

Article

Economic Assessment of Coal-Fired Power Unit Decarbonization Retrofit with High-Temperature Gas-Cooled Reactors

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Abstract: To mitigate global warming, phasing out coal in the global energy system orderly and rapidly is an important near-term strategy. However, the majority of coal-fired plants in China have operated for less than 15 years. Accelerated coal power plant retirements would lead to substantial asset stranding. Coal-to-nuclear (C2N) technology offers a potential solution by replacing coal boilers in existing coal-fired plants with nuclear reactors. In this study, the G4-ECONS model was used to assess the economics of repowering a 600 MW supercritical coal-fired power plant with two 272 MWe high-temperature gas-cooled reactors. The timeline for the C2N project and the additional cost of dispatching electricity from the grid during retrofitting were discussed. Results showed that the C2N total capitalized costs are 19.4% (baseline estimate, USD 5297.6/kW) and 11.1% (conservative estimate, USD 5847.2/kW) lower than the greenfield project (USD 6576.5/kW), respectively. And C2N projects need to reduce LUEC by at least 20% to become competitive. This study can inform engineering design decisions leading to more precise and cost-effective C2N projects.

Keywords: coal to nuclear; economic assessment; high-temperature gas-cooled reactor



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1. Introduction

Reducing CO₂ emissions to mitigate global warming requires decommissioning fossil fuels and spreading low-carbon energy sources like renewables and nuclear [1]. Towards carbon neutrality by 2060, China has announced its climate goal. In 2030, China is expected to reduce coal-fired power generation from 61.3% to 47.5%, while wind and solar power generation will rise from 9.3% to 22.5%, and nuclear power generation will increase to 7.5% [2]. Furtherly, by 2045, the proportion of wind and solar power generation will increase to 43.4%, the percentage of nuclear power will rise in an orderly manner to 11.7%, and coal-fired power will decline sharply to 23.4%.

The Chinese coal fleet, however, is younger than the global average with a total installed capacity exceeding 1100 GW. China's coal-fired plants have operated for less than 15 years, so they have longer lifespans than their counterparts in the United States and Europe [3]. Thus, China will face a higher risk of asset stranding if coal power plant (CPP) retirements are accelerated [4]. At the same time, due to the salient intermittency and volatility, wind and solar energy bring critical challenges to electricity supply security [5]. As a major base load power source in China's electrical system, coal-fired plants are crucial for wind and solar energy consumption. Thus, an alternative base load power source should be developed when CPP retires.

Nuclear technology, owing to its varied fuel sources [6], low greenhouse gas emissions, long electricity generation time, and weather-independent operation, can serve as a major base load power source and might be a compelling solution to carbon neutrality [7]. While

economics is one of the major limitations to the nuclear energy development [8], coal-to-nuclear technology (C2N) offers a potential solution by replacing coal boilers in existing CPPs with nuclear reactors. Such a strategy can solve CPP retirement asset stranding and increase nuclear power plants' share. Moreover, reusing some CPP components, including grid access and infrastructure (e.g., transmission lines, substation equipment, water access, steam cycle components, auxiliary buildings, water supply, and transportation access), can also reduce the construction costs of nuclear power plants (NPPs), making advanced nuclear energy more cost-competitive [9]. Currently, C2N has attracted widespread attention from scholars in China, the United States, Poland, South Korea, India, Indonesia, and other countries [10].

Łukowicz et al. [7] analyzed the program that repowering a supercritical CPP steam cycle with a modular light-water reactor. Due to the significantly lower steam pressure (7 MPa) and temperature (285 °C) produced by the nuclear system, compared to the steam parameters of 28 MPa/560 °C/580 °C of the supercritical turbine unit, the turbine efficiency decreased 5–8 percentage points [7,11]. Using Generation IV nuclear reactors with higher steam parameters can improve turbine efficiency after retrofitting. Bartela et al. [12] conducted a techno-economic analysis for repowering a 460 MW supercritical coal-fired unit by two fluoride-salt-cooled high-temperature reactors equipped with a molten salt TES system. The result showed that the integrated system was flexible to change turbine island loads and could achieve an annual thermal efficiency of 45%. Researchers from different regions assessed the C2N potential and associated benefits in their own countries. Xu et al. [13] described a strategy to retrofit existing Chinese coal-fired power plants with high-temperature gas-cooled reactor-pebble-bed modules (HTR-PM) units. Cruz et al. [1] suggested that 28 coal-fired power generation units, accounting for 6 GW of the total coal capacity of 12 GW in the Philippines, were suitable for retrofitting with a small modular nuclear reactor (150 MWe/471.2 °C/17.8 MPa). This strategy could save around USD 6 billion in total upfront costs and avoid approximately 27,400 kilotons of CO₂-equivalent emissions each year.

Nowadays, two prominent advanced reactor developers, X-energy and TerraPower, have begun planning C2N projects [14]. To assess the economic feasibility and viability of these projects, it is critical to understand the costs associated with coal repowering with nuclear energy. As the high-temperature gas-cooled reactor (HTGR) technology is still in its infancy, the cost model is expected to be accurate by –30% to +50% [15]. However, even less than precise cost models can still identify trends, enabling engineering design decisions to be more cost-effective [16]. Currently, few analyses have been conducted on the economic feasibility of using HTGR for C2N projects in China, especially in relation to the construction timeline. Thus, this paper uses the Generation IV Excel Calculation of Nuclear Systems (G4-ECONS) [17] model to assess the economics of repowering a supercritical coal-fired power plant with an HTGR. The timeline for the C2N project was also discussed in accordance with Chinese nuclear power unit safety licensing procedures. NPP greenfield projects and C2N projects were compared in terms of levelized unit of electricity costs. The study will help future decision-makers to determine whether C2N is suitable for implementation and reduce investment risk.

2. Materials and Methods

This section discusses parameters of the coal-fired reference unit and HTGR, economic estimation methods, and C2N projects' cost estimation items.

2.1. Coal-Fired Reference Unit and HTGR

The retrofitted coal-fired unit has an electric capacity of 600 MW, and other steam parameters are presented in Table 1. And the steam pressure and temperature of this reference unit are typical among coastal CPPs in China [13].

Table 1. Steam parameters of reference coal-fired unit.

Item	Parameter
Gross Electrical capacity, MW	600
Thermal capacity, MW	1450
Main Steam Flow Rat, t ⁻¹	1724.8
Main Steam Pressure, MPa	24.2
Main Steam Temperature, °C	566

The HTGR is an advanced nuclear reactor design that supplies high-temperature heat energy of 750–950 °C [18]. Such high-temperature process heat can be used in a wide variety of applications including industrial process heat (for example, desalination, hydrogen generation, etc.), moderate electricity generation, and cogeneration [19]. Thus, HTGR is considered a promising candidate for C2N projects [20]. Table 2 presents different HTGR designs. Based on the capacity and steam parameters of the original CPP (Table 1), two SC-HTGR units were chosen to replace the boiler in this study.

Table 2. Parameters of different HTGR.

Acronym	HTR-PM [21]	PBMR [22]	Prismatic HTR [23]	SC-HTGR [16]
full name	High-Temperature GC-Pebble-Bed Module	Pebble-Bed Modular Reactor	Prismatic Modular High-Temperature GCR	Steam Cycle High-Temperature Gas-cooled Reactor
Design Org.	Tsinghua University (China)	Pebble Bed Modular Reactor SOC Ltd. (Sunninghill, South Africa)	General Atomics (San Diego, CA, USA)	AREVA NP (Richland, WA, USA)
Thermal capacity	500 MWth	400 MWth	350 MWth	625 MWth
Gross Electrical capacity	210 MW	165 MW	150 MW	272 MW
Primary coolant flow rate	Helium 96 Kg/s	Helium 96 Kg/s	Helium 157.1 Kg/s	Helium 282 Kg/s
Core coolant outlet/inlet temperature	750/250 °C (7 MPa)	750/250 °C (6 MPa)	750/322 °C (6.39 MPa)	750/320 °C (6 MPa)
Steam temperature/pressure	567 °C/13.25 MPa	540 °C/12 MPa (195 Kg/s)	541 °C/17.3 MPa	560 °C/16.7 MPa (140.7 kg/s)
Feedwater temperature/pressure	205 °C	200 °C	193 °C/21.0 MPa	281 °C/24.3 MPa

2.2. Economic Assessment

Economic modeling is performed using the international Economic Modeling Working Group (EMWG) G4-ECONS model [17]. And the levelized unit of electricity cost (LUEC) is chosen as the assessment indicators. The LUEC is defined by the Organisation for Economic Cooperation and Development (OECD) [24] as:

$$\text{LUEC} = \frac{\sum [I_t + \text{FUEL}_t + \text{O\&M}_t + \text{D\&D}_t](1+r)^{-t}}{\sum [E_t(1+r)^{-t}]} \quad (1)$$

where

I_t is the capital expenditures in the period t ;

FUEL_t is the fuel expenditures in the period t ;

O\&M_t is the operation and maintenance expenditures in the period t ;

D\&D_t is the decommissioning and demolition expenditures in the period t ;

E_t is the electric energy production in the period t ;

r is the discount rate.

Assuming constant annual expenditures and energy production, and defining $\sum [(I_t)(1+r)^{-t}] / \sum [E_t(1+r)^{-t}]$ as the levelized cost of capital (LCC), Equation (1) becomes:

$$\text{LUEC} = \text{LCC} + (\text{FUEL} + \text{O\&M} + \text{D\&D})/E \quad (2)$$

Furtherly, the LCC can be calculated by following equation:

$$\text{LCC} = (\text{FCR} \times \text{TCIC})/E \quad (3)$$

where

FCR is the constant fixed charge rate;

TCIC is the total capital investment cost.

TCIC, which is the sum of overnight costs and construction loan costs, is converted to a mortgage that recovers all of the capital investment (principal plus interest) over the operational life of the plant.

An FCR is used to account for return on capital, depreciation, interim replacements, property tax, and income tax effects [25]. Generation IV cost estimation tax and depreciation considerations are ignored at present, and the constant FCR is calculated as a capital recovery factor:

$$\text{FCR} = X/[1 - (1 + X)^{-L_{\text{econ}}}] \quad (4)$$

where

X is the real discount rate (5%);

L_{econ} is the economic or regulatory life of the plant (years), assumed to be the same as the number of years of commercial operation.

2.3. C2N Projects' Cost Estimation

Table 3 lists items that affect the deployment cost of the C2N project.

Table 3. Reduced cost and increased cost items compared to a greenfield nuclear project.

Reduced Cost	Increased Cost
site and components reutilization	CPP decommissioning and demolition potential reduction in system efficiency operation and maintenance alternative electricity use during retrofitting

2.3.1. Site and Component Reutilization

Cost reduction coming from site and components reutilization is presented according to the Code of Account developed by the International Atomic Energy Agency. The results shown in Table 4 are the sum of a more detailed cost-saving breakdown for HTGR, which is based on a study of conventional island retrofit strategies presented in another study. Accordingly, the conservative estimate was defined as the lower limit of cost savings, while the baseline estimate was defined as the upper limit.

Table 4. Estimated C2N project savings for different items when compared to greenfield.

Code of Accounts [17]	Items	C2N Estimated Cost Savings (%)	
		Conservative	Baseline
21	Buildings, Structures, and Improvements on Site	12.	16.9
22	Reactor Plant equipment	0	0
23	Turbine/Generator Plant equipment	3	40

Table 4. Cont.

Code of Accounts [17]	Items	C2N Estimated Cost Savings (%)	
		Conservative	Baseline
24	Electrical equipment	8	90
25	Water intake and heat rejection plant	60	70
26	Miscellaneous plant equipment	28.	36.8

2.3.2. CPP Decommissioning and Demolition (D&D)

Demolishing unneeded CPP infrastructure, dealing with waste capping or removing coal ash, are included in this item. Coal ash contains a non-negligible number of radionuclides derived from the original composition of coal. To meet radiological limits at the site, it will be necessary to seal or remove ash if the coal plant site is to be reused for an NPP. The costs for CPP D&D and CPP ash removal are set as USD 145/kW (in 2022 USD) [26] and USD 123/kW (in 2022 USD) [27], which is consistent with the references.

2.3.3. Potential Reduction in System Efficiency

Considering the steam parameters mismatching between nuclear reaction and reused steam turbine [7], the capacity factor of the new repowering system is decreased from 93% to 90%.

2.3.4. Operation and Maintenance (O&M)

A nuclear reactor that reuses some CPP components will likely experience increased maintenance costs, due to using older components not designed for use in an NPP. These components may be run at off-optimal temperatures and pressures. In this study, the increase in maintenance labor and materials cost, which is about 60% [28] of total O&M cost, would be 1%-to-1% [26] proportional to the decrease in nuclear overnight capital cost (C2N versus Greenfield).

2.3.5. Alternative Electricity Use during Retrofitting

Consumers will receive no electricity from either the CPP or the NPP during retrofitting, so the additional cost of dispatching electricity from the grid should be paid. The cost can be calculated by the following equation:

$$C_a = t_a \times E_a \times \Delta C \quad (5)$$

where

C_a is the alternative electricity cost during retrofitting;

t_a is the time of consumer use alternative electricity;

ΔC is the additional cost of dispatching electricity from the grid.

3. Results and Discussion

This section discusses the C2N project timelines first. Secondly, the estimation process for one of the increased cost items in C2N projects, the additional cost of dispatching electricity from the grid, is described. Last, summing all the increased cost and reducing cost, the total capitalized costs and LUEC for C2N projects are analyzed.

3.1. C2N Project Timelines

The project activities flow graph is used here to analyze the engineering duration of a C2N project, and some simplifications are made. Three activity categories of CPP retrofit, NPP exploration and license, and NPP construction are shown in Figure 1.

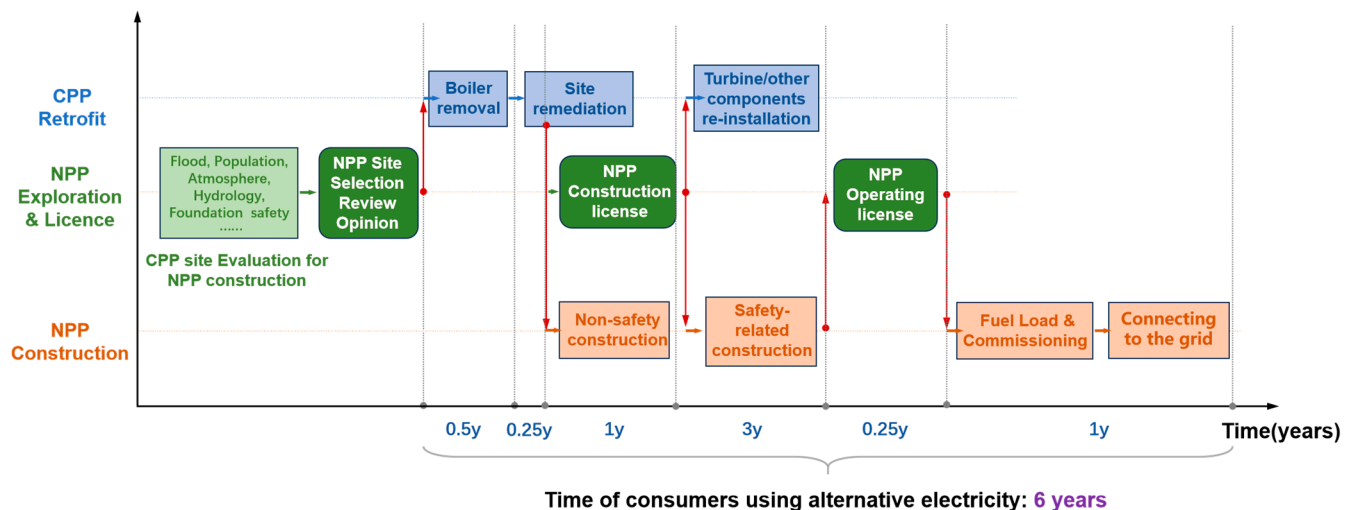


Figure 1. Project activities flow graph of C2N project.

As nuclear power plants require more stringent construction requirements than thermal power plants, a site re-evaluation should be conducted before a C2N project. It includes relevant government planning, flood control levels, geological disaster prevention, earthquake protection requirements, ecological and environmental protection areas, as well as additional assessments of underground rock and soil layers and foundation safety, atmospheric dispersion and population distribution assessments, and emergency plans.

After conducting the safety assessment and demonstration of site selection for nuclear facilities, the nuclear facility operator should submit the application for review of the nuclear facility site selection and report of safety assessment to the National Nuclear Safety Administration. The nuclear facility operator will receive the NPP Site Selection Review Opinion following the examination. And then CPP boiler removal could begin.

As soon as the site is cleaned and repaired, non-safety construction can be undertaken and a preliminary safety analysis can be conducted at the same time. And nuclear power plant safety parts such as the pouring of nuclear island concrete can be constructed once the National Nuclear Safety Administration issues the NPP Construction License. In parallel, steam turbines and other CPP reused components can be installed at the corresponding stage. When the Nuclear Power Plant Operating License is issued, the first loading and trial operation can start. Finally, following the completion of the trial operation period and the final safety analysis, the NPP can be connected to the grid. Typically, a nuclear power plant will take over five years to construct [29], and the construction time of C2N may be 6 years, which is from the boiler removal to the re-connection to the grid. And this is also the time for consumers to use alternative electricity. Such estimation is conservative compared to other study [12]. Design standardization and modular construction should reduce construction times in the future. Then, the financial cost will decrease accordingly.

3.2. Additional Cost of Dispatched Electricity from the Grid

The additional costs incurred by dispatching electricity from the grid were calculated using the difference between the dispatched electricity price and the normal grid electricity sale price (Table 5). It is assumed that the dispatching electricity price is the sum of the electricity feed-in price, transmission and distribution price, general line loss, and governmental funds and surcharges. Retail power prices and medium- and long-term transaction prices in electricity markets in various provinces were used to estimate the electricity feed-in prices. In Liaoning Province, Shandong Province, Zhejiang Province, and Fujian Province, retail prices were used, while in Jiangsu Province and Guangdong Province, medium- and long-term transaction prices were used.

Table 5. Total dispatched electricity price and normal sale price (flat) in different provinces. Industrial and commercial electricity price, single-system electricity price, voltage level 1–10kV.

Electricity Trading Platform	Retail Market (Lowest Prices, USD/kWh)				Medium- and Long-Term Market (Annual Average Price, USD/kWh)	
	Province	Liaoning	Shandong	Zhejiang	Fujian	Jiangsu
Electricity feed-in price	0.0569	0.0522	0.0646	0.0581	0.0629	0.0647
Transmission and distribution price	0.0290	0.0287	0.0298	0.0227	0.0296	0.0239
General line loss rate	4.71%	3.31%	3.53%	3.60%	3.18%	3.31%
Governmental funds and surcharges	0.0037	0.0045	0.0041	0.0038	0.0041	0.0038
Total dispatched electricity price	0.0939	0.0882	0.1019	0.0876	0.0997	0.0955
Normal sale price (flat)	0.0869	0.0846	0.0925	0.0800	0.0890	0.0938
Increased percent	8.0%	4.3%	10.1%	9.5%	12.0%	1.8%

As shown in Table 5, the total dispatched electricity price varies from USD 0.0882/kWh to USD 0.1019/kWh based on supply and demand conditions in different provinces. And dispatched electricity prices increased from 1.8% to 12.0% in different provinces when compared with normal grid electricity sales prices. Consequently, it is estimated that the additional cost of dispatched electricity is approximately 5–15% of the original grid electricity consumption cost.

3.3. Total Capitalized Cost and LUEC for C2N Project

Table 6 presents the breakdown of construction costs for greenfield NPP projects and C2N projects based on two evaluation criteria (C2N-conservative and C2N-baseline). Assessment conditions: construction time is 6 years; real discount rate is 5%; plant life is 60 years. Every project's capitalized pre-construction cost and the first fuel loading cost are the same, all at USD 148.7/kW and USD 326.5/kW.

Table 6. The breakdown of construction costs of different projects (in 2024 USD).

Items	Greenfield	C2N-Conservative	C2N-Baseline
Capitalized Pre-construction Costs	\$148.7/kW	\$148.7/kW	\$148.7/kW
NPP Construc. Capitalized Direct Cost	\$3288.0/kW	\$2532.3/kW	\$2391.6/kW
NPP Construc. Capitalized Indirect Cost	\$1874.2/kW	\$1443.3/kW	\$1363.2/kW
First Fuel Load Cost	\$326.5/kW	\$326.5/kW	\$326.5/kW
Financial Costs	\$939.0/kW	\$811.4/kW	\$748.5/kW
CPP D&D (including ash removal)	—	\$186.1/kW	\$186.1/kW
Dispatching Electricity Costs during retrofitting	—	\$398.9/kW	\$133.0/kW
Total Capitalized Cost	\$6576.5/kW	\$5847.2/kW	\$5297.6/kW

The direct capital investment part of NPP construction for greenfield projects is USD 3288.0/kW. In the conservative estimate, the capitalized direct cost of the C2N project would decrease by 23.0% to USD 2532.3/kW, while in the baseline estimate, it would decrease by 27.3% to USD 2391.6/kW. Since capitalized indirect costs are proportional to capitalized direct costs, their decline was consistent. Accordingly, C2N's financing cost declined by 13.6% in the conservative estimate and by 20.3% in the baseline estimate compared with USD 939.0/kW for the greenfield project.

However, dismantling some CPP components and coal ash cleaning (USD 186.1/kW), and paying for dispatching electricity during the retrofitting (USD 398.9/kW in the conservative estimate, and USD 133.0/kW in the baseline estimate), incurred additional costs for the C2N project. These items offset the cost savings from CPP components reuse and shrank the decline in overall C2N total capitalized cost to 11.1% (conservative estimate, USD

5847.2/kWh) and 19.4% (baseline estimate, USD 5297.6/kWh), compared to the greenfield project (USD 6576.5/kWh).

Figure 2 illustrates the LUEC of different projects. Annual fuel costs and decommissioning cost parts of the different projects were nearly unchanged. LUEC for greenfield was USD 0.0834/kWh for a 60-year operating period, of which USD 0.0426/kWh was the capital component of LUEC and USD 0.0175/kWh was the component of annual O&M cost, while in the conservative estimate, the LUEC of the C2N project would be USD 0.0813/kWh, where the capital part decreased to USD 0.0381/kWh, and the part of annual O&M cost increased to USD 0.0192/kWh. Moreover, the LUEC of the C2N project reduced to USD 0.0791/kWh in the baseline estimate, where parts of capital cost and annual O&M cost were USD 0.0351/kWh and USD 0.0199/kWh. In this study, the estimate for annual O&M cost increasing due to reusing some CPP components is optimistic. For long-serving CPP, this cost part may rise further. In the future, this part of the assessment should be refined for CPP units with different service years.

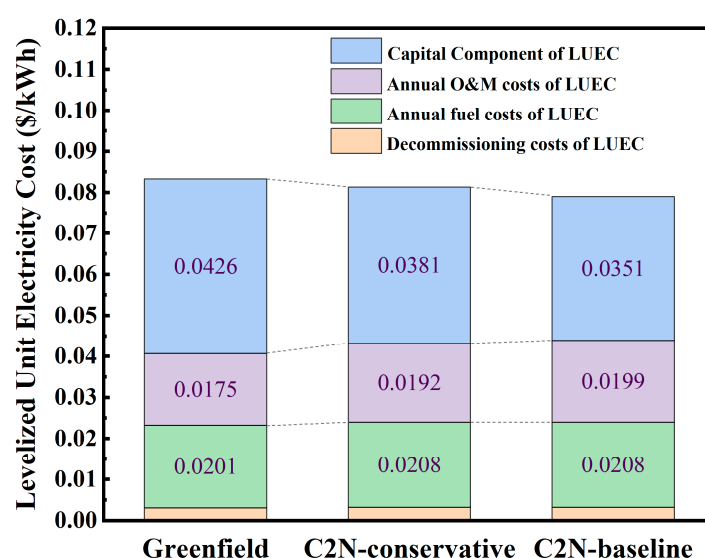


Figure 2. LUEC of different projects (in 2024 USD).

Figure 3 shows the feed-in prices for some NPPs in China since 2019. Combined with local authorities' support, the Chinese government provided financial support to the first batch of third-generation NPPs that included imported technology. Consequently, for the Taishan Phase I Nuclear Power Project in Guangdong, the Sanmen Phase I Nuclear Power Project in Zhejiang, and the Haiyang Phase I Nuclear Power Project in Shandong, the feed-in prices were USD 0.604/kWh, USD 0.584/kWh, and USD 0.0577/kWh during trial operation, respectively. (The exchange rate between RMB and USD was set as 7.2), while the feed-in prices of Jiangsu Tianwan NPP Unit 6th and Hongyanhe NPP Unit 6th were only USD 0.0543/kWh in 2021 and USD 0.0521/kWh in 2022. Compared to the feed-in prices of NPPs in China, the LUEC of C2N projects will have to be reduced by at least 20% to become competitive in the future. As the fourth-generation nuclear technology used in the C2N project has not yet been commercialized, the cost of C2N projects may decline further in the future. Moreover, if the government introduces a carbon tax on the electricity industry, C2N will become an attractive low-carbon power technology.

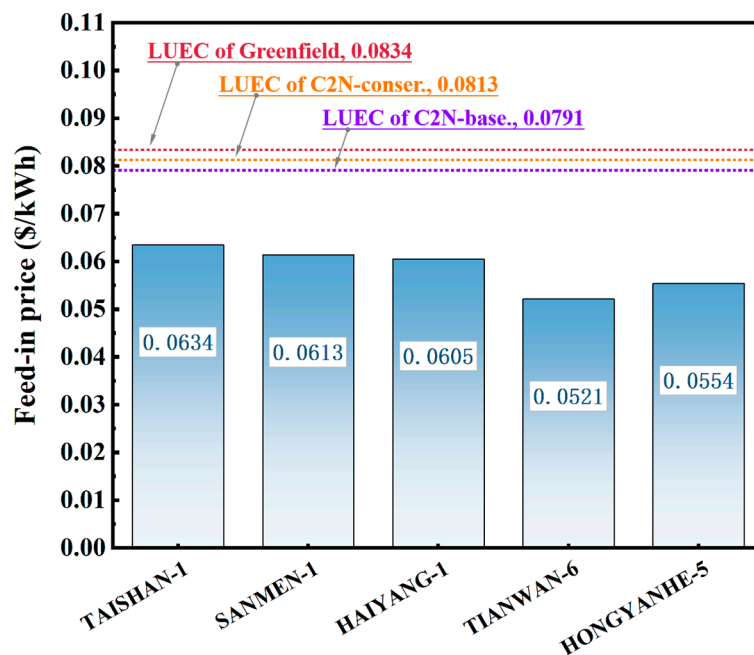


Figure 3. Feed-in prices for some NPPs in China. (in 2024 USD).

4. Conclusions

In this study, the G4-ECONS model was applied to investigate the economics of repowering a supercritical coal-fired power plant in China with a high-temperature gas-cooled reactor. The results once again show that C2N projects perform better economically than stand-alone, greenfield nuclear projects. However, this cost reduction is insufficient. Compared to the feed-in prices of NPPs in China, the LUEC of C2N projects will have to be reduced by at least 20% to become competitive in the future. In future work, it will be necessary to make more precise estimates. A comprehensive ageing management and life assessment for CPPs components should be conducted. And CPP components need to be divided into two categories: replaceable components and reusable components, and analyze different costs for each category.

In addition, the cost of dispatching electricity from the grid during the retrofitting should be given more attention. It may account for 5% of the total capitalized cost. With proper planning in advance, this cost can be reduced.

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Conflicts of Interest: Authors Bixiong Luo, Li Zhang, Wei Li, Yanlin Su, Yongjian Ye, Yi Zhang, and Xinwei Zhu are employed by the company China Power Engineering Consulting Group Co., Ltd. Chenyu Wang and Yixuan Liu are students in the College of Energy at Xiamen University. All authors declare no conflicts of interest.

Abbreviations

C2N	Coal-to-nuclear
CPP	Coal power plant
D&D	Decommissioning and demolition
EMWG	Economic Modeling Working Group
FCR	Constant fixed charge rate
G4-ECONS	Generation IV Excel Calculation of Nuclear Systems
HTGR	High-temperature gas-cooled reactor
HTR-PM	High-temperature gas-cooled reactor–pebble-bed modules
LCC	Levelized cost of capital
LUEC	Levelized unit of electricity cost
NPP	Nuclear power plant
OECD	Organisation for Economic Cooperation and Development
O&M	Operation and maintenance
PBMR	Pebble-bed modular reactor
SC-HTGR	Steam cycle high-temperature gas-cooled reactor
TCIC	Total capital investment cost

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