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RESEARCH ARTICLE

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Levelized costs of the energy chains of new energy vehicles targeted at carbon neutrality in China

Abstract The diffusion of new energy vehicles (NEVs), such as battery electric vehicles (BEVs) and fuel cell vehicles (FCVs), is critical to the transportation sector's deep decarbonization. The cost of energy chains is an important factor in the diffusion of NEVs. Although researchers have addressed the technological learning effect of NEVs and the life cycle emissions associated with the diffusion of NEVs, little work has been conducted to analyze the life cycle costs of different energy chains associated with different NEVs in consideration of technological learning potential. Thus, relevant information on investment remains insufficient to promote the deployment of NEVs. This study proposes a systematic framework that includes various (competing or coordinated) energy chains of NEVs formed with different technologies of power generation and transmission, hydrogen production and transportation, power-to-liquid fuel, and fuel transportation. The levelized costs of three typical carbon-neutral energy chains are investigated using the life cycle cost model and considering the technological learning effect. Results show that the current well-to-pump levelized costs of the energy chains in China for BEVs, FCVs, and internal combustion engine vehicles (ICEVs) are approximately 3.60, 4.31, and 2.21 yuan/GJ, respectively, and the well-to-wheel levelized costs are 4.50, 6.15, and 7.51 yuan/GJ, respectively. These costs primarily include raw material costs, and they vary greatly for BEVs and FCVs from resource and consumer costs. In consideration of the technological learning effect, the energy chains' well-to-wheel levelized costs are expected to decrease by 24.82% for BEVs, 27.12% for FCVs, and 19.25% for ICEVs by 2060. This work also summarizes policy recommendations on developing energy chains to promote the diffusion of NEVs in China.

Keywords energy chain, new energy vehicle, internal combustion engine vehicle, life cycle cost, technological learning

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1 Introduction

The transportation sector is the second largest contributor to global greenhouse gas emissions, and it accounts for 25% of global greenhouse gas emissions and 9% of China's total greenhouse gas emissions (Yu et al., 2021). It poses a considerable challenge to realizing carbon peaking and neutrality goals. The diffusion of new energy vehicles (NEVs) plays an important role in the deep decarbonization of the transportation sector (Milovanoff et al., 2020; Yang et al., 2020). The diffusion of NEVs is influenced by many factors, such as government subsidies (Zhao et al., 2021a), ownership cost (Lopez et al., 2021), safety (Wang et al., 2021), consumer acceptance (Huang et al., 2021), and the maturity of energy chains (Taalbi and Nielsen, 2021), which are the focus of this study. Energy chains are combinations of technologies that are defined at the level of conversion facilities (e.g., power plants or end-user devices such as cars).

NEVs have several energy chains. For example, different energy chains can be formed for fuel cell vehicles (FCVs) by using different technologies for hydrogen production, storage, transportation, and refueling. The different energy chains of FCVs, battery electric vehicles (BEVs), and internal combustion engine vehicles (ICEVs) compete with each other in the same way that FCVs, BEVs, and ICEVs compete in the market. Existing studies have focused on specific energy chains (e.g., Athanasopoulou et al., 2018; Qian et al., 2020; Abdelkareem et al., 2021; He et al., 2021) or a simple framework diagram composed of these energy chains (Watabe et al., 2020), and little attention has been paid to the overall picture of the energy system consisting of these energy chains. In terms of decarbonization, NEVs compete with ICEVs that use clean liquid fuels synthesized via the Fischer–Tropsch process by hydrogen from electrolysis and carbon dioxide (CO_2) captured from emission sources, and they could contribute to deep decarbonization in the transportation sector. As a result, a systematic framework for these energy chains is required, and research in this area could be beneficial to decision-makers who perform overall planning and industry actors who plan to invest in energy chains related to NEVs or ICEVs using clean liquid fuels.

Regardless of whether NEVs are BEVs or FCVs, their diffusion is inextricably linked to the synchronous development of their supporting energy infrastructure. Taalbi and Nielsen (2021) discovered that the reason for failures of early BEV diffusion is that the energy infrastructure is relatively expensive, resulting in a shortage of BEVs relative to ICEVs and limiting the diffusion of BEVs. The costs of energy chains influence the development of NEVs' supporting energy infrastructure and thus play a crucial role in the diffusion of NEVs. Hence, investigating the costs of energy chains for the diffusion of NEVs is critical.

The life cycle cost (LCC) method is widely used to analyze the total costs incurred during the entire life cycle (from production to scrapping) of an equipment or system, and it has become a vital tool for project cost analysis. Lagaros et al. (2015) developed an LCC model that includes limit state dependence and LCC for evaluating wind farms. Basing on the concept of LCC, Gan et al. (2017) proposed to coordinate the process of decision-making and reliability assessment for solving a bi-level probabilistic transmission optimization problem. To address the problem of transitioning to clean energy transportation services, Comello et al. (2021) developed a time-driven LCC model for mobility services. However, most existing studies on the LCC of new energies focused only on a single project (i.e., a single technology in an energy chain) rather than the entire energy chain. For example, the entire life cycle of a BEV spans the entire well-to-wheel process, including well-to-pump and pump-to-wheel (Khan et al., 2019). The raw material supply, production, transmission, distribution, sale, use, storage, and recovery of electric power are closely related to the entire life cycle of a BEV. Levelized cost analysis based on LCC could facilitate cost comparisons between different energy chains, and it has already been applied to research on electricity generation (Fan et al., 2019), hydrogen production (Fan et al., 2022), and fuel production (Shirazi et al., 2019).

Meanwhile, the costs of new technologies tend to decrease with the accumulation of people's experience in and knowledge of the technology, and this phenomenon is known as the technological learning effect (Arrow, 1962; Arthur, 1989). With the technological learning effect, the cost of a new technology is expected to decrease, allowing the technology to be increasingly adopted and permitting further technological learning; as a result, the technology becomes widespread (Rout et al., 2009). Technological learning is regarded as an endogenous driving force for the diffusion of NEVs (e.g., Schwoon, 2007). With regard to the technologies in NEVs' energy chains, Kavlak et al. (2018) discovered that in the last 40 years, the cost of photovoltaic modules had decreased rapidly due to technological learning, thereby lowering the cost of electricity generation. Lane et al. (2021) reported that the high learning rate of electrolyzers, combined with the long-term trend of declining renewable electricity prices, leads to equal shares for new installations by the mid-term and eventually to electrolyzers having the dominant share of new facilities. Zhou et al. (2018) estimated economic parameters in the research on coal-to-liquids for ICEVs and investigated potential future cost changes. Some researchers studied the learning effect of NEVs and the life cycle emissions associated with the diffusion of NEVs (e.g., Shafiei et al., 2019; Watabe et al., 2020). However, little work has been conducted to analyze the LCCs of different energy chains associated with different NEVs while considering various technological learning rates, particularly for the energy chains of NEVs in China, the world's largest NEV market.

Compared with previous studies, the current research provides the following primary contributions: (1) development of a systematic framework with various NEV energy chains, thus providing a panoramic picture of the most potential energy chains, including BEVs, FCVs, ICEVs, electricity generation, electricity transmission, charging station, hydrogen production, hydrogen transportation, hydrogen refueling stations, power-to-liquid fuel, fuel transportation, refueling stations, and other technologies; (2) analysis of how technological learning affects the LCCs of three typical energy chains in China on the basis of the systematic framework; and (3) provision of policy recommendations on developing energy chains for promoting the diffusion of NEVs. The systematic framework developed in this study can also serve as a starting point for future work on system optimization and simulation for the systematic diffusion of NEVs, and the method used in this study to estimate the levelized costs of the three focus energy chains can be employed to estimate the cost of other potential energy chains in the future.

The remainder of the paper is structured as follows. The models and data used in this study are introduced in Section 2. Section 3 presents the levelized costs of the three focus energy chains from well-to-pump and well-to-wheel. Section 4 discusses the findings, and Section 5 concludes this study by providing policy recommendations.

2 Model and data

2.1 Systematic framework with various carbon-neutral energy chains of vehicles

Figure 1 depicts the framework of an energy system showing various demands for society's energy service and various natural resources. Demands and natural resources are linked by various energy chains, which are chains of different energy technologies. This framework is used by many system optimization models in determining the best dynamic technology combinations to meet various constraints, such as demands and emission targets, at the lowest cost (e.g., Gambhir et al., 2013; Victor et al., 2014; Zhang et al., 2017). This framework is also used in the present study.

At present, BEVs are the most common NEVs in use (although plug-in hybrid vehicles have been widely used, they are a transitional form between BEVs and ICEVs; therefore, plug-in hybrid vehicles are not considered in this study). The diffusion of BEVs increases the load on the electricity grid. Although BEVs have zero emission when driven, if the electricity is generated from fossil fuels, the energy chain emissions may not be reduced. Only when the electricity is generated using renewable energy (wind power, hydropower, solar energy, etc.) or carbon capture, utilization, and storage (CCUS) can BEV diffusion truly aid in carbon reduction (Das et al., 2020). FCVs are expected to be another alternative, particularly in logistics and freight transportation (İnci et al., 2021). The ability of FCVs to contribute to deep decarburization in the transportation sector is highly dependent on how hydrogen is produced (Karayel et al., 2021). In short, the energy-saving and emission reduction potentials of NEVs depend on their energy chains.

The integration of various energy chains of NEVs can improve the energy system's supply-demand balance and increase economic benefits. For example, surplus power generated during peak periods of renewable energy generation can be used to produce hydrogen, which can then be utilized as the energy source for FCVs or to generate electricity during peak periods of electricity consumption. The hydrogen produced can also be combined with CO_2 to produce liquid fuel (Fischer–Tropsch reaction), which can be employed in conventional ICEVs (Atsbha et al., 2021; Schäppi et al., 2022). Thus, integrating different energy chains can aid in the absorption of redundant photovoltaic and wind power, resulting in a balanced load of the electricity grid and additional economic and environmental benefits (Koohi-Fayegh and Rosen, 2020). In addition to BEVs and FCVs, the carbon-neutral energy chains of ICEVs, namely, ICEVs using clean liquid fuel, are also considered in this study.

Figure 2 presents our systematic framework model of energy chains of BEVs, FCVs, and ICEVs using clean liquid fuel. It was developed based on the systematic energy framework in Fig. 1.

Our systematic framework model includes two categories of energy chains for BEVs, with the main distinction being where the electricity is generated. In the first category, electricity is generated at the resource side and then transmitted to the consumer side to charge BEVs. The second category generates electricity at the consumer side. The fossil fuel required for power generation (e.g., coal and natural gas) is exploited and then transported to the consumer side to generate electricity for charging BEVs.

The energy chains of FCVs, same as the energy chains of BEVs, are divided into two categories. In the first category, hydrogen is produced at the resource side by electricity (or natural gas) and then transported to the consumer side to refuel FCVs. In the second category, electricity or natural gas is produced or exploited at the resource side before being transmitted to the consumer side to produce hydrogen for refueling FCVs.

The energy chains of ICEVs that use clean liquid fuel are also divided into two categories, with the difference being where the fuel is produced. In the first category, clean liquid fuel is produced at the resource side by combining hydrogen generated by renewable energy and CO_2 captured from the air, fossil fuel combustion, or

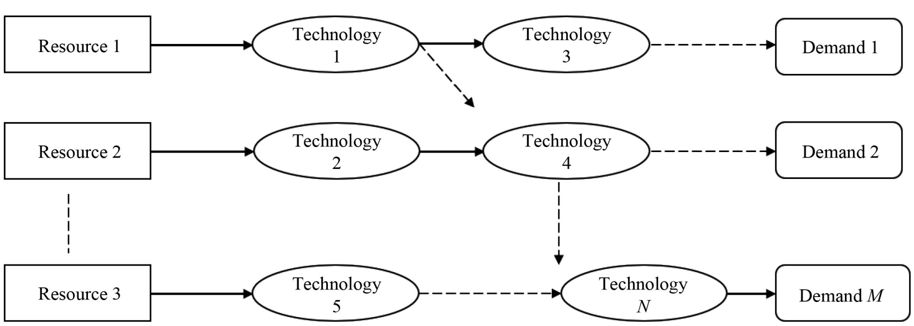


Fig. 1 Framework of an energy system.

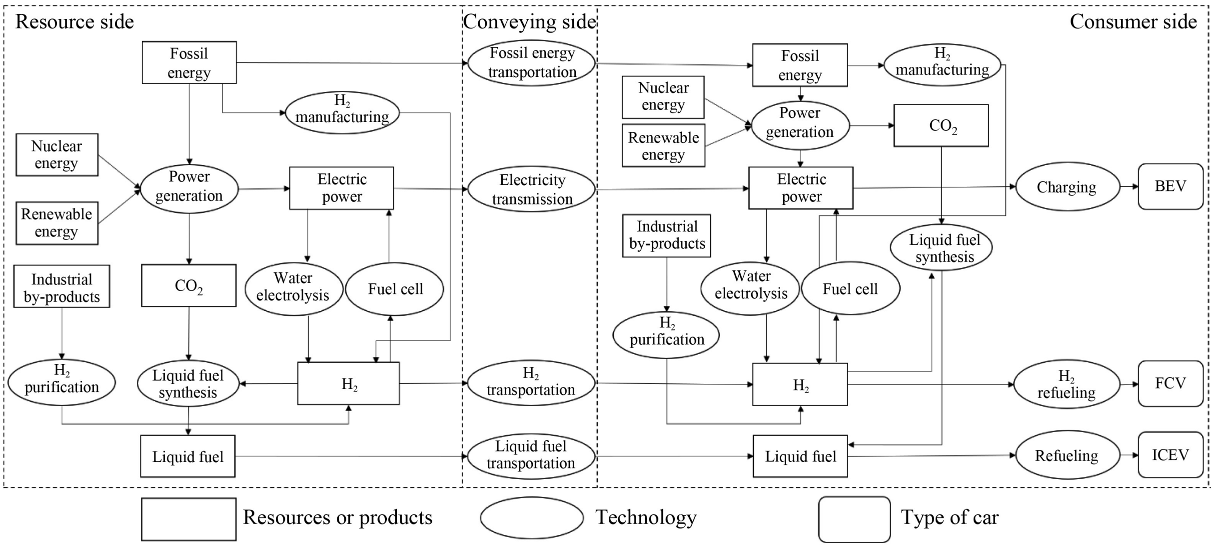


Fig. 2 Systematic framework of carbon-neutral energy chains for various vehicles.

other sources; the clean liquid fuel is then transported to the consumer side to refuel ICEVs. In the second category, clean liquid fuel is produced at the consumer side by using hydrogen generated by renewable energy and the captured CO_2. The clean liquid fuel is then directly used to refuel ICEVs.

The following shows descriptions of the main technologies considered in our systematic framework model.

- Coal power (supercritical, ultra-supercritical, etc.), hydropower, photovoltaic, wind power, nuclear power, biomass power generation, geothermal power generation, and other technologies are used to generate electricity. Flexible direct current/alternating current (DC/AC), high-voltage DC/AC, ultrahigh-voltage DC/AC, superconductivity, frequency division transmission, and other transmission technologies are among those available. Charging technologies include AC slow charging in the home, DC fast charging piles, power exchange, wireless charging, and mobile charging.
- Hydrogen production technologies include hydrogen production from fossil fuels (natural gas and coal), hydrogen production from industrial byproducts (chlor-alkali and coke oven gas byproducts), hydrogen production from biomass, and hydrogen production from power generation and water electrolysis. Gas-hydrogen trailers, gas-hydrogen pipelines, liquid-hydrogen tank cars, liquid organic matter, liquid ammonia, and other hydrogen transportation technologies are available. Different pressures, such as 35 MPa and 70 MPa, are considered by hydrogen refueling technologies.
- The fossil energy and liquid fuel transportation technologies include road or railway coal transportation, pipeline natural gas transportation, pipeline oil transportation, and tanker transportation.

2.2 Model for estimating levelized costs

An energy chain comprises various projects. A project in this context refers to the implementation of the technology depicted in Fig. 2. Wind power generation, for example, is an energy chain technology; the project of this technology is the establishment and use of a wind farm. The costs of various projects are dynamic, based on different learning curves. These complexities and dynamics are reflected in our work estimating an energy chain's LCC. When calculating the LCC of an energy chain, the costs of all components are discounted (considering the time value of money) and accumulated, and taxes are factored in.

The LCC of an energy chain project is divided into five stages (Heralova, 2017), as shown in Fig. 3. These stages are decision-making, design, implementation, operation and maintenance, and scrap recovery.

With the five stages described in Fig. 3, the following LCC estimation model is used in our analysis:

$$LCC = C_{\mathrm{i}} + \sum_{n=1}^{N} \frac{C_{\mathrm{o}}^{n} + R_{\mathrm{v}}^{n} + R_{\mathrm{s}}^{n} + R_{\mathrm{i}}^{n}}{(1+r)^{n}} - \frac{V_{\mathrm{r}}}{(1+r)^{N}}, \quad (1)$$

where C_{i} denotes the initial investment cost of establishing the facilities and C_{o}^{n} denotes the operation cost of the project in the nth year. R_{v}^{n}, R_{s}^{n}, and R_{i}^{n} denote the value-added tax, sales tax and surcharges, and income tax in the nth year, respectively. V_{r} denotes the salvage value of the project. N denotes the total life cycle of the project, and r denotes the discount rate.

The levelized costs of electricity, hydrogen, and fuel (abbreviated as *LCOE*, *LCOH*, and *LCOF*, respectively) are shown in Eq. (2) with *LCOE* as an example:

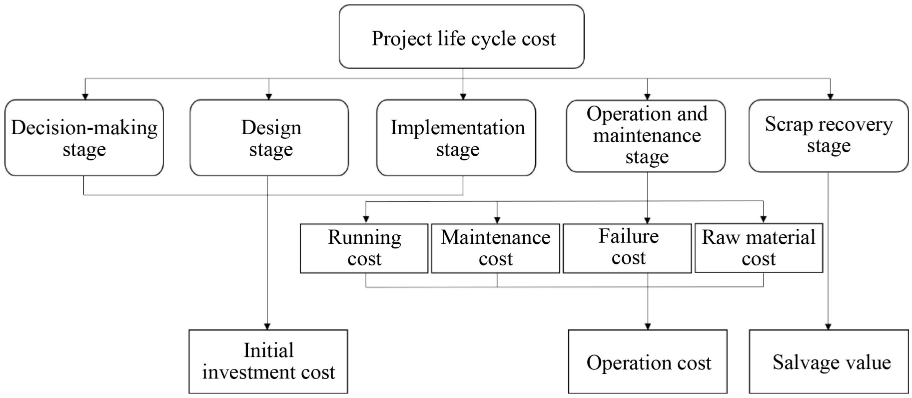


Fig. 3 Components of a life cycle cost.

$$LCOE = \frac{LCC}{\sum_{n=1}^{N} A_n (1+r)^{-n}}, \tag{2}$$

where A_n denotes the annual output of electricity. *LCOH* and *LCOF* are calculated in the same way as *LCOE*.

The initial investment cost, C_i in Eq. (1), is the cost at the beginning of the life cycle, and it refers to the total cost of a one-time investment before the project is put into use. C_i mainly consists of the equipment purchase cost (C_i1), equipment and installation cost (C_i2), construction cost (C_i3), and other costs (C_i4). C_i1 refers to the cost of all kinds of equipment used in equipment transportation and the transit cost and incidental expenses of these equipment from the manufacturer to the site. C_i2 refers to the related costs incurred during equipment procurement and installation. C_i3 consists of related expenses incurred during the construction and production stage and related expenses for project services. C_i4 refers to various expenses other than the three above-mentioned expenses and mainly includes requisition of the construction site. Therefore, C_i can be calculated using Eq. (3):

$$C_\text{i} = C_\text{i1} + C_\text{i2} + C_\text{i3} + C_\text{i4}. \tag{3}$$

The operation cost (C_o^n) in Eq. (1) consists of running cost (C_r^n), maintenance cost (C_m^n), failure cost (C_f^n), and raw material cost (C_rm^n) in the *n*th year.

C_r^n refers to the sum of all expenses incurred during the operation of the project, and it mainly includes labor and energy consumption costs. Labor cost mainly includes the salaries, subsidies, and fees for training operators and the labor cost for other operators.

C_m^n refers to the sum of all costs incurred to ensure the normal operation of equipment or systems during project operation, and it mainly includes maintenance labor, equipment troubleshooting, and technical renovation costs. Different equipment has different maintenance costs. The cost structure of C_m^n is based on the comprehensive consideration of the initial investment cost (C_i), labor cost, material cost, insurance cost, and others. Therefore, C_m^n is calculated for the entire project.

C_f^n refers to the total loss incurred by failure during the operation of the project, and it includes the loss of production stoppage and maintenance cost.

In this study, C_rm^n refers to the cost of production and usage of the main raw materials.

C_o^n can be calculated as

$$C_\text{o}^n = C_\text{r}^n + C_\text{m}^n + C_\text{f}^n + C_\text{rm}^n. \tag{4}$$

V_r in Eq. (1) denotes the salvage value of a project at the retirement stage, and it mainly includes cleaning expenses, environmental restoration cost, and asset reuse cost. The revenue recovered excludes costs at the time of retirement, and the result is generally positive. V_r can be calculated as

$$V_\text{r} = C_\text{i} \times r_\text{v}, \tag{5}$$

where r_v denotes the salvage value rate.

In this study, different projects with different energy chains are given different technological learning rates from existing literature, and the dynamics of the fixed costs (including C_i and the fixed part of C_o^n) is reflected in the widely used learning curve presented in Eq. (6). The technological learning effect is reflected by the accumulation of the outputs of different projects.

$$y = ax^{-b}, \tag{6}$$

where y denotes the direct cost of constructing the xth project, a denotes the cost of constructing the first project, x denotes the number of construction projects, and b denotes the learning efficiency. Thus, the technological learning rate (LR) is $(1-2^{-b})$, indicating that the percentage of direct cost decreases when the amount of construction doubles.

2.3 Data

With the goal of achieving carbon neutrality, this study focused on estimating the levelized costs of three typical (and possibly the most promising) carbon-neutral energy chains in China included in the systematic framework shown in Fig. 2. The three carbon-neutral energy chains primarily refer to wind power, hydrogen production, and clean fuel production, and relevant data on the energy chains of BEVs, FCVs, and IECVs were obtained from existing literature and statistical yearbooks.

In our analysis, the US dollar was converted into RMB at a rate of 7.00, r was set to 5% following Newell and Pizer (2004), the tax rate of R_v^n was set to 9% following the Provisional Regulations of the People's Republic of China on Value-Added Tax, the value of R_s^n was set to 8% of R_v^n following the Provisional Regulations of the People's Republic of China on Urban Maintenance and Construction Tax, and R_i^n was levied at 25% of the project profits following the Enterprise Income Tax Law of the People's Republic of China.

2.3.1 Focus energy chain of BEVs

The focus energy chain of BEVs is based on renewable energy power generation, which is as follows: electricity generation with wind power plant (WPP) at the resource side → electricity transmission through the electricity transmission system (ETS) → BEV charging through the charging station (CS) at the consumer side.

The costs of WPP and CS are reduced in this energy chain as a result of the technological learning effect. ETS is assumed to be a mature technology with no technological learning effect. Table 1 shows the specific parameters of BEV's energy chain.

2.3.2 Focus energy chain of FCVs

In our techno–economic analysis, the focus energy chain of FCVs is based on renewable energy power generation as follows: electricity generation through WPP at the resource side → hydrogen production through the hydrogen production system (HPS) at the resource side → hydrogen transportation through the hydrogen transportation system (HTS) → FCV refueling hydrogen through the hydrogen refueling station (HRS) at the consumer side.

Wind power generation is used in this energy chain for water electrolysis to produce hydrogen, and alkaline electrolysis is selected as the hydrogen production technology. The tank truck is chosen as the hydrogen transportation

Table 1 Parameters of the BEV's energy chain

Item			WPP	ETS	CS
Life cycle			20 year	/	10 year
Scale			400 MW	/	38 sets of 120 kW DC fast chargers
Output/Service quantity			14.26 million kWh/year	/	500 vehicles/day (11500 kWh/day)
Electricity-related cost/tariff			/	5% transmission loss	Retail electricity price
Feed-in tariff/selling price			0.56 yuan/kWh	7% gross profit rate	1.6745 yuan/kWh [a)]
Grid upgrading cost			/	12% [b)]	/
C_i	C_{i1}		$272.80x^{-b1}$ million yuan	/	$0.55x^{-b2}$ million yuan
	C_{i2}		$1692.85x^{-b1}$ million yuan	/	$3.00x^{-b2}$ million yuan
	C_{i3}		$216.25x^{-b1}$ million yuan	/	$2.80x^{-b2}$ million yuan
	C_{i4}		$210.90x^{-b1}$ million yuan	/	$0.25x^{-b2}$ million yuan
C_o^n	C_r^n	Labor cost	0.80 million yuan/year	/	0.13 million yuan/year
		Energy consumption & other costs	0 year: 0 million yuan/year [c)]	/	0–10 year: $5\%C_{i2}$/year
			1–11 year: 8 million yuan/year	/	
			12–16 year: 10.5 million yuan/year	/	
			17–21 year: 17.5 million yuan/year	/	
	C_m^n		0 year: 0 million yuan/year	/	0–10 year: $6\%C_{i2} * (1+5\%)^n$/year [d)]
			1–11 year: $0.5\%C_{i2}$/year	/	
			12–16 year: $1.0\%C_{i2}$/year	/	
			17–21 year: $1.5\%C_{i2}$/year	/	
	C_f^n		$10\%C_{i2}$	/	$10\%C_{i2}$
V_r			$5\%C_i$	/	$5\%C_i$

Notes: a) Electricity selling price includes electricity price (0.8745 yuan/kWh) and service charge (0.8 yuan/kWh); b) With the widespread adoption of BEVs, it is necessary to upgrade the grid (Jenn and Highleyman, 2022), and the cost of upgrading the grid for BEVs was set to 12% of the total cost of its ETS (Sahoo et al., 2019) in our study; c) The first year is the construction period (if one is required), same for Tables 2 and 3; d) It accounts for 6% of C_{i2} in the first year and will increase by 5% each year thereafter.

technology. The energy consumed in the production of liquid hydrogen is high, and evaporation loss occurs in the storage and transportation of liquid hydrogen, resulting in a high cost. However, the transportation capacity of liquid hydrogen is more than 10 times that of a gas-hydrogen trailer, which greatly improves the transportation efficiency and makes it suitable for large-scale, long-distance transportation. As a result, liquid hydrogen transportation is viewed as the future trend, with the cost primarily derived from hydrogen liquefaction (Wulf and Kaltschmitt, 2012). Table 2 shows the specific parameters of this energy chain.

2.3.3 Focus energy chain of ICEVs using clean liquid fuel

The focus energy chain of ICEVs using clean liquid fuel is based on renewable energy power generation as follows: electricity generation through WPP at the resource side → hydrogen production through HPS at the resource side → hydrogen and CO_2 are synthesized into liquid fuel through the Fischer–Tropsch synthesis plant (FSP) at the resource side → liquid fuel transportation through the fuel transportation system (FTS) → ICEV refueling through the refueling station (RS) at the consumer side.

The liquid fuel in this energy chain is obtained from the reaction between CO_2 and hydrogen via the Fischer–Tropsch process (Wei et al., 2017). The costs of FSP and RS are assumed to decrease with technological learning effect. FTS is regarded as a mature technology with no technological learning effect. The specific parameters of this energy chain are shown in Table 3.

2.3.4 Technological learning rates

Table 4 lists the LR and corresponding b value of the technologies that have learning potential, which were obtained from existing literature (listed in the last column).

Table 2 Parameters of the FCV's energy chain

Item			HPS	HTS a)	HRS
Life cycle			20 year	10 year	10 year
Scale			10 MW	/	/
Output/Service quantity			1300 kg/day	4.3 t	500 kg/day
Hydrogen selling price			40 yuan/kg	20% gross profit rate	65 yuan/kg
Hydrogen use price			/	Calculated by the cost of HPS	Calculated by the cost of HTS
Electricity use price			Calculated by the cost of WPP	Calculated by the cost of WPP	Retail electricity price
Electricity consumption			80000 kWh/day	11 kWh/kg (liquefaction of hydrogen) b)	/
Water cost			10000 yuan/year	/	/
Running time			365 day/year	4500 h/year c)	365 day/year
C_i	C_{i1}		$3.90x^{-b3}$ million yuan	0.45 million yuan	$2.00x^{-b4}$ million yuan
	C_{i2}		$25.00x^{-b3}$ million yuan		$10.00x^{-b4}$ million yuan
	C_{i3}		$9.50x^{-b3}$ million yuan		$3.00x^{-b4}$ million yuan
	C_{i4}		$5.02x^{-b3}$ million yuan		$1.00x^{-b4}$ million yuan
C_o^n	C_r^n	Labor cost	0.21 million yuan/year	0.15 million yuan/year	0.20 million yuan/year
		Energy consumption & other costs	0 year: 0 million yuan/year	Fuel cost: 1.5 yuan/km	0–10 year: $5\%C_{i2}$/year
			1–11 year: 0.29 million yuan/year	Road toll: 0.7 yuan/km	
			12–16 year: 0.38 million yuan/year		
			17–21 year: 0.64 million yuan/year		
	C_m^n		0 year: 0 million yuan/year	Insurance cost: 0.01 million yuan/year	0–10 year: $6\%C_{i2} * (1+5\%)^n$/year
			1–11 year: $0.5\%C_{i2}$/year	Maintenance cost: 0.2 yuan/km	
			12–16 year: $1.0\%C_{i2}$/year		
			17–21 year: $1.5\%C_{i2}$/year		
	C_f^n		$10\%C_{i2}$	$10\%C_{i2}$	$10\%C_{i2}$
V_r			$5\%C_i$	$5\%C_i$	$5\%C_i$

Notes: a) The HTS data use a tank truck as an example; b) The liquefaction loss rate is set to 0.5%. The average hourly loss caused by boiling liquid hydrogen during the transportation is 0.01% (Sinigaglia et al., 2017); c) It takes approximately 6.5 h to load and offload the tank truck. The transportation distance is set to 500 km, and the vehicle speed is set to 50 km/h. To summarize, the transportation times for liquid hydrogen liquefied on the resource side and liquid hydrogen transported on the consumer side can be calculated.

Table 3 Parameters of the ICEV's energy chain

Item			FSP [a]	FTS	RS
Life cycle			20 year	10 year	10 year
Output/Service quantity			50000 t/year	18 t	1900 t/year
Fuel selling price			20% gross profit rate	20% gross profit rate	15% gross profit rate
Hydrogen use price			Calculated by the cost of HPS	/	Calculated by the cost of FTS
Electricity use price			Calculated by the cost of WPP	/	Retail electricity price
Electricity consumption			800 kWh/t	/	/
Carbon cost			S [b]	/	/
Running time			365 day/year	4500 h/year [c]	365 day/year
C_i	C_{i1}		$15.00x^{-b5}$ million yuan	0.25 million yuan	$0.10x^{-b6}$ million yuan
	C_{i2}		$73.00x^{-b5}$ million yuan		$0.15x^{-b6}$ million yuan
	C_{i3}		$22.00x^{-b5}$ million yuan		$3.10x^{-b6}$ million yuan
	C_{i4}		$6.00x^{-b5}$ million yuan		$0.50x^{-b6}$ million yuan
C_o^n	C_r^n	Labor cost	110 yuan/t	0.15 million yuan/year	0.60 million yuan/year
		Energy consumption & other costs	0 year: 0 million yuan/year	Fuel cost: 1.5 yuan/km	0–10 year: $5\%C_{i2}$/year
			1–21 year: $5\%C_{i2}$/year	Road toll: 0.7 yuan/km	
	C_m^n		0 year: 0 million yuan/year	Insurance cost: 0.01 million yuan/year	0–10 year: $6\%C_{i2}*(1+5\%)^n$/year
			1–11 year: $0.5\%C_{i2}$/year	Maintenance cost: 0.2 yuan/km	
			12–16 year: $1.0\%C_{i2}$/year		
			17–21 year: $1.5\%C_{i2}$/year		
	C_f^n		$10\%C_{i2}$	$10\%C_{i2}$	$10\%C_{i2}$
V_r			$5\%C_i$	$5\%C_i$	$5\%C_i$

Notes: a) The H_2/CO_2 ratio of the feed gas is set to 1, and the hydrocarbon ratio of the gasoline fraction is set to 0.6. In the Na–Fe_3O_4/HZSM-5(160) catalyst, the selectivity for gasoline fraction is 78%, and the CO_2 conversion rate is 22% (Wei et al., 2017). The cost of product upgrading is set to 10% of the total cost of the Fischer–Tropsch synthesis (Zhao et al., 2021b). To summarize, the amount of hydrogen and CO_2 can be calculated; b) The cost of using CO_2 in this study could be different. Using CO_2 could be profitable if captured CO_2 is used by other economic entities. The profit from using CO_2 is set to 0–40 yuan/t in this case. When CO_2 is captured by the project, the CCUS cost is set to 0–240 yuan/t (Hu et al., 2021). Thus, the carbon cost (denoted as S) ranges from −40 to +240 yuan/t, where the negative cost denotes the profit from CO_2 utilization and the positive cost denotes the cost of CCUS implementation; c) It takes approximately 4 h to load and offload the oil tank car at a time. The transportation distance is set to 500 km, and the vehicle speed is set to 50 km/h. To summarize, the transportation time and total transportation volume of liquid fuel can be calculated.

Table 4 Learning rate and b value of each technology

Technology	The selected value of LR	Value of b	Based on
Wind power plant (WPP)	12%	$b_1 = 0.1844$	Rubin et al. (2015)
Charging station (CS)	22%	$b_2 = 0.3585$	Estimated, see Borlaug et al. (2020)
Hydrogen production system (HPS)	20%	$b_3 = 0.3219$	Schoots et al. (2008)
Hydrogen refueling system (HRS)	18%	$b_4 = 0.2863$	Anandarajah et al. (2013)
Fischer–Tropsch synthesis plant (FSP)	10%	$b_5 = 0.1520$	Estimated, see Detz et al. (2018)
Refueling station (RS)	4%	$b_6 = 0.0589$	Kahouli-Brahmi (2008)

3 Results

3.1 LCC of relevant projects and levelized costs of the three energy chains

Table 5 shows the current *LCC*, *LCOE*, *LCOH*, and *LCOF* of each project (i.e., application of different technologies), with WPP, HPS, and FSP representing the consumer side costs and CS, HRS, and RS representing the resource side costs. The C_o in Table 5 denotes the total operation cost, that is, $C_o = \sum_{n=1}^{N} \frac{C_o^n}{(1+r)^n}$. R_v, R_s, and R_i denote the total value-added tax, sales tax and surcharges, and income tax, respectively.

The dynamics of *LCC*, *LCOE*, *LCOH*, and *LCOF* are also estimated using the LRs in Table 4, as shown in Fig. 4, where *LCOE*, *LCOH*, and *LCOF* are unified into low heating values (the calorific values of electricity,

Table 5 Life cycle cost and levelized costs of each project

Item	WPP	ETS	CS
C_i (million yuan)	$+2392.80x^{-b1}$	/	$+6.60x^{-b2}$
C_o (million yuan)	$+142.93+332.53x^{-b1}$	/	$+16.50+9.20x^{-b1}+3.32x^{-b2}$
V_r (million yuan)	$-45.09x^{-b1}$	/	$-0.21x^{-b2}$
R_v (million yuan)	+895.91	/	$+3.93-0.73x^{-b1}$
R_s (million yuan)	+71.66	/	$+0.31-0.06x^{-b1}$
R_i (million yuan)	$+2211.08-670.05x^{-b1}$	/	$+9.52-1.83x^{-b1}-2.43x^{-b2}$
LCC (million yuan)	$+3321.57+2010.16x^{-b1}$	/	$+30.26+6.58x^{-b1}+7.28x^{-b2}$
LCOE (yuan/kWh)	$+0.19+0.11x^{-b1}$	$+0.45+0.27x^{-b1}$	$+0.89+0.19x^{-b1}+0.21x^{-b2}$
Unify units (yuan/10^5 kJ)	$+5.19+3.14x^{-b1}$	/	$+24.70+5.37x^{-b1}+5.94x^{-b2}$
Item	HPS	HTS	HRS
C_i (million yuan)	$+43.42x^{-b3}$	+0.45	$+16.00x^{-b4}$
C_o (million yuan)	$+77.11+41.15x^{-b1}+4.91\ x^{-b3}$	$+147.24+35.44x^{-b1}+35.86x^{-b3}$	$+40.01+8.87x^{-b1}+9.56x^{-b3}+11.05x^{-b4}$
V_r (million yuan)	$-0.82x^{-b3}$	−0.01	$-0.52x^{-b4}$
R_v (million yuan)	$+15.16-3.70x^{-b1}$	$+2.18+0.47x^{-b1}+0.60x^{-b3}$	$+5.32-0.80x^{-b1}-0.86x^{-b3}$
R_s (million yuan)	$+1.21-0.30x^{-b1}$	$+0.17+0.04x^{-b1}+0.05x^{-b3}$	$+0.42-0.06x^{-b1}-0.07x^{-b3}$
R_i (million yuan)	$+35.76-9.29x^{-b1}-11.88x^{-b3}$	$+1.06-0.67x^{-b1}+1.51x^{-b3}$	$+12.61-2.00x^{-b1}-2.16x^{-b3}-6.63x^{-b4}$
LCC (million yuan)	$+129.24+27.86x^{-b1}+35.63x^{-b3}$	$+151.09+35.27x^{-b1}+38.01x^{-b3}$	$+58.35+6.01x^{-b1}+6.47x^{-b3}+19.90x^{-b4}$
LCOH (yuan/kg)	$+21.86+4.71x^{-b1}+6.03x^{-b3}$	$+25.69+6.00x^{-b1}+6.46x^{-b3}$	$+39.44+4.06x^{-b1}+4.38x^{-b3}+13.45x^{-b4}$
Unify units (yuan/10^5 kJ)	$+15.35+3.31x^{-b1}+4.23x^{-b3}$	/	$+27.70+2.85x^{-b1}+3.07x^{-b3}+9.45x^{-b4}$
Item	FSP	FTS	RS
C_i (million yuan)	$+116.00x^{-b5}$	+0.25	$+3.85x^{-b6}$
C_o (million yuan)	$+2337.93+515.40x^{-b1}+587.01\ x^{-b3}+59.83x^{-b5}+2.57S$	$+146.49+25.98x^{-b1}+29.59x^{-b3}+8.47x^{-b5}+0.13S$	$+88.54+15.57x^{-b1}+17.74x^{-b3}+5.08x^{-b5}+4.40x^{-b6}+0.08S$
V_r (million yuan)	$-2.19x^{-b5}$	−0.01	$-0.12x^{-b6}$
R_v (million yuan)	$+40.00+9.28x^{-b1}+10.57x^{-b3}+0.05S$	$+2.09+0.47x^{-b1}+0.53x^{-b3}+0.15x^{-b5}+0.002S$	$+0.11+0.02x^{-b1}+0.02x^{-b3}$
R_s (million yuan)	$+3.20+0.74x^{-b1}+0.84x^{-b3}$	$+0.17+0.37x^{-b1}+0.43x^{-b3}+0.01x^{-b5}$	/
R_i (million yuan)	$+6.50+8.95x^{-b1}+10.19x^{-b3}+0.04S$	$-2.37+1.17x^{-b1}+1.34x^{-b3}+0.38x^{-b5}+0.01S$	$+0.61+0.58x^{-b1}+0.66x^{-b3}+0.19x^{-b5}-0.11x^{-b6}$
LCC (million yuan)	$+2647.41+591.63x^{-b1}+673.91\ x^{-b3}+192.93x^{-b5}+2.95S$	$+146.62+27.66x^{-b1}+31.51x^{-b3}+9.02x^{-b5}+0.14S$	$+89.26+16.17x^{-b1}+18.42x^{-b3}+5.27x^{-b5}+4.17x^{-b6}+0.09S$
LCOF (yuan/t)	$+4248.70+949.48x^{-b1}+1081.53x^{-b3}+309.63x^{-b5}+4.74S$	$+5358.32+1010.80x^{-b1}+1151.37x^{-b3}+329.63x^{-b5}+5.04S$	$+5794.36+1049.73x^{-b1}+1195.73x^{-b3}+342.33x^{-b5}+270.79x^{-b6}+5.24S$
Unify units (yuan/10^5 kJ)	$+9.66+2.16x^{-b1}+2.46x^{-b3}+0.70x^{-b5}+0.01S$	/	$+13.74+2.39x^{-b1}+2.72x^{-b3}+0.78x^{-b5}+0.05x^{-b6}+0.01S$

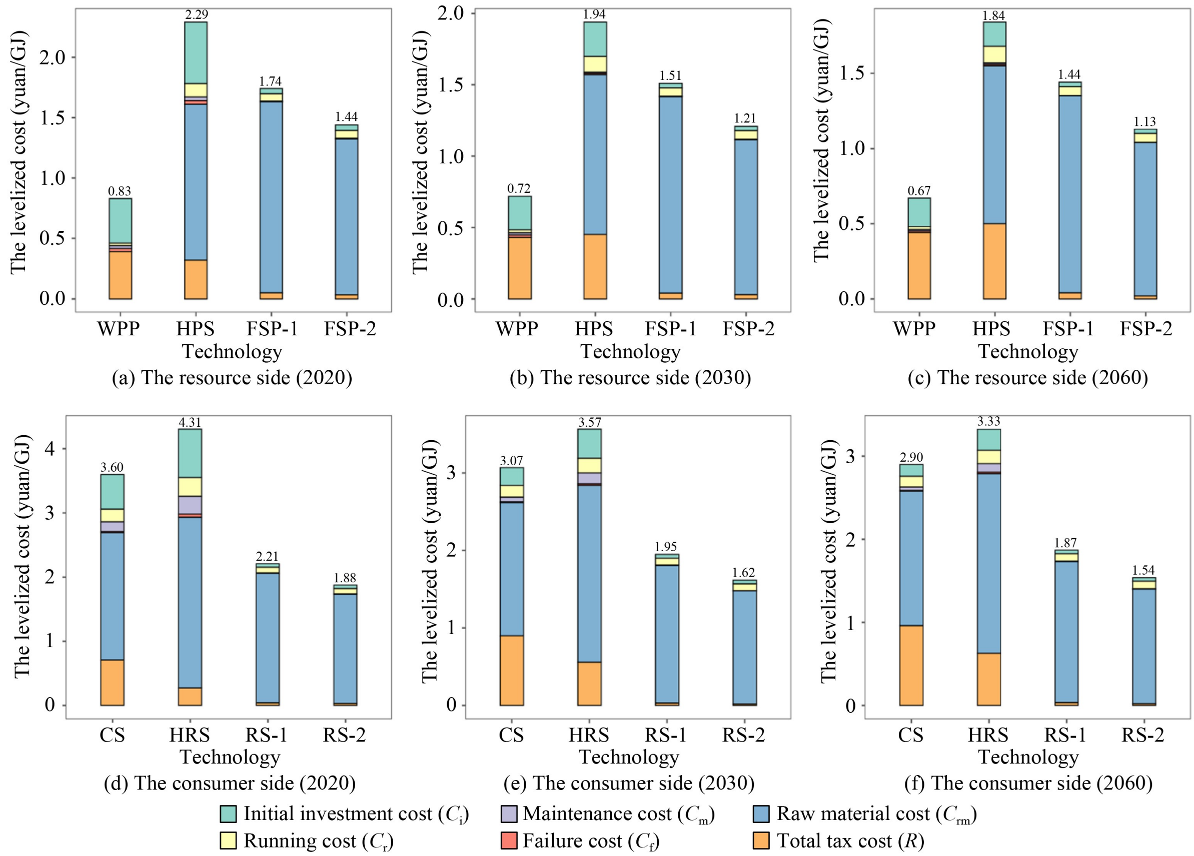


Fig. 4 Production cost of different technologies in different years (Notes: WPP is the electricity generation cost at the resource side, HPS is the hydrogen generation cost at the resource side, FSP-1 is the clean fuel generation cost at the resource side (S = +240), FSP-2 is the clean fuel generation cost at the resource side (S = −40); CS is the electricity generation cost at the consumer side, HRS is the hydrogen generation cost at the consumer side, RS-1 is the clean fuel generation cost at the consumer side (S = +240), and RS-2 is the clean fuel generation cost at the consumer side (S = −40)).

hydrogen, and clean fuel are 3600 kJ/kWh, 142351 kJ/kg, and 44000 kJ/kg, respectively), C_{rm} denotes the total raw material cost, that is, $C_{rm} = \sum_{n=1}^{N} \frac{C_{rm}^{n}}{(1+r)^{n}}$, and R is the sum of R_v, R_s, and R_i (i.e., $R = R_v + R_s + R_i$). At the resource side, *LCOE* in 2020, 2030, and 2060 is 0.83, 0.72, and 0.67 yuan/GJ, respectively, according to Fig. 4. With the technological learning effect, *LCOE* in 2030 and 2060 decreases by 13.25% and 19.28%, respectively, compared with that in 2020. In 2020, 2030, and 2060, *LCOH* is 2.29, 1.94, and 1.84 yuan/GJ, respectively. With the technological learning effect, *LCOH* decreases by 15.28% and 19.65% in 2030 and 2060, respectively, compared with that in 2020. In 2020, 2030, and 2060, *LCOF* is 1.44–1.74, 1.21–1.51, and 1.13–1.44 yuan/GJ, respectively. *LCOF* decreases by about 0.23 yuan/GJ from 2020 to 2030 and by about 0.08 yuan/GJ from 2030 to 2060 as a result of the technological learning effect.

Given that the source of electricity is renewable energy, *LCOE* excludes C_{rm}, and C_i and R account for a sizable proportion. The C_i of WPP gradually decreases with the learning effect (44.50%, 33.13%, and 27.69% in 2020, 2030, and 2060, respectively), whereas R gradually increases (46.66%, 59.19%, and 65.19% in 2020, 2030, and 2060, respectively). With regard to the *LCOH* of HPS, the proportion of C_i gradually declines (22.43%, 12.23%, and 8.51% in 2020, 2030, and 2060, respectively), but the proportion of C_{rm} (electricity and water) remains high (56.45%, 57.66%, and 57.89% in 2020, 2030 and 2060, respectively). C_{rm} (hydrogen, electricity, and CO_2) accounts for a sizable proportion of the *LCOF* of FSP. When the project captures the source of CO_2 (i.e., S = +240), C_{rm} accounts for more than 90% (90.69%, 91.20%, and 91.51% in 2020, 2030, and 2060, respectively), and when CO_2 utilization is profitable (i.e., S = −40), the proportion of C_{rm} decreases noticeably (74.13%, 72.12%, and 71.40% in 2020, 2030, and 2060, respectively).

At the consumer side (well-to-pump), the *LCOE* in 2020, 2030, and 2060 is 3.60, 3.07, and 2.90 yuan/GJ, respectively. With technological learning effects, the *LCOE* in 2030 and 2060 decreases by 14.72% and 19.44%, respectively, compared with that in 2020. In 2020, 2030, and 2060, *LCOH* is 4.31, 3.57, and

3.33 yuan/GJ, respectively. In 2030 and 2060, with the technological learning effect, *LCOH* decreases by 17.17% and 22.74%, respectively, compared with that in 2020. The *LCOF* in 2020, 2030, and 2060 is 1.88–2.21, 1.62–1.95, and 1.54–1.87 yuan/GJ, respectively. With the technological learning effect, *LCOF* decreases by about 0.26 yuan/GJ from 2020 to 2030, and it decreases by about 0.08 yuan/GJ from 2030 to 2060.

The main cost of CS is C_{rm} (electricity) (55.04%, 56.06%, and 55.79% in 2020, 2030, and 2060, respectively) and R (19.65%, 29.34%, and 33.18% in 2020, 2030, and 2060, respectively). The main cost of HRS is C_{rm} (hydrogen) (61.85%, 63.76%, and 64.83% in 2020, 2030, and 2060, respectively). For RS, the main cost is also C_{rm} (clean liquid fuel) when the source of CO_2 is captured by the project itself (i.e., S = +240), and C_{rm} accounts for more than 90% (91.35%, 91.10%, and 91.06% in 2020, 2030, and 2060, respectively). When CO_2 utilization in the upstream is profitable (i.e., S = −40), similar to the situation at the resource side, the proportion of C_{rm} decreases (77.11%, 74.98%, and 74.17% in 2020, 2030, and 2060, respectively).

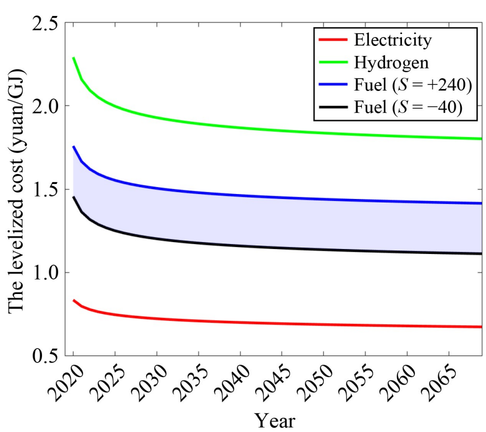
The technological learning effect is assumed to affect only fixed costs in our estimation. Thus, the R and C_{rm} of renewable energy electricity generation account for a relatively high proportion of the energy chain of BEVs. To reduce R, relevant policies and subsidies should be implemented while reducing the cost of C_{rm}, and a reasonable price should be set for electricity. Meanwhile, the cost of the energy chain of FCVs is affected by the cost of electricity generation because C_{rm} accounts for more than 50% of the total cost of the energy chain of FCVs. The cost of C_{rm} can be effectively reduced by lowering the cost of electricity generation and improving hydrogen production and transportation technology. In the energy chain of ICEVs, C_{rm} is affected by the cost of electricity generation and hydrogen production. Hydrogen production upgrading, electricity generation, and Fischer–Tropsch synthesis technology can help lower the cost of C_{rm}. Furthermore, the higher the profit is from using CO_2, the smaller the proportion of C_{rm} is in the levelized cost.

3.2 *LCOE*, *LCOH*, and *LCOF*

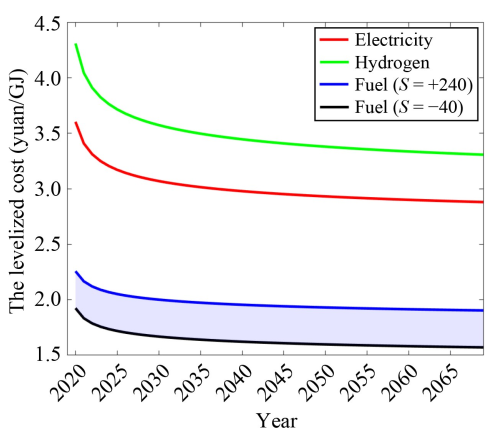
Figures 5(a) and 5(b) show the levelized costs (in low heating value) on the resource and consumer sides, respectively.

On the resource side, *LCOE* is the lowest among the three, and *LCOH* is the highest. The cost of clean fuel production is between those of electricity generation and hydrogen production because the Fischer–Tropsch synthesis technology considered in this study has high selectivity for the catalyzer, and a large amount of electricity is used for raw gas circulation to reduce the cost of hydrogen. The cost of hydrogen production shows the steepest downward trend over time due to technological LR (20%) of the fixed cost of hydrogen production. The cost of raw materials belonging to the variable cost also decreases with the learning of power generation technology. The cost structure of clean fuel production is similar to that of hydrogen production, with raw materials accounting for the majority of the cost. *LCOF*'s downward trend is primarily due to the low electricity and hydrogen prices.

On the consumer side, through the respective transmission/transportation technology, *LCOE* still increases to about four times that on the resource side over time. This occurrence is due to the fact that the electricity price in China in 2020 was regulated and did not reflect the market value, whereas our estimate considers an electricity price that reflects the market value in 2060. This analysis of electricity prices is not comprehensive, and it may not fully reflect the downward trend of future electricity prices. *LCOH* always doubles from the resource side to the consumer side. To transport liquid hydrogen via



(a) Resource side



(b) Consumer side

Fig. 5 Dynamics of well-to-pump levelized costs.

trailers, hydrogen must be liquefied first. Liquid hydrogen evaporates during storage and transportation. This process requires a large amount of electricity, which is the main reason for the cost increase. *LCOF* does not increase considerably compared with the other energy sources due to the relatively mature technology of liquid fuel storage, transportation, and refueling stations; the technology allows liquid fuel to be transported from the resource side to the consumer side at a low cost.

The cost of each energy source has a greater potential for cost reduction on the consumer side than on the resource side. Notably, technological learning does not occur naturally over time and instead requires financial investment. Thus, improving consumer infrastructure is an efficient way to reduce costs.

Furthermore, the impact of carbon costs on economic performance should be assessed to achieve carbon neutrality. If utilizing CO_2 is profitable, the cost of Fischer–Tropsch synthesis can be considerably reduced (the blue and black lines in Fig. 5 are the upper and lower bounds of cost change, respectively). As a result, the advancement of CCUS technology and the formulation of reasonable carbon trading policies can help reduce *LCOF*.

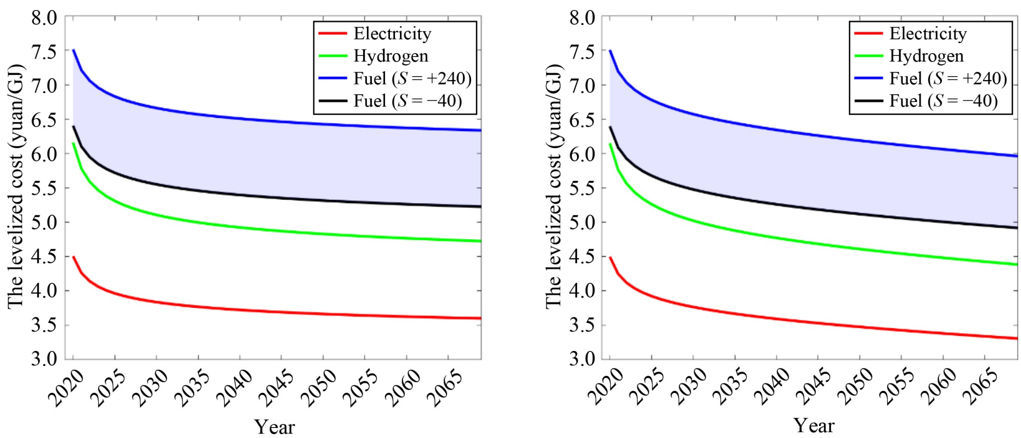
3.3 Energy efficiency of BEVs, FCVs, and ICEVs

The lowest heating values of the various energy chains were analyzed and compared in the previous section under the assumption that the fuel was completely burned, and the water vapor in its combustion products was in the gaseous state. However, the energy efficiency of various types of vehicles varies. In the following analysis, the energy efficiency of ICEVs, FCVs, and BEVs is assumed to be 30%, 70%, and 80%, respectively (Xiong et al., 2019) on the basis of the current average level of different technologies. According to this assumption (Fig. 6(a)), at the well-to-wheel stage, the cost of electricity in 2020, 2030, and 2060 is 4.50, 3.83, and 3.62 yuan/GJ, respectively; the cost of hydrogen in 2020, 2030, and 2060 is 6.15, 5.10, and 4.76 yuan/GJ, respectively; and the cost of clean fuel in 2020, 2030, and 2060 is 6.40–7.51, 5.55–6.66, and 5.26–6.37 yuan/GJ, respectively. In 2060, the energy chains' well-to-wheel levelized costs are expected to decrease by 19.56% for BEVs, 22.60% for FCVs, and 15.18% (S = +240) and 17.81% (S = −40) for ICEVs.

The energy chain of BEVs is the most economical in this scenario because of the high energy conversion efficiency of BEVs and the *LCOE* on the consumer side, and the well-to-wheel levelized cost of this energy chain is always low. Although *LCOH* is the highest on the consumer side, the energy conversion efficiency of FCVs is second only to that of BEVs, resulting in a lower well-to-wheel levelized cost of the energy chain of FCVs compared with that of ICEVs. The consumer-side *LCOF* is the lowest, but the energy conversion efficiency of ICEVs is only 30%, resulting in the highest well-to-wheel levelized cost of the energy chain of ICEVs. Even with a profit of 40 yuan/t of CO_2, the well-to-wheel levelized cost of ICEVs is slightly higher than that of FCVs.

The energy efficiency of BEVs, FCVs, and ICEVs can be gradually improved. Following Kosai et al. (2018)'s work, we assumed that the energy efficiency of BEVs, FCVs, and ICEVs will increase by 0.17%, 0.15%, and 0.12% per year, respectively. The well-to-wheel levelized costs of the energy chains will be reduced by 24.82% for BEVs, 27.12% for FCVs, and 19.25% (S = +240) and 21.76% (S = −40) for ICEVs in 2060 compared with those in 2020, as shown in Fig. 6(b).

According to the preceding analysis, the well-to-wheel levelized costs of the various energy chains can be reduced by the technological learning effect of the energy infrastructure and by improving vehicle energy efficiency. The policy implications of the findings are as follows. To achieve deep decarbonization in the transportation sector,



(a) No improvement in vehicle energy efficiency (b) With improvement in vehicle energy efficiency

Fig. 6 Dynamics of well-to-wheel levelized costs.

governments need to encourage investments in energy infrastructure through various measures (e.g., subsidies) to induce the technological learning effect. Moreover, governments need to gradually enhance regulations on vehicles' energy efficiency.

4 Discussion

4.1 Panoramic view of the energy chains of NEVs

Various technology combinations were reviewed in this study, and a panorama of the energy chains of NEVs was formed as a systematic framework (Fig. 2). The energy chains primarily included electricity generation, transmission, charging, hydrogen production, transportation, refueling, power-to-liquid fuel, fuel transportation, and refueling technologies.

Although the technologies on the consumer and resource sides are similar, regional climate, natural resources, economic development level, and infrastructure conditions influence the adoption of various technologies. In China, the resource is mostly concentrated in areas with large amounts of land and a small population (especially Northwest China), making them ideal for constructing large-scale power plants with economies of scale. Consumption is concentrated in areas with dense populations and good infrastructure (particularly in Southeast China). Hence, this research focused on renewable energy used for resource-side electricity generation, hydrogen production, and clean fuel production, all of which will eventually be used as energy sources for BEVs, FCVs, and ICEVs on the consumer side. The following shows the representative energy chains.

The energy chain of BEVs is as follows: wind power generation at the resource side → electricity transmission → charging at the consumer side.

The energy chain of FCVs is as follows: wind power generation at the resource side → hydrogen production at the resource side → hydrogen transportation → refueling hydrogen at the consumer side.

The energy chain of ICEVs is as follows: wind power generation at the resource side → hydrogen production at the resource side → hydrogen and CO_2 are synthesized into clean fuel (Fischer–Tropsch reaction) at the resource side → clean fuel transportation → refueling at the consumer side.

Beginning with renewable energy, the aforementioned energy chains provide the transmission process of each energy source from the resource side to the consumer side. This study has focused primarily on the techno–economic analysis of these energy chains. Other factors related to these energy chains, such as water consumption and environmental toxicity, should be investigated in future research.

4.2 Life cycle cost

The LCC model was used to calculate the levelized costs of representative energy chains, namely, *LCOE*, *LCOH*, and *LCOF*. In terms of well-to-pump levelized costs, the order from low to high was determined to be *LCOE*, *LCOF*, and *LCOH* on the resource side, and *LCOF*, *LCOE*, and *LCOH* on the consumer side. These findings are primarily the result of factors, such as the high cost of hydrogen transportation and refueling, regulated electricity prices, and mature liquid fuel transportation technology. Therefore, a market-based electricity price and the development of hydrogen energy technologies may be beneficial to the diffusion of BEVs and FCVs. In terms of well-to-wheel levelized costs, which are also affected by vehicle efficiency, the order from low to high was found to be *LCOE*, *LCOH*, and *LCOF*, indicating that vehicle energy efficiency is important. The technological learning effect is primarily responsible for lowering the fixed costs of energy infrastructure. Vehicle energy efficiency improvements can considerably reduce well-to-wheel levelized costs.

BEVs have the advantages of high energy conversion efficiency and low cost, with the goal of carbon neutrality being based on renewable energy for power generation. The disadvantages of BEVs include the fact that their widespread use will increase grid load, and BEVs do not work well for long-distance and heavy-cargo transportation. FCVs have the advantage of using the hydrogen produced by excess renewable energy generation during peak periods, and they may perform better than BEVs in long-distance and heavy-cargo transportation. The main disadvantage of FCVs is the high costs of hydrogen production, storage, transportation, and hydrogen refueling facilities. ICEVs that use clean liquid fuel have a similar advantage as FCVs in that they can use hydrogen produced by surplus electricity during the peak period of renewable energy generation and liquid fuel produced by the synthesis of hydrogen and CO_2. Another advantage of ICEVs that use clean liquid fuel is that the automobile engine does not need to be transformed, and the fuel supply can rely on existing gasoline stations, resulting in a minimal impact on automobile manufacturers and consumers. However, if ICEVs' energy efficiency is not improved considerably, BEVs and FCVs will become more cost-effective options in the future, particularly in scenarios with high carbon costs.

4.3 Different scenarios of technological learning

Historical evidence indicates that technological learning is uncertain and that this uncertainty follows a lognormal distribution (McDonald and Schrattenholzer, 2001). If the decision is based on a specific assumed value of LR (e.g., the mean of its lognormal distribution), the future investment may be misled. For example, if the technological LR is overestimated, the cost of technology investment will be underestimated and may potentially result in severe economic risks in the future. Thus, we performed calculations under various technological learning scenarios. The range of LRs was based on existing literature (Kahouli-Brahmi, 2008; Detz et al., 2018; Greene et al., 2020; Thomassen et al., 2020). Table 6 compares the changes in levelized costs under various scenarios of technological LRs to those in Subsection 3.1, which is considered the baseline scenario.

Table 6 shows that despite having different LRs, the *LCOE* of WPP and the *LCOH* of HPS have similar fluctuation ranges on the resource side. The *LCOF* of FSP is influenced by the LRs of electricity generation, hydrogen production, and itself. If the learning rates with the lowest values in Table 6 are compared with our calculation in Subsection 3.1, the *LCOF* of FSP will increase by about 6% and 7% in 2030 and 2060, respectively. The fixed costs of consumer facilities account for a small portion of the total cost. Hence, the fluctuation of levelized costs on the consumer side (CS, HRS, and RS) is primarily due to the resource side. In summary, the energy chain of ICEVs using clean fuel faces great risks due to the uncertainty of technological learning.

5 Conclusions and policy recommendations

This study developed a systematic framework that provides a panoramic view of the energy chains of NEVs starting from renewable energy. The framework is combined with various technologies to estimate the levelized costs of three representative energy chains of BEVs, FCVs, and ICEVs using clean liquid fuel. This research can be used as a starting point for an in-depth examination of diffusion of NEVs and the development of their supporting energy infrastructure in China. This study's levelized cost estimation method can also be adopted to estimate the levelized costs of other energy chains. Despite some limitations discussed at the end of this paper, we make the following policy recommendations based on the analysis presented in this paper.

- The energy chain of BEVs is the most cost-effective among the three representative energy chains, and policymakers are advised to encourage the establishment of energy infrastructures supporting BEVs in order to promote the diffusion of BEVs. Furthermore, developing and implementing a market-based electricity price policy could aid in the long-term diffusion of BEVs.
- In terms of the energy efficiency of the energy chains, FCVs are uneconomical compared with BEVs. However, hydrogen can be used to store the energy generated by "light and wind" that would otherwise be lost, and hydrogen production technology based on water electrolysis does not emit carbon. Water resources are the focus of consideration in hydrogen production by water electrolysis, while water resources in China are frequently mismatched with renewable electricity-producing areas, implying that policymakers should consider both water resources and electricity transmission. Low-cost hydrogen production technology, large-scale hydrogen storage and transportation technology, and low-cost and high-efficiency hydrogen utilization technology are the key research and development directions for the future hydrogen industry. Policymakers are advised to pay close attention to energy chains with high technological learning potential and to direct investment toward these energy chains to benefit from the economies of scale and technological learning.
- When Fischer–Tropsch synthesis of liquid fuel is based on green hydrogen and captured CO_2, it is also a carbon-neutral energy chain for ICEVs. This energy chain has the advantage of existing and mature fuel transportation and refueling technology and facilities. The benefit of using CO_2 and the energy efficiency of ICEVs are important factors in this energy chain. In the short and middle terms, policymakers are advised to gradually increase energy efficiency regulations, which will make this energy chain increasingly competitive.
- According to the systematic framework depicted in

Table 6 Technological learning rate ranges and levelized cost intervals of different technologies

Technology	Baseline learning rates (%)	Ranges of learning rates (%)	Fluctuation range of levelized costs in 2030 (%)	Fluctuation range of levelized costs in 2060 (%)
Wind power plant (WPP)	12	8–16	95.83–104.17	94.12–105.88
Charging station (CS)	22	18–26	96.74–103.26	96.55–104.14
Hydrogen production system (HPS)	20	15–21	97.94–104.12	97.81–104.92
Hydrogen refueling system (HRS)	18	12–24	96.08–105.60	95.80–106.91
Fischer–Tropsch synthesis plant (FSP) (S = −40)	10	4–16	98.35–106.61	97.35–107.96
Fischer–Tropsch synthesis plant (FSP) (S = +240)	10	4–16	98.68–105.30	98.60–106.29
Refueling station (RS) (S = −40)	4	2–5	99.38–106.79	99.35–107.79
Refueling station (RS) (S = +240)	4	2–5	99.49–106.15	99.47–106.42

Fig. 2, the energy chains for BEVs, FCVs, and ICEVs using clean fuel compete with each other, but they can also be complementary. Coordination of these energy chains, for example, could balance the load on electricity grids. Given that new technologies and their supporting infrastructure typically take a long time to mature and be adopted, ICEVs could remain dominant vehicles in the short and possibly middle terms. Furthermore, BEVs and FCVs may have different strengths and drawbacks when used for different purposes and in different climates. With these considerations, policymakers are advised to focus on improving all of these energy chains (at least the three representative ones) rather than focusing on just one and ignoring the others.

The first limitation of this study is that it focuses only on three representative energy chains rather than all of the energy chains in the systematic framework depicted in Fig. 2. The second limitation is that in the estimations, the interactions of different energy chains are not considered. For example, a wind power project could serve both hydrogenation production for FCVs or ICEVs and electricity production for BEVs; thus, to some extent, the fixed capital investment and the technological learning effect should be considered based on different energy chains. We intend to conduct a systematic analysis of the diffusion of NEVs and the development of their supporting energy infrastructure in China in the future by considering the competition and coordination among different energy chains and heterogeneous climates, development levels, and other variables. The above-mentioned limitations will be addressed in our future work.

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