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Why coal-fired power plants should get nuclear-ready

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ABSTRACT

Nuclear power plant designs are becoming smaller so that the capacity of these small modular reactors (SMRs) is similar to that of coal-fired power units. The need to decarbonize the energy sector will leave infrastructure and workers of retired coal-fired power plants behind. From an environmental point of view coal-fired power plants should neither be built nor operated. If these plants are built/operated though, they should be designed in a way that they can be swiftly transformed to provide low-carbon energy. They should be designed to be nuclear-ready. The idea to transform coal-to-nuclear (C2N) is receiving increased attention. In this Perspective, we argue that akin to an earlier EU directive on carbon capture and storage (CCS) that made CCS readiness assessments necessary to obtain a building permit in the EU, C2N assessments could be provided by utilities of new and operating coal-fired power plants on a voluntary basis today, to maximize the utilization of existing infrastructure for clean energy production tomorrow.

1. Introduction

The energy sector is the predominant contributor to climate change. The World Economic Forum estimates that global carbon dioxide (CO_2) emissions from fossil fuels and cement production have increased by 1% in 2022 to a new record high of 36.6 billion tonnes [1]. There is general agreement that CO_2 emissions from energy production need to decrease and that they need to decrease rapidly. All options for carbon mitigation action can and should be considered in the process for clean energy transition. Nuclear power can produce energy reliably with minimal CO_2 emissions of around 15–50 g of CO_2 per kilowatt hour (gCO_2/kWh) [2]. The same study estimates that the average CO_2 emissions of gas-fired power plants is around 450 gCO_2/kWh and a staggering 1050 gCO_2/kWh for coal-fired power plants. New innovative nuclear power plant designs have a real chance to reduce upfront construction costs that are probably the largest obstacle to widespread use of nuclear power today [3–7]. The United States Department of Energy (US-DOE) distinguishes different generations (Gen I, Gen II, Gen III, Gen III+, Gen IV) of nuclear power plants. After early prototype reactors from the 1950s and 1960s (Gen I), first commercial reactors (Gen II) with improved safety characteristics were deployed in the 1970s to early 1990s. Most of today's nuclear power plants consist of more than one large Gen II nuclear reactor (usually two or more reactors form a nuclear power plant at one site) with nameplate capacities exceeding 1000 MW_{el} per reactor unit. Gen III and Gen III + reactors, deployed after the turn of the century are essentially still Gen II designs with incremental design improvements to increase cost-effectiveness, safety, security, and nonproliferation [8–10]. Most notably the nuclear reactors deployed became even larger, if compared to Gen II designs, to increase energy production while keeping other costs such as those for licensing fairly constant. The overall strategy of Gen III and Gen III+ reactor designs is economies of volume.

Gen IV reactors that have not been fully commercially utilized yet are the first to break in some configurations with the initial naval based light water reactor designs developed for submarines in a way that different cooling/moderator materials are used that will for instance enable higher-temperature (>600 °C) process heat applications beyond simple electricity production [11–15]. Low carbon emission, higher-temperature process heat applications are considered important for deep decarbonization of the economy [16]. Besides, the Gen IV reactor designs also break with the Gen III and Gen III+ reactor designs in a way that a larger number of the new designs stopped becoming bigger, but actually decreased in size with the promise that more of these smaller reactors can be built in shorter time as companies optimize their

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production. This class of nuclear reactors are called small and medium-sized reactors (SMRs) with typical nameplate capacity of 300–700 MW_{el} per reactor unit and/or small modular reactors (also abbreviated as SMRs) if they can be constructed in a modular fashion. The overall strategy of Gen IV SMR designs is economies of scale [17,18].

The International Atomic Energy Agency (IAEA) is taking note of promising advanced nuclear reactor designs. On its Advanced Reactors Information System (ARIS) platform[1] the IAEA is currently listing 78 different reactor designs from 16 countries (and the EU). Among these 78 reactor designs, 48 are SMRs of which 13 are light water-cooled. Light water-cooled SMRs such as the Chinese ACP100 [19] or the NuScale reactor design from the United States [20] (to name two prominent examples) are probably the furthest developed SMRs given the long experience of building and operating (usually larger) light water-cooled nuclear power plants and light water-cooled naval reactors.

Nuclear power plant designs, and here specifically SMRs that use coolants beyond light water are developing considerable momentum though, and the Generation IV International Forum (GIF) consisting of thirteen members (Argentina, Brazil, Canada, China, Euratom, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom and the Unites States) that joint forces in 2001 to lead international collaborative efforts to develop the next generation nuclear energy system, recognizes six reactor concepts, listed in Table 1, that were selected from a list of 130 designs by experts from the GIF for further research and development [21,22]. VHTRs are usually considered to be the furthest developed GIF Gen IV design as a result of the relatively rich history of research reactors, pilot- and demonstration plants operated and operating in different countries [23].

The reduced capacity of SMRs is primarily a result of dramatically increased inherent safety features that are based on physical phenomena that can be accomplished with reduced reactor core sizes [24]. Besides, the idea is that this class of smaller reactors can be built much faster at dramatically reduced capital costs if compared to the many times larger nuclear power reactors that characterize the Gen III and Gen III+ generation and are operated today. In this context it is noteworthy to mention that the installed capacity of an of 300 MW_{el} “small” sized nuclear reactor is still a hundred times the nameplate capacity (ca. 3 MW_{el} [25]) of an average wind turbine, and roughly that of a coal-fired power unit (here again multiple units form a larger power plant) although Tong et al. ([26]) shows well that the capacity of coal-fired units can vary significantly.

The construction time of a SMR, or the time before first electricity is produced, and thus income is generated is supposed to be dramatically shorter than that of larger nuclear power plants, hopefully improving the overall economics of the endeavor [27,28]. As of now the beforementioned novel SMR designs still need to prove their economic and environmental competitiveness [29–37]. This process is well under way though with the HTR-PM (High-Temperature gas-cooled Reactor Pebble-bed Module) [38], a helium-cooled, graphite-moderated SMR demonstration plant (a VHTR in Table 1) that reached criticality in Shandong Province, China, in 2021. Interestingly the smaller size of these advanced nuclear reactors does not only allow integrating them better in future energy grids than large, water-cooled reactors [39], but also allows them to replace coal-fired boilers that often have similar nameplate capacities and are also mostly operated as base-load power plants.

1.1. Coal to nuclear (C2N)

The idea to transform retired coal-fired power plants to nuclear ones and using as much of the otherwise idle infrastructure, as schematically shown in Fig. 1, is receiving increased attention as a result of the similar nameplate capacities of SMRs and coal-fired power units as well as the large amount of coal-fired power plants that will be phased out in the near future [40,41]. The US-DOE identified not less than 125 sites in the United States with an accumulated capacity potential of nearly 200 GW_{el} (more than 15% of the country’s electricity generation capacity) that could profit from a C2N retrofit [42]. Qvist et al. [43] provided a technical analysis for the C2N potential in Poland, a country that currently generates more than 80% of its electricity from fossil fuels, and Bartela et al. [44,45] provided additional economic considerations for retrofitting coal-fired power plants in Poland with fluoride-salt-cooled high-temperature reactors (FHRs), a specific group of promising advanced nuclear reactors that are presently being developed in China and the United States [46]. Xu et al. [47] further analyzed the C2N potential in China and found a staggering retrofit decarbonization potential of 906 GW_{el} if 2264 coal-fired power units would be transformed to nuclear powered ones.

While the largest potential for C2N maybe found in China that is the country responsible for operating half of the global coal-fired power plant fleet today [48] the first coal-fired power unit to actually be transformed into a nuclear one may well be found in Kemmerer, Wyoming in the United States [49]. Here, TerraPower LLC., a company founded and owned by Bill Gates, plans with help of the US-DOE, that covers half of the USD 4 billion project costs, to erect an advanced sodium-cooled reactor [50], to demonstrate that C2N can work. Bill Gates is not the only one betting big on C2N. Holtec International Inc. (also from the United States) has recently developed a multi-stage compressor system that, according to the company, allows its SMR-160 pressurized water reactor to replace most fossil-fuel power plants without additional external energy input [51]. If successful, such a system can be considered game changing as it allows water-cooled reactors, for which most construction and operation experience exists today, to provide the super-heated steam needed to replace coal-fired boilers. Recent work carried out by Łukowicz et al. [52] indicates, however, that adapting steam turbines (even for supercritical steam parameters) of LWRs is technically possible, but economically challenging.

The idea to “simply” replace coal-fired burners with nuclear powered ones and use as much of the existing infrastructure (cooling towers, grid lines, turbogenerators, etc.) as well as the existing workforce of well-trained engineers, practitioners and other staff that is needed to operate a power plant is extremely appealing. So appealing that we argue that the approach to transform coal-fired power units into nuclear ones should be promoted in a similar way that carbon capture and storage (CCS) was and still is promoted for fossil fuel plants today. A 2009 EU directive [53] does for instance require that all new coal-fired power plants show that they are CCS-ready. We believe that from an environmental point of view coal-fired power plants should neither be built nor operated. If these plants are built/operated, as is still the case in many places around the world though, we believe that both new and old coal-fired power plants should show on a regular basis that they are not only CCS- but also nuclear-ready. Unlike the initial idea of CCS-ready [54], the nuclear-ready approach would in no way promote the prolonged operation of coal-fired units but foster swift transition to clean energy production, thus offering the security that energy is produced permanently with no direct carbon emissions. Reporting on the nuclear-readiness level of a coal-fired plant would support that as much of the existing plant infrastructure, investments and resources as possible are utilized for future clean energy production. If compiled, the reported data about the nuclear-readiness level of different coal-fired plants would provide a map that summarizes economic opportunities to site owners and surrounding communities as well as investors that want to promote clean energy transition. This data can be used to better compare the perceived economic and environmental risks and benefits of C2N if compared to other technologies such as CCS for which considerably more data already exists [55,56]. We thus advocate for a

[1] https://aris.iaea.org/sites/SMR.html.

Table 1
Overview of the Gen IV reactors identified by the Generation IV International Forum (GIF) [16,17].

System		Neutron Spectrum	Coolant	Outlet Temp. (°C)	Fuel Cycle	Size (MW_e)
VHTR	Very-High-Temperature Reactor	Thermal	Helium	900-1000	Open	250–600
SFR	Sodium-Cooled Fast Reactor	Fast	Sodium	550	Closed	30-1000
SCWR	Supercritical-Water-Cooled Reactor	Thermal	Water	510–625	Closed	300-1000
GFR	Gas-Cooled Fast Reactor	Fast	Helium	850	Closed	1200
LFR	Lead-Cooled Fast Reactor	Fast	Lead	480–800	Closed	20-1000
MSR	Molten-Salt Reactor	Epithermal	Salt	700–800	Closed	250-1000

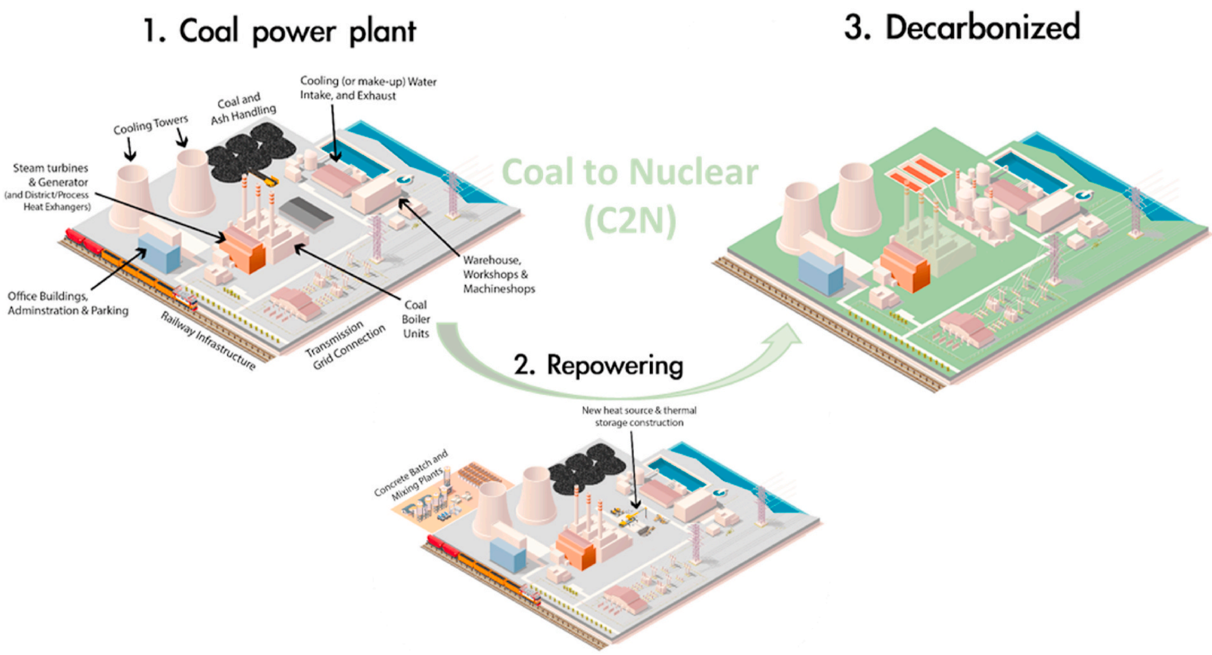

Fig. 1. Schematic overview of Coal to Nuclear (C2N) transformation.

voluntary approach in which coal-fired power plant owners can signal their increased value to potential investors over other stranded assets by showing that they are more nuclear-ready than other utilities or possible greenfield construction sites. Declaring the nuclear-readiness level would thus not be a direct CO_2 reduction option as is the case with CCS-readiness, but a way to completely eliminate direct CO_2 emissions during energy production at a certain location in the near future. Since today the majority of coal-fired power plants are operated outside the EU, and new power plants are (with very few exceptions) also all licensed outside the EU, we argue for a global initiative to coordinate the nuclear-readiness assessments. Specifically, we believe that such a task could be supported by the GIF and the IAEA, or a similarly authoritative and accepted international body.

1.2. *What it takes to get nuclear-ready*

The nuclear readiness or the ability to utilize otherwise idle infrastructure of a coal-fired power plant, and thus create cost savings depends on:

1. The coal-fired power plant and its location,
2. The potential nuclear reactor used as a replacement.

Advanced Gen IV SMRs that can produce steam at elevated pressure and temperature, matching the parameters of the turbogenerator of today's fossil fuel powered plants obviously have an advantage over larger Gen III+ light water reactors that do not reach these high temperatures. If successful, the innovation of Holtec International Inc., might change this as briefly discussed earlier. The motivation of the nuclear readiness level should, however, not be the evaluation of the nuclear part (this can best be done by the nuclear industry itself who is already actively promoting their products), but a technology neutral assessment of the feasibility of a potential C2N retrofit of the fossil fuel power plant. In this way thermal power plant developers, nuclear, but also others such as concentrated solar power (CSP) plant developers [57,58] are provided with data that can help them evaluate the opportunities of using otherwise stranded assets for future clean energy production.

In this Perspective, we want to initiate a discussion about reporting of nuclear-readiness levels and propose a simple classification that could consider coal-fired plant specific factors, site specific factors and potentially others as indicated in Fig. 2. Belles et al. [59], Hansen et al. [42] and Xu et al. [47] did previously consider rated capacity and relevant equipment age for their analysis on replacing coal-fired power plants in the United States and China with advanced nuclear reactors. We also considered these criteria in the exemplary classification here. We further added the investment type and the potential cost savings of C2N if compared to greenfield construction of the nuclear plant to the list of coal plant specific factors. For the site-specific factors, we propose considering among potentially other factors the availability of a heat sink, the population density as well as the seismic activity. Safety is obviously an outermost concern if traditional fossil fuel powered thermal plants are to be replaced with large numbers of advanced nuclear reactors. Omitaomu et al. [60] provide an excellent method (developed for the United States) for siting of advanced nuclear reactors that systematically lists additional information (protected land, landslide hazard, risk of floods, etc.) that could also be relevant here.

	Coal-to-Nuclear-Readiness		
	Class C	Class B	Class A
Coal Plant Specific Factors			
Rated Capacity	<100 MWth	100-250 MWth	>250 MWth
Relevant Equipment Age	>20 years	10-20 years	<10 years
Investment Type	Brownfield	Brownfield to Repowering	Repowering to Retrofit
Potential Cost Savings	<15%	15-25%	>25%
↓	...	...	...
Site Specific Factors			
Heat Sink Availability	Low	Medium	High
Population Density	High	Medium	Low
Seismic Activity	High	Medium	Low
↓	...	...	...

Fig. 2. Exemplary coal-to-nuclear readiness evaluation sheet of a plant in three classes.

After identification of the specific factors, utilities could self-report their C2N readiness level and ideally get a quantitative score based on the provided data that would group them into three classes (Class A, B, C) indicating the amount of infrastructure that could be re-used, and thus total costs saved if a certain coal-fired power plant would be retrofitted with an advanced nuclear reactor. The potential cost savings in Fig. 2 only refer to the cost savings at the plant level and might include the reuse of a cooling tower, but not the overall cost savings if comparing the retrofit of the coal-fired power plant with an advanced nuclear reactor at a certain location to the construction of this advanced nuclear reactor in a greenfield, in which case additional costs for the construction of for instance grid lines may apply.

2. Conclusions and research direction

Coal-fired power plants are usually remediated within 10 years after usage. The large amount of coal-fired power plants that are presently ripe for retirement constitutes a tremendous investment in power structure that can be put to good use for future clean energy production if retrofitted with advanced nuclear power reactors that can take advantage of these otherwise lost investments. To take full advantage of this opportunity the coal-fired power plants that can best be equipped with a nuclear reactor need to be identified. In this Perspective we advocate for a voluntary system managed by the GIF, IAEA or a similarly authoritative and accepted international body, to which utilities can provide information about the nuclear-readiness level of their coal-fired power unit. In a first step a quantitative evaluation system that goes beyond the preliminary suggestions provided here needs to be developed. This should ideally already be done under the umbrella of the organization that will later manage the system and include all concerned stakeholders (utilities, regulators, communities, advanced reactor developers, etc.). Research supporting the idea of nuclear-readiness for swift C2N transition should also help identify the most relevant technical but also social parameters that can be used to assess the nuclear-readiness level of a coal-fired power plant. Besides, further studies on the technical feasibility, as well as the engineering development of replacing coal-fired boilers with nuclear powered ones are encouraged, and detailed country specific studies, as they were previously done for China, Poland, and the United States are helpful.

CRediT authorship contribution statement

Nils Haneklaus: Writing – original draft, preparation, Conceptualization, Methodology, Visualization. **Staffan Qvist:** Visualization, Writing – review & editing. **Paweł Gładysz:** Methodology, Writing – review & editing. **Łukasz Bartela:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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