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Linking Cost Decline and Demand Surge in the Hydrogen Market: A Case Study in China

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Abstract: Hydrogen is crucial in achieving global energy transition and carbon neutrality goals. Existing market estimates typically presume linear or exponential growth but fail to consider how market demand responds to the declining cost of underlying technologies. To address this, this study utilizes a learning curve model to project the cost of electrolyzers and its subsequent impact on hydrogen market, aligning with a premise that the market demand is proportional to the cost of hydrogen. In a case study of China's hydrogen market, projecting from 2020 to 2060, we observed substantial differences in market evolution compared to exponential growth scenarios. Contrary to exponential growth scenarios, China's hydrogen market experiences faster growth during the 2020–2040 period rather than later. Such differences underscore the necessity for proactive strategic planning in emerging technology markets, particularly for those experiencing rapid cost decline, such as hydrogen. The framework can also be extended to other markets by using local data, providing valuable insights to investors, policymakers, and developers engaged in the hydrogen market.

Keywords: learning curve model; hydrogen; market dynamics; China; electrolyzer

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1. Introduction

Energy transition is crucial for mitigating climate change as most greenhouse gas emissions originate from energy usage [1]. Solar and wind power have made significant contributions to decarbonizing the energy sector but face challenges in decarbonizing industrial sectors like steel, chemicals [2], and heavy-duty transportation [3]; at the same time, the instabilities in solar and wind power generation have increased the demand for energy storage and flexible resources [4].

Hydrogen is a key secondary energy source that serves as an energy storage medium [5], carbon-free industrial raw material [6], and transportation fuel [7]. However, current hydrogen production predominantly relies on fossil fuels, resulting in considerable emissions [8]. To facilitate the energy transition, cleaner methods like electrolysis powered by renewable electricity are needed to produce green hydrogen. One barrier to widespread adoption of green hydrogen is its high cost [9]. Experience from the solar and wind industries has shown that large-scale deployments and solid policy support can accelerate cost reduction through the learning-by-doing process [10]. Identifying the optimal timing and policy incentives for hydrogen development is a key question. Previous research suggests the existence of a tipping point, where minimal support can catalyze significant change [11]. Determining this tipping point requires projecting the market evolution, which is essential for companies planning to enter the hydrogen industry [12].

Many estimates on market demand of hydrogen come from energy planning models, which are either optimization or equilibrium models. These models do not provide sufficient information on how the market demand grows from one estimate to the next.

Yang et al. adopted a least-cost optimization to estimate how much hydrogen is required to decarbonize heavy industries, such as chemicals and steel, and heavy-duty transport [13]. Similarly, Chang et al. estimated the hydrogen demand in the steel industry [14], and Navas-Anguita estimated the hydrogen demand in transportation sector [15], both adopting an optimization model at the five-year time length and linearly interpolating it to obtain an annual estimate.

There is also a group of research using system dynamic models and technology diffusion models to estimate the market. Odenweller et al. adopted a logistic technology diffusion model to estimate the hydrogen demand growth, which assumed exponential growth, but no direct response to cost decline was included [16]. They considered the cost decline as a part of drivers to the increase of final saturated market size, which would then accelerate the technology diffusion rate through market pull. Park et al. specifically focused on the hydrogen fuel cell vehicles and adopted the bass diffusion model, which also put exponential growth as the key underlying assumption and had no linkage to the cost decline [17].

Beyond the hydrogen sector, previous researchers have applied the learning curve model in the energy technology diffusion model to simulate the market evolution with declining cost, especially in solar photovoltaic (PV) and electric vehicles (EV). As early as 1997, Neij used the learning curve model to estimate the diffusion of solar and wind powers [18]. The adoption was estimated based on the price difference between renewable and traditional generators. In 2003, Masini and Frank explored the adoption of solar PV in niche markets where cost followed the learning curve [19]. They set a cost threshold for adoption and employed a traditional logistic diffusion model beyond that threshold. More recently, Williams et al. [20] and Tibebu et al. [21] translated cost changes into net present value (NPV) of technology investment and assumed a normal distribution for solar PV adoption. Dong et al. [22] adopted a similar approach, describing NPV as the moving average of the normal distribution of adoption. For electric vehicles, Xian et al. used a price-adjusted diffusion model [23], similar to the model proposed by Bagchi et al. [24] to project the diffusion of cell phones.

However, while these analyses combine the learning curve with technology capacity growth, the patterns of market growth are predetermined as either exponential or logistic growth. Hydrogen technologies, especially electrolyzers and other industrial-scale applications, may not follow the same adoption behavior as personal use. According to the National Renewable Energy Laboratory (NREL) analysis [25], the demand curve for hydrogen resembles more of a staircase line, and the influence of cost on demand growth may exhibit a more linear relationship, distinct from the adoption patterns observed in solar PV or EV adoption.

From a modeling method perspective, this paper represents the first endeavor to incorporate the learning curve model with a linear demand response assumption in hydrogen market estimation. This novel approach allows us to capture the market dynamics and sheds light on how cost decline influences market growth. The capture of the intricate relationship between cost decline and market growth is crucial for effective decision making and policy formulation in the context of energy transition. In doing so, we offer an alternative modeling framework beyond the commonly employed technology diffusion models in renewable energy research. By going beyond the commonly used technology diffusion models, we expand the theoretical toolkit available to researchers and practitioners in the field. This not only enriches the academic discourse, but also opens up new avenues for exploring the complexities of hydrogen market dynamics.

From an application perspective, our contribution holds practical implications for various stakeholders involved in the hydrogen sector. By providing valuable insights into how cost decline influences market growth, we equip policymakers, industry players, and investors with a deeper understanding of the market's behavior. This knowledge can inform strategic decision making, investment planning, and the design of supportive policies that accelerate the adoption and deployment of hydrogen technologies.

We apply this modeling framework in a case study in China that mainly aims to answer two questions. The first is when the most rapid growth of the hydrogen-related market will be observed between 2020 and 2060 in China. The answer to this question will influence and guide the hydrogen-related strategy and policy development. China is the largest greenhouse gas emitter and has set ambitious targets to peak emissions by 2030 and to achieve carbon neutrality by 2060 [26]. China is also the largest hydrogen producer in the world, and the Chinese government has set the hydrogen development agenda [27]. The analysis on China will be influential to help understand the hydrogen market in the world, and the analytic framework can be also applied to other countries.

The second question is whether the exponential growth assumption is appropriate or at least aggressive enough if the cost declining factor is considered. The learning curve has been widely used to estimate the cost declining factor of renewable technologies [28], and it is better than expert elicitation when projecting the future cost [29]. A paper published in 2015 applied cost projection from the learning curve model into market estimation for solar PV [30], which was larger than the market estimates in the business-as-usual scenario projected by IEA [31], even though both estimates underestimated the market growth. Therefore, we could draw a hypothesis that, once the cost decline factor from the learning curve model is applied to the market estimations for hydrogen technologies, the observed market growth will be faster than the situation with an exponential growth at a constant growth rate, which is a common practice to project market growth in the industry.

2. Materials and Methods

This paper aims to estimate future hydrogen market evolution pathway, not just the point estimate of the market demand. The hydrogen market analyzed in this study includes green hydrogen production, steelmaking, methanol production, ammonia production, hydrogen combustion turbines, and hydrogen fuel cell vehicles. Although hydrogen can act as a key electric storage option in the electricity system, the storage does not consume much hydrogen, and thus it is not included in the analysis. For green hydrogen production, this study considers two technologies, alkaline electrolysis (ALK) and proton exchange membrane electrolysis (PEM). These two have a relatively high technology readiness level and are deployed at scale worldwide [32]. Other low-carbon hydrogen production technologies, such as biohydrogen [33], are not considered, but they may prosper in the future. For steelmaking, the analysis considers two technology options, blast furnace-basic oxygen furnace (BF-BOF) iron and direct reduction iron (DRI). In BF-BOF, hydrogen acts as the reducing gas that can only partially replace coke or coal, but in DRI, the process can be 100% powered by hydrogen, leading to a higher emission reduction potential [34]. In chemical industry, hydrogen is mostly used in the ammonia and methanol production [35], and thus, this research selects these two aspects to represent the hydrogen market evolution in the chemical industry.

The analysis can be divided into four steps as shown in Figure 1. First of all, through a literature review, temporal milestones are determined, corresponding to the installed capacity or similar indicators of the relevant technologies. For transportation, hydrogen production, and hydrogen usage in power generation, the market refers to the equipment installed capacity, and details are shown in Table 1. Table 2 presents the hydrogen consumption in steel, ammonia, and methanol market. Again, the main focus of this analysis is not to give a point estimate of the market size at these temporal milestones, and the market size figure of each sector comes from the existing literature.

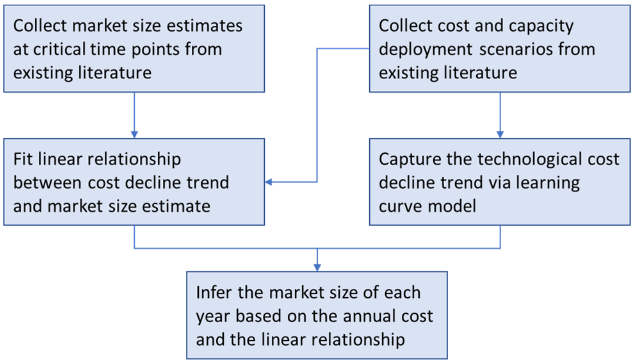

Figure 1. Flow chart of the analysis.

Table 1. Hydrogen equipment market in hydrogen production, hydrogen gas turbine, and hydrogen vehicle.

Field	Technology	2020	2060	Data Source
Hydrogen production	ALK	0.7 GW	419.3 GW	[36]
	PEM	0.006 GW	512.5 GW	[36]
Hydrogen gas turbine		0	200 GW (1)	[37]
Hydrogen vehicle		8000 vehicles	72.75 million vehicles	[38]

(1) According to the data source (Global Energy Internet Development Cooperation Organization [37]), it is predicted that the hydrogen gas turbine installed capacity will be 100 GW in 2050.

Table 2. Hydrogen consumption estimate in steelmaking, methanol production, and ammonia production.

Field	2020	2030	2060	Data Sources
Steelmaking	0 tons	BF-BOF: 5.6394 million tons; DRI: 1.275 million tons	BF-BOF: 0 tons; DRI: 6.12 million tons	[39]
Methanol	10.932 million tons	13.4355 million tons	9.3377 million tons	[40]
Ammonia	10.849 million tons	8.685 million tons	15.516 million tons	[40]

The second step is to set two scenarios that connect the point estimates of the hydrogen market to delineate the market evolution pathway. The first scenario represents exponential growth, in which all installed capacity or annual consumption is assumed to develop according to a stable compound annual growth rate (CAGR). Such exponential growth assumption underpins most of the technology diffusion models [16,17,41] and is also widely used in industry reports [36,39,40]. The second scenario assumes a linear relationship between market demand and technology costs, following Equation (1). $y_{i,t}$ is the market size of technology i in year t. x_t is the corresponding technology cost in year t, and $\beta_{i,k}$ is the response coefficient of technology i in period k. The period k is segmented by the existing point estimates of the market; for example, if the technology has market estimates at two time points, it will only have one period, and if it has estimates at three time points, it will have two periods.

$$y_{i,t} = \beta_{i,k} x_t + \varepsilon_i \tag{1}$$

The third step is to capture the cost decline of the technology. Among all cost factors, this paper takes the cost of electrolyzer as the example to demonstrate the analytic framework. Future work can incorporate cost of storage, electricity cost, and other cost components into the analysis. It should be noted that the hydrogen price is also correlated to the fossil fuel price [42]. In reality, fossil fuel contributes to some hydrogen production methods as a part of raw material, but it also competes against hydrogen in some application scenarios. To estimate the cost reduction trend of electrolyzers, this study adopts a learning curve model, as shown in Equation (2).

$$\ln\left(p_{j,t}\right) = \gamma - \alpha \ln\left(q_{j,t}\right) \tag{2}$$

$$LR = 1 - 2^{-\alpha} \tag{3}$$

In this study, $p_{j,t}$ represents the global average cost of technology j in year t, and $q_{j,t}$ represents the global total installed capacity of technology j in year t, where j can be either ALK or PEM. The term LR refers to the learning rate and is defined in Equation (3). The initial cost and future global installed capacity forecasts for both technologies are sourced from the International Energy Agency [43], with the PEM cost being 1750 USD/kW in 2020 and the ALK cost being 1200 USD/kW. This cost is much higher than the real price in China. In May 2023, an open bid showed that the ALK system is about 1660 CNY/kW (246.41 USD/kW) (SunGrow and Longi win the ALK bids from Dalian Clean Energy Group (in Chinese) https://m.bjx.com.cn/mnews/20230523/1308368.shtml, accessed on 28 May 2023). This price difference does not affect our analysis since we just focus on the cost declining trend and not the specific cost figure. The future installed capacity scenario chosen is the net-zero scenario. The learning rate is sourced from the Hydrogen Council's report, with the PEM learning rate being 13% and the ALK learning rate being 9%. It should be noted that, while the data on hydrogen production costs and installed capacity used in this paper are mostly from international research, the corresponding cost reduction trends in domestic markets are also quite similar due to the global supply chain involved in these technologies [44]. Moreover, since the starting point and the final point of the market size is fixed, the value of the learning rate and the cost of the technology will not change the shape of the market evolution pathway. Thus, different parameters in learning rate and technology cost would not qualitatively affect the comparison with the CAGR scenario. To quantitatively demonstrate, we construct a high learning rate scenario and a low learning rate scenario. In the high learning rate scenario, we assume the learning rate for PEM is 20% and 15% for ALK; in the low learning rate scenario, we assume that the learning rate for PEM is 7% and 3% for ALK. Only the electrolyzer market is analyzed under the high and low learning rate scenarios.

The relationship between x_t and $p_{j,t}$ can be expressed as Equation (4). In other words, if technology i is the electrolyzer, then x_t is the corresponding cost. Otherwise, the technology cost x_t is the capacity weighted average of two electrolyzer technologies.

$$x_t | y_{i,t} = \begin{cases} p_{j,t} \; when \; i \in \{PEM, ALK\}, \; j = i \\ \frac{\sum_j p_{j,t} \times q_{j,t}}{\sum_j q_{j,\,t}} when \; i \notin \{PEM, ALK\}, \; j \in \{PEM, ALK\} \end{cases} \tag{4}$$

There is a fourth step for estimating the market of hydrogen consumption. The market of hydrogen consumption in steel and chemical sector can be estimated as the product of hydrogen quantity consumed and hydrogen price. Pan et al. calculated the price of hydrogen by taking China's electricity price and renewable energy resources into account but not the cost dynamic of electrolyzers [45]. Thus, this paper adopts their results to multiply by the hydrogen consumption calculated from previous steps. Since the exchange rate may be a critical factor in affecting results [46], all the monetary units in this paper are converted to 2022 US Dollar (USD) values based on the average value of OECD exchange rates for the year of announcement. Specifically, 1 USD = 6.7366 CNY.

All the data used in this paper are enclosed in the Supplementary Materials as an Excel file.

3. Results

3.1. Electorlyzers Cost and Their Market

According to Equation (2), the cost of renewable hydrogen production technologies is shown in Figure 2. The costs of both types of renewable hydrogen production technologies decrease rapidly in the first five years and reach at about 20% of the 2020 cost by 2050, with PEM cost falling to around 265 USD/kW and the ALK cost falling to around 334 USD/kW, which are within the cost range predicted by the Potsdam Institute for Climate Impact Research [47] and slightly lower than the expectations of EU experts [48]. The comparison of our results with other estimates is to demonstrate that the data are reasonable but not necessarily representative. As discussed in the Methods and Materials Section, the specific cost, either the initial or final cost, will not affect the general shape of the market growth curve, which is the main focus of this analysis.

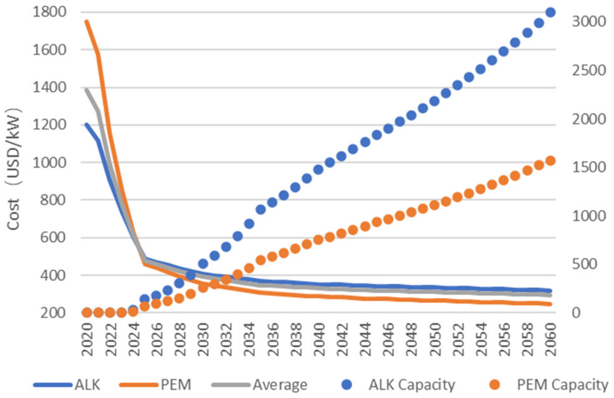

Figure 2. Global electrolyzers' capacity and related cost.

Although the newly installed capacity from 2030 to 2050 is higher than that from 2020 to 2030, the cost reduction effect is smaller. In the first 10 years, the total newly installed capacity of the two technologies is 828 GW, and the average cost is reduced by 71% compared with 2020. In the following 20 years, the newly installed capacity is 2757 GW, but the average cost is only reduced by 20% compared with 2030. This feature is an inherent feature of the learning curve that the initial large-scale deployment will bring larger cost reduction.

Assuming a constant annual growth rate is a common way for market forecasts, but if the analysis considers the promoting effect of cost reduction on the market, the whole development path of the market will be significantly different. By plugging the results of Figure 2 and Table 1 into Equation (1), the market evolution pathway in the dynamic scenario can be calculated and shown in Figure 3. As costs decrease rapidly in the early stages, most of China's installed capacity occurs before 2030 when considering the dynamic relationship between cost and installed capacity. The slow down in capacity growth observed around 2024–2026 is a result of the rapid cost decline in global electrolyzer, driven by the fastest percentage-based capacity growth as determined by IEA Net-Zero Scenarios. With the assumption of a constant annual compound growth rate, most of the growth will occur after 2040. None of learning rate, initial cost, and final cost of the global electrolyzer could slow down market growth to a pace lower than that in the exponential growth case during the early period of planning, since the starting market size, final market size, and the types of market growth curve are already decided. For those planning to participate in the renewable hydrogen production market, it is necessary to enter the market early to seize the opportunity, taking the cost reduction factor into account.

The markets for hydrogen turbine and hydrogen vehicles are important, but the differences between the two approaches are similar to the results in electrolyzer capacity and the steel capacity. The results are displayed in the Supplementary Materials document under the section 'Turbines and Vehicles'.

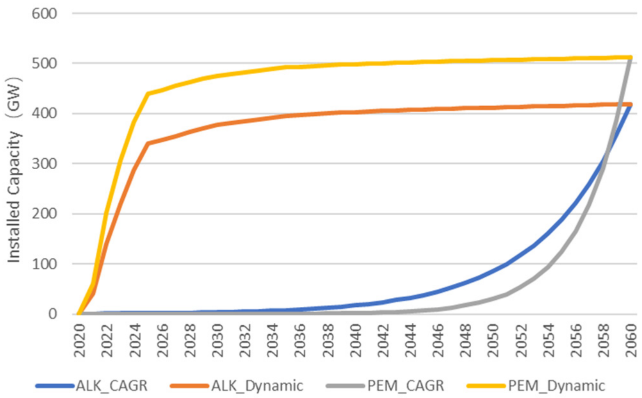

Figure 3. Electrolyzer capacity evolution in China under two scenarios.

3.2. Evolution of Hydrogen Consumption in Steel and Chemical Industries

As shown in Figure 4, after considering the reduction in technology costs, the growth of new technology installations, including both BF-BOF and DRI, will be faster than that of the CAGR scenario. Therefore, there will be more hydrogen consumption each year. Even when phasing out the BF-BOF technologies for deep decarbonization, the decrease in dynamic scenario will still be slower than that in the CAGR scenario due to the impact of technology cost reduction. The faster growth and slower decrease will result in significant market differences in hydrogen consumption. In the CAGR scenario, the cumulative hydrogen consumption from 2020 to 2060 is 127.25 million tons, while in the market dynamic scenario, the cumulative hydrogen consumption is as high as 243.77 million tons, which is 1.9 times higher than the former.

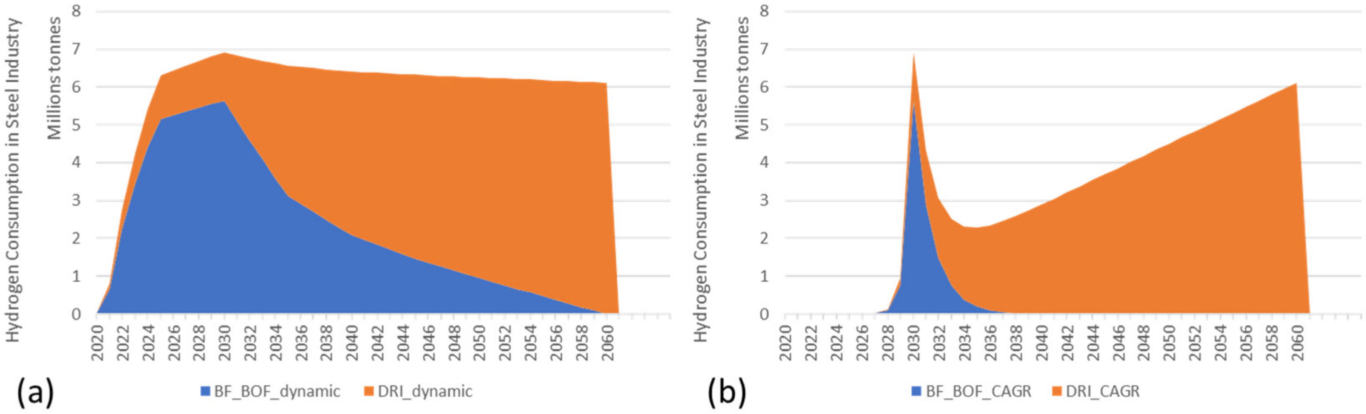

Figure 4. (**a**) Hydrogen consumption in the steel industry under dynamic scenario (**b**) and CAGR scenario.

The results in the chemical market are somewhat different as shown in Figure 5. Regardless of whether hydrogen is used to produce ammonia or methanol, considering market dynamics with cost reductions results in faster market growth in the demand growth period, while the CAGR scenario yields greater hydrogen consumption in the demand decline period. Looking at cumulative consumption from 2020 to 2060, the market for hydrogen consumption in ammonia production yields 9% higher consumption in the dynamics scenario than the CAGR scenario, while for the hydrogen consumption of methanol production, the CAGR scenario yields 3% more consumption than the market dynamics scenario.

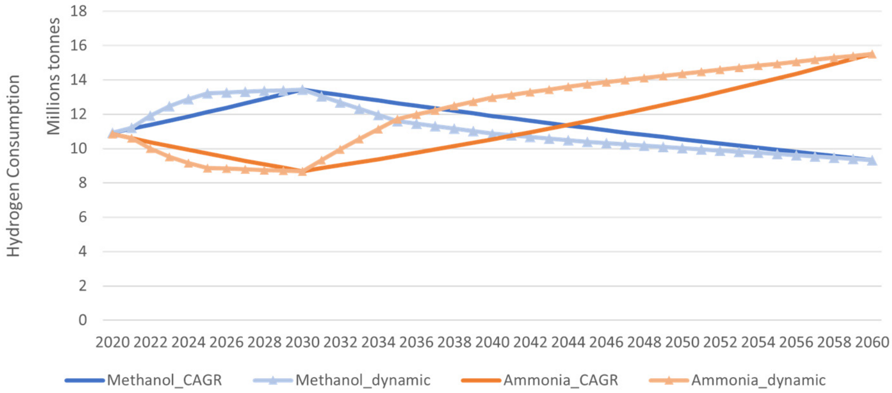

Figure 5. Hydrogen consumption for methanol production and ammonia production under dynamic scenario and CAGR scenario.

3.3. Evolution of Hydrogen Market in Steel and Chemical Industries

By combining the results of Figure 4 with hydrogen price data from reference [45], the hydrogen market is estimated for the steel industry (Figure 6), in which changes in hydrogen consumption drive market changes rather than price. Under the dynamic scenario, the annual market size is projected to peak in 2025 at 36.17 billion USD (253.2 billion RMB). Although market demand continues to grow, decreasing hydrogen prices lead to a sustained decline in market size, ultimately falling to 14.87 billion USD (104.1 billion RMB) by 2060. In terms of temporal distribution, 50% of the cumulative market value occurs within a 16-year interval before 2036, during which rapid growth in hydrogen demand and gradually declining hydrogen prices converge. Under the CAGR scenario, 50% of the market is concentrated in a 15-year interval from 2045 to 2060. The annual market size reaches its peak of 32.7 billion USD (229 billion RMB) in the same year as the maximum hydrogen consumption. Thereafter, the overall market gradually declines with the rapid phasing out of the BF-BOF technology and declining hydrogen prices, until it slowly rises again around 2036 with the widespread application of DRI technology.

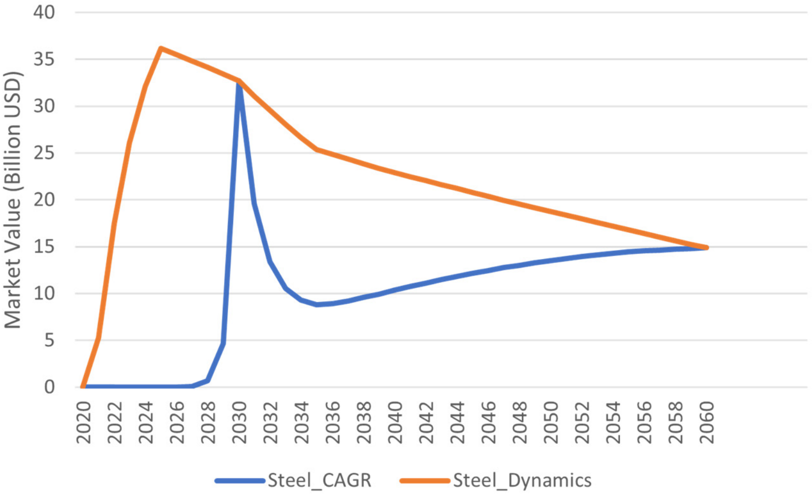

Figure 6. Hydrogen market in steel industry under dynamic scenario and CAGR scenario.

Unlike the steel industry, the hydrogen market size in the chemical industry (Figure 7) is primarily driven by hydrogen prices, and the difference between the CAGR scenario and the dynamic scenario is relatively small. The total market size shows a continuous downward trend, declining from 149.67 billion USD in 2020 to 60.4 billion USD in 2060. Despite the eventual increase in hydrogen consumption, the decrease in hydrogen cost is sufficient to reverse the impact of the consumption. However, the hydrogen price selected here is the price for green hydrogen, whereas the chemical industry mostly use hydrogen produced from fossil fuels such as coal, resulting in lower costs and smaller market sizes. In the future, with stricter requirements in carbon emissions, these low-cost, high-emitting hydrogen sources will be gradually eliminated, thereby creating opportunities for green hydrogen in the chemical industry.

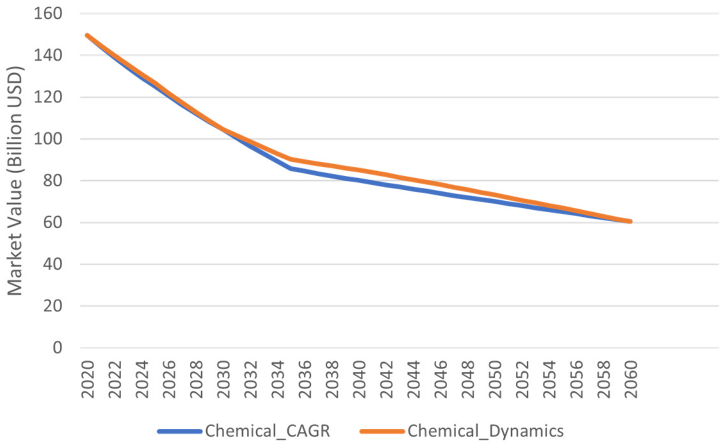

Figure 7. Hydrogen market in chemical industry under dynamic scenario and CAGR scenario.

4. Discussion

The research findings can be organized into two distinct categories. The primary category addresses emerging applications of hydrogen in the market, including, but not limited to electrolyzers, hydrogen turbines, hydrogen vehicles, and hydrogen use in steelmaking. The secondary category includes established applications of hydrogen that have maintained a relatively constant demand over the years like petrochemical industry. Given the relatively stable demand within this secondary category, the specific trajectory of market evolution may not present substantial significance, thereby resulting in similar cumulative market results across different pathways.

However, the growth pattern for the primary market category is heavily influenced by the assumptions related to market dynamics and CAGR. With an exponential pattern in the CAGR assumption, more portion of growth is allocated to later period, showing a steep increase. In contrast, a dynamics assumption, correlating demand growth with cost reduction, tends to allocate more growth to initial period. Because the cost reduction, as defined by the learning curve model, follows an exponential pattern, the inverse proportionality between demand and cost reduction results in an inverted exponential curve, as illustrated in Figure 3. Additionally, considering a logistic growth curve, it would be positioned between the exponential and inverted exponential curves as the logistic pattern allocates more rapid growth during the intermediate period.

Therefore, regardless of fluctuations in learning rates or other uncertainties associated with the learning curve, the dynamic scenario consistently outperforms the CAGR scenario in achieving a market penetration of 50%. This is also demonstrated in the electrolyzer market as shown in Figure 8. A higher learning rate leads to larger market size before 2024, aligning with the learning curve of electrolyzer cost. After 2024, the discrepancies in market sizes of different learning rate scenarios may reduce, as the framework presumes the ultimate market size to align with the results from the optimization model. Likewise, global capacity deployment scenarios will also affect the learning curve and then the trajectory of market growth. Nevertheless, the market growth, following an inverted learning curve, will exceed the pace following an exponential curve during the early growth phase.

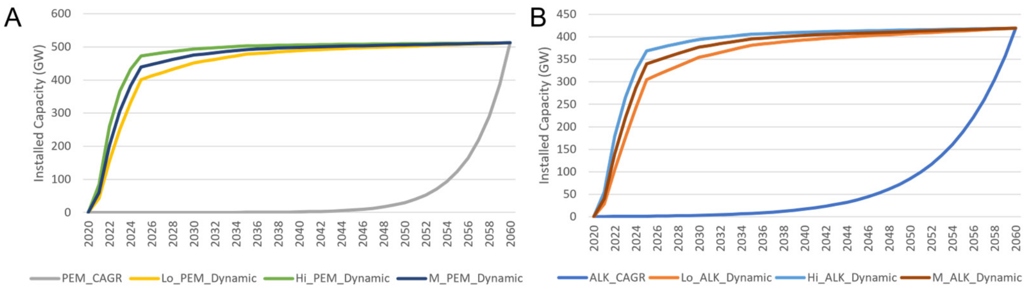

Figure 8. Hydrogen electrolyzer market with high (Hi), middle (M), and low (Lo) learning rates. (**A**) PEM market; (**B**) ALK market.

Recall the first question in the Introduction Section, the study under the dynamic scenarios in this paper suggests some important time nodes for different players in China's hydrogen industry. For steelmaking or hydrogen vehicle manufacturing, the demand on hydrogen will skyrocket before 2024, requiring the companies and policymakers to start preparing for the fast-growing demand since the very beginning. The companies along the value chain of hydrogen gas turbine should also plan for a rapid growth in demand appearing between 2035 and 2040, earlier than the rapid growth period under the CAGR scenario (2045–2050). For the hydrogen companies serving chemical market, taking the cost decline into consideration actually shows limited differences between the market evolution pathways under the dynamic and CAGR scenarios; under the dynamic scenario, the most rapid growth on hydrogen demand in methanol production emerges between 2020 and 2025 and that in anomia production is between 2030 and 2035.

Regarding the hypothesis related to the second question, it is safe to conclude that the hypothesis is validated. The hydrogen markets, especially related to gas turbine, hydrogen vehicles, and hydrogen steelmaking, will experience a faster-than-exponential growth when considering the cost decline factor from learning curve. In the learning curve model, the cost experiences a higher declining rate in the beginning and gradually lower rates later on, leading to a similar pattern in market growth. Since the ultimate market size and key time nodes are assumed to be the same, the market growth under the dynamic scenario will grow faster than that under the CAGR scenario.

5. Conclusions

In summary, this study introduces an innovative methodology that connects market size estimates at specific time points, considering the market's response to technology cost changes. Unlike recent studies adopting the technology diffusion model, this study embraces a fundamental economic concept where market demand increases linearly with cost reduction. Compared to previous studies providing interpolated market size estimates, this methodology reveals significant differences in market evolution pathways and suggests distinct development strategies for market participants.

While this methodology is currently applied to estimating the hydrogen market in China, focusing on electrolyzer costs, it has the potential to be extended to other technologies and regions with sufficient data.

Several limitations require further investigation. Firstly, the assumption that global technological cost reduction fully reflects in domestic markets may not be effectively realized, given fluctuating international relations. Secondly, the analysis does not consider limitations of hydrogen energy infrastructure, such as the progress of refueling stations, pipelines, and storage equipment. Lastly, the market should include other hydrogen production methods, which could influence total market demand and evolution.

Despite these limitations, policymakers and market participants, not only in China, can gain valuable insights from this analysis. Considering cost decline in the hydrogen market suggests faster-than-exponential demand growth, necessitating early infrastructure planning and policy adjustments. Market participants must prepare early for their technologies, products, marketing strategies, and organizational expansion.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16124821/s1, Excel file contains data for reproducing all figures displayed in the manuscript.

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Abbreviations

Solar PV	solar photovoltaic
EV	electric vehicles
IEA	International Energy Agency
NREL	National Renewable Energy Laboratory
ALK	alkaline electrolysis
PEM	proton exchange membrane electrolysis
BF-BOF	blast furnace-basic oxygen furnace
DRI	direct reduction iron
CAGR	compound annual growth rate
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
OECD	Organization for Economic Co-operation and Development

Nomenclature

$y_{i,t}$	market size of technology i in year t
x_t	PEM, ALK or the average cost in year t
$\beta_{i,k}$	cost response coefficient of technology i in period k
$p_{j,t}$	global average cost of technology j in year t
$q_{j,t}$	global total installed capacity of technology j in year t
LR	learning rate

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