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Cost–Benefit Analysis of Pumped Hydroelectricity Storage Investment in China

Paolo Sospiro [1,2,3,4,*], Leonardo Nibbi [1], Marco Ciro Liscio [2,4,*] and Maurizio De Lucia [1,*]

1 CREAR/Dipartimento di Ingegneria Industriale, Università di Firenze, 50139 Firenze, Italy; leonardo.nibbi@unifi.it
2 DII Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, 60121 Ancona, Italy
3 Uniecampus, 22060 Novedrate, CO, Italy
4 EUAbout, 1000 Brusselles, Belgium
* Correspondence: paolo.sospiro@unifi.it (P.S.); marcociro.liscio@gmail.com (M.C.L.); maurizio.delucia@unifi.it (M.D.L.)

Abstract: In this study, the energy scenario in China was analyzed by retracing the trend of exponential population growth, gross domestic product (GDP), and electricity production and consumption. A forecast up to 2050 was made based on the history and forecasts of other field studies. It was possible to deduce data on pollutants in terms of CO_2 equivalent (CO_2-eq) emitted over time if there were no changes in the way energy was produced. Moreover, different scenarios were hypothesized for the use of pumped hydroelectricity storage plants, namely 4.5%, 6%, 8%, 11%, and 14% (percentage of electricity compared to requirements in 2050), to balance variable renewable energy sources and avoid curtailment, thereby reducing the use of energy produced by coal-fired plants. For this implementation, direct and indirect costs and benefits were considered, with interesting results obtained from an economic standpoint and very positive results from environmental, social, and territorial perspectives.

Keywords: pumped hydro storage; renewable energy sources; electricity; cost–benefit analysis

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1. Introduction

With a population of over 1.4 billion inhabitants, China is the most populous country in the world. It currently has one of the highest annual GDP growth rates owing to the industrial momentum that has characterized the country in recent decades. All this justifies the parallel trend in terms of electricity production and consumption in the country. The main Chinese energy source by far is coal due to its abundant presence in the country and its relatively low cost.

Pumped hydro storage (PHS) plants are electric energy storage systems based on hydropower operation that connect to two or more reservoirs (upper and lower) with a hydraulic head. They are usually also referred to as pumped hydro energy storage (PHES) plants, pumped storage hydropower (PSH) plants, or pumped storage plants (PSP) and operate from the exchange of water between two reservoirs.

In production mode, also known as turbine mode, the water released from the upper reservoir passes through the turbines to generate electricity. In pumping mode, electrical power from the grid is used to pump water from the lower reservoir to the upper one. This is a very efficient way (round-trip efficiency in the range of 75–85%) to store excess electric energy during periods where there is no demand in the form of potential energy for later on-demand generation.

The objective of this study was to conduct a cost–benefit analysis (CBA) on the possibility of implementing PHS plants to reduce curtailment of variable renewable energy sources (VRES) and stabilize energy production in China by reducing the use of coal in existing plants. The environmental impact and long-term costs were also analyzed. The installation of a series of PHS plants, along with the implementation of smart grids [1], smart metering, energy efficiency policies and action, liberalization of the electricity market, and better integration of RES, will be part of the solution to balance electricity supply and demand in China. This study took into account the costs and benefits of the installation of PHS in terms of coal and CO_2 emission reduction. However, in the future, we will add other modules that will take into consideration the effects of other policies on PHS in China. Furthermore, another interesting aspect that the next step should take into consideration is the best available technology (BAT) for PHS, which will improve the results of the PHS plants installed in the future in China.

Flexibility is the capability of a power system to cope with the variability and uncertainty that VRES, mainly wind and solar, introduce at different time scales. Among the three basic types of flexibility provisions related to residual load smoothening (downward, shifting, and upward flexibility), the role of PHS is shifting flexibility. PHS can shift surplus feed-in of renewable energy to periods with positive residual load and vice versa. This is one of the main tools to cope with VRES curtailment, which plays the role of upward flexibility by dissipating VRES energy that is surplus to system demand [2].

Several key drivers for the development of China's PHS can be summarized as follows:

- Governmental and regional targets for carbon reduction have been stimulating the integration of renewable energy sources (RES) for years. The rapid development of wind energy in the north and west of China can be considered as the prime driver for increased PHS development. In 2020, China reached record wind capacity of 288 GW (278 GW on-shore and 10 GW off-shore), accounting for 39% of the global installed capacity, while solar PV capacity reached 254 GW, accounting for 36% of the global capacity.
- In October 2020, more than 400 companies in the Chinese wind industry adopted the Beijing Declaration, which aims for 50 GW of annual installations from 2021 to 2025 and 60 GW from 2026 onwards. This would bring China's cumulative wind capacity to 800 GW by 2030 and 3000 GW by 2060. Storage strategies are necessary to cope with this new amount of variable renewable energy sources to avoid curtailment [3].
- Variable renewable energy curtailment in China is mainly due to the rapid growth of wind and PV installations in the remote northwestern areas of China, while most of the electricity demand is located in the populated and industrialized urban areas of the southeastern coast of China. Wind energy curtailment reached a global average of around 17% in 2016, while around 11% of solar energy was curtailed in 2015. Regarding economic impact, as an example, the cost of curtailment was evaluated at around $1 billion in the period 2011–2017. The situation is getting better, with wind energy curtailment in 2019 coming down to 4%, although this still accounted for 17 TWh lost [4].
- Electricity consumption has been growing due to China's rapid industrial development, so PHS is urgently needed to bridge the valley-to-peak gap.
- Because the security of the electric power supply has been emphasized by regulators, PHS needs to be widely used to contribute to the reliability of the power grid as it can provide ancillary services [5].

This article presents parts of the results of an ongoing research project supported by the China Europe Water Platform (CEWP) aimed at studying the potential of PHS in reducing the climate impact of Chinese electricity production. The rest of the article is organized as follows. A literature review on CBA, PHS, and China is given in Section 2. Section 3 presents a case study on the CBA of PHS. Section 4 explains the different scenarios considered in this work. The application of the model on the CBA of PHS is discussed in Section 5. Section 6 provides the data gathered for study of the CBA of PHS. Finally, Section 7 discusses the main findings and conclusions.

2. Literature Review

In recent decades, many authors and scholars have studied PHS and energy storage in general and their contribution to stabilizing energy production and distribution as well as their role in transitioning from fossil fuel to RES for electricity production.

The current national plans in China for RES can reduce 35.8 billion tons of CO_2 by 2050. The average CO_2 abatement cost of promoting RES power is \$9.98/tCO_2 during 2015–2050. Every 1% increase in the capacity factors of RES would decrease the average CO_2 abatement cost by \$0.86/tCO_2 [6].

The global effort to decarbonize electricity systems has led to widespread deployments of variable renewable energy generation technologies. PHS is the overwhelmingly established bulk electrical energy storage (EES) technology (with a global installed capacity of around 158 GW) and has been an integral part of many markets since the 1960s [7] An effort was made by the EU JRC to implement PHS in France by assessing the potential of high-energy sites. This analysis found PHS ranging from 14 GWh when only existing lakes were considered to 33 GWh [8].

At the global level, more than 350 PHS stations are operating with a total capacity of 158 GW. In China, PHS has also enjoyed booming development in the last 10 years, although a lot of problems have occurred in the aspects of management mode and electricity pricing mechanism. Currently, PHS in China accounts for installed capacity of 30.3 GW [9]. The State Grid Corporation of China (SGCC) is considered a role model in its effort to develop PHS in China.

A number of authors have analyzed the role of PHS on RES price mechanisms and economic aspects of electricity markets [7,10–19], while others have studied the technical aspects of implementation and energy contribution of PHS systems [8,20–26]. In addition, many authors have developed CBA on the subject of RES [27–42].

In the present study, we used a different approach to highlight the costs and benefits of PHS installation and found significant social and economic benefits for China. The installation of additional PHS to balance the needs of the electricity system represents an additional shifting flexibility for the grid, thereby reducing the need for VRES curtailment. Shifting flexibility capacity in the system fosters VRES penetration that, combined with GHG savings targets, can facilitate the phase-out of fossil-based capacity. In China, this means reducing the footprint of coal power in the system.

Regarding this last aspect, a number of authors have studied this in the Chinese context [6,43–49] and in the European context [50–56].

3. Zhanghewan Case Study Model

This study took into consideration the model applied by the Asian Development Bank to assess the Hebei Zhanghewan PHS and Rural Electrification Project in 2002. The model analyzed the benefits, adverse effects, recommended mitigation, and monitoring measures related to the construction and operation of the abovementioned project [57].

From a general operational point of view, the project provides 1000 megawatts (MW) of new peak load generating capacity that can be operated with high flexibility. It also includes a new 500 kV transmission line extending 63 kilometers (km) that was installed to expand rural electrification. Indeed, the installation of this PHS station in Hubei province (Figure 1) made it possible to close inefficient coal-fired power plants and expand irrigation capacity in the surrounding area, with positive effects on emissions, grid stability, and water availability for agriculture.

Figure 1. Project map. The main components and the installation area of the Zhanghewan PHS Project [57].

The project's general objective is to provide capability for "peak shaving" and "valley filling", thereby reducing the frequency and duration of power supply interruptions.

The cost of installing a plant with 1 GW capacity includes capital costs for equipment and pump turbines to produce electric power and participate in balancing VRES production (Table 1).

The total cost of the project has been reported as about $775 million. Therefore, using the average change from 1 April 2017 to 12 June 2019 and ECB euro reference exchange rate of 1 USD = 0.8617 EUR, more than half a billion euros would be needed to install a system with capacity of 1 GW.

Table 1. Total cost for 1 GW capacity installed in a PHS plant (assuming Zhanghewan costs), assuming the average from 1 April 2017 to 12 June 2019 as the change value.

Installed Capacity 1 GW Zhanghewan PHS Plant	
Costs	**Value**
Pumped storage powerplantsTransmission line	$422,100,000.00 $16,500,000.00
Rural electrification	$135,500,000.00
Closure of coal-fired power plants	$1,600,000.00
Afforestation	$10,600,000.00
Institutional strengthening	$1,400,000.00
Irrigation	$12,900,000.00
Subtotal	$600,600,000.00
Contingencies	$117,100,000.00
Interest and other charges during construction	$57,100,000.00
TOTAL	$774,800,000.00
TOTAL (€)	€667,645,160.00

4. Scenario Development

Although it is very difficult to generalize costs for this kind of installation, due to the different situations in which it needs to operate, it has recently been confirmed that the average cost per MW for PHS implementation in China and India is in general considerably lower than in the rest of the world.

The average cost of a PHS in China can be preliminarily assumed at $794 million per/GW [58], a value that is aligned with the Zhanghewan case.

Statistics on installed PHS capacity at the global level are available from the "International Hydropower Association (IHA)'s Hydropower Status Report 2020" [9], as in Table 2.

Table 2. Pumped storage installed capacity at global and Chinese levels.

Data	GW
Global pumped storage installed capacity 2019	158
China's pumped storage installed capacity 2019	30.3

The total installed power capacity in China in 2019 was about 1900 GW according to the China Energy Portal based on China Electricity Council data [59].

$$\frac{\text{China Pumped storage installed capacity 2019}}{\text{Total installed China power capacity 2019}} = \frac{30.3\text{GW}}{1900\text{GW}} \approx 1.6\% = R_0 \quad (1)$$

The 1.6% obtained by Equation (1) represents the portion of PHS capacity compared to the total power capacity in China in 2019; therefore, R_0 represents the starting ratio.

R_0 agrees with the research paper "Overall Review of Pumped Hydro Energy Storage in China: Status Quo, Operation Mechanism and Policy Barrier" [15], which explains that the capacity of PHS and the number of PHS have been increasing for years but that PHS as a proportion of total installed capacity has nowadays stayed near 1.6%. Scholars in Japan have studied the reasonable proportion of PHS by utilizing mathematical programming methods, and their research showed that the optimal proportion of PHS in the power grid in China is between 8% and 14% [60]. Therefore, three different starting ratio scenarios, each one characterized by a representative index (R_i), were used, namely $R_{8\%}$ = 8%, $R_{11\%}$ = 11%, and $R_{14\%}$ = 14%.

The following formula indicates the level of PHS capacity that should be installed today in order to achieve the target for each scenario:

$$\text{Target level per scenario} = \frac{\text{China Pumped storage installed capacity2019} * \text{Ri}}{\text{Ro}} \quad (2)$$

In particular, according to Equation (2), $R_{8\%}$ target = 152 GW—$R_{11\%}$ target = 209 GW—$R_{14\%}$ target = 266 GW.

The needed capacity was calculated by the difference between each scenario target and China's PHS installed capacity in 2019.

Needed additional capacity to achieve $R_{8\%}$ scenario = 121.7 GW

Needed additional capacity to achieve $R_{11\%}$ scenario = 178.7 GW

Needed additional capacity to achieve $R_{14\%}$ scenario = 235.7 GW

Two other scenarios were also considered, namely 4.5% and 6%, representing the lowest scenario and a European-like scenario, where the average level of PHS is about 6.2% according to IHA [61] and ENTSO-E transparency tool [62]. The results of the new scenarios were as follows:

$R_{4.5\%}$ target = 85.5 GW → Needed additional capacity for $R_{4.5\%}$ = 55.2 GW
$R_{6\%}$ target = 114 GW → Needed additional capacity for $R_{6\%}$ = 83.8 GW

5. Application of the Model on PHS in China

In this study, an analysis of the general situation in China from the point of view of economic and demographic growth was first carried out.

$$\text{GDP}_\text{i} = \text{GDP}_{\text{i}-1} + \text{GDP}_{\text{i}-1} * \text{Expected Growth Rate\_i} \quad (3)$$

This preliminary analysis was fundamental for the rest of the work because GDP is closely correlated to electricity production and consumption, both for residential consumption, which is related to the population, and for the use of energy in industry and services, which is related to economic growth.

Energy production (EP) is the pivotal data on which the study was carried out:

$$\text{EP}_\text{i} = \text{FORECAST.ETS}(\text{YEAR}_\text{i}; \text{EP}_{2000} : \text{EP}_{\text{i}-1}; \text{YEAR}_{2000} : \text{YEAR}_{\text{i}-1}) - \text{EP}_{\text{i}-1} * 0.3\% \quad (4)$$

Capacity data up to 2040 was taken from the IEA forecast [63], while capacity between 2040 and 2050 was forecast according to the linear regression model previously applied for electricity production:

$$\text{CAPACITY}_\text{i} = \text{FORECAST.ETS}(\text{YEAR}_\text{i}; \text{CAPACITY}_{2000} : \text{CAPACITY}_{\text{i}-1}; \text{YEAR}_{2000} : \text{YEAR}_{\text{i}-1}) - \text{CAPACITY}_{\text{i}-1} * 0.3\% \quad (5)$$

Based on the study conducted by Zhang Diansheng, Chen Tao, and Yongxing Li [60], which identified 8%–14% as the optimal range for PHS implementation in Japan, these percentages were applied to the values of the total Chinese energy capacity forecast for each year from 2018 to 2050 to obtain the average value of PHS plants in terms of GW required to be implemented annually to reach the target for each scenario by 2050 following this model:

$$\text{ANNUAL GROWTH REQUIRED} = \frac{\text{CAPACITY}_{2050} * \%_{\text{SCENARIO}} - \text{CAPACITY}_{2018}}{2050 - 2019} \quad (6)$$

On this basis, it was possible to estimate two important data points.

The first was the average PHS plant implementation cost considering the inflation rate and the discount rate:

$$\text{ANNUAL IMPLEMENTATION COST} = \frac{\left[(\text{COST per GW} * \text{ANNUAL GROWTH}_{\%\text{SCENARIO}}) * (1 + \text{IR})^{\text{year}-2020}\right]}{(1 + \text{DR})^{\text{year}-2020}} \quad (7)$$

The second was the PHS plant implementation cost with O&M cost after the fifth year, when the first plants will be operative:

$$\text{ANNUAL IMPLEMENTATION COST WITH O\&M COSTS} = \frac{\left[([7]) + \left(\text{O\&M per GW} * \text{ANNUAL GROWTH}_{\%\text{SCENARIO}-5\text{years}}\right) * (1+\text{IR})^{\text{year}-2020}\right]}{(1+\text{DR})^{\text{year}-2020}} \quad (8)$$

The second was the PHS plant implementation cost with O&M cost after the fifth year, when the first plants will be operative:

The equivalent value of coal and CO_2 avoided through the use of PHS installations and the closure of the corresponding coal-fired power plants in terms of power generated was calculated by taking into account the fact that the first environmental benefits will be found after five years, the expected time for a PHS plant to come into operation.

$$\text{MASS OF COAL AVOIDED} = (6)/(\text{Coal plant efficiency} * \text{Heat value for coal}) \quad (9)$$

$$\text{MASS OF CO}_{2\text{eq}}\ \text{AVOIDED} = (6) * \text{Mass of CO}_{2\text{eq}}\ \text{per kWh} \quad (10)$$

$$\text{ANNUAL AVOIDED COST}_{\text{COAL}} = \text{COAL COST} * \text{MTon}_{\text{Coal per year}} \quad (11)$$

$$\text{ANNUAL AVOIDED COST}_{\text{CO}_2-\text{eq}} = \text{EU ETS PRICE} * \text{MTon}_{\text{CO}_2-\text{eq per year}} \quad (12)$$

Once the economic costs and benefits of this implementation were obtained, a comparison was made between them.

6. Data

As mentioned in the previous section, a comparison was first carried out on the trend between energy production and GDP growth in the country. These data were derived and processed using the World Bank's historical data on China's historical percentage GDP growth [64]. The OECD long-term forecast reported on the Knoema portal was used to forecast the GDP trend from 2018 to 2050 [65].

The electricity production data was forecast using the AAA version of the exponential smoothing (ETS) algorithm adjusted with 0.3% reduction over the previous year to match long-term forecasts based on the World Bank's historian [64] and integrated with studies on the sector and data regarding installed capacity in the country until 2040 from agencies such as the IEA [63] and EIA [66]. The results indicated a total capacity of all energy plants in China as 3314 GW by 2040. According to this forecast, it is expected that electricity production (EP) will reach about 13.17 million GWh/y and the total capacity in the country will be 3633 GW in 2050.

Historical data up to 2018 on the use of coal in power generation was considered, which showed a very high value in percentage terms, reaching 81% in 2007. This value dropped to 70.3% in 2015 [67], equal to about 4.03 million GWh/y with estimated use of over 1575 Mton.

To quantify the mass of coal and CO_2-eq, the following values were considered:

- Heat value for hard black coal: 23.9 MJ/kg [68];
- Coal-fired power plant average efficiency in China: 38.6% [69];
- Mass of CO_2-eq per kWh: 1.018 kg/kWh [70].

Therefore, to produce 1 GWh of electricity, given the Chinese average efficiency, it is necessary to burn around 390 tons of hard black coal.

The World Bank forecast [71] was used as the reference to forecast the coal price and calculate the benefits of avoiding coal usage for the next 30 years, while the "EU Energy, Transport and GHG emissions: Trends to 2050" publication [72] was used as the reference to calculate the value of CO_2-eq emissions avoided according to EU ETS terms. The proposed forecast was disregarded due to the actual trend, so we considered a forecast based on the European data shifted 10 years in the future with a consequent increase in the price forecast for 2050, as shown in the following graphs (Figures 2 and 3).

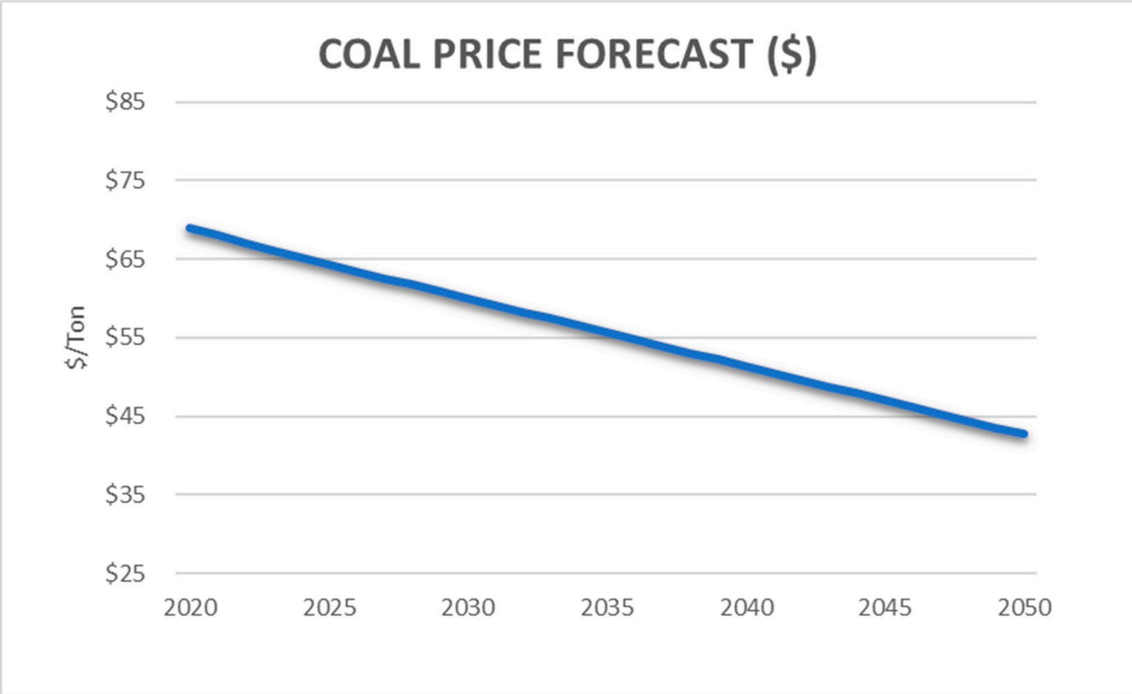

Figure 2. Coal price forecast 2020–2050.

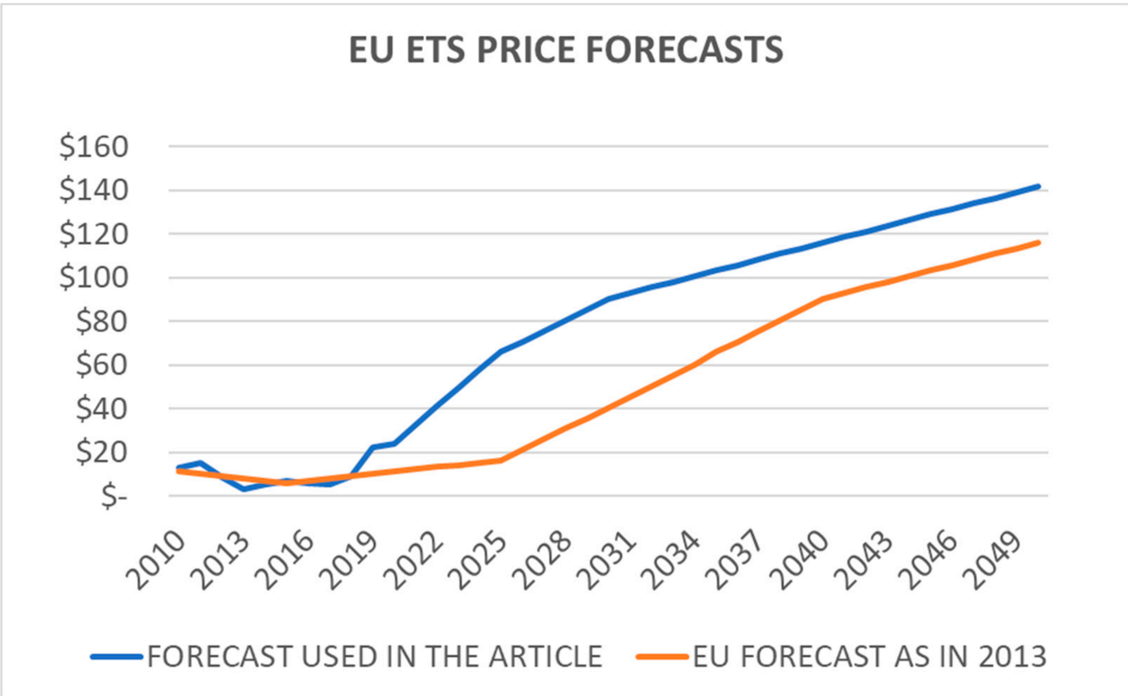

Figure 3. Projection of the ETS price from "EU Energy, Transport and GHG emissions: Trends to 2050" publication compared with the new forecast.

The EU ETS system was used as China is still developing its own system and because this is the most advanced system globally for calculating the price of CO_2, assuming that a Chinese index is in line with the proposed one.

To estimate the annual implementation cost of PHS plant, the following were considered:

- The discount rate (DR) as 8.5% according to EPPA assumption [73];
- The inflation rate (IR) as 2.81%, the average value between 1995 and 2019, according to World Bank data [74].

Both applied to the implementation cost per GW reported in the Zhanghewan case study [57].

7. Results and Discussion

First of all, historical data on GDP and population were considered, and this data was compared with the historical production and consumption of electricity in China. This analysis showed a very similar trend between the curves, even during the economic upsurge observed in the last 20 years, which saw the GDP climb to $13,608 billion in 2018 and the amount of energy produced increase to 6.99 million GWh/y, corresponding to about 1818 GW of plant capacity. With the trend and historical data, it was possible to apply a linear regression model to obtain forecasts up to 2050. Starting from the long-term forecasts on the OECD's GDP percentage trend and the IEA and EIA's energy production forecasts, a figure of 13.49 million GWh/y was obtained for 2050.

The projection in Figure 4, based on real data until 2018, does not consider the effects of the COVID-19 pandemic. This is because it is expected that the 2020 loss of GDP due to the pandemic will be recovered, as has already been happening, in the next few years, and its influence in 2050 can be considered negligible.

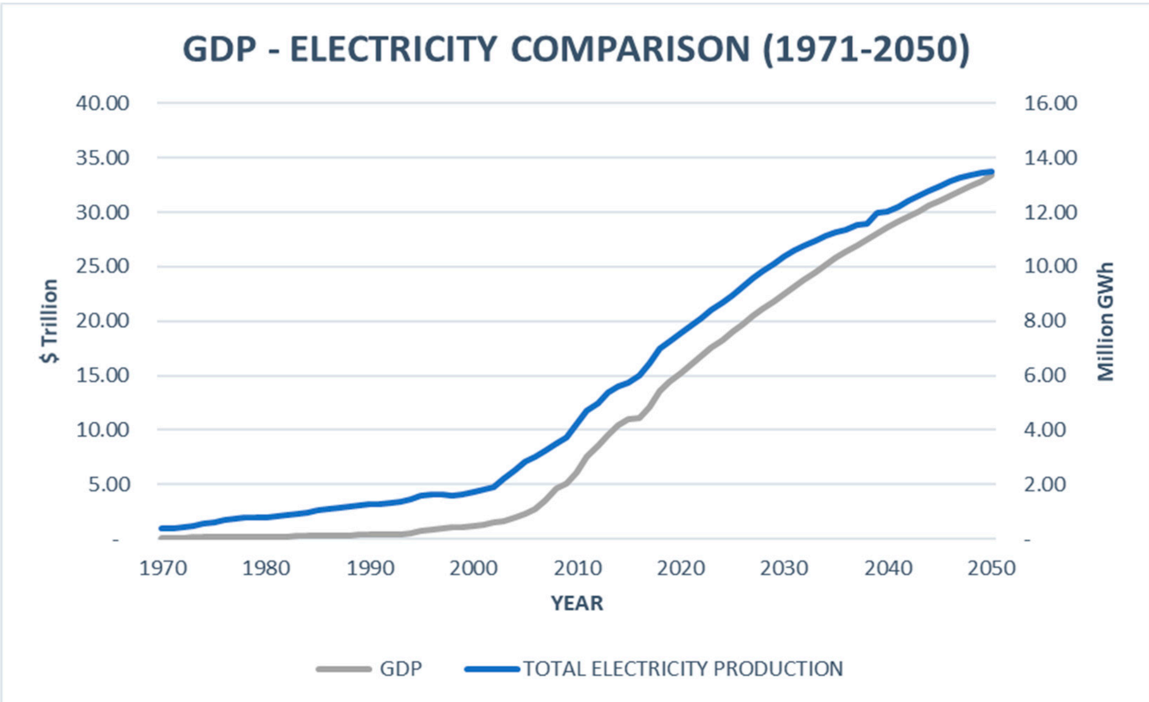

Figure 4. GDP and electricity production from 1971 to 2050 (historical data and forecast) in China.

Based on this and the IEA and EIA forecasts on capacity by energy source, the total energy capacity per year in China was calculated, with the figure expected to increase from 1818 GW in 2018 to 3314 GW in 2040 and up to 3721 GW in 2050 (Figure 5).

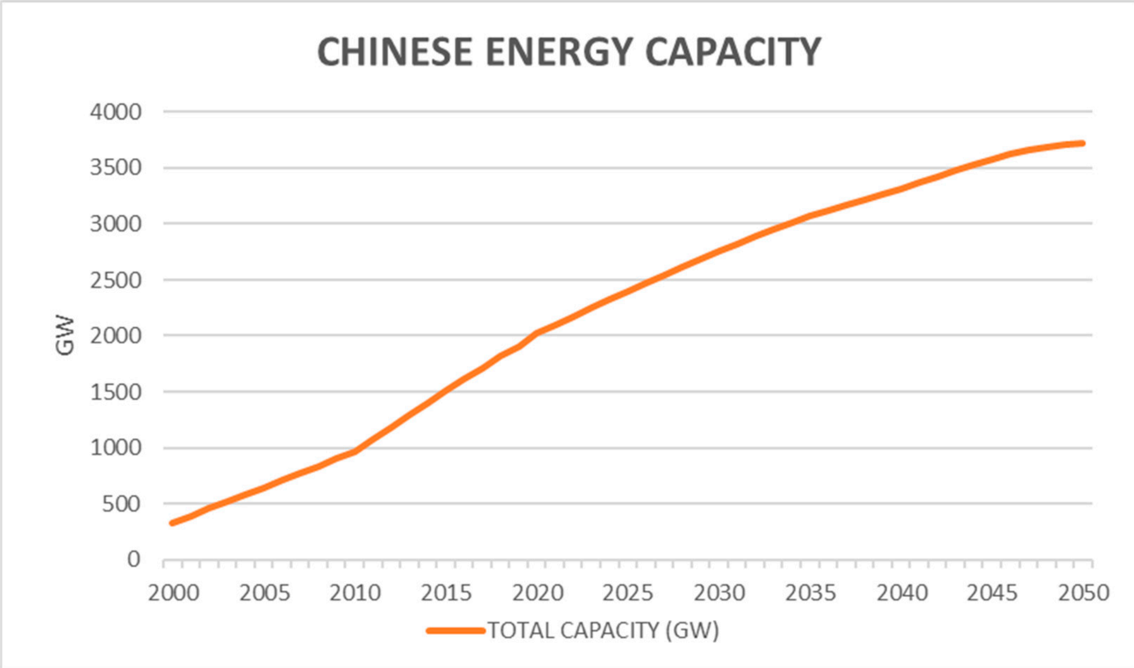

Figure 5. Total capacity in China from 2000 to 2050 (historical data and forecast).

In 2018, about 67.5% of the total capacity was represented by coal-fired plants, meaning the amount of coal necessary was about 1842 Mton according to the model used. This value is expected to grow slightly and then decrease again to around 1983 Mton in 2050 as the percentage of coal used decreases according to sources such as the EIA, which expects coal-fired power to account for 47% of the capacity in 2040 [66] owing to the development of energy from alternative and renewable sources (Figures 6 and 7).

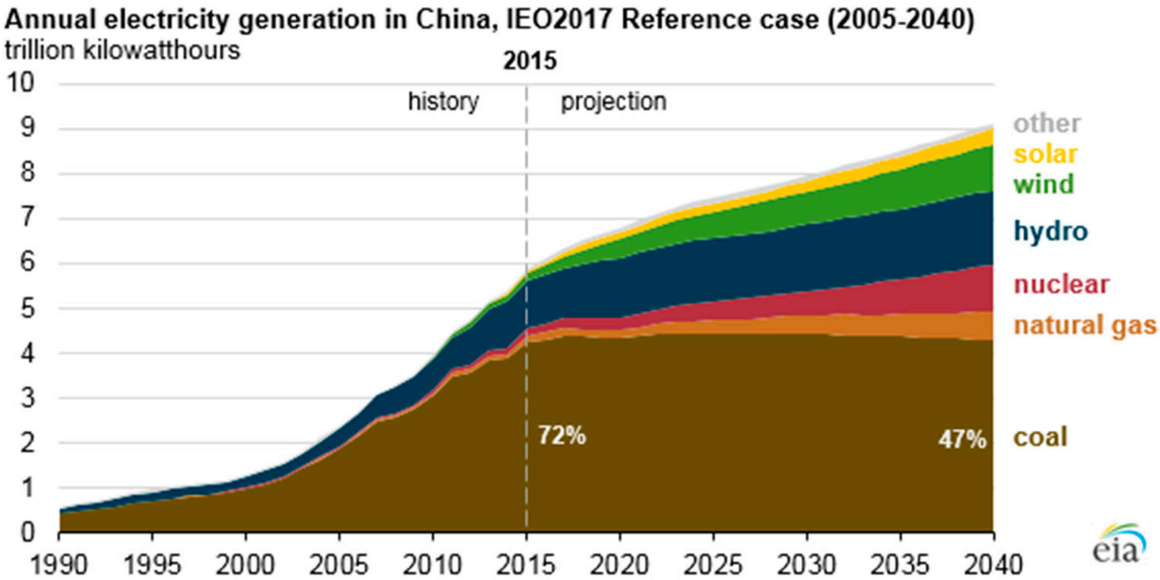

Figure 6. Annual electricity generation in China. Source: U.S. Energy Information Administration, International Energy Outlook (Sept 2017) [66].

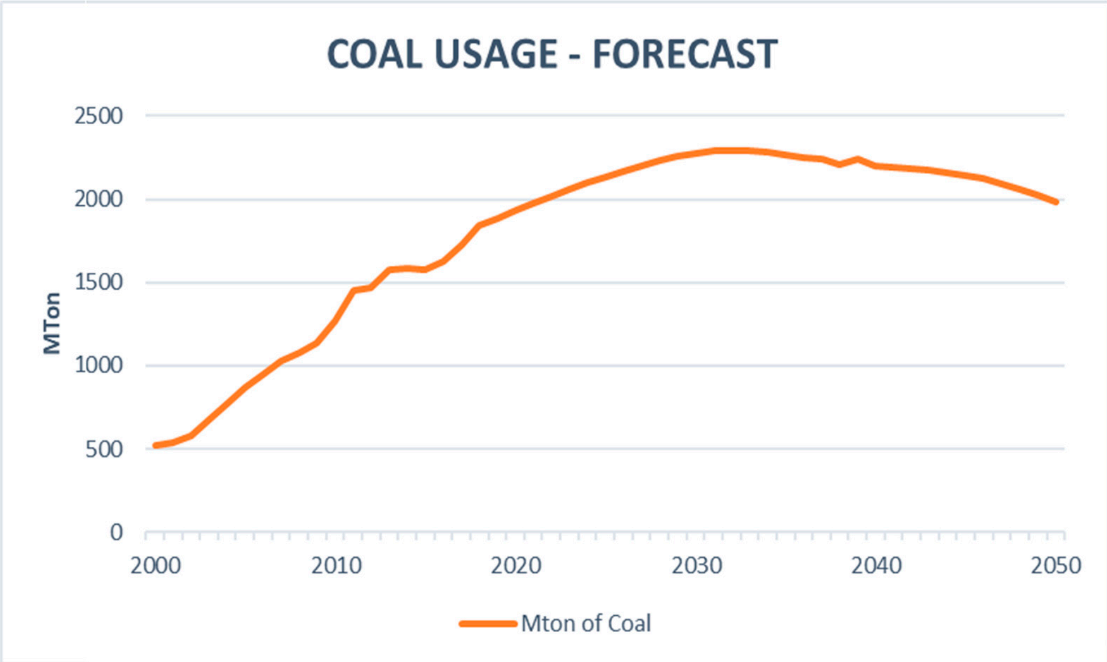

Figure 7. Coal usage according to EIA forecast.

In September 2020, speaking at the UN General Assembly, China's President Xi Jinping pledged that the country would become net-zero GHG emission by 2060 and that China's GHG emissions would peak before 2030.

Both targets will be achieved mainly by reducing the activities and technologies responsible for polluting emissions and implementing decarbonization technologies, including carbon capture and storage (CCS).

Even after the issue of the 14th Five-Year Plan in early 2021, it is presently still not fully clear through which scenarios the targets will be reached. Once the future energy scenarios will at least be roughly given by the Chinese administration, it would be possible to update the present study by applying the developed methodology to the new forecasted scenario.

This study uses the EIA forecasted context, although it would be a depressing scenario to think that energy production from coal will only see a slight decline until 2040 in absolute terms, to try and predict the effect of further reducing this percentage by increasing the PSPs able to foster the VRES penetration into the grid, thus accelerating the phase-out of coal plants.

Based on these values, the target PHS percentage was calculated, which corresponded to about 167, 223, 297, 409, and 520 GW in scenarios 4.5%, 6%, 8%, 11%, and 14%, respectively. Of these, 30.3 GW has already been achieved by 2019 [9].

These target scenarios would be reached annually with the creation of 4.4 GW in the 4.5% scenario, 6.2 GW in the 6% scenario, 8.6 GW in the 8% scenario, 12.2 GW in the 11% scenario, and 15.8 GW in the 14% scenario (Table 3).

Table 3. Main assumption per scenario. PHS capacity needed in order to reach the goals by 2050.

Scenario	Actual Capacity	Forecasted Capacity in 2050	Annual Capacity to Be Installed
4.5%	30.3 GW	167 GW	4.4 GW/y
6%	30.3 GW	223 GW	6.2 GW/y
8%	30.3 GW	297 GW	8.6 GW/y
11%	30.3 GW	409 GW	12.2 GW/y
14%	30.3 GW	520 GW	15.8 GW/y

Turning to the economic aspect, the implementation costs were calculated based on the Bloomberg NEF data, according to which a 1 GW plant would cost approximately $794 million [58].

Applying this unit cost to the entire forecast and discounting the costs year by year with an estimated discount rate of 8.5% according to EPPA assumptions [73] and an inflation rate in China assumed as the average value from 1995 to 2019 according to the World Bank data [74], we reached an average implementation cost per year for 30 years (from 2020 to 2050) ranging from about $2 billion in the 4.5% scenario to $7.16 billion in the 14% scenario (Table 4).

Table 4. Annual implementation costs, including O&M costs, for years 2020, 2030, 2040, and 2050.

Scheme 4.	4.5%	6%	8%	11%	14%
2020	$3.51 bn	$4.94 bn	$6.85 bn	$9.71 bn	$12.56 bn
2030	$2.28 bn	$3.21 bn	$4.45 bn	$6.31 bn	$8.16 bn
2040	$1.56 bn	$2.19 bn	$3.04 bn	$4.30 bn	$5.57 bn
2050	$1.04 bn	$1.46 bn	$2.03 bn	$2.88 bn	$3.72 bn
Avg. Cost Per Year	$2.00 bn	$2.82 bn	$3.90 bn	$5.53 bn	$7.16 bn

The social, environmental, and economic benefits of such an implementation were analyzed considering the phase-out of coal-fired power plants for the equivalent GWh/y produced.

The first environmental benefits would start five years after starting the implementation of the first PHS plants due to the time necessary for installation and commissioning. The main benefits would be related to the savings made on purchasing coal and especially CO_2-eq emissions produced by coal-fired power plants. These data see a reduction of coal quantities ranging from 5.5 to 10.1 Mt and CO_2-eq quantities ranging from 14.4 to 26.5 Mt in relation to the 8% and 14% scenarios, respectively, for each annual target set. These values are cumulative as the plants installed in the new year will add to those of previous years by decreasing the quantities of coal and CO_2-eq otherwise produced by coal-fired plants.

All this was then monetized using the forecasted cost of coal per year and the forecasted EU ETS price for CO_2-eq, with results showing savings of $355.48 million to $652.29 million for coal and $953.76 million to $1.75 billion for CO_2-eq from 2025 in the 8% and 14% scenarios, respectively. The avoided coal and CO_2-eq was found to double in 2026, triple in 2027, and so on, with an increasing trend in the forecasted EU ETS price and a decreasing trend in the coal cost. By 2050, this will lead to savings of $6.14 billion to about $11.26 billion for coal and $53.01 billion to $97.42 billion for CO_2-eq for the 8% and 14% scenarios, respectively (Tables 5 and 6).

Table 5. Avoided coal cost per year based on coal price forecast and quantity expected to be avoided according to each scenario for 2025, 2035, 2045, and 2050.

Scenario	4.5%	6%	8%	11%	14%
2025	$0.18 bn	$0.26 bn	$0.36 bn	$0.50 bn	$0.65 bn
2035	$1.74 bn	$2.44 bn	$3.38 bn	$4.80 bn	$6.21 bn
2045	$2.80 bn	$3.94 bn	$5.46 bn	$7.74 bn	$10.02 bn
2050	$3.09 bn	$4.43 bn	$6.14 bn	$8.70 bn	$11.26 bn
Avg. Cost Per Year	$1.91 bn	$2.70 bn	$3.72 bn	$5.28 bn	$6.83 bn

Table 6. CO_2-eq avoided per year based on EU ETS price forecast and quantity expected to be avoided according to each scenario for 2025, 2035, 2045, and 2050.

Scenario	4.5%	6%	8%	11%	14%
2025	$0.49 B	$0.69 B	$0.95 B	$1.35 B	$1.75 B
2035	$8.4 B	$11.82 B	$16.38 B	$23.22 B	$30.06 B
2045	$20.02 B	$28.16 B	$39.02 B	$55.32 B	$71.61 B
2050	$27.23 B	$38.31 B	$53.09 B	$75.26 B	$97.42 B
Avg. Cost Per Year	$11.99 B	$16.87 B	$23.37 B	$33.13 B	$42.89 B

After summarizing the average terms of these values, the results showed an average saving over 25 years (from 2025 (when the first PHS plants go into operation) to 2050) of $3.72 billion for coal and $23.4 billion for CO_2-eq for the 8% scenario and up to $6.83 billion for coal and $42.9 billion for CO_2-eq for the 14% PHS implementation scenario.

Because the forecast showed very high figures, it is necessary to also highlight scenarios that are less appealing in terms of implementation but which nevertheless allow considerable benefits from both economic and environmental points of view.

The percentages considered for less appealing scenarios were 4.5% and 6%. The 4.5% scenario showed an average saving over 25 years of $1.91 billion for coal and $12 billion for CO_2-eq, while the 6% scenario showed an average saving over 25 years of $2.70 billion for coal and $16.9 billion for CO_2-eq.

Table 7 presents an assessment of the total costs and benefits.

Table 7. Implementation cost of PHS plants compared with coal avoided and EU ETS benefits.

Scenario	Coal Benefit (Avg per Year)	CO_2-Eq Benefit (Avg per Year)	Implementation Cost (Avg per Year)
4.5%	$1.91 B	$11.99 B	$2.00 B
6%	$2.69 B	$16.87 B	$2.82 B
8%	$3.72 B	$23.37 B	$3.9 B
11%	$5.28 B	$33.13 B	$5.53 B
14%	$6.83 B	$42.89 B	$7.16 B

EU ETS prices, as well as coal prices, are variable for very obvious financial reasons. Moreover, the implementation costs of PHS installations are subject to variations ranging from geographical and orographic reasons to legislative reasons in various regions of the country as well as the considered discount rate and inflation rate.

The graphs in Figures 8–12 show that the sum of the savings obtained from CO_2 avoidance in terms of EU ETS and purchased coal owing to progressive implementation of PHS plants by far exceeds the implementation costs of the necessary installations for each of the scenarios considered. It has to be taken into account that the average implementation costs were obtained by forecasting a constant increase in PHS installations each year to reach the 2050 scenario target. The benefits are commensurate to this constant increase. There will be values far below the average for the first years of implementation, but this will then balance and exceed the implementation costs after 2033.

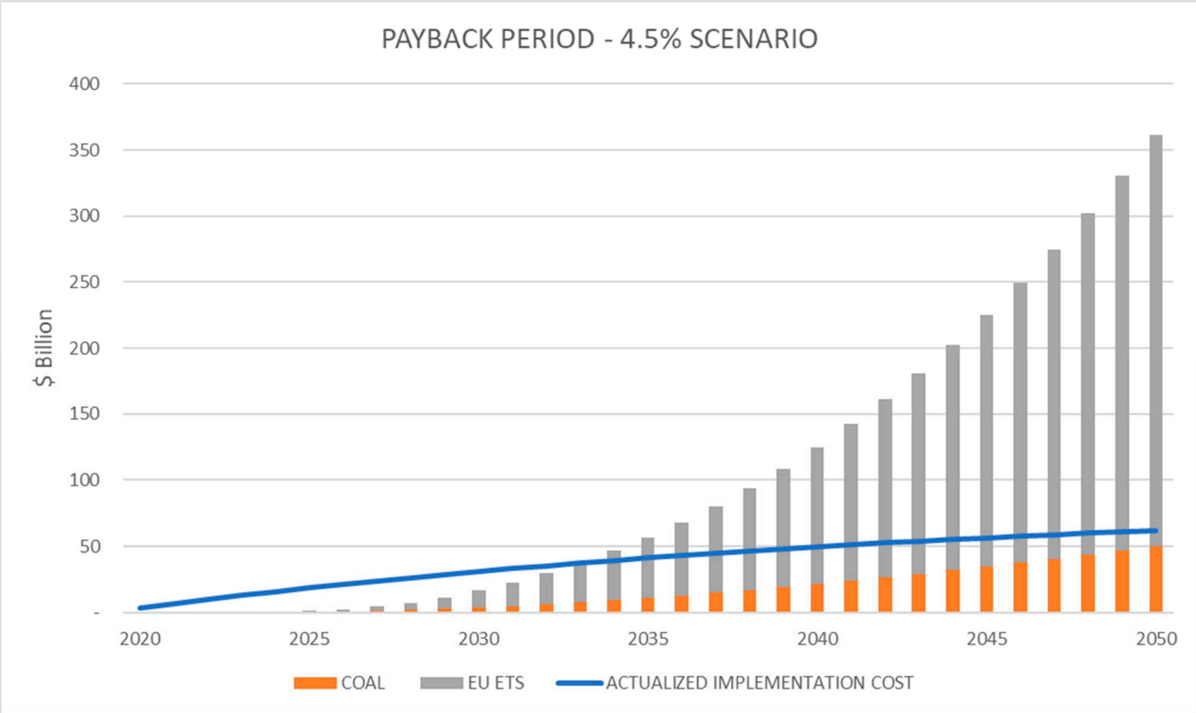

Figure 8. Payback period in the 4.5% scenario.

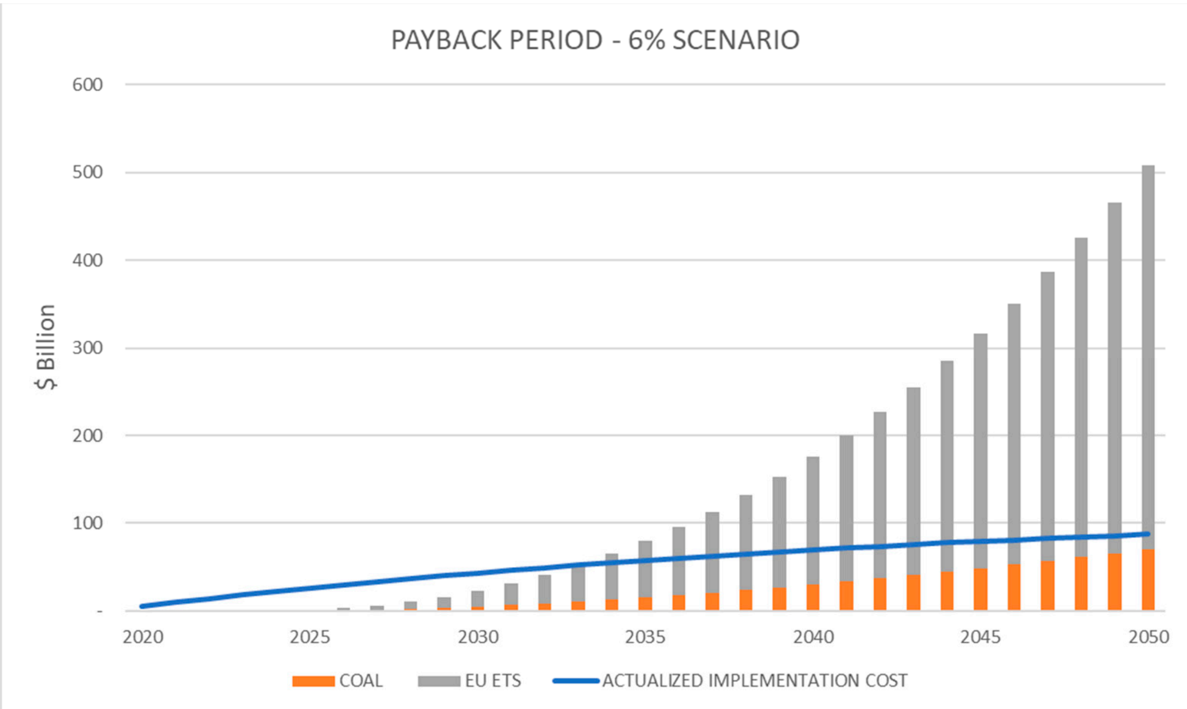

Figure 9. Payback period in the 6% scenario.

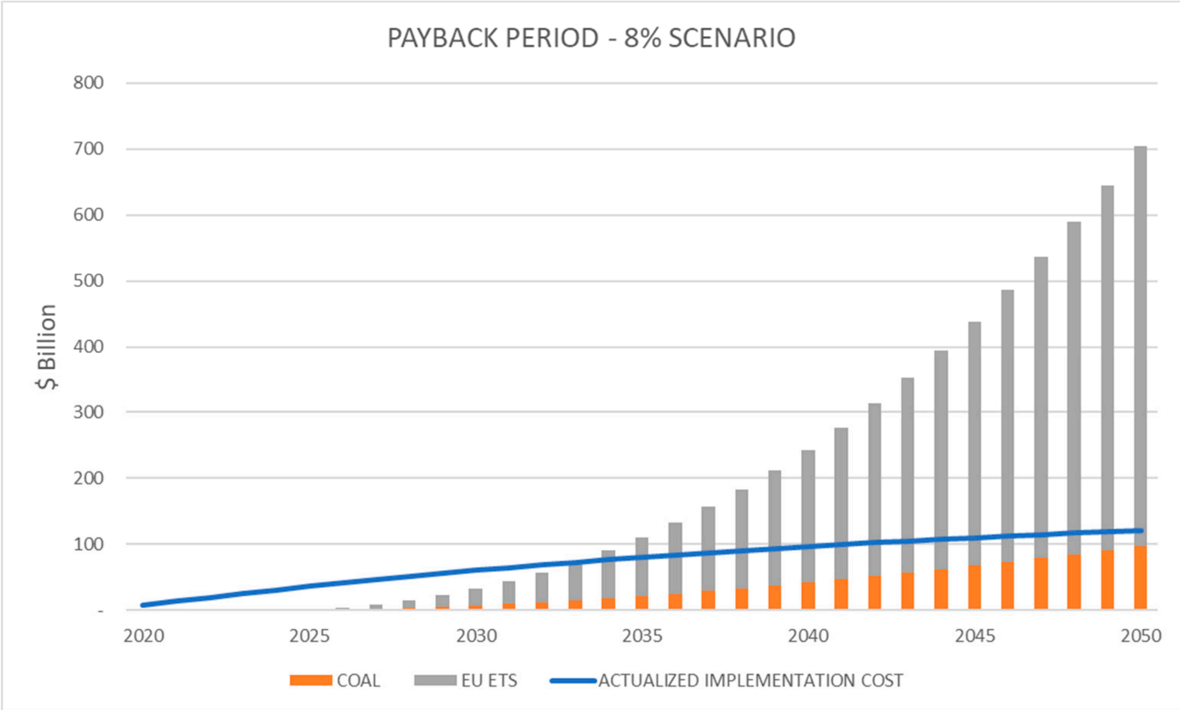

Figure 10. Payback period in the 8% scenario.

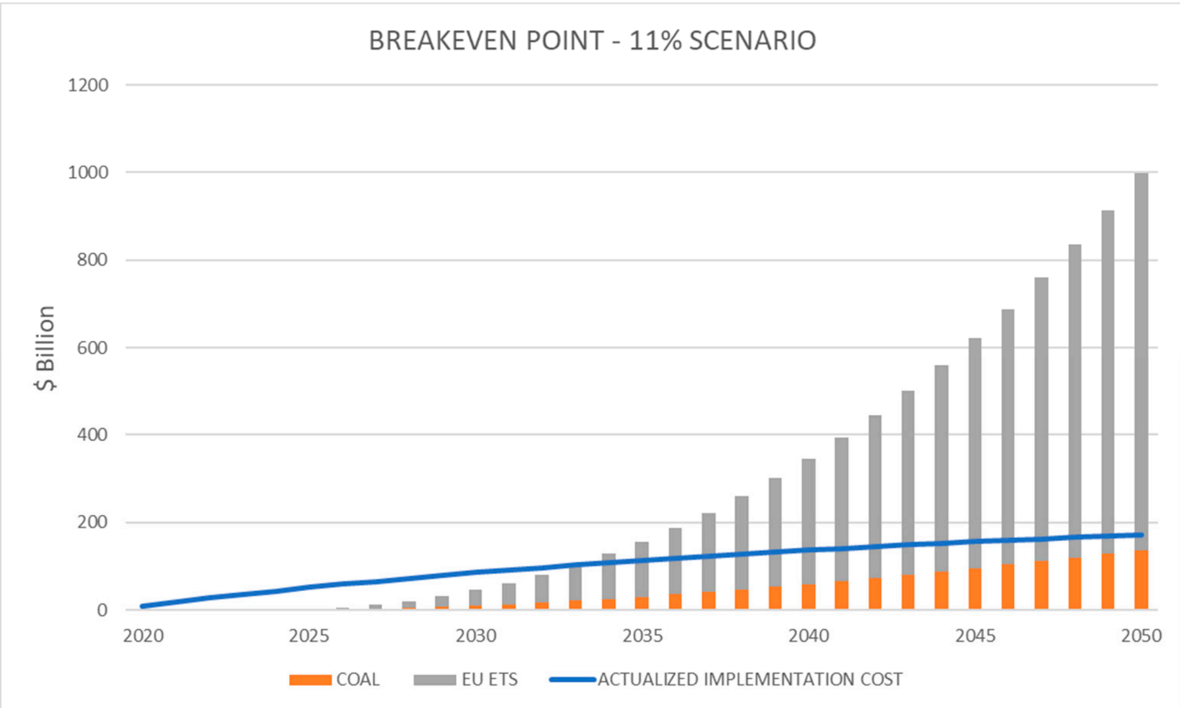

Figure 11. Payback period in the 11% scenario.

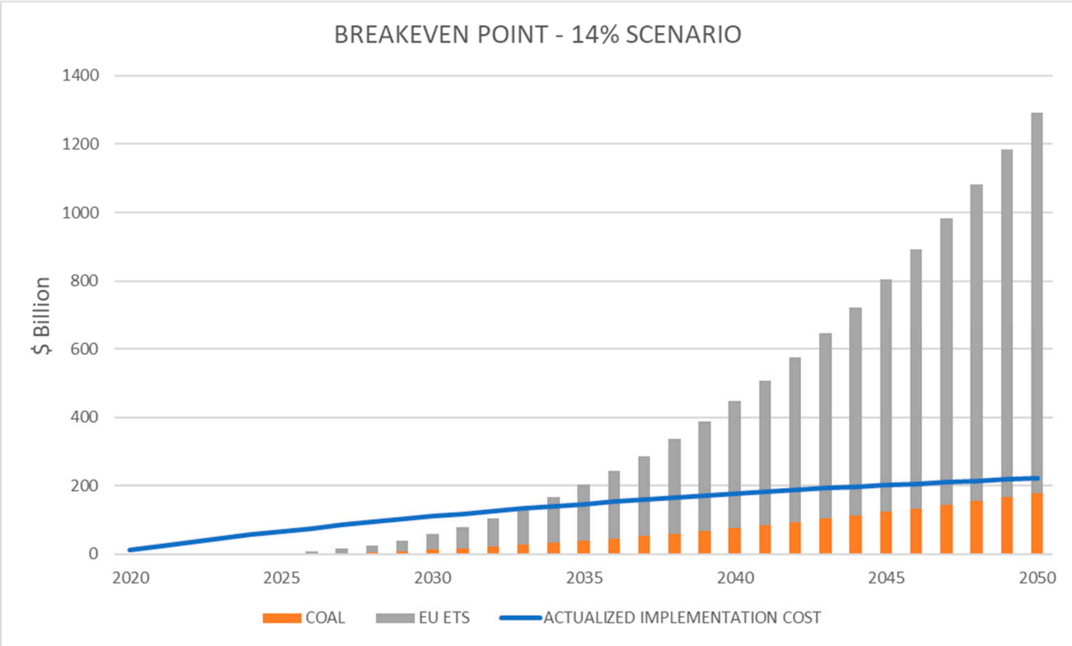

Figure 12. Payback period in the 14% scenario.

8. Conclusions

This study aimed to highlight how pumped hydroelectricity storage (PHS) implementation could support the penetration of variable renewable energy sources, therefore facilitating the phase-out of coal plants. This action considerably improves on the present scenario, not only regarding pollutants and economics but also providing significant social and functional benefits:

- The "peak shaving" and "valley filling" of PHS help coal-based stations save fuel, avoid restart, smooth the output, and improve load efficiency. This is one of the system-wide effects of PHS, and it is known as levelling the load curve (LLC). While adjusting the demand–supply balance, PHS reduces the gap between the peak and off-peak demand. This provides thermal/nuclear power plants an "apparent" load curve (improved load curve), which allows them to operate continuously for a long time at stable output, thereby increasing fuel efficiency and decreasing operational stresses.
- PHS can adapt quickly to load changes and modulate frequency as well as maintain voltage. Therefore, it can just be used as an emergency backup to prevent system collapse.
- PHS is complementary in balancing the disequilibrium of renewable power generation and regulating the frequency of the grid [75].

We drew on various scientific sources on the subject as well as data from the World Bank to make forecasts on China's energy needs in the years to come, proposed a development plan, and analyzed already operational situations such as the Zhanghewan Pumped Storage Power Station in Hubei province. The aim was to highlight the results of increased implementation of these systems in an area where hydroelectricity is already widely used.

Renewable power may reduce the security and stability of the power system. Therefore, an effective and economic energy storage method is needed in China [75].

Several plans have been proposed for implementation between now and 2050 to predict long-term costs and benefits, with an estimated economic return around 2035. Implementing scenarios from 8% to 14% of the total capacity in China would be ideal according to a study reported by Zhang Diansheng, Chen Tao, and Yongxing Li [60]. However, it has also emerged that 4.5% and 6% scenarios would result in considerable reduction in CO_2-eq and coal emissions in addition to economic return.

In conclusion, as highlighted in the introduction, this article aimed to present the costs and benefits of the installation of a series of PHS plants in China in order to reduce use of coal for electricity as well as CO_2 emissions, taking into account the current situation and the IEA and EIA forecasts already mentioned. However, further work should be carried out to analyze the effects of BAT, implementation of smart grids [1], smart metering, energy efficiency policies and action, liberalization of the electricity market, and better integration of RES. The authors will be highly engaged in working on the next steps.

The results of the CBA are based on the electricity scenario in Figure 6, where Chinese coal power production would stay more or less stable in absolute terms until 2050. In fact, the model basically takes into account the business-as-usual scenario in other contexts, such as smart grid and smart metering deployment, RES development, etc., as mentioned above. Therefore, it is important to note that the results may lead China to leave the Paris Agreement. For this reason, we believe that it is necessary to add other modules to this CBA analysis and scenario in order to take into account the deployment of PHS with other policies. Indeed, the deployment of the PHS alone will bring results that can enable China to meet its contribution to the Paris Agreement.

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