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Opportunities and challenges of converting coal-fired power plants to nuclear power plants

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Abstract. The constant increasing of world's energy needs and meanwhile the adopted environmental protection policies in the last decade, have led to a reassessment of the sources and technologies used for production of thermal energy and electricity. The policy of carbon neutrality imposes the shut down and replacement of the most environmentally polluting power plants by 2050 which usually are Coal-Fired Power Plants (CPP). They could be replaced by Renewable Power Plants (RPP) or Nuclear Power Plants (NPP). The most promising is the conversion of CPP to NPP (C2N) using nuclear technologies and especially Small modular reactors (SMR) which are the most suitable for the task. This paper provides an overall assessment of the possibilities for C2N transformation with SMR, taking into account the aspects of site selection requirements, available water resources, the possibilities of using existing equipment, systems and infrastructure, the available nuclear technology, as well as non-technical factors. The different options for C2N are examined, focusing on retrofitting and repowering because both options could be the most beneficial ones according to the initial evaluations. However, they face many challenges to overcome due to the combination of different types of equipment that will have to operate with vastly different parameters than originally designed in the case of repowering. The available solutions are discussed here reading the level of development of SMR technologies and the possibilities for their industrialization in a short time, but also the most significant challenges and obstacles to the transformation of CPPs into NPPs.

1. Introduction

The ever growing world's population, the intensive industrialization and improvement in the quality-of-life lead to a continuous increase in the world's energy needs, which necessitates the development of new energy technologies compatible with the adopted environmental protection policies. As a result, most of the newly built power plants use renewable energy sources or cogeneration. According to the International Energy Agency (IEA), in 2023 the global annual renewable capacity increased by almost 50 % to nearly 510 GW, forecasting almost 3 700 GW of new renewable capacity in the next five years, due mostly to solar and wind energy [1]. It is expected that power generation from renewable energy sources will surpass that from coal in 2025. Nuclear power is also recognized as a low-carbon source of electricity with a key role in the clean energy transition, and it provides more than 10 % in the global electricity supply and 15 % in the European total energy production [2,3]. Nuclear energy is labelled as a strategic technology for European decarbonisation, as advanced nuclear technologies with minimal waste from the fuel cycle and the Small modular reactors (SMRs) are considered as net-zero technologies in the Net Zero Industry Act of the European Commission [4]. However, there are newly build Nuclear Power Plants (NPPs) but far few in numbers and overall capacity. The policy of carbon neutrality by 2050 imposes the shut down and replacement of the most environmentally polluting Coal-Firing Thermal Power Plants (CPPs) by the countries ratifying Paris agreement for resilience to climate change [5]. CPPs have been considered to produce the most significant part of the emitted greenhouse gasses, but the negative impact of energy production by burning coal is not only related to the greenhouse effect contribution, but also to the contamination of the atmosphere with fine dust particles, acid gases from sulphur and nitrogen oxides, vapours of heavy metals, as well as the generation of a large amount ash residue and flue gas desulfurization products that require disposal [6]. In this regard, it is of particular importance to find the most expedient economic solutions for transformation of CPPs into zero-carbon power plants, instead of their closing and decommissioning. Sustainable transition paths of CPPs were discussed in Ref. [7]. Different opportunities for retrofitting the former CPPs have been studied to use the residual resource of energy equipment, systems, grid connections, etc., for example, adapting the existing CPPs to less or zero-carbon emission fuels, as natural gas or biomass [7], or converting them to storage plants for renewable electricity (thermal and electrical batteries, compressed air, flywheels) [7-9]. Investment in the installation of carbon dioxide capture technologies to fossil fuel thermal power plants is considered a reliable solution to the transition to low carbon energy, but the investment costs are estimated to be too high for plants at the end-of-life cycle [7]. The possibility for using hybrid power plants supplied by coal and renewables has been also studied in order to improve the plants' environmental impact [10,11]. It has to be taken into consideration that CPPs cover the base and the medium (sub peak) electric power loads and thermal energy demands, but also, they are flexible enough to balance the fluctuations in the 24 hour and week electricity and thermal energy consumption. This is related to the stability of the electric power system. However, most of the Renewable power plants (RPPs) cannot produce electricity continuously and cannot ensure a flexible electricity production base on the needs. The existing nowadays NPPs cover the base electric power load but lack flexibility to cover the fluctuations in the 24 hour and week electricity consumption.

Another perspective opportunity for the reconstruction of existing CPPs that has the potential to meet some of these challenges is the installation of SMRs on the existing sites, as zero-carbon energy solution, using the already created infrastructure, access to water resources, water treatment systems, cooling circuits, etc. and possibly using steam turbine equipment. Possible solution covering CPPs entire role in the electric power system is the usage of hybrid power plants of nuclear and renewable energy sources combined with Thermal Energy Storages (TES). These technological approaches are still poorly studied, and systematic in-depth analyses are absent in the literature. The main reason is that the SMRs are in development and only few of them are licensed or under construction, and one or two are in operation, and that few models of already in use nuclear reactors are suitable for CPP to NPP conversion (C2N). Furthermore, most of the TES technologies are either not efficient enough or require specific conditions to be met, and others, such as those using hydrogen, are under development. At the same time, the replacement technologies have to be readily available and to produce electricity at a low cost, which is an essential resource in the modern economy, as economic growth and competitiveness are highly dependent on the price of energy.

The present paper aims to examine the main aspects, advantages and obstacles that need to be explored in details when converting a CPP to NPP and to highlight the possible nuclear technologies that could be used for C2N.

2. Available nuclear technologies and their suitability for C2N

The use of nuclear energy for peaceful purposes began approximately 75 years ago and the first NPP in the world was connected to the grid in 1954. Many and different models of nuclear reactors has been designed along the years. Some of the models were cancelled during the design phase, others did not reach beyond experimental model. Other specific thing for the nuclear industry is that none of the models wasn't and is not in batch production due the relatively low number of NPPs in the world, and the different requirements and conditions in the different countries. The nuclear reactor models are classified based on several different criteria but the most important are: depending on the used coolant and moderator, and depending on the number and the level of the safety systems and the overall safety of the design.

The world's nuclear fleet at the end of 2020 consists of 96% reactors that use light or heavy water as coolant and/or moderator [12]. These include 68% Pressure Water Reactors (PWR), 14% Boiling Water Reactors (BWR), 11% Pressure Heavy Water Reactors (PHWR), 3% Light Water Graphite Reactors (LWGR), 3% Gas-cooled Reactor (GCR) and 1% Fast Breeder Reactors (FBR). All reactors that use light or heavy water as coolant have low thermal efficiency, usually 30÷33%. The BFRs and some of the GCRs can reach 40÷45% thermal efficiency. The nuclear reactors are divided in four generations based on the amount and the level of the safety systems and the overall safety of the design. Currently, reactors from Generation III and III+ are build [12] and is expected that nuclear reactors from Generation IV to be built in the near decade or two.

Another classification of the nuclear reactor models is also relevant for C2N – the one based on the electrical power of the nuclear units. This classification is not unified, however, in general, nuclear reactors with electrical power of more than 600 MWe are large reactors (LR), and those between 300 and 600 MWe are medium reactors (MR). At present, LR and small number of MR provide the world's nuclear energy capacities. Nuclear reactors with electrical capacity up to 300 MW are classified as Small reactors. Historically, there are reactors from Generation I and II in this group but the modern models are called SMR [13]. SMRs are mostly Generation IV and their active development started about 15 years ago. Despite their name, not all of them are of the modular type, but due to their relatively small size and weight, they can be manufactured and assembled in the factory, and then transported to the site. Many SMR models are under development, as some of them have already been cancelled, but the main part of them is in the design phase. Few SMR are licensed, some of the licensed models are under construction, and only one model suitable enough for C2N is in operation. There are also few models seeking licensing. There is subgroup of SMR called microreactors, which according to IAAE are with electrical capacity up to 10 MWe, but according to another classification they are up to 50 MWe [13]. The latter fit well for C2N purposes, as the most of the CPP are with electrical capacity of at least 200 MW. The licensed nuclear reactors of Generation III and above are as follow:

LR – ABWR, APR-1400, ACPR-1000, HPR-1000, VVER-1000 different modifications, VVER-1200 different modifications, VVER-TOI, AP1000, CAP1400, ERP, IPHWR, BN-800;

MR – CFR-600;

SMR – HTR-PM, ACP100, BREST-300, CAREM, KLT-40S, RITM-200N, VOYGR, SMART.

It could be seen that Rolls-Royce SMR and SMR-300 are seeking licensing. KP-FHR, SMR-160, BWRX-300, Xe-100, SSR-W300, AP300, ARC-100, PRISM, Natrium and IMSR400 are in the phase of pre-application activities. KLT-40S is floating nuclear reactor model and the current CAREM model is of low output power which makes them both suitable for C2N in specific cases. RITM-200N is land base modification of KLT-40S.

Some CPPs sites could be suitable for deploying LR with low thermal efficiency due to the capacity of the heat sink and the possibility of using facilities and equipment from the CPP but the majority won't be suitable and therefore only BN-800 model should be considered for C2N. The available nuclear reactor models that could be used for C2N are listed in Table 1.

Table 1. Suitable nuclear reactors for C2N[a] [14-24]

Model Name	Type and Generation	Gross Power (MWe)	Thermal Efficiency %	Turbine Inlet Temperature ˚C	Turbine Inlet Pressure MPa	Status
HTR-PM	HTGR-IV	211	42	570	14.1	In operation
ACP-100	PWR-III	125	32.5	>290	4	Construction
BREST-300	LFR-IV	300	43.5	505	17	Construction
CAREM-25	PWR-III+	32	32	290	4.7	Construction
RITM-200N	PWR-III+	55	30	≈295	3.82	Construction
VOYGR	PWR-III+	77	30	343	3.5	Licensed
SMART	PWR-III+	100	30	296.4	5.2	Licensed
Rolls-Royce SMR	PWR-III+	470	36.8	292	7.6	Application
Holtec SMR-300	PWR-IV	300	30	≈313	≈4.82	Application
CFR-600	SFR-IV	600	40	480	14	Build
BN-800	SFR-III+	880	42	490	13.7	In operation

[a] The data reflects the current situation and could vary depending on model's modifications and the adaptation to different standards per example the electric power system frequency in use.

3. Main aspects and factors in C2N conversion

In order to evaluate possible safe and cost-effective C2N transition three groups of factors should be considered: the level of suitability of the CPP site; the infrastructure, facilities and equipment that could be reused in the NPP in order to minimize the expenses and to shorten the construction time, specifics. The main issues to be analysed for C2N transition are summarized in Fig.1.

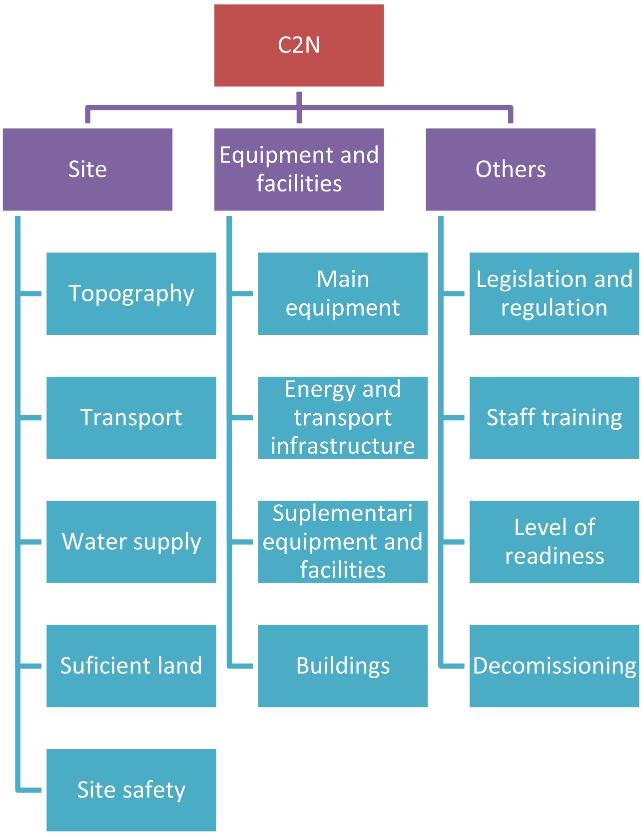

Figure 1. Main aspects of C2N transition.

3.1 Site evaluation

Considering a site already in use does not lower the requirements, but nevertheless it has the advantage that the site is developed and well known, which lower some expenses compared to green or brown field. Site selection is a process based on complex technical and economic analyses to re-evaluate the impact of site factors, which differs of importance for constructing NPP against CPP [13,25] but nevertheless follows the usual pattern as shown in Fig. 2 [13].

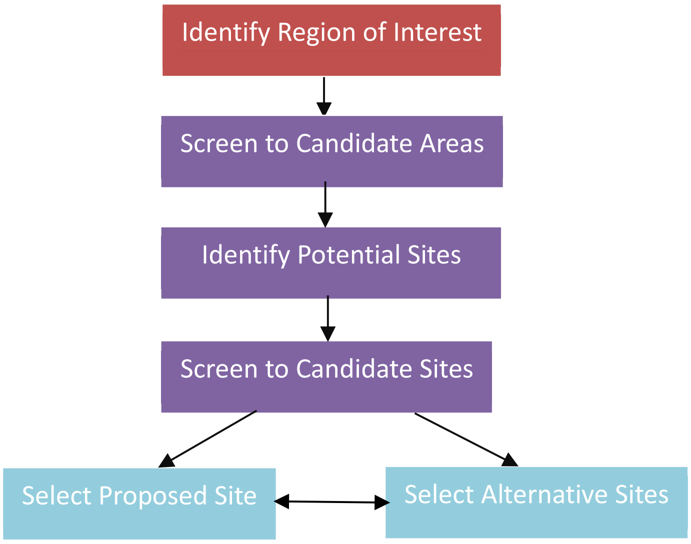

Figure 2. Process of site selection.

3.1.1. Topography and geology – flat sites with slight slope for water draining are most suitable otherwise much more excavation work will be needed. The soil should be solid enough to withstand the weight of the constructions, and low groundwater level is required, as NPPs have much more massive fundamentals than a CPP and there is a possibility of building underground radioactive waste (RAW) storage facilities.

3.1.2. Easy access to consumers and fuel – the former is important for power plants that produce thermal energy which could not be transported over long distances, while the latter is important for coal-supply of CPP. Both could be problematic for NPPs. Sites located near coal mines are exposed on higher risk of earthquakes and land collapses, and need to be further strengthened [26]. Proximity to large populated areas is in most cases not desirable for NPPs due to emergency preparedness zones and the required radiation protection measures in case of a nuclear accident. However, this is a matter of state policy and legislation, for example all NPPs in China are built near the ocean where the biggest cities in China are situated and the population density is higher.

3.1.3. Transport availability – the availability of railway and water transport for delivering equipment and materials on site is of most importance in the construction of a power plant due to the large size of the main equipment.

3.1.4. Access to water supply and cooling water – this is of necessity for operation of CPPs and NPPs, and for NPP safety systems. At the same electrical capacity, NPP requires much more cooling water than CPP because of its lower thermal efficiency and the need of taking away the residual heat release of the spent fuel. NPPs need water supply for taking away the residual heat release of the spent fuel and for other safety purposes, while CPPs consumes water for the slag removal and transportation.

Assuming that, the water consumption of a NPP for spent fuel cooling and other safety needs is approximately the same as for slag removal and transportation in CPP, it means that the electrical capacity of the NPP that could be deployed at the site without expanding or changing the water source can be calculated by the following formula:

$$P_e^{NPP} \cong P_e^{CPP} \frac{(\eta^{NPP} - \eta^{NPP}\eta^{CPP})}{(\eta^{CPP} - \eta^{NPP}\eta^{CPP})} \tag{1}$$

Where: P_e^{NPP} is the electrical capacity of the NPP, P_e^{CPP} is the electrical capacity of the NPP, η^{NPP} is the gross thermal efficiency of the NPP and η^{CPP} is the gross thermal efficiency of the CPP.

Equation (1) is deduced from the formula for gross thermal efficiency of a Thermal Power Plant (Eq. 2) equating the thermal energy that is taken away in the condenser:

$$\eta_{gross} = \frac{P_e}{Q_t} = \frac{P_e}{Q_c + P_e} \tag{2}$$

Where: P_e is the electrical capacity of the power plant, Q_t is the thermal capacity of the power plant, η_{gross} is the gross thermal efficiency of the power plant and Q_c is the thermal energy that is taken away in the condenser.

The thermal efficiency of more than 95% of the current NPPs in the world is 30-33%, while the efficiency of a CPP is between 40 and 45%, which means that the water source available for CPP would be usually sufficient for NPP with an electrical capacity roughly 50-75% of those of the CPPs on the site. These rough calculations are mainly applicable for artificial lakes and cooling towers, while more precise calculations are needed taking into account the water source type and the nuclear reactor technology.

3.1.5. Sufficient land – the approximate land needs for deploying NPP depend on the site specifics and on the number of modules in case of SMR. Typical land area needed for different size NPPs is presented in Table 2.

Table 2. Typical land area needed for different size NPPs [13].

Size	Operating (MW)	Output (MWe)	Typical Land Area Needed (km^2)
Microreactors	≤150	≤50	0.012-0.072
SMR	150 ≤ 900	50 ≤300	0.400-2.400
MR	900 ≤ 1800	300 ≤ 600	1.300-4.000
LR	> 1800	> 600	2.400 -10.000

Approximately 2.85 km^2 of land is needed for deploying NPP with electrical power of 1000 MWe, and the land needed for deploying TPP is similar and depends on the plant capacity and on the boiler layout. Deployment of a solar power plant with the same capacity requires 176 km^2, while for a wind power plant of the same output power a larger area is needed (696 km^2) [27]. Such differences in land requirements mean that it is not justified to locate wind or solar power plants on the CPP site due to the small capacity that can be installed. Also, a wind or solar power plant could reuse less equipment of CPP than NPP. Their implementation in hybrid power plants together with PWR or BWR, or PHWR, for C2N, is also not reasonable due to the vast additional land that would be needed.

3.1.6. Factors related to nuclear safety, radiation protection and defence in depth concept – these factors are more relevant to NPP than to TPP site and are mainly related to natural and human induced hazards. Such hazards are earthquakes, slope and ground instability, volcanism, river flooding, dam failure or tsunami, extreme meteorological conditions, human caused accidents as aircraft crashes, explosions, gas releases, external fires, etc. [25]. Sea, ocean and underwater currents are also an important aspect in case of accident, such as in Fukushima Daiichi NPP in March 2011. The rose of winds at the site is also essential in case of a large release of radionuclides into the atmosphere.

3.2 Facilities and equipment

One of the advantages of C2N over building from green on a new site is the ability to use existing facilities, equipment and buildings. The waste heat facilities could be used, as well as the switchyard and the grid connection. In such a case, the construction of new pumping stations and cooling facilities, new energy lines to the site and the distribution station can be saved. Modernization and/or expansion of these facilities will most likely be required. The water chemistry facility could also be used. This is no small advantage, since the water treatment process is already established.

Another possibility is related to the further use of various buildings such as administrative buildings, buildings of the internal fire unit, buildings of the health care unit, and etc. Some of the existing buildings will have to be demolished because construction facilities, machines and equipment have to be set down on their place.

The remaining lifetime of the equipment could also be used, especially of the main equipment such as steam turbine with its regenerative system. In this case, there are two options: retrofitting and repowering. The former variant allows the steam turbine to operate with close parameters to the designed, and the latter option means that the steam turbine will have to operate with much lower parameters than the designed, which means that its output power will be significantly lower.

3.3 Other factors

3.3.1. Legislation

Other factors should be considered during the C2N decision process. National legislation comes first, including nuclear regulatory law, ordinances and procedures. For example, in some states of the USA the construction of NPPs is prohibited, in some countries NPP can be owned and operated by private entities, but in others it is exclusively a state priority. Also, a very important thing is public opinion not only in the region where the NPP construction is planned, but also at national level, and in some cases also in neighbouring countries, especially when the emergency planning area includes territory of a neighbouring country. This is related to the measures in case of a nuclear accident and the activities, resources and cost of managing the consequences of the accident. The nuclear accident at the Fukushima Daiichi NPP clearly showed that even in the case of private owner, it is the state that organizes and pays for the containment of the consequences of the nuclear accident. The issue related to the management of RAW from NPPs is also of national importance.

3.3.2. State of the art and readiness

Another important issue is the planning of the transformation and organizing it in such a way to minimize the time between the shutdown of the CPP and the commissioning of the NPP. This includes: new plant design, the shutdown and decommissioning of the CPP, the licensing of the new design and plant and its construction. C2N is something new and has not been done anywhere in the world. So far, it is being considered as a possibility in three countries – USA, China and Poland. Moreover, the three countries face completely different situations. There is one licensed SMR in USA and one such project is planned [29] but far from complete, even the selected SMR is not yet licensed but pre-application activities had started. Nevertheless, the plan is the NPP to be connected to the grid by 2030, and at the same time only the licensing of the first SMR in USA took 6 years. China has connected its first SMR to the grid and has no C2N ongoing projects, only evaluating it as an option, but at the same time admitting a lack of knowledge about operating NPPs farther offshore, where water sources are limited [30]. The situation in Poland is completely different. Poland is heavily dependent on the CPPs for electricity production and neither operates any NPP nor designed one, but a Polish company participates in the designing of Rolls-Royce SMR. It is highly probable that Poland has not have nearly sufficient nuclear expertise on national level, and the first thing it needs to do is train enough staff and experts to be ready to build the country's first NPP. For now, there is too little information for C2N except several guides giving general direction and describing different factors that should be taken into account and the possible advantages that such a project could have. Also, there are few articles related to the matter, but they are mainly focused on the financial aspects of such a project and lack detailed technical aspects.

3.3.3. Human capacity

There is also a human factor that have to be considered. Preserving as much as possible the majority of CPP staff and organizing retraining, and recruiting and training of new staff. The nuclear technology selected determines the training required for the staff of the new NPP, but also the staff training needed on national level, for the regulator and for the technical support organisations. A very important aspect is whether it will be the first NPP in the country or the first NPP of a certain type in the country, for example if a country already operates a PWR but wants to build and operate a Sodium-cooled fast reactor (SFR) or a Lead-cooled fast reactor (LFR), or High Temperature Gas Reactor (HTGR). The new technology could be designed domestically or imported. Licensing time, construction time and the time required to train the necessary staff depend on the level of knowledge of the nuclear technology. For example, the construction of an EPR in Finland took 18 years instead of the planned 4 years, even though Finland operates other PWR reactors. Also, it took Turkey about 20 years to train nuclear experts at national level before starting the construction of the country's first NPP.

3.3.4. Specific factors related to the existing CPP and decommissioning – such factors mainly include decommissioning activities at the CPP site, which should be taken in any case and, from that point of view, do not raise the expenses further. Such activities include removal of underground facilities and pipes, removal of facilities for storage, preparation and combustion of coal, clean up polluted soils and waters. It is also important to remove ash and slag from the site to prevent possible contamination and vast increase in RAW [28]. There may be other activities related to C2N, for example strengthening the ground fundament in the case of nearby lignite or brown coal mines, which adds additional expenses.

4. Retrofitting and repowering

C2N can be done from brown field or by using only the heat sink, the switchyard and the connection to the grid, or by using main equipment from the CPP. The last option has the greatest potential and could be the most beneficial in terms of cost savings and shortening of the construction time. However, it is the most challenging and risky for additional unpredicted expenses. Different cases for retrofitting [26,30] and repowering [31,32] has been analysed and evaluated.

Number of things should be considered in case of retrofitting or repowering. The reheating of the steam is completely different in a CPP compared to NPP. CPP steam reheats in the boiler to about 250 ˚C compared to 50 ˚C in most NPPs, which means that the thermodynamic cycle in the secondary circuit is organized in completely different way making the direct change of energy source almost impossible. So even in retrofitting certain changes have to be made and therefore some calculations, evaluations and analysis are needed. In most cases, the CPP equipment doesn't meet the standards in the nuclear industry and therefore a medium circuit has to be used between the nuclear island and the CPP equipment. Moreover, the new nuclear equipment will be designed according to different standards and different methodologies, it is even possible that the new supplier will be from different country and the equipment manufactured in different way. In such, a new plant design has to be performed using both the new nuclear and the old CPP equipment. New safety analysis for the combined plant is needed. Something similar has been done only ones in nuclear history in the design and construction of Bushehr NPP. However, there is no guarantee that such a combination will be successful, and this is quite evident from the attempts for replacement of steam generators in NPPs in continuous operation – the success rate is about 50 %. The remaining life of the equipment must be assessed before any decision is made to retrofit or repower. The usual assumption is that equipment with no more than 20 years of service, especially one that has been in operation no more than 10 years, is fit to the task but this is an initial rough evaluation. It should be taken into account that almost all modern NPPs operate with saturated steam with low parameters (270 ÷ 290 ˚C turbine inlet temperature and 6 ÷ 8 MPa turbine inlet pressure) due to the low parameters in the primary circuit as a result of the use of light or heavy water for coolant and/or moderator. Modern CPPs work with superheated steam with high parameters (at least 540 ˚C turbine inlet temperature and at least 13 ÷ 14 MPa turbine inlet pressure). If the selected nuclear reactor cannot produce steam with parameters close to those of the CPP, additional superheating should be used, preferably from a boiler using biogas or natural gas as a fuel, which turns the new power plant into a hybrid power plant, or TES could be used if the reactor and/or the turbine is easily manoeuvrable. CPP steam turbine can also operate with saturated steam with low parameters, but further research, analysis and calculations are needed. The least that needs to be done is to retrofit the turbine for wet steam operation, or erosion will shorten the life of the blades in the final stages of the turbine, so their frequent replacement is inevitable.

5. Conclusions

SMR models, combined or not with renewables and/or TES, could lead to a successful solution to the energy transition and the replacement of the CPPs. SMR could significantly reduce the energy uncertainty and contribute to the stability of the electric power system. At the same time C2N will significantly reduce the carbon footprint of the power industry, without the need to use new land, but with the option to use existing grid connection, infrastructure, facilities and equipment.

C2N has economic, financial and environmental potential and advantages, but there are many challenges to overcome, which are not only of technical or technological nature but also include other factors specific to different regions and individual countries.

The current models that could be used for retrofitting are CFR-600, HTR-PM, BREST-300, and VOYGR, SMART could be applied for repowering or for hybrid power plants in C2N. Rolls-Royce SMR, CAREM (the future 100 MWe model), VBER-300, SMR-160 and SMR-300 are possible future candidates for repowering. KP-FHR, Natrium, Xe-100, SSR-W300, ARC-100, PRISM, and IMSR400 are attractive options for retrofitting in the near future.

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