Uncovering the potential of Coal-to-Nuclear in the new energy system

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Reducing the share of coal-fired power while increasing the proportion of nuclear energy is one of the important strategies to achieve the goal of carbon neutrality as early as possible.[1] In recent years, the concept of "Coal-to-Nuclear (C2N)" has been introduced globally, i.e., transforming existing coal-fired power plants into nuclear ones.[2] This approach, also known as repowering or repurposing, aims to leverage the geographical advantages, existing grid feed-in facilities, and relevant permits of a power plant. The core value is to transition from high-emission coal-fired power to low or even near-zero carbon nuclear power, addressing the severe challenges posed by global climate change and accelerating the decarbonization of energy systems.

So far, coal-fired power still dominates the energy supply globally including China. C2N presents a novel strategy for energy transition. This strategy has the potential to lower down the construction costs of nuclear power plants, promote the development of advanced nuclear systems, and ensure energy equity for phasing out the whole coal power industry. As such, C2N could play a significant role in advancing the development of new energy systems.

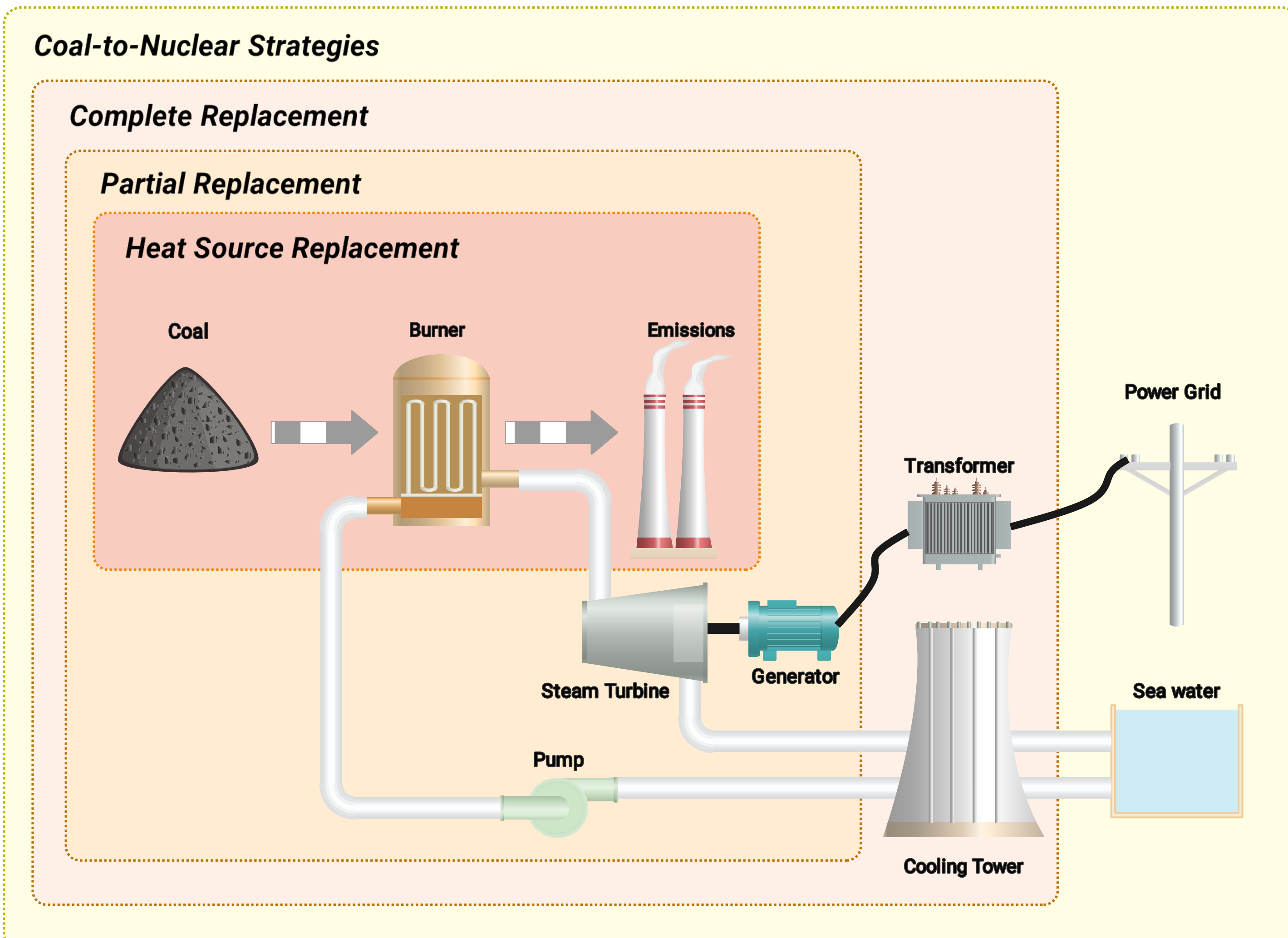

Figure 1. Schematic of C2N

CURRENT SITUATION OF C2N

C2N mainly encompasses three implementation schemes[3] (see Figure 1):

1. Heat Source Replacement: This involves substituting coal-fired boilers with nuclear reactors while retaining the steam turbines and other infrastructure.

2. Partial Replacement: This scheme replaces the coal-fired boilers and steam turbines, but some infrastructure, such as the cooling systems, grid feed-in facilities (e.g., transmission lines, and substations) is all preserved.

3. Complete Replacement: This scheme retains only the exiting site and grid feed-in facilities, with all other infrastructure being rebuilt entirely.

Typically, the required steam temperature exceeds 450°C for the steam turbines of coal-fired power plants, whereas the most common pressurized water reactors (PWRs) can only provide steam temperatures up to 350°C. Therefore, conventional PWRs are suitable only for Partial or Complete Replacement schemes. Only a few reactor types, such as the high-temperature gas-cooled reactors and sodium-cooled fast reactors, are suitable for the Heat Source Replacement.

It is known that the economic viability of nuclear power is a critical factor limiting its development. While the orientation of C2N concept at its inception was to reduce the costs of nuclear power plants. Early studies on C2N claimed that the Heat Source Replacement scheme could reduce the construction costs of nuclear power plants by 20-30%. However, significant differences exist between the steam turbines of coal-fired power plants and those of nuclear power plants. Direct replacement of coal-fired boilers would require additional technological modifications to enable the reuse of these steam turbines. Thus, a 20-30% cost reduction appears overly optimistic; a more reasonable estimate might be around 10%. For the Partial and Complete replacement schemes, the most valuable components retained are the site and grid feed-in facilities, which are expected to reduce construction costs by 5-10%. Hence, the Heat Source Replacement scheme is suitable for coal-fired power plants with shorter operating lifespans, while the Complete Replacement scheme is more applicable to decommissioned or near-decommissioned coal-fired power plants. Currently, the Complete Replacement scheme seems more feasible, as it avoids the complexities associated with retrofitting coal-fired power plants and employee issues. TerraPower, backed by Bill Gates, plans to construct a sodium-cooled fast reactor near a decommissioned coal-fired power plant.[4]

The potential scale of C2N directly relates to its practical values. For instance, considering the Complete Replacement scheme of C2N, approximately 563 GW of coal-fired power units exist with over 40 years operation globally. This figure is 1.5 times the current installed capacity of nuclear power worldwide. If we disregard operational lifespan and only consider coal power units within 20 km of a water source as having potential for C2N, the installed capacity rises to 1,376 GW, i.e., 3.7 times the current global nuclear power capacity.

Note that not all sites of coal-fired power plant are suitable for transformation into nuclear ones. Several key criteria need to be assessed for the suitability of C2N, such as geological conditions, distance to water sources, proximity to urban areas, and surrounding population density, etc. Additionally, different countries' standards for nuclear power plant construction would influence these criteria. For instance, China currently prohibits the construction of inland nuclear power plants, indicating only coastal coal-fired power plants could be viable candidates for C2N.

CHALLENGES AND OPPORTUNITIES OF C2N

Currently, C2N remains in the conceptual stage, with no global precedents for directly transforming coal-fired power plants into nuclear ones. As such, the potential for C2N to deliver greater value within future energy systems faces multifaceted uncertainties.

To achieve carbon neutrality before 2060, many coal power plants will need to be shut down or transformed as fast as possible. C2N presents a more favorable option for transitioning from coal-fired power compared to carbon capture, utilization, and storage (CCUS) due to its superior techno-economic feasibility generally. Furthermore, in countries with limited natural resources of renewables, where solar, wind, and hydropower may not provide affordable electricity, C2N could play a crucial role potentially.

Just as coal-fired power plants are essential to participate actively in our power systems for balancing the highly intermittent renewables when its penetration rate is considerable, the power plants implementing C2N can also fulfill similar balancing roles in the future power landscape. Thus, C2N can serve as a stabilizer in addressing the challenges posed by large-scale penetration of intermittent renewables.[5]

As for the nuclear power system itself, it needs to be redesigned to meet the demands of C2N. Note that while coal-fired and nuclear power plants share similarities in thermal energy conversion principles, the thermal conversion equipment (steam turbines) and processes they employ differ significantly. Hence, to enable the Heat Source Replacement scheme of C2N and further play the power balancing role, customized nuclear power systems need to be designed. For example, a customized C2N nuclear power plants could be integrated a heating storage.

Regulatory and licensing challenges could be significant hurdles for C2N. This not only involves oversight and certification of nuclear power plants but also encompasses issues related to the decommissioning and repurposing of coal-fired power plants. Coordination among various regulatory departments is essential to establish guidelines that ensure the development and implementation of C2N projects.

SUMMARY AND THE WAY FORWARD

C2N implies significant potential for large-scale application in the decarbonization of our energy systems. It represents one of the most feasible strategies for replacing coal-fired power plants to mitigate climate change, while also reducing the construction costs of nuclear power plants, promoting the development of advanced nuclear systems, and more importantly, ensuring energy equity for local coal-fired power phase-out by supporting the continuity of local electricity production and economics.

As a nascent field of research, C2N presents numerous questions that warrant further investigation. Key exploration areas include project timelines and procedure, site remediation and plant siting requirements, regulatory and certification processes, the establishment of emergency planning zones, and issues related to public acceptance.

In conclusion, while C2N offers a promising strategy toward a more sustainable energy future, addressing these challenges will be crucial for its successful implementation and integration into the global decarbonized energy landscape.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.