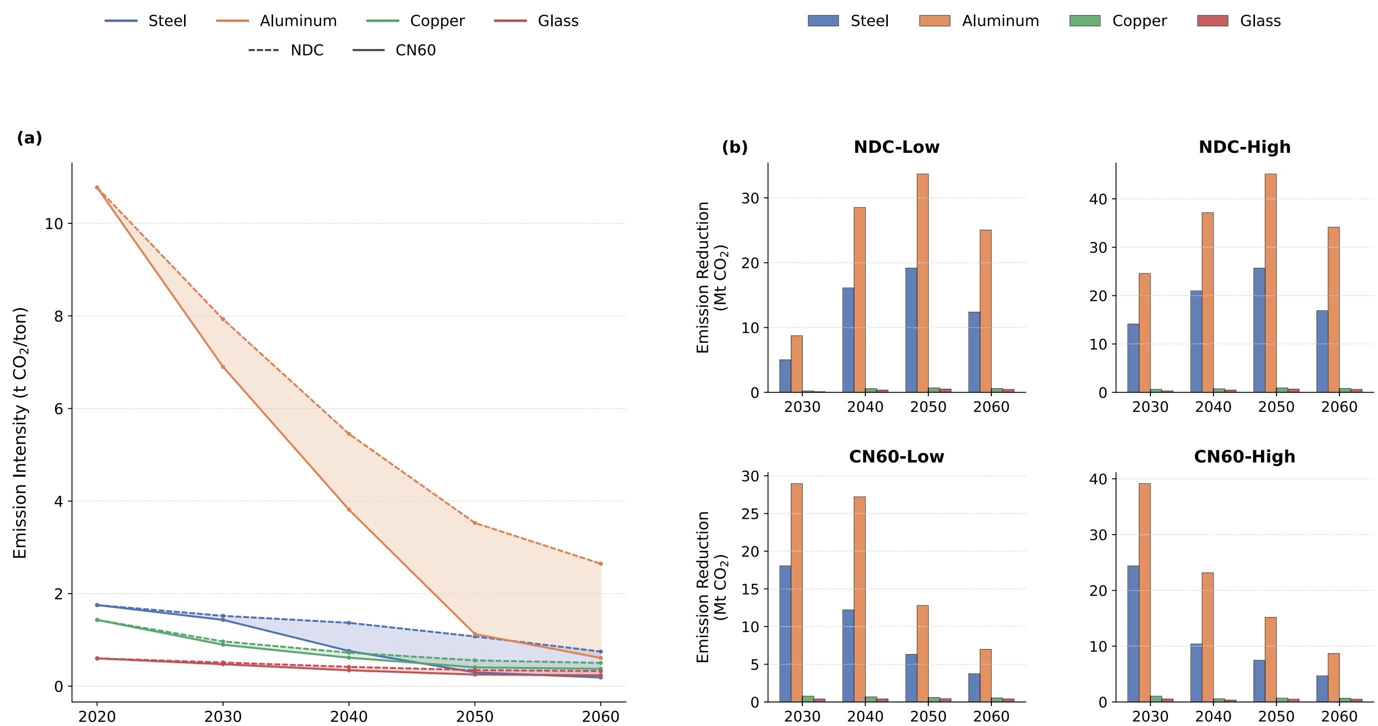

Fig. 5. Emission reductions from key industrial products used in vehicle manufacturing. (a) Emission intensity of steel, aluminum, copper, and glass under the NDC and CN60 pathways. (b) Annual emission reductions from these materials under Low-SAEV and High-SAEV relative to the corresponding No-SAEV case.

CN60, while steel falls to 1.074 and 0.298 t CO_2/t, respectively. This helps explain the composition of the annual reductions in Fig. 5(b), where aluminum accounts for roughly 60–67% of the total industrial-emission reduction under High-SAEV across the reported years, while steel contributes about 30–36%. The timing pattern differs across pathways: under NDC, the annual reduction rises to about 72.4 Mt in 2050 before moderating to about 52.5 Mt by 2060, whereas under CN60 the reduction peaks earlier and then declines more quickly as industrial decarbonization lowers the remaining emissions associated with each unit of material.

Beyond major vehicle materials, battery manufacturing is also associated with upstream CO_2 emissions, and those emissions vary across lithium-ion battery chemistries and climate pathways [7,12]. Fig. 6(a) shows the corresponding battery-manufacturing emission intensities by chemistry. Under both NDC and CN60, per-kWh battery-manufacturing intensity declines over time as the power sector decarbonizes, with CN60 consistently below NDC. Across chemistries, LFP remains the lowest-emission option, whereas higher-nickel chemistries are more emission-intensive throughout the horizon. Chemistry-specific differences also remain notable: by 2050, battery-manufacturing intensity is 10.71 vs. 16.84 kg CO_2/kWh for LFP and NCM811 under NDC, and 7.16 vs. 11.58 under CN60, indicating a persistent manufacturing-emission gap of roughly 50–60% between these two representative chemistries.

Fig. 6(b) presents total battery-manufacturing emissions aggregated across the adopted chemistry mix. Under NDC-No and CN60-No, annual battery-manufacturing emissions reach about 37.2 and 33.1 Mt CO_2 in 2040, respectively. High-SAEV deployment reduces these totals to about 20.4 Mt under NDC-High and 18.9 Mt under CN60-High in 2040, and further to about 11.6 and 7.0 Mt by 2050. These totals also reflect the larger LFP share in the adopted chemistry mix. SAEV benefits therefore extend beyond vehicle operation to the manufacturing stage by lowering both the scale of battery deployment and the associated upstream CO_2 burden during the transition.

3.4. Cross-scenario comparison and monte carlo analysis

Across the main energy, material-demand, and combined indicators considered here, the scenario comparison remains broadly favorable to High-SAEV, although direct-emission comparisons become much more compressed under the binding CN60 carbon constraint and can reverse relative to the No-SAEV reference in later periods.

Monte Carlo uncertainty analysis. One unified MCA design is implemented using Latin Hypercube Sampling (LHS). For each of the four SAEV scenarios (NDC-Low, NDC-High, CN60-Low, CN60-High), 100 independent model solves are performed, producing 400 scenario evaluations in total. The same sampled solve set is then used to extract both the energy-and-emissions outcomes reported in Fig. 7 and the gross battery-metal-demand outcomes reported in Fig. 8.

The unified MCA samples SAEV occupancy, vehicle energy efficiency, annual mileage, and an additional rebound increment beyond the deterministic baseline case, which already includes the central share-linked rebound adjustment described in Section 2.6. These same sampled runs are then used to report gross battery-metal demand for Li, Co, Ni, and Mn under the fixed battery-chemistry pathway. Detailed perturbation ranges, distributions, and implementation settings are reported in the Supplementary Information. In Fig. 7, the direct-CO_2 panel reports only direct passenger-LDV emissions, whereas the total CO_2 panel additionally reflects production-phase contributions from vehicle-material production and battery manufacturing together with power-side emissions.

Under the NDC pathway, the sampled direct-CO_2 distributions move more clearly below the NDC-No reference after the initial transition period, while the 2030 comparison remains more compressed. The energy outcome is less uniformly favorable: the NDC cases also move below the reference more clearly in the later periods, but the sampled energy distribution can still overlap or slightly exceed NDC-No under adverse assumptions at the beginning of the transition. By 2060, the NDC-High median final energy is about 2354 PJ with an interquartile range of 2223–2491 PJ, compared with 4464 PJ in NDC-No, while the median

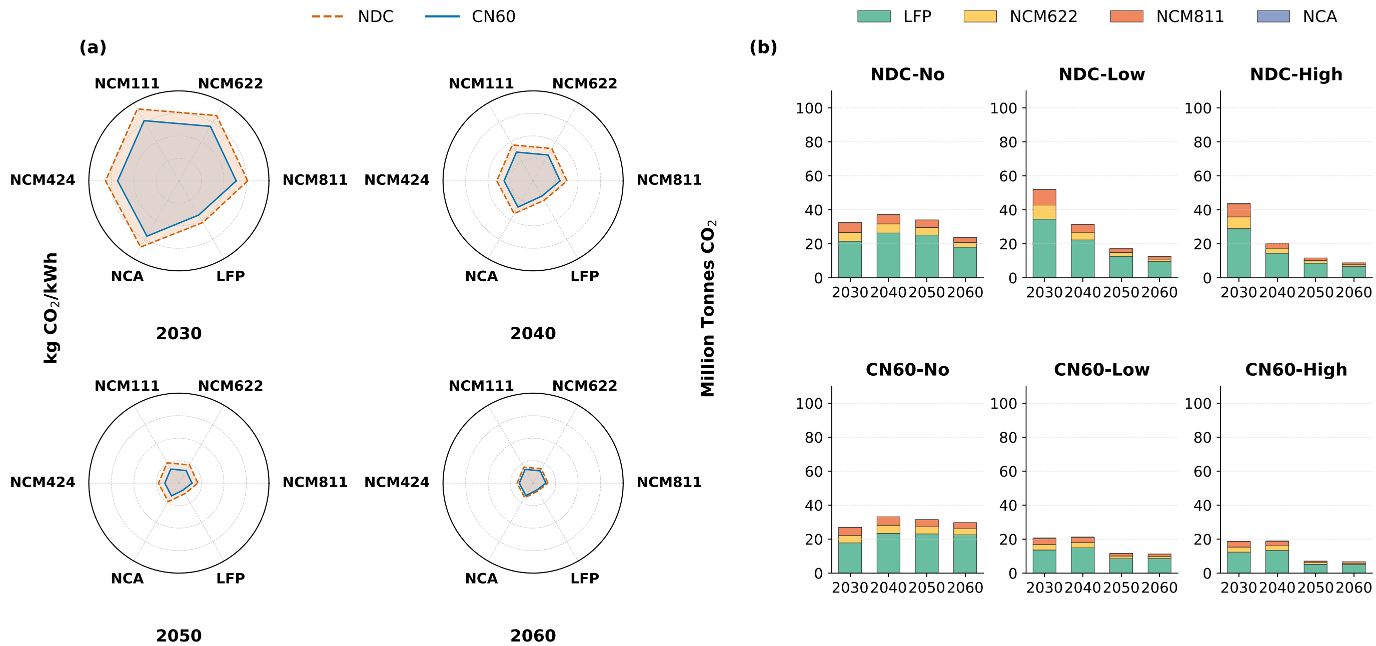

Fig. 6. Battery manufacturing emissions. (a) Battery-manufacturing emission intensity (kg CO_2/kWh) for six lithium-ion battery chemistries under the NDC and CN60 pathways (radar charts). These chemistry-specific intensities are literature-anchored values aligned with the electricity conditions used in this study. (b) Total battery-manufacturing emissions (Mt CO_2) under different SAEV scenarios and climate pathways (stacked bar charts).

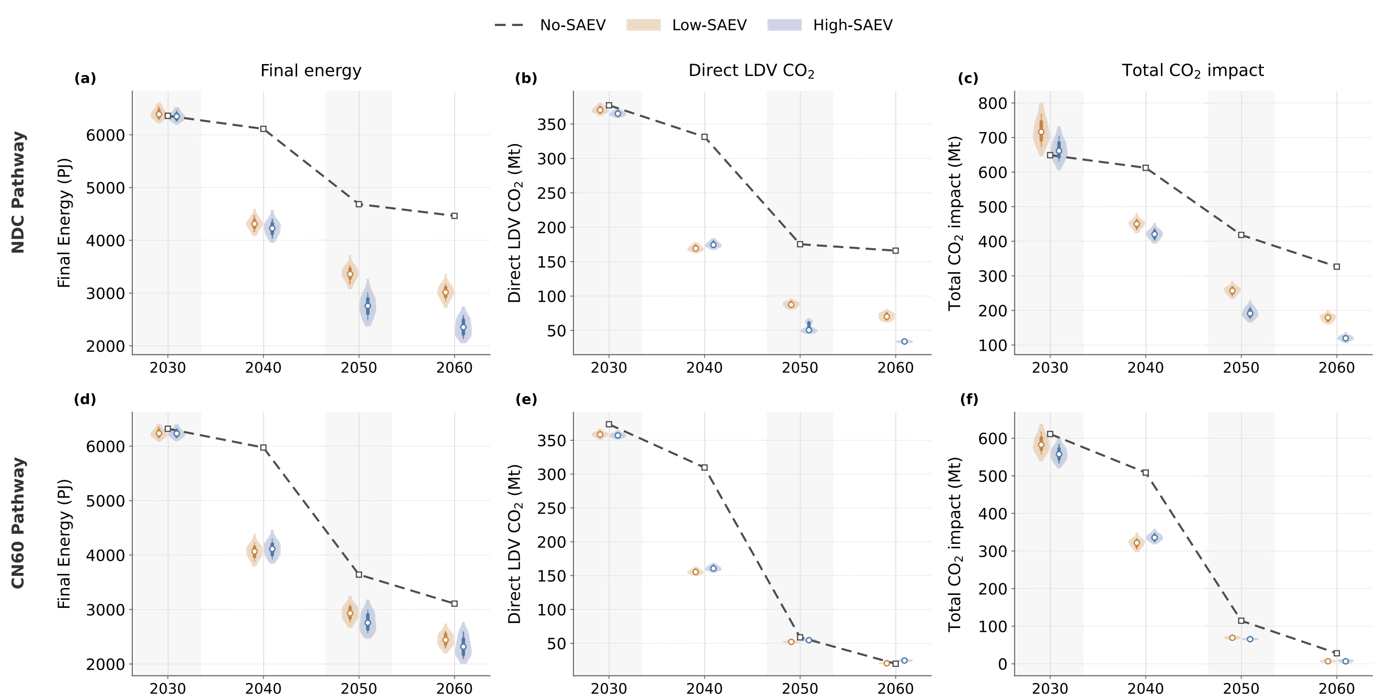

Fig. 7. MCA results for LDV final energy consumption, direct passenger-LDV CO_2 emissions, and total CO_2 impacts. Violin plots show 100 LHS-sampled realizations per scenario; white dots mark medians and thick bars denote the interquartile range. Dashed lines indicate the deterministic No-SAEV references. Sampled inputs and uncertainty settings are reported in Table S2 of the Supplementary Information.

direct passenger-LDV CO_2 falls to about 33.9 Mt. The total CO_2 panel nevertheless indicates that the broader climate effect becomes more favorable once the transition advances, because lower production-phase emissions offset part of the adverse operational cases. The CN60 pathway shows a different pattern: the sampled final-energy distributions lie close to the CN60-No reference in 2040 and move more clearly below it by 2050 and 2060, while direct CO_2 becomes tightly clustered once the stringent system-wide carbon constraint becomes binding. Under CN60-High, the median direct passenger-LDV CO_2 remains slightly below CN60-No in 2050 (54.6 vs. 58.8 Mt), but rises slightly above the reference by 2060 (24.6 vs. 19.8 Mt) even though median final energy remains lower (2318 vs. 3108 PJ). The total CO_2 comparison remains more favorable than the direct-CO_2 comparison because production-phase reductions are still material. Under a binding carbon cap, uncertainty in

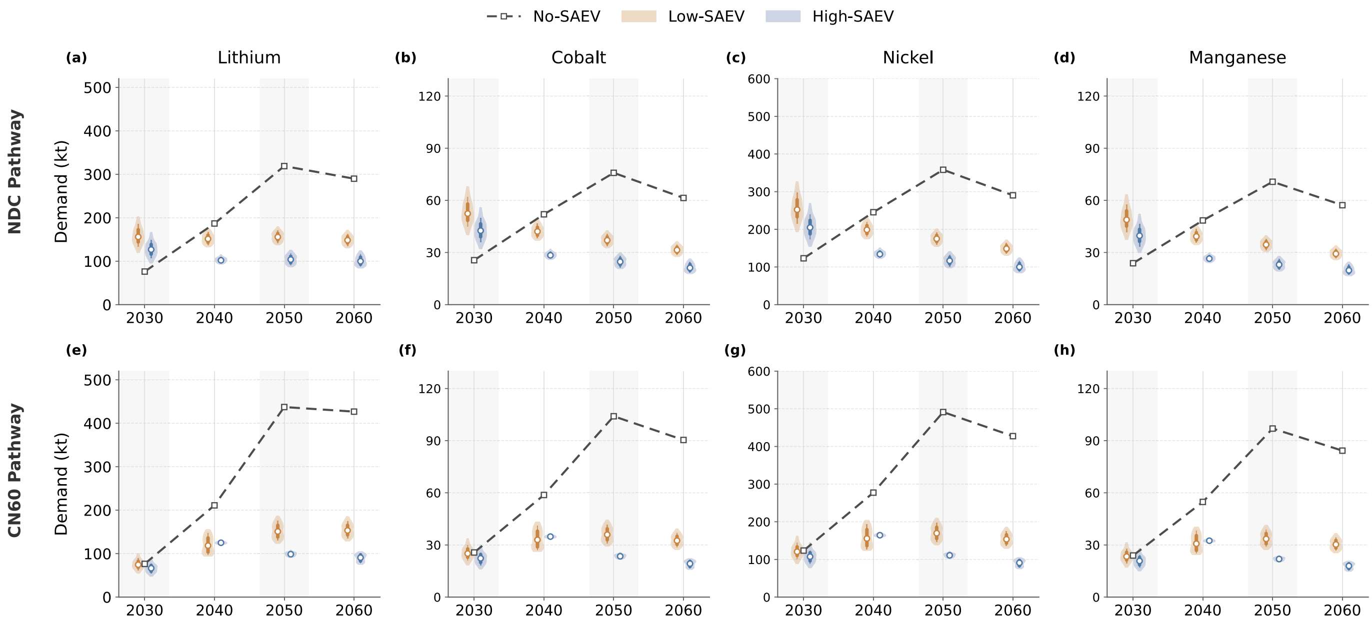

Fig. 8. MCA results for gross critical metal demand (Li, Co, Ni, Mn) for passenger-LDV batteries. Violin plots show 100 LHS-sampled realizations per scenario for 2030–2060; white dots mark medians. Dashed lines indicate the deterministic No-SAEV references. The sampled inputs include SAEV occupancy, energy efficiency, annual mileage, and an additional rebound increment as reported in Table S2 of the Supplementary Information.

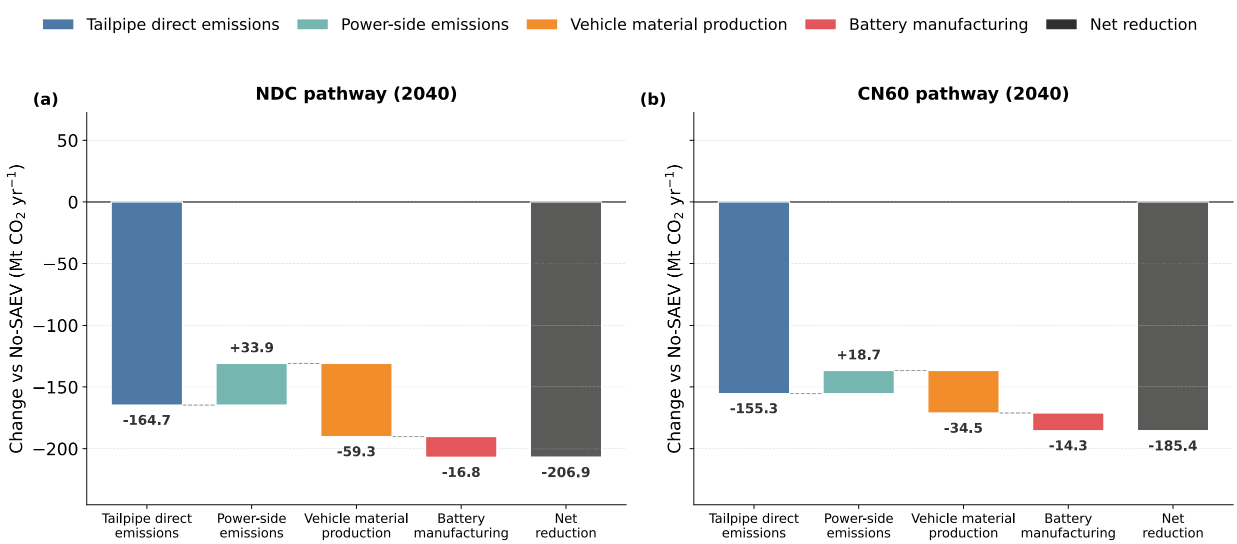

Fig. 9. Waterfall decomposition of annual SAEV-related CO_2 change at 2040 relative to the corresponding No-SAEV case. Sequential bars show four components under High-SAEV: tailpipe direct emissions, power-side emissions, vehicle material production, and battery manufacturing, followed by the resulting net annual change. Negative values indicate lower annual CO_2 impacts under High-SAEV. These bars are annual component-specific differences rather than the scenario-level totals shown in Fig. 3. Battery manufacturing follows the scenario-specific CO_2 intensity assumptions used in Fig. 6.

SAEV occupancy, utilization, and moderate induced demand therefore affects energy use more strongly than direct passenger-LDV emissions.

The gross battery-metal results extracted from the same unified MCA solve set remain consistent with the main critical-metal findings (Fig. 8). Across the four scenario combinations, the High-SAEV distributions remain centered well below the corresponding No-SAEV references for Li, Co, Ni, and Mn in the later periods, indicating that lower fleet and battery requirements continue to dominate the sampled outcomes overall even after allowing rebound to expand travel demand, although some early-period outcomes still reflect the transition in the composition of new battery-vehicle additions. By 2050 under CN60-High, the median gross demand falls to about 98.7 kt Li, 23.5 kt Co, 110.9 kt Ni, and 21.9 kt Mn, compared with 437.4, 104.0, 491.3, and 97.0 kt in CN60-No. The remaining spread is largest for lithium and nickel, reflecting how the fixed chemistry pathway concentrates the residual battery demand across metals once the total battery requirement changes.

Fig. 9 decomposes the 2040 annual CO_2 change from the No-SAEV case to High-SAEV into four components: tailpipe direct emissions, power-side emissions, vehicle material production, and battery manufacturing. The figure focuses on 2040 because this is the first period in which the operational and manufacturing components are all simultaneously large and clearly distinguishable, whereas later CN60 differences are increasingly compressed by deep power-sector decarbonization. Under the NDC pathway, three components contribute strongly to mitigation, while power-side emissions offset part of that gain because higher electrification draws more grid electricity under the less deeply decarbonized NDC pathway. Tailpipe direct emissions, avoided vehicle material production, and lower battery manufacturing change annual CO_2 by about −164.7, −59.3, and −16.8 Mt CO_2, respectively, while power-side emissions add about +33.9 Mt CO_2. The resulting net annual reduction is about 206.9 Mt CO_2 in 2040. This decomposition complements the scenario-level totals reported in Fig. 3.

Under the CN60 pathway, tailpipe direct emissions remain the largest mitigation channel in 2040, while lower vehicle material production and battery manufacturing provide additional production-phase reductions and higher power-side emissions offset part of the gain. Tailpipe direct emissions, vehicle material production, and battery manufacturing change annual CO_2 by about −155.3, −34.5, and −14.3 Mt CO_2, respectively, while power-side emissions add about +18.7 Mt CO_2. The resulting net annual reduction is about 185.4 Mt CO_2. On this annual accounting basis, the two production-phase channels together account for about 26.3% of the net annual CO_2 reduction under CN60, compared with about 36.8% under NDC. Operational and production-phase channels therefore remain complementary under CN60: the former still delivers the larger mid-century reduction, but the latter provides an additional reduction that would be missed if attention were limited to operational emissions alone. As power-sector decarbonization deepens further after 2040, operational comparisons become increasingly compressed, which is why total CO_2 provides a more complete basis for interpretation in the later periods.

3.5. Rebound-effect results

The CN60 rebound stress test shows that final energy, operational CO_2, and total CO_2 differ in their sensitivity to rebound (Fig. 10). Final-energy benefits remain substantial but can be eroded under strong induced demand; operational CO_2 is more sensitive in the late transition; and total CO_2 remains comparatively robust because lower vehicle-material production and battery manufacturing continue to offset part of the rebound-induced operational increase.

Final energy. Under CN60, High-SAEV lowers passenger-LDV final energy use in every modeled year from 2030 to 2060. The corresponding rebound threshold is about **+9.6%** in 2030, then rises to approximately **+79.4%** in 2040, **+53.1%** in 2050, and **+53.4%** in 2060. This pattern indicates that the energy advantage is relatively easy to offset at the beginning of the transition, but becomes harder to offset once the smaller-fleet effect starts to dominate the additional travel demand.

Operational CO_2. Operational CO_2 shows a different pattern. In 2030, CN60-High retains only a small operational advantage over CN60-No (448.3 vs. 457.2 Mt), so the threshold is reached at about **+4.7%** induced demand. In 2040, that margin becomes much larger (247.2 vs. 383.8 Mt), pushing the threshold out to approximately **+90.3%.** By 2050, however, the operational advantage narrows again (46.4 vs. 49.6 Mt) and the threshold falls back to about **+11.0%**. By 2060, CN60-High is already slightly above CN60-No at RB0 (−3.8 vs. −19.6 Mt), so the operational breakeven is **RB0**. This late-horizon reversal does not imply weaker overall climate performance of SAEVs. Once the power system is deeply decarbonized, operational differences become highly compressed, and the lower electricity demand under CN60-High also means that less net-negative electricity is attributed to LDV operation. Operational CO_2 is therefore more sensitive under deep decarbonization.

Total CO_2 impacts. The picture changes once vehicle-material production and battery manufacturing are included. CN60-High maintains a total-CO_2 advantage over CN60-No throughout the modeled horizon, with total CO_2 remaining lower in 2030 (527.7 vs. 610.0 Mt), 2040 (323.2 vs. 508.5 Mt), 2050 (64.2 vs. 115.7 Mt), and 2060 (7.6 vs. 29.3 Mt). The corresponding rebound threshold therefore shifts much farther outward: approximately **+14.0%** in 2030, **+108.4%** in 2040, and **+141.4%** in 2050, while no crossing is reached by RB200 in 2060. This pattern reflects the persistence of production-phase co-benefits: even when induced demand substantially weakens the

Fig. 10. CN60 rebound stress-test summary for High-SAEV relative to CN60-No. Top row: breakeven thresholds for (a) LDV final energy, (b) operational CO_2, and (c) total passenger-LDV-related CO_2 in 2030, 2040, 2050, and 2060. Green indicates retained benefits, red indicates exhausted benefits, and markers denote interpolated breakeven thresholds. RB0–RB200 denote additional induced-demand increments of 0–200%, and the gray band marks the empirically informed 10–20% range. Bottom row: corresponding metric values for selected rebound cases together with the CN60-No benchmark.

operational advantage, lower vehicle-material production and lower battery-manufacturing requirements continue to keep total CO_2 below the CN60-No benchmark, although cleaner battery manufacturing and vehicle-material production slightly narrow that margin at later dates.

Overall, the CN60 stress test shows that rebound has different implications across metrics: operational CO_2 can lose its advantage relatively quickly in a deeply decarbonized system, whereas total CO_2 remains more robust because production-phase reductions persist even under strong induced demand.

4. Discussion

4.1. System value of SAEVs

In this analysis, the value of SAEV deployment arises not only from powertrain change, but also from a structural shift in how passenger-LDV mobility is provided. The climate benefit therefore combines operational channels and production-phase channels, and their relative importance changes across pathways and over time.

Under less stringent decarbonization, operational reductions remain the largest visible contributor. Under deeper decarbonization, however, power-side differences become increasingly compressed, while lower vehicle-material production and lower battery-manufacturing requirements remain important for interpreting the total climate benefit. The system implication is therefore not simply cleaner driving, but lower fleet and battery throughput in providing the same mobility service, which is consistent with recent evidence that the electricity-system effect of ride-hailing electrification depends strongly on the underlying energy structure [64].

This shift is most visible around mid-century, when SAEV deployment has already reduced vehicle additions and battery demand substantially while industrial emission intensities are still high enough for those reductions to be expressed clearly in annual terms. By the late horizon, annual production-phase gains are moderated by broader industrial decarbonization, but they remain important for interpreting total climate benefit. The uncertainty results point in the same direction: adverse operating assumptions and stronger rebound weaken the energy and operational advantages more quickly, whereas the material-demand results and the broader total-CO_2 comparison remain more persistent beyond the initial transition period.

4.2. Policy relevance

The results suggest a complementary rather than substitutive role for SAEV deployment in broader transport decarbonization. For policymakers, these findings point to four practical priorities: establishing a clear regulatory pathway for autonomous mobility services, aligning safety certification and operational rules with staged deployment, coordinating shared electric mobility with charging and power-system planning, and strengthening battery traceability, recycling governance, and data-management safeguards. These requirements are institutional as well as technical. In China's context, recent policy experimentation, demonstration activity, and ongoing standard-setting efforts indicate improving regulatory readiness, but robust safety governance, privacy protection, cybersecurity, and operational accountability remain necessary conditions for large-scale deployment.

The electricity implications also point to the need for a coordinated transition strategy. Under CN60, annual passenger-LDV electricity demand is not uniformly lower under High-SAEV: it remains above CN60-No in 2040, but becomes about 31% lower by 2050–2060 once the long-run service-efficiency effect dominates. This pattern suggests that the electricity implications of SAEV deployment should not be interpreted as a one-directional consequence of electrification alone. Rather, it reflects a net balance between service-efficiency gains, which reduce the electricity required per unit of passenger mobility service, and offsetting burdens such as deadheading and rebound travel. At the level of the present analysis, the most direct planning implication therefore concerns annual system-scale effects rather than dispatch-level charging timing.

The broader transport-policy role of SAEVs should likewise be interpreted through complementarity rather than simple substitution. From a transport-system perspective, metro, bus rapid transit (BRT), and high-speed rail (HSR) are generally better aligned with concentrated passenger flows and corridor-based fixed infrastructure, whereas SAEVs in this study are introduced only for passenger-LDV road mobility and primarily improve the efficiency and material intensity of flexible road-based passenger service [65–67]. Public-transit upgrades and HSR therefore remain better aligned with high-capacity corridors, while demand-management measures operate by reducing travel demand itself. SAEVs, by contrast, primarily affect the utilization, occupancy, and fleet size of passenger-LDV service. Within this boundary, the present results suggest that SAEVs are best interpreted as a complementary decarbonization lever for flexible passenger-road mobility rather than as a substitute for high-capacity corridor modes.

These gains may also be accompanied by adjustment pressures. Meeting the same mobility-service demand with fewer vehicles and lower material throughput could improve service accessibility for some user groups, but it could also create transition pressure for driver-dependent mobility services, parts of the vehicle maintenance and aftermarket ecosystem, and regions more exposed to vehicle and battery manufacturing activity. This issue is not trivial in China's current mobility market: by the end of June 2024, 7.126 million ride-hailing driver permits and 3.015 million vehicle permits had already been issued nationally [68]. For industry and fleet operators, the same mechanism implies fewer vehicles and batteries, greater importance of centralized charging and asset management, and a gradual shift in value creation away from unit sales toward fleet services and closed-loop battery management [43,69]. Because employment and regional distribution are not modeled endogenously here, these socio-economic implications should be interpreted as grounded qualitative consequences of the fleet-contraction and material-throughput results rather than as quantified welfare outcomes. Labor-transition support, battery-recycling governance, and region-specific adjustment measures would therefore remain important complements to any rapid SAEV transition [70,71].

4.3. Limitations and scope

The present framework captures long-run national system outcomes under exogenously bounded SAEV deployment conditions. The analysis is implemented in a national energy-system optimization framework, with SAEV deployment represented through scenario-specific service-share ceilings, cost trajectories, and rebound-adjusted passenger-LDV demand instead of explicit consumer-choice dynamics. The reported pathways therefore clarify the system-wide implications of these SAEV conditions. Realized deployment will still depend on trust in autonomous-driving safety, willingness to use pooled services, and relative generalized travel cost. In practice, these behavioral factors also condition rebound: if shared autonomous mobility becomes both trusted and highly convenient, part of the realized service benefit may appear as additional travel demand rather than only as lower vehicle ownership [51,60,61,72,73].

Second, the present paper focuses on long-run national system outcomes and therefore reports electricity implications at annual resolution. Questions such as charging timing, peak-load effects, renewable-curtailment interactions, and vehicle-to-grid (V2G) value are important for understanding how SAEV deployment may interact with a decarbonizing power system, but they are not directly quantified here. Related studies suggest that centrally managed shared electric fleets may exhibit more schedulable charging behavior and greater flexibility for coordinated grid interaction than dispersed private charging [74]. The electricity-system implications reported in this paper should therefore be interpreted as annual-system evidence on the net electricity burden of SAEV deployment, rather than as dispatch-level estimates of charging operations. Higher-temporal-resolution coupling would be a valuable next step.

Third, long-run results remain sensitive to battery chemistry evolution, material intensities, vehicle lifetimes, and recycling performance. These assumptions affect not only the absolute level of critical-metal demand and battery-manufacturing emissions, but also the relative importance of production-phase reductions within the total CO_2 benefit of SAEV deployment. Lower long-run annual vehicle and battery production also does not preclude temporary transition-phase production pressure or short-lived emissions spikes, because accelerated turnover can temporarily raise manufacturing requirements before the fleet-contraction benefit fully materializes. Second-hand vehicle market dynamics and residual-value effects are likewise not quantified explicitly, and long-run reductions in gross and net metal demand do not eliminate supply-chain risk if mineral bottlenecks, recovery shortfalls, or chemistry shifts emerge [12,31,39,75,76].

Direct validation against observed national outcomes is not yet possible, because no national-scale SAEV system yet exists in China. Available empirical evidence therefore supports the plausibility of the operating assumptions and near-term deployment conditions adopted in this study, but does not provide direct validation of the modeled national pathways.

The scope of the findings is also context-dependent. China's dense urban demand, existing mobility-as-a-service ecosystems, centralized regulatory capacity, large EV and battery manufacturing base, and rapidly decarbonizing power sector all strengthen the conditions under which SAEV deployment could deliver large system-level effects. The broader mechanisms identified here—fleet contraction, lower material demand, and stronger interaction with electricity decarbonization—may also remain relevant for other rapidly motorizing economies. However, the exact quantitative magnitudes should not be transferred directly across contexts. Their external relevance will depend on urban density, electricity carbon intensity, digital-regulatory capacity, liability and data-governance arrangements, and the structure of the domestic automotive industry.

4.4. Future research

Three directions appear particularly important for future research. First, linking national energy-system analysis with richer behavioral and diffusion modeling would help assess how consumer acceptance, service quality, and induced demand shape achievable SAEV deployment. Second, extending the transport-energy analysis toward higher-temporal-resolution power-system coordination would help clarify how renewable-output timing, managed charging, and the flexibility value of centrally coordinated fleets interact in practice, including possible V2G-related system benefits [74]. Third, broader sustainability assessment should examine alternative battery-chemistry pathways, recycling performance, labor-market transitions, and regional distributional effects in greater detail.

5. Conclusions

This study shows how SAEV deployment could reshape China's passenger-LDV transition under the NDC and CN60 pathways, with particular attention to energy use, climate impacts, and material requirements. The main conclusions are as follows.

1. **The system value of SAEV deployment lies primarily in service efficiency rather than electrification alone**: By enabling much higher vehicle utilization, SAEVs allow passenger-LDV mobility demand to be met with a fundamentally smaller fleet. Under the deep-decarbonization pathway, this smaller-fleet effect becomes a central driver of lower long-run energy use and resource requirements.
2. **SAEV climate benefits arise through both operational and production-phase channels**: SAEV deployment reduces direct passenger-LDV CO_2 emissions, while lower vehicle-material production and reduced battery-manufacturing requirements strengthen the total climate benefit. As power-sector decarbonization deepens, these production-phase channels become increasingly important for interpreting total climate impacts.
3. **Higher utilization and battery recycling can substantially ease long-run critical-metal pressure**: Under rapid SAEV deployment, gross demand for critical battery metals falls markedly, and high recycling further lowers mid-century net primary demand. Over time, however, the recycling-adjusted advantage becomes increasingly metal-specific because larger No-SAEV fleets also generate larger end-of-life battery flows.
4. **Uncertainty mainly affects the timing and magnitude of SAEV benefits**: The MCA and rebound analyses show that final-energy and operational-CO_2 outcomes are more sensitive to adverse assumptions, whereas the material-demand advantage and the broader total-CO_2 comparison become more consistently favorable beyond the initial transition period.

Overall, the findings suggest that the main value of SAEVs lies in providing passenger-LDV mobility with fewer vehicles, lower battery deployment, and lower material throughput, rather than in cleaner vehicle operation alone. Realizing this value in practice will depend on whether automation, electrification, and shared mobility can be translated into sustained efficiency gains while limiting rebound effects and aligning deployment with charging, recycling, and governance conditions.

CRediT authorship contribution statement

Qi Ding: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jinhui Ren:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Shu Zhang:** Writing – review & editing, Validation, Supervision, Software, Methodology, Conceptualization. **Wenying Chen:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data for this article can be found online at doi:10.1016/j.apenergy.2026.128259.

Data availability

Data will be made available upon request.

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