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Multi-dimensional integrated development strategy for urban rail transit optimized via a carbon emission model driven by new quality productive forces

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ABSTRACT

Urban rail transit is an energy-intensive sector with substantial carbon emissions, particularly during its operational phase. Despite the rapid emergence of energy-saving technologies, the lack of systematic quantification of their carbon emission reduction efficiencies hinders comparative evaluation and informed decision-making. This study addresses this gap by developing a carbon emission calculation framework for key energy-saving technologies, incorporating an enhanced Bass diffusion model to forecast future emissions. A marginal abatement cost analysis and a Multi-Constraint Interior Point Method are further employed to formulate an optimized, multi-dimensional integrated strategy encompassing energy, vehicle, storage, and network systems. Results reveal that, in terms of carbon emission impact, the technologies rank as follows: Permanent Magnet Synchronous Motors (PMSM) traction systems, Regenerative Braking Systems (RBS), Life-Cycle Smart Environmental Control Systems (LCSMS), and various energy storage systems. While Flywheel Energy Storage (FES) technology and LCSMS initially exhibit high marginal abatement costs, these decline significantly before 2030. In contrast, Photovoltaic (PV) generation technology maintains the lowest marginal costs throughout. Investment optimization shows that the shares allocated to PV and LCSMS increase linearly, jointly approaching 85% by 2060. Consequently, investment in PV and LCSMS should be progressively scaled up to enhance carbon reduction performance. This study provides a theoretical basis for the formulation of urban rail transit policies and supports the achievement of the dual carbon strategy goals, holding significant theoretical and social value.

1. Introduction

Urban rail transit remains an energy-intensive sector with significant carbon emissions, particularly during its operational phase. For instance, Shanghai's rail transit network exceeds 800 km, making it the world's largest. In 2024, it consumed approximately 886,000 tons of standard coal, or 2.95 billion kW·h of electricity—accounting for 1.5 % of the city's total electricity use. The full life cycle of urban rail transit spans planning, construction, operation, maintenance, and demolition. Among these stages, the operational phase dominates in both duration and carbon footprint (Ye et al., 2018). In Shanghai, the life-cycle carbon emissions reach 109.64 thousand tons CO_2-eq/kW·h, with over 92 % of emissions generated during the operation and maintenance phase (Ye et al., 2018; Chen et al., 2022), as shown in Fig. 1.This phase alone offers a carbon reduction potential of 40–50 %, compared to only 10–15 % during construction. To meet the 2060 carbon neutrality target, emissions must be reduced by 8.75 to 17.5 million tons CO_2-eq annually.

Leveraging clean energy and advanced technologies such as Permanent Magnet Synchronous Motors (PMSM) traction systems, Regenerative Braking Systems (RBS) (Wu et al., 2018), and Life-Cycle Smart Environmental Control Systems (LCSMS) could significantly mitigate operational emissions. Emerging technologies like photovoltaic (PV) (Zhao et al., 2020) generation technology, Flywheel Energy Storage (FES) technology, and integrated energy management (Yang, 2017) solutions are gradually being implemented. For example, in April 2022, China's first megawatt-scale flywheel energy storage system began operation in Qingdao, reducing emissions by 50,000 tons CO_2-eq annually. In Shenzhen, PV systems at 12 elevated stations on Metro Line

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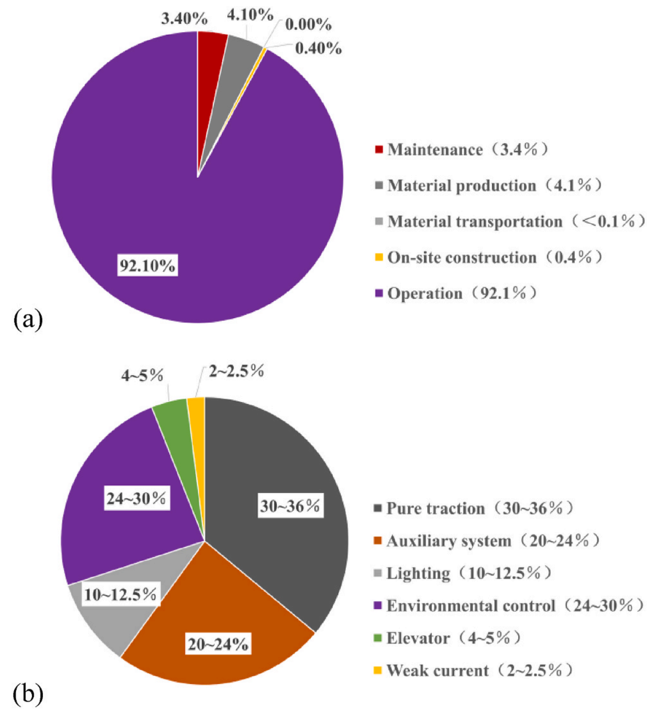

Fig. 1. Life cycle carbon emissions of urban railway system (Ye et al., 2018; Chen et al., 2022), (a) carbon emission share at each phase, (b) carbon emission share of each system during the operation and maintenance phase.

6 generate over 2 million kW·h per year, achieving 35 % energy savings.

Scholars have proposed smart grid frameworks integrating PV and storage systems to optimize energy supply and reduce emissions (Liu and Li, 2023; Jia et al., 2022). However, current approaches in China's urban rail sector often focus on single technologies and lack holistic coordination. There is an urgent need for a flexible, adaptive, and multi-dimensional integrated strategy that aligns energy, vehicles, storage, and network systems to support national targets of carbon peaking by 2030 and neutrality by 2060. Currently, the operation phase of urban rail transit in China has the following characteristics: (1) Urban rail transit has a high energy consumption share and is highly dependent on externally supplied energy. While it has significant carbon reduction potential, the carbon reduction and energy-saving technologies are limited and inefficient, and no systematic multi-dimensional integrated development strategy has been formed; (2) The carbon reduction assessment and evaluation system for urban rail transit remains underdeveloped. A scientific and rational calculation model for the energy-vehicle-storage-network multi-dimensional integrated strategy in new urban rail transit has not yet been developed.

To address these gaps, this study develops a comprehensive carbon reduction quantification model that leverages new quality productive forces to guide urban rail decarbonization. It introduces an enhanced Bass diffusion model to project technology adoption trends and employs both marginal abatement cost analysis and the multi-constraint interior point method to optimize technology investment allocations. This enables the development of an energy-vehicle-storage-network integrated strategy tailored for urban rail systems.

2. A novel carbon emission calculation model

2.1. *Brief introduction of multi-dimensional integrated strategy*

The operation and maintenance phase of urban rail transit consists of four core systems: energy, vehicle, storage, and network. The integration of advanced productivity technologies in each system is crucial for enhancing energy efficiency and sustainable development capabilities. In the energy system, PV converts solar energy into electricity, providing clean energy for rail transit. In the vehicle system, PMSM and RBS improve the energy efficiency and energy recovery rate of the power system. In the storage system, FES, Supercapacitor (SC) technology, and Compressed Air Energy Storage (CAES) technology optimize energy storage and distribution. In the network system, LCSMS enables real-time monitoring and optimized allocation of energy demand, reducing energy waste. Integrating and applying these technologies significantly reduce the carbon emissions of urban rail transit, providing essential technical support for achieving carbon peak and carbon neutrality goals.

Operational carbon emissions of urban rail transit primarily originate from three aspects: energy supply, train traction power, and environmental control systems. With the energy structure adjustments and the development of new quality productive forces such as these key technologies, a traditional multi-dimensional integrated energy-vehicle-storage-network strategy (Fig. 2) has been initially proposed for the energy saving and emission reduction. This strategy will reduce urban rail transit's dependence on external energy supply, establishing a new pattern for systematic and multidimensional integration and development. However, existing carbon emission calculation models have not fully incorporated this development strategy. Therefore, it is urgent to establish a carbon emission calculation model based on the multi-dimensional integrated strategy, which can provide a reference for the formulation of policies guiding China's urban rail transit toward carbon peak and carbon neutrality.

2.2. *Carbon emission calculation model for the operation phase of urban rail transit*

Traction system, environmental control systems, and other components are the main carriers of energy consumption during the operation phase of urban rail transit. The energy supply for these systems is primarily in the form of electricity. Therefore, the operational-phase carbon emissions can be calculated based on its electricity consumption. With the development of new quality productive forces, a multi-dimensional carbon reduction strategy involving energy, vehicle, storage, and network has gradually been established in the urban rail transit sector. As a result, the operational-phase carbon emissions of urban rail transit in China can be calculated as the difference between the baseline carbon emissions (C_e, representing electricity consumption carbon emissions) and the carbon reduction achieved through new quality productive forces (C_r).

$$C = C_\mathrm{e} - C_\mathrm{r} \tag{1}$$

2.2.1. *Baseline carbon emission estimation*

According to the annual report on comprehensive transportation development in Shanghai (2022) published by the Shanghai urban and rural construction and transportation development research institute, the electricity consumption during the operation phase of Shanghai's urban rail transit grows at an annual rate of 3.3 %. Its carbon emissions can be calculated using the following formula:

$$C_\mathrm{e} = W_n \cdot C_0 = W_0 \cdot (1+\gamma)^{n-1} \cdot C_0 \tag{2}$$

where C_e represents the baseline carbon emissions during the operation phase of urban rail transit (electricity consumption carbon emissions), W_0 denotes the electricity consumed during the operation phase of urban rail transit in the base year, W_n represents the electricity consumed during the operation phase in the n-th year, C_0 is the carbon emission factor for electricity in the base year (using the statistical average value), n represents the n-th year, and γ represents the annual energy consumption growth rate. The research results show that the carbon emission factor of the power system is closely related to geographical location and time, as shown in Table 1.

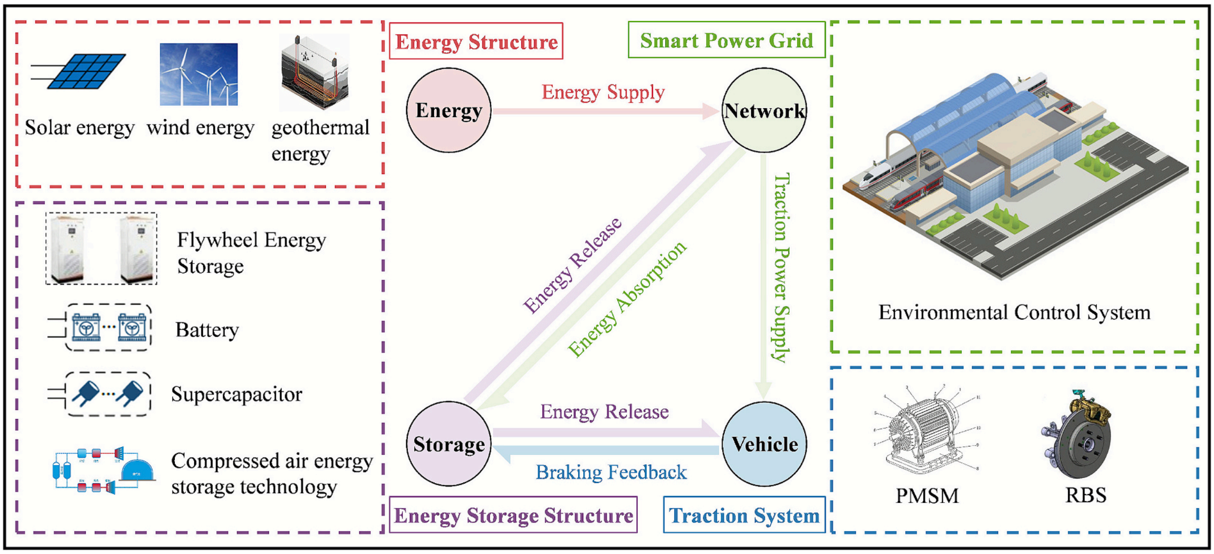

Fig. 2. Traditional multi-dimensional integrated strategy of energy-vehicle-storage-network.

Table 1
Carbon emission factor of electricity power (Wang and Chen, 2024).

Year	Region	Carbon emission factor (kg CO_2-eq/kW·h)
2014	U.S. Electricity	0.68
2017	France Power Grid	0.048
2018	Indian Power Grid	0.84
2014	Brazilian Power Grid	0.14
2015	Guangdong Power Grid	0.92
2013	Beijing Power Grid	0.95
2020	Northwest Power Grid	0.69
2019	North China Power Grid	0.71
2019	East China Power Grid	0.59
2019	Central China Power Grid	0.58
2020	Provincial Power Grids	Minimum 0.09
		Maximum 0.86
		Average 0.59
2021	Provincial Power Grids	Minimum 0.085
		Maximum 0.86
		Average 0.58
2022	Shanghai Power Grid	0.42

2.2.2. *Carbon reduction estimation of new quality productive forces*

New quality productive forces in urban rail transit enhance system efficiency through technological innovation. Their advancement in energy, vehicle, storage, and network domains will enable widespread operational-phase application, significantly accelerating carbon emission reduction. The main sources of carbon reduction include clean energy technologies, vehicle traction energy-saving technologies, and other energy-saving measures such as lightweight materials, optimized train power systems, and intelligent environmental control systems. The carbon reduction from new quality productive forces can be expressed as:

$$C_{\mathrm{r}} = C_{\mathrm{c}} + C_{\mathrm{m}} + C_{\mathrm{s}} \tag{3}$$

where C_{c} represents the carbon reduction from new clean energy technologies, C_{m} represents the carbon reduction from vehicle traction energy-saving technologies, and C_{s} represents the carbon reduction from other new energy-saving technologies.

(1) New clean energy technologies

Shanghai's urban rail transit operational emissions will decline through clean energy technologies such as solar, wind, hydrogen, geothermal, and biomass energy. For instance, ten subway bases, including Chuanyanghe, Zhibei, Jinqiao, Longyang Road and Sanlin, had integrated PV systems by 2022. The carbon reduction from clean energy technologies (C_{c}) can be determined by the proportion of electricity converted from clean energy and the carbon emission factor of China's power network, as detailed below:

$$C_{\mathrm{c}} = \lambda W_n C_0 \tag{4}$$

where λ represents the proportion of electricity converted from clean energy.

(2) Train traction energy-saving technology

Train traction power consumption is a key component of energy use in urban rail transit. Through new quality productive forces such as RBS, the energy converted during the train's operation is transformed into electrical energy. The converted electrical energy is directly utilized, while unused energy is stored using technologies such as FES, SC, and CAES. Therefore, the carbon reduction from train traction energy-saving technology (C_{m}) can be calculated using the following formula:

$$C_{\mathrm{m}} = \delta P_{\mathrm{b}} C_0 + (1-\delta)\beta P_{\mathrm{b}} C_0 \tag{5}$$

where δ represents the proportion of energy directly utilized during train operation, P_{b} denotes the electrical energy converted during train operation, and β represents the energy storage efficiency.

(3) Other new energy-saving technologies

The application of other new energy-saving technologies, such as lightweight materials, vehicle power system optimization, and intelligent environmental control systems, is also an important source of energy saving and carbon reduction in urban rail transit. The carbon reduction from other new energy-saving technologies (C_{s}) can be calculated using the following formula:

$$C_{\mathrm{s}} = \eta P_{\mathrm{w}} C_0 \tag{6}$$

where P_{w} represents the total electricity consumed when new energy-saving technologies are not applied, and η represents the energy-saving efficiency.

2.3. *Model parameters forecasting*

2.3.1. *Energy efficiency forecasting using an enhanced Bass diffusion model*

As urban rail transit advances, the energy efficiency of new quality productive forces evolves temporally. To predict this evolution, a forecasting model for the time-dependent energy efficiency of new quality productive forces is established based on an enhanced Bass diffusion model.

Adapted from the Bass diffusion model, which quantifies innovation adoption through mass media influence (coefficient p) and word-of-mouth imitation (coefficient q), an enhanced Bass diffusion model Eq. (7) is established to predict the temporal evolution of energy efficiency in new quality productive forces. This reformulation replaces the cumulative adoption rate up to year t with new quality productive forces efficiency metrics, capturing technology diffusion dynamics across urban rail transit systems.

$$E(t) = 1 - p\cdot e^{-(p+q)t} \tag{7}$$

where $E(t)$ represents the energy efficiency corresponding to year t, while p and q are model parameters.

The energy efficiency data for energy-saving technologies were compiled from an extensive review of academic literature, industry reports, and field data. The corresponding parameters p and q for each technology were then estimated by applying a nonlinear least squares fitting procedure, as presented in Table 2.

2.3.2. Energy efficiency forecasting analysis

Based on the fitting results, the trends of energy efficiency changes for each energy-saving technology after 2022 are forecasted, as shown in Fig. 3. CAES maintains the highest energy efficiency, approximately 90 % by 2060, delivering substantial emission reductions in urban rail transit. SC exhibits the lowest energy efficiency with minimal growth, while RBS demonstrates the most rapid acceleration, reflecting the country's strong focus on the innovation and development of this technology in recent years.

Integrated energy efficiency forecasting drives our carbon emission model, revealing urban rail transit could achieve carbon neutrality by 2049—decade ahead of the original target (Fig. 4). While the trend for each energy-saving technology remains consistent with those of 2022 in the future, declining growth rates reflect increasing research and development challenges. Therefore, the carbon emission development trend under this forecasting represents an idealized scenario, allowing for a deeper analysis of the impact of each energy-saving technology on carbon reduction in urban rail transit, followed by relevant discussions.

3. Scenario analysis based on carbon emission calculation

3.1. Baseline scenario assumption

The scenario analysis method is a technique used to study and analyze potential future situations. This method is widely applied in fields such as forecasting, strategic planning, and policy formulation (Chen et al., 2022). Based on the energy-vehicle-storage-network multidimensional strategy and research findings, the baseline scenario for carbon emission calculation in urban rail transit is established.

(1) According to Shanghai's carbon neutrality policy, non-fossil clean energy targets are 25 % by 2030 and 80 % by 2060. Thus, clean energy proportions for urban rail transit are assumed at 15 % in 2030 and 70 % in 2060.

(2) The traction system of vehicles mainly includes traction power supply and braking systems. PMSM and RBS will be widely applied in urban rail transit to reduce carbon emissions.

(3) RBS of subway vehicles account for 67 % of traction energy consumption, with approximately 36 % utilized by other vehicles on the track and 64 % available for storage and reuse (39 % of total traction consumption) (Xu, 2017). Consequently, it is assumed that 70 % of RBS-generated energy undergoes storage while 30 % is directly reused. For Shanghai's metro storage composition in 2030, FES and SC are projected at 50 % and 45 % respectively. By 2060, FES proportion increases linearly to 70 %, SC decreases to 25 %, and CAES remains constant at 5 %.

Table 2
Model parameters forecasting for new quality productive forces.

Technology type	Year	p	q	Energy efficiency
PMSM	2019	0.924	−0.907	15% (Cao et al., 2019)
	2022			29% (Wu et al., 2022)
	2006			2%-8% (Dong, 2006)
	2018			30% (Dong, 2006)
	2018			13% (Dong, 2006)
	2016			15% (Feng, 2018)
	2007–2009			20% (Zhang, 2020)
	2015			15% (Kawai and Tasaka, 2010)
	2018			31% (Kawai and Tasaka, 2010)
	2011			10% (Ma et al., 2015)
LCSMS	2023	0.719	−0.715	35% (Liu, 2011)
	2020			38% (Qiu et al., 2023)
	2019			30% (Luo et al., 2020)
	2018			32% (Wang and Wu, 2019)
	2015			5% (Xu, 2019)
	2018			12% (Zhao et al., 2015)
	2021			13% (Wang et al., 2021)
	2017			30% (Dong, 2017)
	2016			57% (An and Qian, 2016)
RBS	2008	0.804	−0.780	15% (Yang, 2008)
	2022			44% (Lv et al., 2022)
	2014			40% (Liu, 2014)
	2014			70% (Wu, 2014)
	2014			20% (Cui, 2014)
	2015			20% (Yu and Wang, 2015)
	2016			40% (Lu et al., 2018)
	2020			35% (Qiao and He, 2020)
	2008			30%-50% (Barrero et al., 2008)
	2023			40% (Feng et al., 2023)
FES	2018	0.833	−0.827	20% (Wang et al., 2018)
	2023			23% (Gulina and Li, 2012)
	2023			31% (Qiu et al., 2023)
	2001			18% (Ma and Zhou, 2004)
	2022			10%-18% (Qu, 2022)
	2014			10%-18% (Shen and Cao, 2020)
	2019			20%-30% (Liu, 2019)
	2020			19% (Zhang, 2022)
CAES	1978	0.436	−0.404	42% (Li et al., 2023)
	1991			54% (Li, 2022)
	2021			70% (Zheng et al., 2024)
	2022			70% (Wu et al., 2016)
	2022			60% (Li et al., 2020)
	2024			70% (Liang et al., 2020)
	2016			66% (Dong et al., 2019)
	2020			60% (Deng et al., 2023)
	2013			52% (Chen, 2022)
	2018			60% (Hu et al., 2020)
	2020			70% (Wang, 2015)
	2014			60% (Zhou et al., 2019)
SC	2023	0.814	−0.808	13% (Tang and Zhang, 2023)
	2022			22% (Gao et al., 2015)
	2020			50% (Zuo et al., 2023)
	2015			40% (Ahmadi et al., 2018)
	2019			74% (Chen et al., 2022)
	2023			80% (Wu et al., 2018)
	2015			19% (Zhao et al., 2020)
	2023			22% (Yang, 2017)
	2018			20% (Liu and Li, 2023)

(4) It is assumed that LCSMS will be promoted and applied in Shanghai starting in 2023, and by 2060, the entire Shanghai urban rail transit system will fully adopt this technology.

(5) China's power system emission factor has decreased progressively through the promotion and application of new clean energy and energy-saving technology. According to the data from Shanghai statistics bureau and ecology and environment bureau, the electricity consumption of urban rail transit in Shanghai in

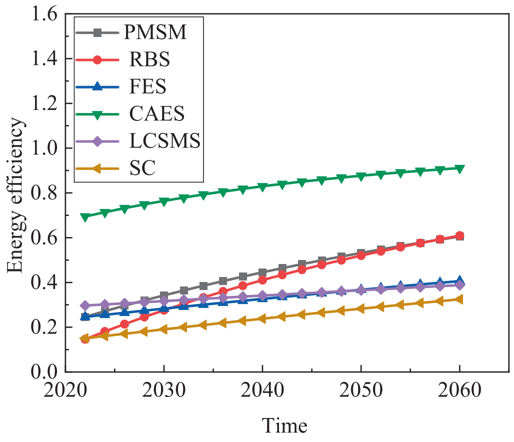

Fig. 3. Forecasting results of new energy-saving technology efficiency.

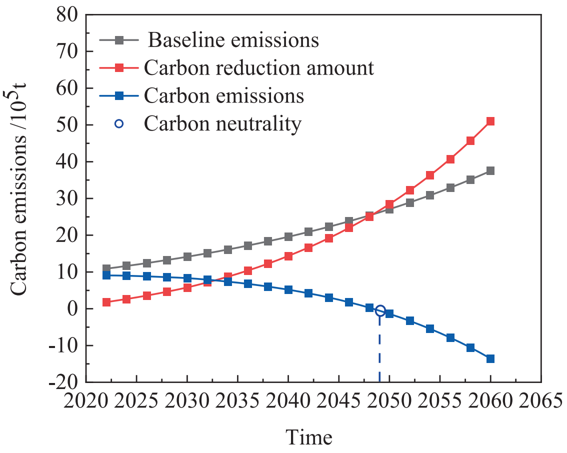

Fig. 4. Carbon emission reduction curve in urban rail transit over time.

2022 was approximately 2.6 billion kW·h, with a carbon emission factor of 0.42 kg CO_2-eq/kW·h. Therefore, in the baseline scenario, the electricity consumption of Shanghai's urban rail transit is set at 2.6 billion kW·h, and the carbon emission factor is 0.42 kg CO_2-eq/kW·h.

3.2. Carbon peak and neutrality analysis under different scenarios

Model forecasting results suggest CAES energy efficiency will reach 90 % by 2060, which is likely unattainable in practice. Given the critical carbon reduction roles of RBS and PMSM, these two technologies using the above model are projected 2060 doubling of 2022 energy efficiency. While FES, SC and LCSMS show relatively smaller impacts on carbon reduction in urban rail transit, the projected energy efficiency growth is large. Therefore, for the sake of conservatism, the proposed Scenario, as shown in Table 3, assumes that the energy efficiency of the other four technologies will peak in 2022. Each technology's energy efficiency will be discussed separately.

Table 3
Scenario assumption.

	PMSM	RBS	FES	SC	CAES	LCSMS
Scenario 1	60.54%	14.67%	24.63%	15.07%	69.48%	29.95%
Scenario 2	24.68%	60.93%	24.63%	15.07%	69.48%	29.95%
Scenario 3	24.68%	14.67%	40.63%	15.07%	69.48%	29.95%
Scenario 4	24.68%	14.67%	24.63%	32.51%	69.48%	29.95%
Scenario 5	24.68%	14.67%	24.63%	15.07%	91.10%	29.95%
Scenario 6	24.68%	14.67%	24.63%	15.07%	69.48%	38.82%

The design of the six scenarios, as summarized in Table 3, is to evaluate the respective contributions of key technologies within China's "carbon peak and carbon neutrality" strategic framework and their alignment with the dual carbon goals. Scenario 1 (PMSM) focuses on high-efficiency traction systems, aiming to facilitate carbon peaking during the operational phase and lay the foundation for achieving operational carbon neutrality. Scenario 2 (RBS) emphasizes regenerative braking to directly reduce operational carbon emissions and support the low-carbon transition of the transportation system. Scenarios 3 (FES) and 4 (SC) assess the role of high-power energy storage in grid stabilization and renewable energy integration, providing technical pathways for building a clean energy system. Scenario 5 (CAES) explores the potential of long-duration energy storage to support deep decarbonization of the power system, serving as a key technological safeguard for achieving carbon neutrality. Scenario 6 (LCSMS) achieves systematic energy savings and emission reduction through intelligent energy management, significantly accelerating the realization of carbon neutrality in the rail transit system.

In each scenario, the energy efficiency of the target technology is elevated to a high-potential value, while other technologies are maintained at their 2022 baseline levels. This approach allows for clear isolation and evaluation of their maximum potential impact on the urban rail transit carbon pathway, providing a scientific basis for achieving the carbon neutrality goal.

The calculation results based on the proposed Scenarios are shown in Fig. 5. The details of carbon peak and carbon neutrality targets for each Scenario are presented in Table 4. Using the preset model, scenario 1 achieves earliest carbon peak in 2023 and carbon neutrality in 2053, with the least carbon emission of 9.10 × 105 t. Therefore, the innovation and development of PMSM should be prioritized in the efforts for carbon reduction in urban rail transit. Scenario 2 peaks later (2026) and neutralizes by 2056, confirming the secondary impact of RBS. Scenario 3—6 achieve the carbon peak with high carbon emission and carbon neutrality targets at similar times. Suggesting that, PMSM plays a more important role in promoting the development of carbon peak efforts in urban rail transit.

4. Multi-dimensional integrated development strategy optimization guided by marginal abatement cost

4.1. Marginal abatement cost optimization

As mentioned above, this study is based on an enhanced Bass diffusion model to forecast the energy efficiency of the model parameters, and in order to further combine the calculation model to propose a supportive multi-dimensional integrated development strategy, the marginal abatement cost optimization algorithm and the multi-constraint interior point method are introduced for discussion.

(1) Marginal abatement cost model

The marginal abatement cost (MAC) of carbon refers to the additional cost required to reduce one unit of CO_2 emissions. The marginal abatement cost curve is a common tool used to display the abatement potential and marginal abatement costs at both macro (national, regional) and micro (industry, enterprise, urban area) levels, aiding policy decision-making. Research shows that abatement measures with MAC ≤ 0 are economically competitive and have abatement potential throughout their lifecycle, with lower implementation challenges. Therefore, based on the marginal abatement cost method, an in-depth analysis is conducted on the emission reduction potential of new energy-saving technologies in urban rail transit.

The marginal CO_2 abatement cost is equal to the ratio of the additional cost incurred by implementing abatement technologies relative to the baseline proposal to the amount of carbon abated. The specific calculation formula is as follows:

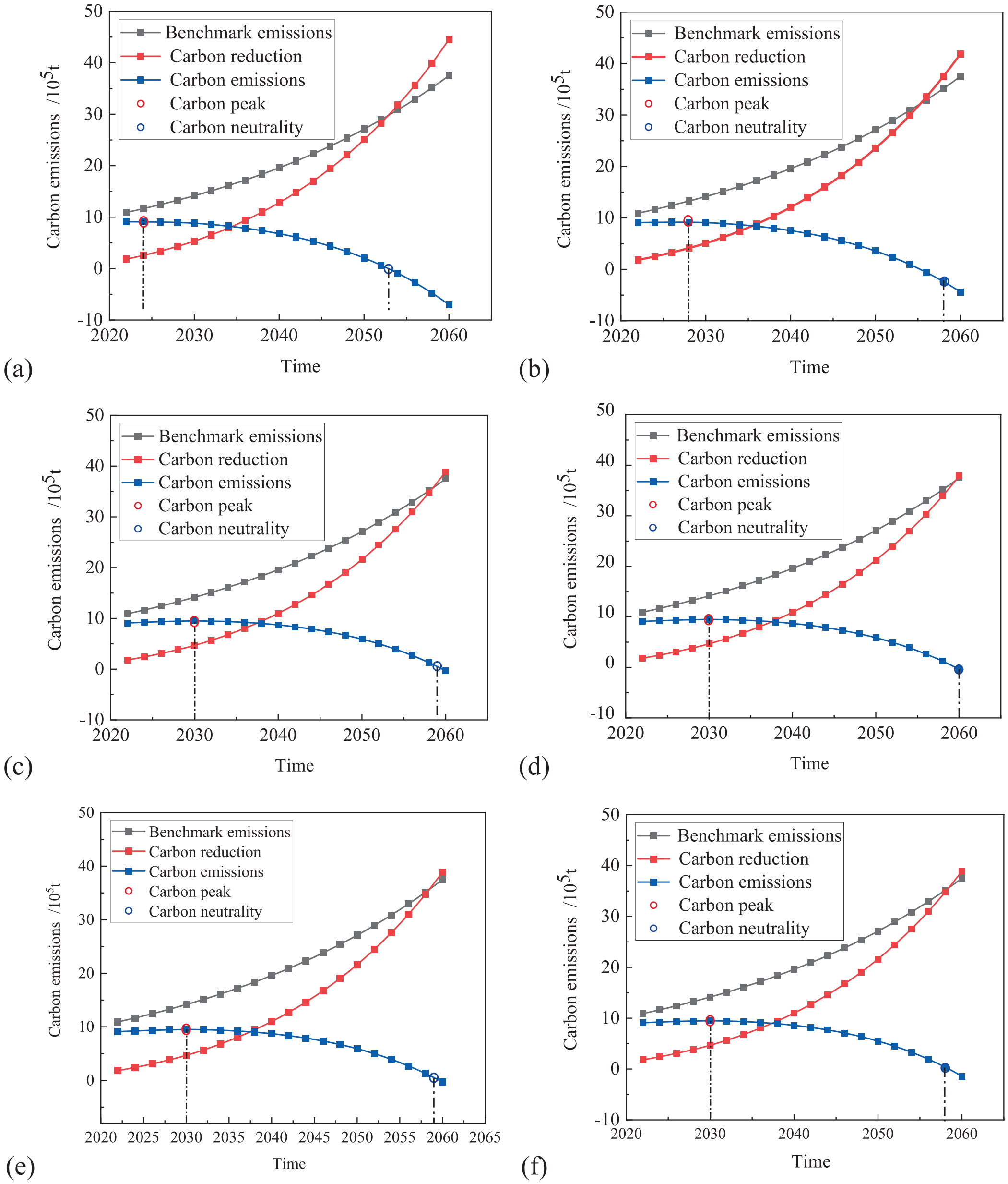

Fig. 5. The trend of carbon emissions over time under different scenarios, (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4, (e) scenario 5, (f) scenario 6.

Table 4
Carbon peak and neutrality under different scenario.

Scenario No.	Technology type	Carbon peak		Carbon neutrality	
		Carbon emission CO_2-eq/t	Year	Carbon emission CO_2-eq/t	Year
Scenario 1	PMSM	9.10×10^5	2023	0	2053
Scenario 2	RBS	9.16×10^5	2026	0	2056
Scenario 3	FES	9.50×10^5	2030	0	2060
Scenario 4	SC	9.50×10^5	2030	0	2060
Scenario 5	CAES	9.51×10^5	2030	0	2059
Scenario 6	LCSMS	9.50×10^5	2030	0	2059

$$C_{\mathrm{MA}} = \frac{\Delta C}{\Delta R} = \frac{\Delta K + \Delta C_{\mathrm{operat}}}{\Delta R} \tag{8}$$

where ΔC represents the incremental investment cost of the abatement technology, ΔR represents the carbon abatement amount, $\Delta C_{\mathrm{operat}}$ is the incremental operational cost of the abatement technology, and ΔK is the investment cost of the abatement technology.

$$\Delta K = K_{\mathrm{delta}} \frac{(1+d)^L \times d}{(1+d)^L - 1} \tag{9}$$

where K_{delta} is the investment cost of the energy-saving technology, L is the technology's whole life cycle, and d is the discount rate.

The discount rate is used to convert expected future benefits into present value and divided into the social discount rate and the private discount rate. The social discount rate reflects the government's borrowing rate and is considered risk-free, typically ranging from 5 % to 8 %. In contrast, the private discount rate reflects the opportunity cost and risk premium. A higher discount rate implies that the expected returns of a project are assumed to carry greater risk. For ease of comparison, a 5 % social discount rate is used in this study to discount the annual cash flow costs, in order to reflect the time value of money and to adjust the investment costs of low-carbon technologies during their investment recovery period.

$$\Delta C_{\text{operat}} = \Delta C_{\text{energy}} + \Delta C_{\text{OM}} \tag{10}$$

where ΔC_{energy} is the fuel cost difference, and ΔC_{OM} is the operational and maintenance cost difference, Since the operational and maintenance costs account for a small proportion of the total cost, they can be neglected. Therefore, the incremental cost of implementing an abatement technology equals the increase in investment cost minus the energy savings benefit.

$$C_{\text{energy}} = C_{AET} - C_{\text{ET}} = e_1 \times p_1 - e_2 r \times p_2 \tag{11}$$

where C_{AET} represents the energy cost of the abatement technology; C_{ET} is the energy cost of the existing technology, e_1 represents the consumption of alternative energy, and if no energy replacement exists, then $e_1 = 0$, P_1 is the unit price of the alternative energy, e_2 is the energy consumption of the existing technology, r is the energy-saving rate of the technology, and P_2 is the unit price of the existing technology, calculated based on the non-residential electricity price in Shanghai at 0.636 CNY/kW·h, with the photovoltaic power generation unit price at 0.48 CNY/kW·h.

Currently, commonly used energy-saving technologies in urban rail transit include PMSM, RBS, LCSMS, and various energy storage technologies. This paper primarily discusses three technologies: SC, FES, and CAES. Additionally, the conversion of clean energy into electrical energy also incurs marginal costs. The marginal cost of clean energy is mainly discussed with respect to PV. The investment costs of are shown in Table 5.

(2) Multi-constraint interior point method

The multi-constraint interior point method (MCIPM) solves nonlinear optimization problems with multiple constraints by: (1) transforming constraints into barrier functions within the objective; (2) progressively reducing barrier parameters to generate unconstrained subproblems; (3) solving subproblems through Newton's method. This approach maintains feasibility while converging efficiently to optimal solutions, making it ideal for complex constrained optimizations like technology investment allocation.

The MCIPM is particularly applicable across various technologies in urban rail transit. In the proposed model, the objective function is first established, as shown in Eq. (12). This function is constructed based on the product of the emission reduction potential per unit cost of each technology, the fixed investment cost, and the corresponding investment proportion. Subsequently, the constraints are defined: the total investment cost is fixed, and the investment proportions allocated to each technology must lie between 0 and 1, with the sum of all proportions equal to 1. Three barrier functions, as shown in Eq. (13) are introduced to incorporate these constraints into the objective function. Through this modeling approach, the investment proportions for each technology are optimized under a fixed total investment cost, thereby maximizing the carbon emission reduction of the urban rail transit system.

Table 5
Investigation results on investment costs of various technologies.

Technology name	Investment cost	Lifetime (Years)	Source
PMSM	Research and development cost: 100 million CNY, Operating cost, 10 billion CNY	20	National Natural Science Foundation
RBS	Investment cost, 6 billion CNY	20	Regenerative Braking System Market
CAES	Investment cost, 6 billion CNY	30	Zou et al. (2024)
FES	Construction cost, 6000 CNY/kW·h	20	Zou et al. (2024)
SC	Construction cost, 10,000 CNYkW·h	30	Zou et al. (2024)
LCSMS	Investment per kilometer, 700,000 CNY, Total investment, 7.12 billion CNY for 10165 km of metro lines	20	China Railway Design Institute Group
PV	0.42 CNY/kW·h	25	Liu et al. (2023)

$$F(objective) = -\sum_{i=1}^{i=n}\left(x_i \times K \times \frac{E_i}{\Delta K_i}\right) \tag{12}$$

$$W(barrier) = \begin{cases} \phi_i(x_i) = -\log(x_i - 0) - \log(1 - x_i) \\ \phi_{\text{budget}}(x) = -\log\left(K - \sum (x_i \cdot C_i)\right) \\ \phi_{\text{sum}}(x) = -\log\left(1 - \sum x_i\right) \end{cases} \tag{13}$$

where E_{i} represents the reduction potential of the i-th technology (unit: t/year); x_i is the investment share of the $i -$ th technology; and n is the number of technologies, K is the total fixed investment cost.

4.2. Cost-benefit investment of new quality productive forces

Based on the MAC calculation model, the cumulative costs and marginal abatement costs of each technology were calculated by researching and compiling the energy efficiency and investment costs of each energy-saving technology. The results are shown in Figs. 6 and 7.

Fig. 6 illustrates the trends in incremental operating costs for different technologies from 2020 to 2060. The incremental operating costs of each technology gradually decline over time. Among them, PMSM dominates cost reduction and reaches approximately −17.5 billion CNY by 2060, indicating its significant advantage in reducing operational costs. Second only to it, PV shows a smaller cost reduction and reaches about −7 billion CNY, suggesting that its economic benefits gradually improve. FES and LCSMS is relatively gradual and achieve moderate cost reductions, while SC and CAES show minimal economic benefit improvement.

Fig. 7 shows the trend of MAC for each new energy-saving technology over time. Overall, the MAC for all technologies exhibit a downward trend, indicating that as the technologies advance, their abatement costs decrease annually, demonstrating strong economic efficiency and carbon reduction potential. Among them, the MAC of LCSMS is the highest in 2022 and decreases rapidly, but falling below other technologies by 2030, reaching the lowest level by 2060. This suggests that the technology has significant carbon reduction potential in the future. PV sustains negative MAC throughout and reaches its lowest point by 2060,

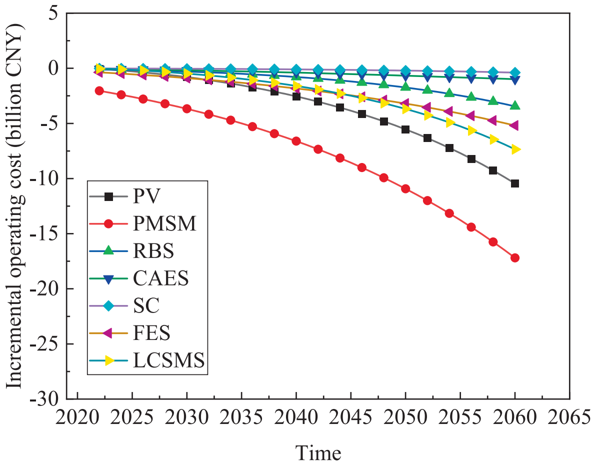

Fig. 6. Incremental operating costs of each technology.

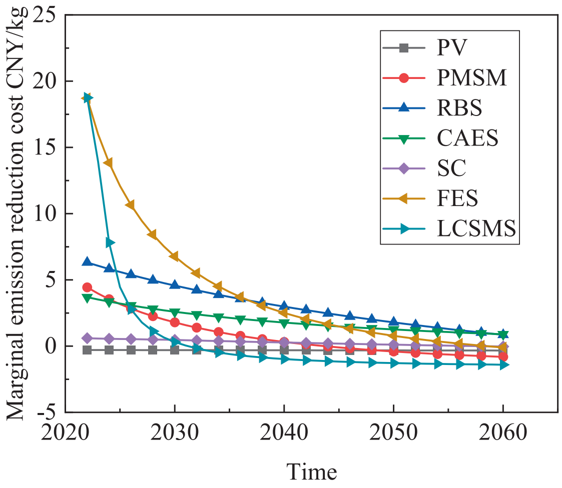

Fig. 7. The marginal emission reduction cost curve of various technologies.

indicating that PV not only has low abatement costs but also offers substantial carbon reduction capacity. In the meantime, PMSM also decreases steadily and turning negative after 2045. In contrast, FES and SC maintain positive MAC with gradual reduction, suggesting that these two technologies still have certain economic viability and carbon reduction potential. In summary, the coordinated development of these technologies will accelerate the achievement of carbon reduction targets for urban rail transit.

4.3. Optimization analysis on the cost share for each technology

According to the data from 2022 annual statistics and analysis report on urban rail transit, the urban rail investment as a fixed budget amounts to 544.39 billion CNY, assuming that future investment amounts will remain unchanged. Using the above optimization model, which performs dynamic, year-by-year optimization through the Multi-Constraint Interior Point Method to generate optimal investment portfolios by integrating the evolving marginal abatement costs (Fig. 7) and technology efficiency forecasts, the investment costs for each new energy-saving technology in urban rail transit are optimized. Fig. 8 shows the proportion of investment costs for various new energy-saving technologies resulting from this continuous optimization process that rebalances allocations annually based on cost-effectiveness, while Fig. 9 presents the carbon emission reductions of each technology calculated based on the optimization model.

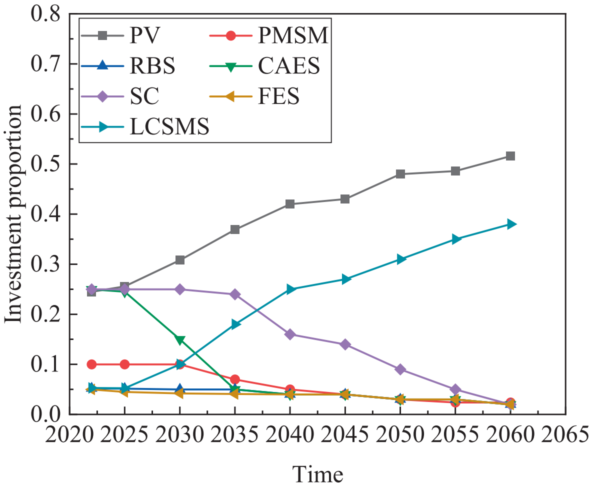

Fig. 8. Investment cost optimization ratio.

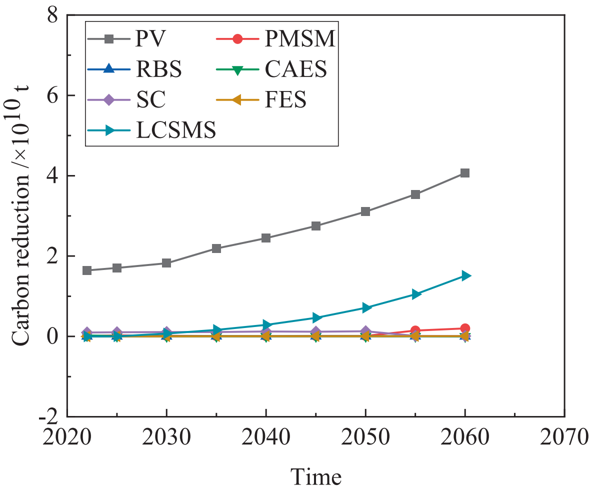

Fig. 9. Carbon emission reduction of various technologies calculated based on the optimization model.

Fig. 8 reveals strategically significant investment trends: PV and LCSMS show linearly increasing shares, reaching nearly 50 % and 35 % by 2060 respectively, which demonstrating their emerging dominance in the optimal technology portfolio as identified by yearly optimization model. This contrasts with strategically planned reductions for other technologies. SC maintains stable investment at approximately 25 % until 2035 before gradually decreasing to 3 % by 2060, serving as a transitional technology. In contrast, CAES declines sharply from 25 % to 5 % between 2025 and 2035, indicating its limited long-term role in the optimized portfolio. PMSM maintains a stable investment share of about 10 % before 2035 before rapidly decreasing to 4 %, reflecting its initial cost-effectiveness in the early stages, while RBS and FES maintain consistently lower proportions, being optimized for specialized applications rather than system-wide deployment.

Fig. 9 demonstrates PV's dominant carbon reduction under fixed-budget optimization, consistently achieving the highest emission reductions throughout the planning horizon, reaching 4.07 × 10^{10} t by 2060. LCSMS ranks second with 1.51 × 10^{10} t and SC declines after 2050, while SC provides modest but measurable contributions during the early phases, with its role gradually diminishing after 2050 as PMSM's allocation shows a corresponding increase. This yearly optimization model enables the development of tailored implementation strategies: initial substantial investment in PMSM and energy storage technologies (2030–2040) to establish system foundations, followed by strategic reallocation toward PV and LCSMS (2040–2060) to maximize long-term cost-effectiveness and emission reduction. In summary, with the given budget, PV plays a decisive role in the future development of carbon reduction in urban rail transit, followed by LCSMS, with their combined 85 % investment share by 2060 representing the optimal pathway to carbon neutrality. Therefore, budget allocation should progressively prioritize these two technologies while maintaining complementary investments in other technologies at strategically determined levels.

4.4. Energy-vehicle-storage-network multi-dimensional integrated development strategy

Urban rail transit is evolving into an intelligent, clean, and integrated system through a multi-dimensional integrated development mode of energy-vehicle-storage-network collaborative scheduling. Based on the MAC and MCIPM optimization results, Fig. 10 proposes relevant policies and a self-consistent multi-dimensional integrated energy-vehicle-storage-network development strategy highly applicable to urban rail transit, enabling significant reduction of energy consumption.

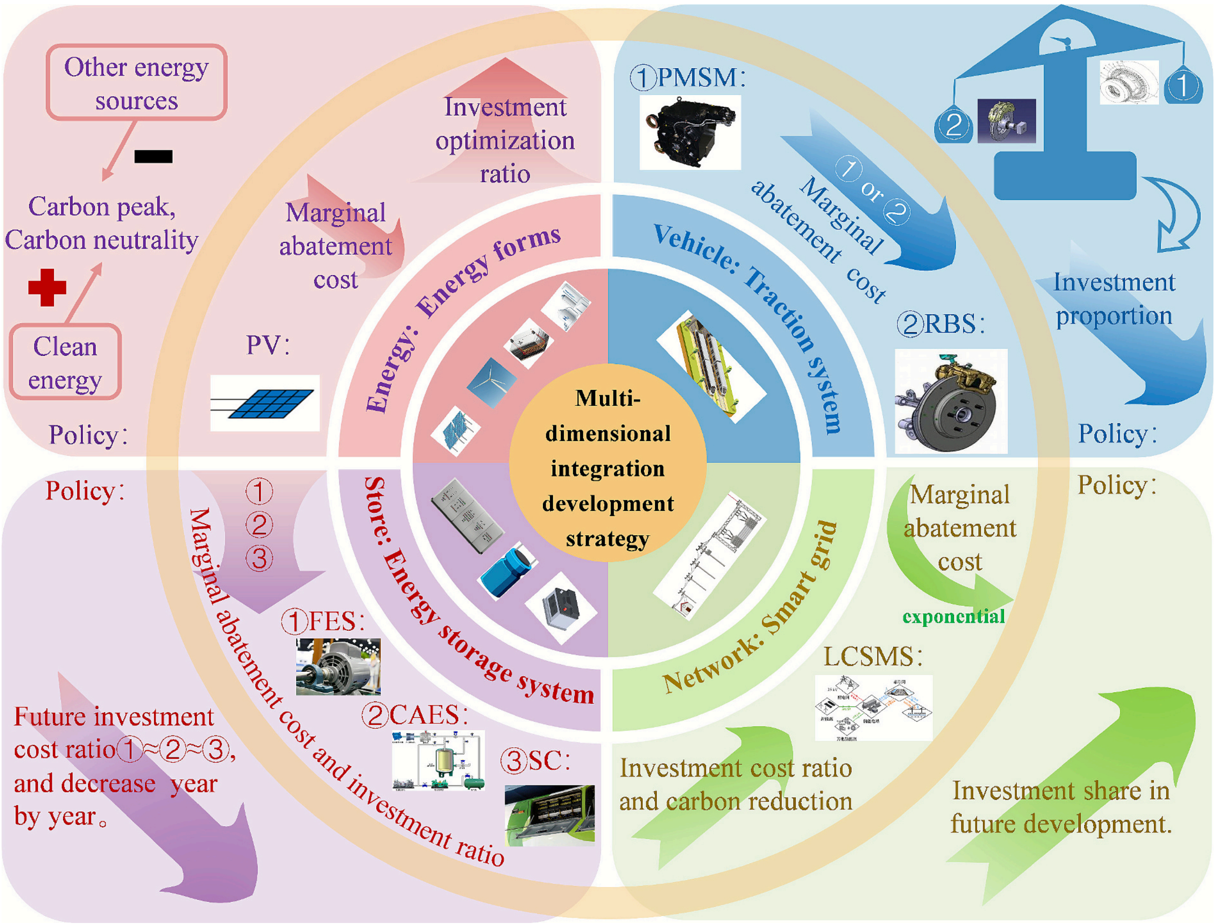

Fig. 10. Energy-vehicle-storage-network multi-dimensional integrated development strategy.

(1) Optimized strategy and technological pathway

This integration establishes a "grid + storage" power system where clean energy dominates the source dimension, prioritizing PV due to its low marginal abatement cost (MAC) and economic viability. Policy-driven investment growth must increase PV's share linearly to 0.5 by 2060—yielding 4.07×10^{10} t emission reductions—while scaling subsidies for solar integration and mandating renewable procurement quotas. Non-renewables should supplement only during transition phases, with coal phased out by 2040.

This integrated model utilizes a dedicated new energy system for urban rail transit and forms a "grid + energy storage" power supply system, prioritizing PV technology due to its relatively low MAC and strong economic viability. The fixed investment cost show PV's linear growth to 0.5 share by 2060, delivering 4.07×10^{10} t emission reductions. Given the crucial role in the sustainable development of urban rail transit, clean energy must dominate the energy dimension with linearly increasing investments, supplemented by non-renewables to accelerate carbon neutrality.

To prevent excessive energy delivery to other systems, LCSMS optimizes energy distribution by monitoring system consumption while exhibiting rapidly declining marginal abatement costs, becoming negative after 2030 and following an exponential trend. Under fixed investment costs, the MCIPM optimization results show the carbon reduction will rise annually and yield 1.51×10^{10} t by 2060—second only to PV. Therefore, combing with the trend of linear investment growth suggests that increasing the investment for LCSMS is essential to urban rail transit.

PMSM delivers energy-efficient train traction, yet optimization indicates linearly decreasing investment ratios. Its 2060 carbon reduction (2.00×10^{9} t) remains significant despite moderate marginal costs. RBS convert braking energy into electricity, which is partially reused directly while the surplus is stored. Despite low marginal abatement costs, optimized investment ratios for RBS and storage technologies decline gradually, yielding only 2.73×10^{8} t reductions by 2060—significantly below PV and LCSMS contributions. Therefore, investment in these technologies should be gradually reduced each year, with the investment ratio remaining similar and low level for FES, CAES and SC to ensure the most efficient energy-saving effect of the integrated model. Combined with the large investment operating cost reduction for PMSM, the investment for PMSM should decrease at a slower rate than RBS.

According to the calculation results based on the multi-constraint interior point method, by adopting this multi-dimensional integrated development model with a fixed investment of 544.39 billion CNY, the carbon emission reduction of urban rail transit is projected to reach 2.05×10^{14} t by 2030, and 5.81×10^{14} t by 2060. Therefore, the implementation of the aforementioned energy-vehicle-storage-network multi-dimensional integrated development model can accelerate the achievement of the carbon peak and carbon neutrality goals.

(2) Policy recommendations

To ensure the effective promotion and application of key technologies such as photovoltaic (PV) and Life-Cycle Smart Environmental Control Systems (LCSMS), a tripartite collaborative governance mechanism characterized by "government guidance, corporate leadership, and technological support" must be established. Within this framework, government agencies are responsible for top-level design and market environment creation, leveraging policy instruments such as fiscal subsidies, carbon reduction funds, and the inclusion of rail transit in carbon markets to guide and incentivize low-carbon technology investments; metro operators, as the implementing entities, are tasked with formulating detailed investment and retrofit plans, overseeing the on-site deployment and system integration of PV and LCSMS, and establishing a unified smart energy management platform to ensure emission reduction performance; technology providers deliver customized, highly reliable solutions and full lifecycle technical services, serving as the innovation backbone for technology implementation and continuous iteration. These policy recommendations facilitate the effective translation of strategic optimization into practical engineering outcomes.

It is recognized that the strategic-level optimization presented in this study may encounter systemic barriers during practical implementation, such as spatial constraints for PV installation or interoperability challenges with existing control systems. The proactive identification and resolution of these precisely such technical and physical conflicts constitute a core function of the aforementioned collaborative governance mechanism, ensuring that the optimized strategy can be successfully translated into on-the-ground reality.

5. Conclusion

By establishing a carbon emission measurement model and utilizing the Bass diffusion model to predict and analyze the carbon emission trends of new quality productive forces in urban rail transit, combined with marginal abatement costs and the multi-constraint interior point method, strategies and recommendations suitable for the future multi-dimensional integrated of energy-vehicle-storage-network in urban rail transit are proposed. Based on the above analysis, the following main conclusions are derived:

(1) Based on the calculation results of the Bass diffusion model, the influence on carbon emissions from urban rail transit, ranked by significance, is as follows: PMSM, RBS, LCSMS, and various energy storage technologies. Although energy-saving technologies have a relatively minor impact on carbon emissions from urban rail transit, they contribute to accelerating the achievement of the carbon neutrality goal by 2060.

(2) According to the calculation results of the marginal abatement cost, various new energy-saving technologies show a gradual decreasing trend over time. Compared to other technologies, PV maintains persistently low marginal abatement costs, while LCSMS's decreases rapidly, dropping below other technologies by 2030.

(3) Using the multi-constraint interior point method optimization model, the investment proportions of various new energy-saving technologies were optimized under a fixed investment cost. The optimization results indicate that PV dominating both investment share (50 % by 2060) and carbon reduction (4.07×10^{10} t), with LCSMS as secondary contributor (35 % share, 1.51×10^{10} t). The remaining technologies show similar levels of carbon reduction after optimization, all of which play a positive role in helping urban rail transit achieve the carbon peak and carbon neutrality goals.

(4) Based on the energy-vehicle-storage-network multi-dimensional integrated development strategy, feasible recommendations were proposed. In future development, the investment proportions of PMSM, RBS, and various energy storage technologies can be gradually reduced. Clean energy should be prioritized as the main supply source, with investment proportions in clean energy and LCSMS increasing linearly year by year. Non-renewable energy sources can be used as supplementary energy supplies.

CRediT authorship contribution statement

Feiyang Wang: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Wenwen Zhang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Yuxin Chen:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yi Li:** Writing – review & editing, Validation. **Jinzhou Bai:** Writing – review & editing, Conceptualization.

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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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