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Nuclear Cogeneration for Climate Change Mitigation and Sustainable Development Goals

IAEA
International Atomic Energy Agency

NUCLEAR COGENERATION FOR CLIMATE CHANGE MITIGATION AND SUSTAINABLE DEVELOPMENT GOALS

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INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The United Nations recognizes climate change as one of the greatest threats facing humankind, and IAEA Member States are conducting national and joint efforts to tackle this challenge. All low carbon technologies that can contribute towards achieving the climate goals set by the 2015 Paris Agreement need to be considered in energy planning and energy strategies. Nuclear is expected to play an increasing role in supporting the deep decarbonization needed to keep the average rise in global temperatures below 1.5°C compared with pre-industrial levels and to combat climate change.

As IAEA Member States plan their low carbon energy strategies for the future, nuclear cogeneration — using nuclear power plants not only to generate electricity but also to provide process heat for other non-electric applications such as district heating, hydrogen production, water desalination and other industrial facilities — is emerging as an attractive option for decarbonizing various energy consuming sectors while also boosting the efficiency of nuclear power plants.

Nuclear power reactors can deliver process heat over a wide range of temperatures, from low temperature process heat for applications such as district heating and desalination to high temperature heat for hydrogen production and the steel industry. Many of these processes are energy intensive and rely on fossil fuels. Switching from fossil fuels to nuclear energy for such processes would reduce carbon emissions while also providing an additional revenue stream for nuclear power plant operators, thereby enhancing the viability of nuclear power as a mitigator to climate change and contributing to global sustainability. Nuclear cogeneration can contribute to several of the Sustainable Development Goals (SDGs), such as SDG 6, ensure availability and sustainable management of water and sanitation for all; SDG 7, ensure access to affordable, reliable, sustainable and modern energy for all; SDG 9, build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; and SDG 13, take urgent action to combat climate change and its impacts. Other SDGs would be achieved indirectly. For example, SDG 8, promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all, would be supported by the development and deployment of new technologies linked to the emerging small modular reactor technologies and their non-electric applications.

Nuclear cogeneration options may be different depending on the type of application and the technology, reactor type, fuel type and output temperature.

This publication includes an overview of the use of nuclear energy and waste heat for cogeneration applications to achieve a clean and sustainable energy future. The publication aims to increase the understanding of the role of nuclear cogeneration in climate change mitigation and review a selection of Member State experiences in nuclear cogeneration.

The IAEA officer responsible for this publication was A. Constantin of the Division of Nuclear Power.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

During the past decades global warming has become a major concern when it comes to sustainability of the ecosystem and human well-being. According to the Intergovernmental Panel on Climate Change (IPCC) scenarios, mitigating the consequences of climate change to an acceptable level requires reducing the global net carbon emissions to zero by year 2050 [1]. Such drastic reductions require decisive actions within the entire energy sector.

In the worldwide perspective of the climate neutrality by 2050, the decarbonization of the heating sector plays an important role. Nuclear cogeneration has a large potential to increase the efficiency of a NPP by utilizing more on the heat it provides and reduce the carbon emissions associated with heat processes that are currently supported by fossil fuels. However, due to the political and public disputes on nuclear energy it is quite improbable to have major investments in nuclear cogeneration in the short-term. In the long run, some changes may appear, and these are discussed in this publication.

Nuclear energy production has the potential to acquire an important role in a context where reduction of carbon emissions, reduction of fossil fuels use, and improvement of energy supply security are pursued by all governments.

Regarding the reduction of carbon emissions, substantial efforts are to be undertaken to decarbonize the electricity generation sector, and nuclear is one of the key technologies to meet this objective. At the same time, nuclear energy production will have to be integrated in electricity systems with increasing shares of intermittent renewables. Therefore, the nuclear reactor technologies have to make the necessary changes to allow a more flexible operation and provide the opportunity for inclusion in hybrid energy systems.

On the other hand, decarbonization of the electricity production alone will not be sufficient to meet the carbon emissions reduction targets: non-electric industries and transportation sector offer significant potential for further emissions reduction through the direct use of nuclear heat and/or via hydrogen as an energy vector. Consequently, the operation of nuclear energy production has to consider new constraints and parameters: carbon emissions reduction, contribute to decarbonization of the primary heat, and the support the production of clean hydrogen.

Advanced nuclear reactors and SMRs appear to be specifically suitable to address both the environmental and economic challenges, due to their potential to be integrated in energy mixes with high shares of renewables and with cogeneration approaches. Some of these systems are operating at high temperature which is an asset for non-electric industrial processes. There are existent nuclear cogeneration projects available worldwide that illustrate the use of direct heat from different types of reactors for various applications.

1.2. OBJECTIVE

The main objective of this publication is to illustrate the potential of nuclear cogeneration projects to contribute to climate change goals. Several different nuclear cogeneration systems were chosen to reflect the experience of some Member States. The main objective of these systems varies from one country to another but generally involves:

- Increasing energy saving and efficiency;
- Decreasing carbon emissions;
- Reducing pollutants and pollution related health problems;
- Decreasing the capital and operating cost of energy production.

1.3. SCOPE

The scope of this publication consists of the insights gathered from several Member States that have experience or are planning for nuclear cogeneration projects to support climate change goals. These nuclear cogeneration systems include water desalination, hydrogen production, hot water production for district heating, and production of electricity and heat in an efficient and environmentally attractive manner.

1.4. STRUCTURE

The publication is structured in 7 sections and 4 Appendixes that offer an insight on the following key aspects:

- Section 1 introduces the objective, scope and structure of the publication.
- Section 2 discusses climate change projections and challenges, clean electricity generation technologies and sustainable development and international climate change policy.
- Section 3 discusses the role of nuclear cogeneration to address the climate change and explain the potential to use nuclear beyond solely electricity generation to support various applications.
- Section 4 presents a simplified methodology based on multi-criteria decision analysis for evaluating nuclear cogeneration projects using technical, economic, and environmental features of each technology option considered.
- Section 5 illustrates several case studies providing the approach of different Member States in using nuclear cogeneration to support climate change goals.
- Section 6 highlights briefly the involvement of international organizations in supporting nuclear cogeneration.
- Section 7 presents the conclusions of this publication and the recommendations to the Member States considering nuclear cogeneration.
- Appendix 1 includes nuclear hydrogen projects worldwide.
- Appendix 2 includes nuclear desalination projects worldwide.
- Appendix 3 includes nuclear district projects worldwide.
- Appendix 4 includes nuclear cogeneration for industrial applications worldwide.

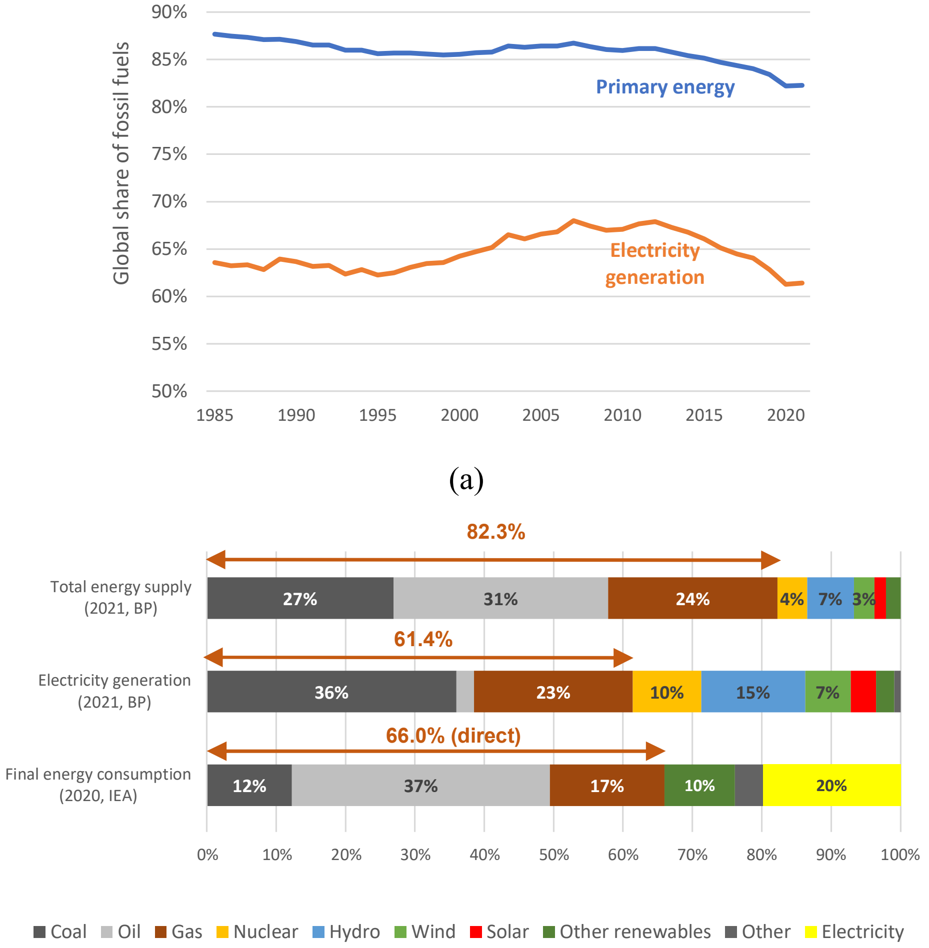
2. GLOBAL ENERGY CONTEXT AND CLIMATE CHANGE

Climate change is closely linked with the development of the global energy system. This section discusses recent trends and projections of greenhouse gas emissions and climate change along with the potential of clean electricity generation technologies to reduce emissions and contribute to broader aspects of sustainable development. International climate change policy developments, including national commitments, are also explored.

2.1. ENERGY AND GREENHOUSE GAS EMISSIONS

The production and use of energy accounts for around two thirds of global greenhouse gas (GHG) emissions. This large share can be attributed to the continued dominance of fossil fuels (principally coal, oil and gas) in the global energy system, which supply more than 80% of global primary energy [2].

Figure 1a indicates that this share has declined by only a few percentage points over the past decades (from 88% in 1985 and 82% in 2021) [3]. In electricity production, fossil fuels have also remained dominant over recent decades with their share decreasing slightly from 64% in 1985 to 61% in 2021 [3]. Figure 1 is based on data from Refs. [2, 3].



(a)

(b)

FIG. 1. Evolution of fossil fuel share in global energy and electricity mixes, 1985-2021 (a) and share of energy carriers in primary energy, electricity generation and final energy consumption (b).

Electricity supplies about 20% of total final energy consumption in industry, buildings and transport (Fig. 1b) and accounts for over one fifth of global GHG emissions as shown in Fig. 2 (based on data from Refs. [1, 2, 4]), up from 12% in 1970. In comparison, the direct use of fossil fuels in industry, buildings and transport accounts for around two-thirds of final energy consumption and (together with other industrial processes) more than 40% of global GHG emissions [1, 2]. Notably, around half of global final energy consumption is connected to the production of heat for industrial processes, space and water heating in buildings and other heating applications [5].

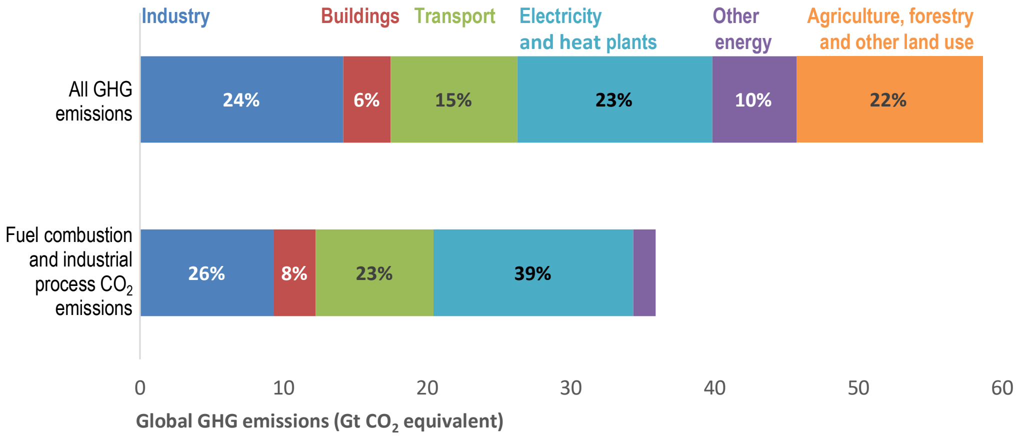


FIG. 2. Global greenhouse gas emissions by sector, as of 2019.

Carbon dioxide (CO_2) emissions from fuel combustion, which account for the vast majority of energy sector GHG emissions, have grown steadily over recent decades as shown in Fig. 3 (based on data from Refs. [6, 7]). While emissions from fossil fuel combustion declined significantly in 2020 due to the pandemic crisis, they rebounded strongly in 2021 — with growth in coal and gas demand estimated at 4.5% and 3.2%, respectively [7] — to return almost to pre-pandemic levels (~33 Gt) due to growing demand in emerging markets and post pandemic recovery measures.

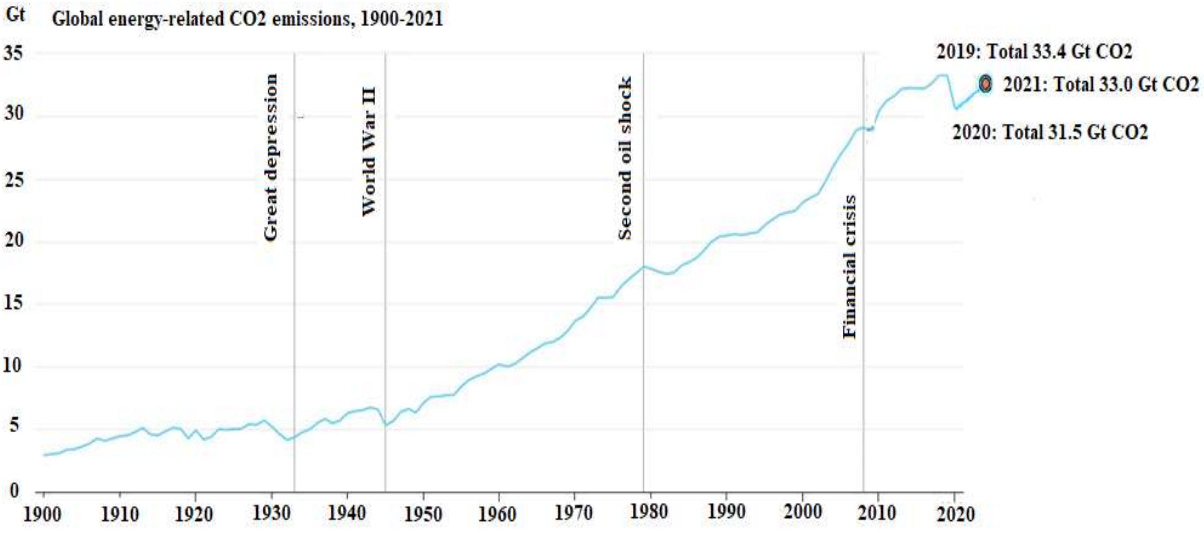


FIG. 3. Global energy related CO_2 emissions between 1900-2021.

2.2. CLIMATE CHANGE PROJECTIONS AND CHALLENGES

The long-term growth in CO_2 and other GHG emissions has already led to an increase in the average temperature of the Earth's surface by around 1.1°C above pre-industrial levels [8]. With current policies implemented by the end of 2020, emissions are projected to continue growing, as shown in Fig. 4 (based on data from Ref. [1]). The IPCC estimates that this could lead to a median temperature increase of 3.2°C by 2100 (with a range from 2.2–3.5°C) [1], which exceeds the goal adopted by the international community in 2015 in the Paris Agreement to hold the increase in global temperature to well below 2°C and pursue efforts to limit the increase to 1.5°C [9].

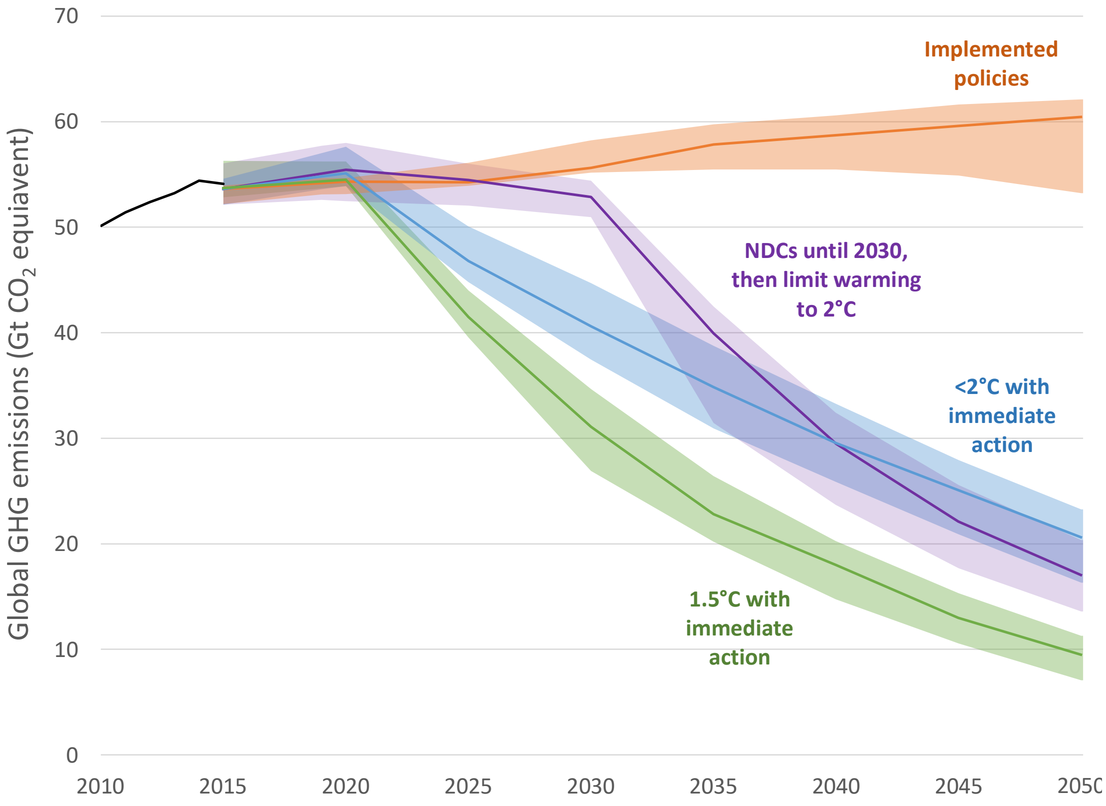


FIG. 4. Projected global greenhouse gas emissions under different scenarios. Note: Gt — gigatons; NDCs — nationally determined contributions.

The latest scientific findings in the Sixth Assessment Report of the IPCC estimate that such warming above 1.5°C would affect all components of the climate system and exacerbate climate risks in every region — leading to intense droughts, rising sea levels, vegetation fires, flooding, melting of polar and glacial ice, intense storms and powerful winds — with profound effects for both the ecosystems and human wellbeing and development, likely falling disproportionately on the most vulnerable [8].

To keep the warming below 1.5°C, the IPCC along with the International Energy Agency (IEA) and others identify the need to reduce net emissions to close to zero by around the middle of the century [1, 10] as shown in Fig. 4.

A large number of long-term global energy scenarios developed by scientific experts indicate that this will require extensive electrification of the global economy powered by low carbon sources such as renewables and nuclear power as well as the deployment of other low carbon energy carriers (including heat, hydrogen and synthetic fuels) to replace fossil fuels in applications that are more difficult to electrify (such as the cement and chemicals industries, shipping and aviation). For example, the IEA's Net Zero Emissions scenario envisions that electricity will supply almost half of total energy consumption by 2050 [10], up from around 20% today.

It is important to note, however, that even if emissions are reduced rapidly, the global temperature would continue to increase for another 20–30 years, so it will be necessary to also adapt human settlements, economies and infrastructure (including the energy sector), as well as management of land and water resources to a profoundly different climate [8, 11].

2.3. CLEAN ELECTRICITY GENERATION TECHNOLOGIES IN CLIMATE CHANGE MITIGATION AND SUSTAINABLE DEVELOPMENT

While switching to low carbon electricity from the direct use of fossil fuels can substantially reduce direct GHG emissions, every electricity generation technology — including renewables and nuclear power — produces GHG emissions over its full life cycle, for example during its manufacture, transportation, assembly, maintenance and disposal [12].

A recent assessment by the United Nations Economic Commission of Europe estimates that nuclear power produces 5.1–6.4 g of CO_2-equivalent per kilowatt-hour (CO_2 eq/kWh) for pressurized water reactors (representative of most nuclear capacity globally) when emissions from its full life cycle are taken into account (from uranium mining and processing, fuel fabrication, plant construction, operation and decommissioning, and waste disposal) [12]. Similarly, wind (on- and offshore) is estimated to produce 7.8–23 g CO_2 eq/kWh and solar (photovoltaic and concentrated solar) 8–122 g CO_2 eq/kWh, well below the life cycle emissions of natural gas or coal fired electricity generation (reaching almost 1100 g CO_2 eq/kWh) [12].

In addition, all energy technologies have the potential to impact the environment, such as by contributing to freshwater eutrophication, human toxicity, land occupation, and depletion of water and other resources. In some cases, low carbon energy technologies can have a larger impact that fossil fuel options, so several effects are likely to become increasingly significant as the world shifts towards net zero energy systems [12]. To illustrate, Fig. 5 (based on data from [12-14]) compares life cycle GHG emissions as well as land, water and critical mineral resource use for a selection of electricity generation technologies. The figure also shows the breakdown between direct operational impacts occurring at the power plant and life cycle impacts. As Fig. 5 shows, wind and solar plants tend to occupy relatively large land areas, although on a lifecycle basis their land requirements are estimated to be well below those of coal generation (principally for mining). For water, while thermal power plants (e.g., coal, natural gas and nuclear) demand large amounts of water during the operations for cooling, many technologies consume significant quantities of water over their life cycles. Mineral resource requirements are relatively small during the operational phase for all generation technologies but can be very high over the life cycle for some renewable options — for example, each MWh of electricity generated from solar photovoltaics (PV) is estimated to require up to ~600 g of critical materials (specifically, aluminum, chromium, cobalt, copper, manganese, molybdenum, nickel, silicon and zinc), compared to <100 g for nuclear power [12].

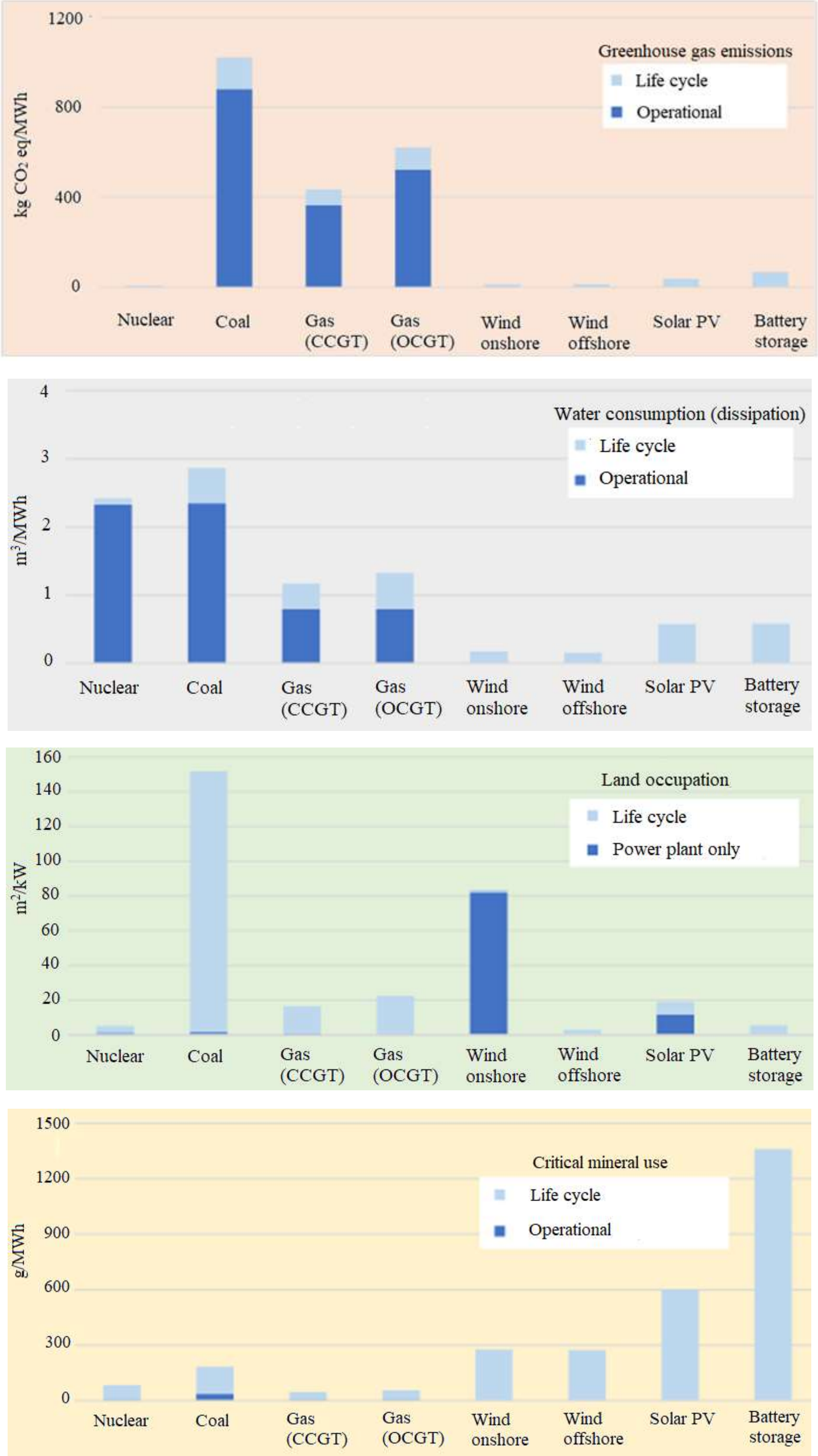


FIG. 5. Life-cycle impacts of selected electricity generation and storage technologies, from top to bottom, on GHG emissions, water consumption, land occupation and critical material use (CCGT — combined cycle gas turbine; OCGT — open cycle gas turbine).

The relatively low impact of nuclear energy across several of these dimensions illustrates its potential to contribute to multiple aspects of sustainable development, including the United

Nations Sustainable Development Goals (SDGs), adopted in 2015. These comprise 17 interlinked global goals intended to create a more sustainable world by 2030 — see Fig. 6. Nuclear energy contributes directly to selected SDGs by providing affordable and clean energy (SDG 7) and supporting economic development and job creation (SDG 8). Nuclear energy has also proven to be resilient to the impacts of extreme weather, contributing to a climate-resilient energy system (SDG 13) [15]. Nuclear energy can also contribute to several other SDGs (SDGs 2, 3, 11–15) owing to its lower GHG emissions and land and resource requirements compared to other energy technologies — illustrated in Fig. 5 — and relatively lower impacts on human health [12]. In addition, given that affordable, reliable, and clean energy is critical to many other aspects of economic and social development, nuclear energy can also contribute indirectly to almost all SDGs. Finally, aside from nuclear energy, other nuclear technologies used in medicine, agriculture, land and water management and climate change monitoring (among others) also contribute across several SDGs [15, 16].

● Nuclear technologies contribute ● Nuclear energy performs well compared to other energy technology ● Nuclear energy indirectly contributes ● Nuclear energy directly contributes

FIG. 6. Sustainable Development Goal linkages with nuclear energy technologies.

2.4. INTERNATIONAL CLIMATE CHANGE POLICY

The need for urgent action on climate change mitigation and adaption, with the goal of limiting global warming to 1.5°C, was reaffirmed in the Glasgow Climate Pact adopted at the 26th United Nations' Conference of the Parties (COP26) in November 2021 [17]. Notably, at COP26 the crucial role of nuclear energy in responding to climate change was increasingly reflected in the interventions from many countries, international organizations, experts, and non-governmental organizations. The IAEA organized several key events at COP26 to facilitate an informed debate on the benefits of nuclear power and applications, bringing together high-level decision makers, experts, and members of civil society.

Although COP26 reiterated the need for strong action to reach the 1.5°C goal, most countries have yet to fully align their near term (2030) national climate change mitigation targets and commitments with the level of urgency and ambition required. These targets and commitments are reflected in so called 'nationally determined contributions' (NDCs) submitted by 192 countries (plus the EU) under the Paris Agreement, which cover approximately 95% of global GHG emissions [18] (as shown in Fig. 7, based on data from Refs. [18-21]). The latest estimate from the secretariat of the United Nations' Framework Convention on Climate Change (UNFCCC) is that NDCs submitted up until late 2021 imply a long-term temperature increase of ~2.7°C [22].

For the longer term, however, many countries have adopted more ambitious targets and pledged to achieve net zero around the middle of the century, including 18 of the world's top 20 emitters (of which 6 have legislated this goal) [15].

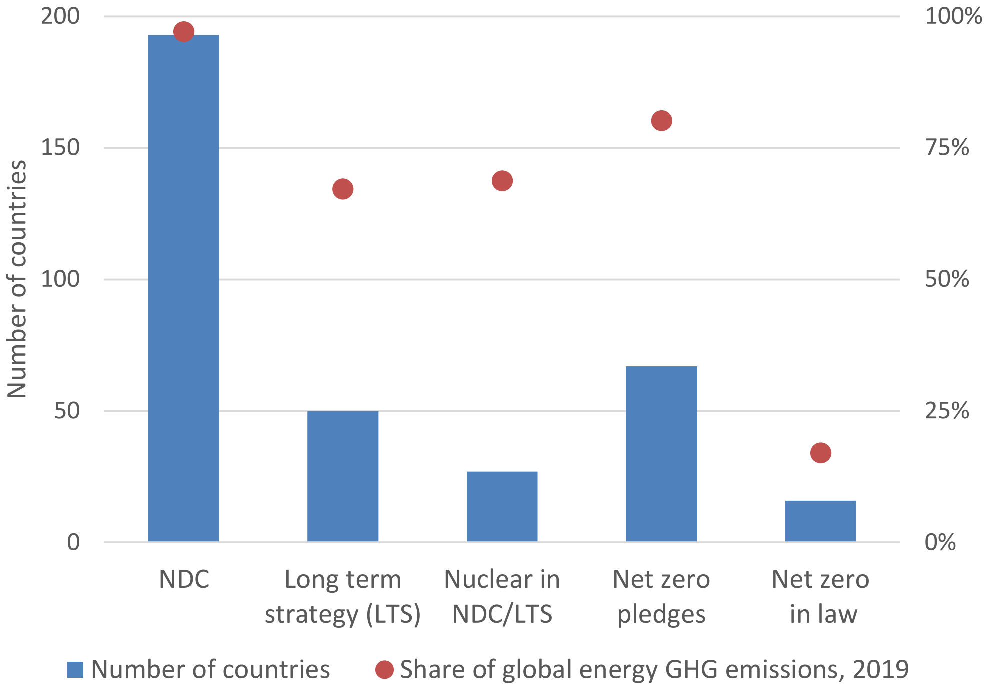


FIG. 7. Number of countries with NDCs, long term strategies and net zero emissions (NZE) pledges and corresponding shares of global energy GHG emissions, mid 2022. Energy GHG emissions refers to emissions of CO_2, methane and nitrous oxide from fuel combustion.

Even with the current inadequate levels of climate ambition, as of mid-2022, 14 countries include an important contribution from nuclear energy in their NDCs. Since European Union

(EU) countries do not submit separate NDCs, this excludes the 13 EU countries that currently use nuclear energy and are covered by the NDC submitted by the European Commission, which does not mention nuclear power.

In addition to commitments in NDCs, close to 20 countries include nuclear energy in their plans to achieve net zero emissions communicated under the Paris Agreement in so-called “long term low GHG emission development strategies” [19]. Together, these countries accounted for more than 70% of global energy-related emissions in 2019 [20].

A number of these countries anticipate important contributions to climate change mitigation from nuclear production of heat and hydrogen, along with other advanced nuclear energy technologies.

In this context, nuclear energy is also being included in sustainable finance classification frameworks (or ‘taxonomies’) being developed around the world to drive investment in the clean energy transition. For example, the EU recently adopted criteria for nuclear energy activities to qualify as contributing substantially to climate change mitigation and adaptation under its Taxonomy for Sustainable Activities. This covers advanced pre-commercial nuclear technologies, lifetime extension of existing nuclear plants (for electricity generation) and new nuclear plants (for electricity, heat or hydrogen production) [23]. In addition to the EU Taxonomy, China, the Republic of Korea and the Russian Federation are among other countries that have included nuclear energy in their sustainable financing frameworks, with more expected to follow [15].

3. NEXUS BETWEEN NUCLEAR COGENERATION AND CLIMATE CHANGE

Nuclear power plants have the potential to support clean energy mixes by supplying low carbon heat and electricity [24]. They are also capable of providing several diversified and value-added products such as fresh water and hydrogen through nuclear cogeneration processes like seawater desalination and electrochemical or thermochemical water splitting [25]. These processes are of high importance for managing water stress in arid areas and facilitating the clean energy transition in sectors still dependent on fossil fuels.

The IAEA publication “Nuclear Energy in a Net Zero World” [16] emphasizes the applications of nuclear energy beyond electricity production. Another publication, developed by the Canadian Nuclear Association, Nucleareurope, the Japan Atomic Industrial Forum, the Nuclear Energy Institute, the Nuclear Industry Association and the World Nuclear Association highlights the role of nuclear towards achieving each of the 17 SDGs [26].

3.1. POTENTIAL FOR PROCESS HEAT BY NUCLEAR ENERGY

The heat provided by nuclear reactor systems may be used for industrial processes, in a large variety of applications (for paper industry, oil refinery, coal liquefaction, extraction of tertiary oil resources, hydrogen and synthetic fuel production, etc.). The associated challenges of using nuclear heat for industrial processes come, among others, from the following:

- The discrepancy between the lifetime of the process heat application (15–20 years) and the NPP lifetime (60 years);
- The period for the return of investment (usually 20–30 years);
- Co-existence of nuclear regulatory and chemical safety frameworks that may lengthen and make more difficult the regulatory process of the cogeneration system;
- Reengineering of existing industrial plants, as well as of the NPP to operate in cogeneration mode, in an optimized way;
- Public acceptance of nuclear energy.

Heat produced by NPPs is not only low-carbon and available in large quantities, but it could also be economically viable. A recent study by Columbia University in the United States [27] found that heat from a NPPs is the cheapest source of low carbon heat as compared to alternative sources.

3.2. POTENTIAL OF DESALINATION USING NUCLEAR ENERGY

Due to the diminishing of water resources and increasing population, the demand for water desalination plants is increasing worldwide. As compared to the more limited resource of fresh water, seawater is much more abundant. Hence, desalination of seawater is of high importance not only for the countries with the lack of fresh water due to hot climate or absence of freshwater reserves but also for highly populated countries that have access to abundant sweater resources. According to Global Water Intelligence DesalData, the new seawater and brackish water desalination plant capacities exceeded globally 5 million m^3/d at the end of 2021, an 8% increase compared to the previous year [28]. In recent years, the emergence of low-cost solar power significantly reduced the cost of desalinated water, with values well below than 1 USD/m^3 reached in countries with an abundance of solar power. Using nuclear reactor technologies for desalination can provide a clean and low-cost energy alternative. Since most desalination plants today still use energy coming from fossil fuels, and thus contribute to increased levels of greenhouse gases [29].

There are two major technologies represented worldwide for water desalination: thermal processes and membrane desalination processes. The thermal processes involve feedwater heating under an operating temperature and pressure to change its phase state to vapor. Water vapor condenses as pure water, leaving behind salts and impurities in a concentrated brine [30]. Examples of thermal processes are multi-stage flash (MSF) distillation, multi-effect distillation (MED), as well as thermal vapor compression (TVC) method. The MED process is becoming lately more attractive especially when coupled with TVC in a hybrid configuration. For many years, MSF was very popular for seawater desalination, but currently is under competitive pressure from technologies like reverse osmosis (RO) and TVC/MED hybrids. The energy consumption of the different thermal desalination processes is presented in Table 1 [31].

TABLE 1. ENERGY CONSUMPTION OF THE DIFFERENT THERMAL DESALINATION PROCESSES

	MSF	MED	MED-TVC
Thermal energy, kJ/kg	250–300	150–220	220–240
Electrical consumption, kWh/m^3	3.5–5	1.5–2.5	1.5–2

In electric energy driven processes, water remains in liquid state. The principle to separate water from salt uses the aid of special membranes. The main membrane process is reverse osmosis. Combination of MED method with RO or solely MED method is best suitable to work with low temperature waste heat from NPPs.

The minimum separation energy for desalination processes is determined by chemical free energy considerations, and it is function of concentrations of feed water, brine, product water, temperature, and percent recovery. It is independent of the process of separation. In addition to the energy consumed in the separation step, there are other energy needs of the desalination plant, such as feed water pumping, pre-treatment, post-treatment, product water pumping to customer, brine disposal pumping, instrumentation, and control. These together may equal or even exceed the energy requirements of the separation step. For example, a RO system with a net energy consumption of 1.5 kWh/m^3 for the separation step may have a plant consumption of about 3 kWh/m^3 [30].

There are already more than 20 000 desalination plants worldwide [32] but to date a very few of these plants use heat or electricity provided directly from commercial NPPs. Energy may be provided from the nuclear reactor to the desalination plant in form of thermal, electrical or both energies. This depends on the selected desalination technology and the reactor type. Water cooled reactors like pressurized water reactors (PWR) and pressurized heavy water reactors (PHWR) are the most utilized reactors for desalination as in Japan, India, and Pakistan.

As illustrated in Fig. 8, nuclear desalination involves the coupling of two different technologies in a way that ensures the safe operation and the economic excellence of the overall plant.

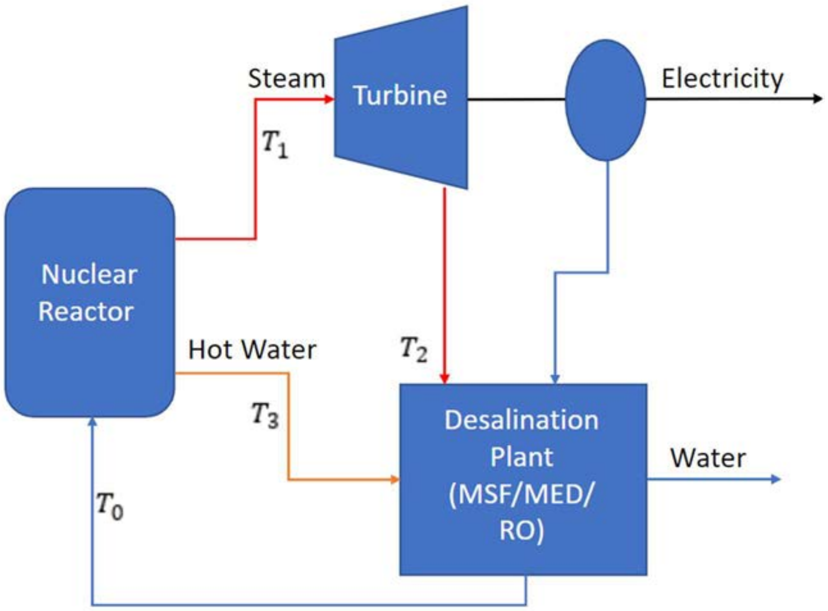


FIG. 8. Coupling of a nuclear reactor with a desalination plant.

Table 2 contains the developments in Member States (past, current, forecasted) on the use of nuclear energy for water desalination.

TABLE 2. DEVELOPMENTS IN MEMBER STATES ON THE USE OF NUCLEAR ENERGY FOR WATER DESALINATION

Country	**Key aspects**
China	Hongyanhe NPP seawater reverse osmosis project (with a capacity of 10,000 m^3/d) is the first to demonstrate nuclear desalination in China [33]. Plans for a large-scale desalination plant coupled to Haiyang NPP (AP1000 reactors) [34].
India	Two nuclear desalination plants are currently in operation [35]: — MVC/MED desalination plant coupled to Kudankulam NPP (VVER 1000 MWe), capacity of desalted water production: 2560 m^3/d each unit (total: 7680 m^3/d); — Hybrid nuclear desalination system (MSF and RO) at Madras Atomic Power Station, Kalpakkam.
Egypt	Considering nuclear power for desalination purposes [36].
Japan	Desalination facilities coupled to PWRs operating for electricity production yield some 14,000 m^3/d of potable water [37].
Jordan	Considering an SMR to be coupled with desalination plant (several candidate technologies are investigated). The site for desalination plant is already chosen [38].
Kazakhstan	BN-350 fast reactor in the Aktau NPP was coupled with a seawater desalination plant supplying up to 135 MWe of electric power while producing 80,000 m^3/d of potable water until 1999 [24].

Country	Key aspects
Pakistan	A MED desalination plant (capacity of desalted water: 1600 m^3/d), coupled to the Karachi NPP (KANUPP-1, a 137 MWe PHWR) was commissioned in 2009 [24].
Russian Federation	Since 2010, Rostov NPP has produced make-up water using 8 MED units, totalling a capacity of 9600 m^3/d desalted water [35].

Small modular reactors offer a new opportunity to use nuclear energy for desalination, providing the advantage of a more flexible operation, flexibility in siting and possibility to optimize from the planning stage the desalination option. Some examples include:

- The CAREM-25 reactor (an integrated 100 MWt PWR) is suitable for cogeneration or desalination alone.
- The NuScale module can be coupled with water desalination plant. One module (77 MWe), coupled with a reverse osmosis plant can produce 290,000 m^3/d of potable water [39].
- There is also now interest in using floating vessels equipped with desalination systems powered by nuclear reactors. For example, Core Power [40] plans to use a vessel that has a nuclear reactor on board, with a power output in the range 5–70 MWe. At 5 MWe, it could produce 35,000 m^3/d of freshwater [40].

3.3. POTENTIAL FOR HYDROGEN PRODUCTION BY NUCLEAR ENERGY

Hydrogen is a valuable energy source that is often considered key to implementation of a clean energy future as a replacement for fossil fuels [41]. Hydrogen is known as an energy carrier that can transport useable energy created elsewhere to another location; it has the highest energy per mass of any fuel (e.g., the energy of 1 kg of hydrogen is the same as approximately 2.8 kg of gasoline); however, hydrogen has a low volumetric energy density, which means that cost-effective distribution and storage have to be worked out.

The hydrogen production may be discussed in the context of needs for decarbonization. Generally, hydrogen is seen as a sustainable energy carrier for fuel cell electric vehicles and some experts advanced this option as a good approach for the storage of variable electricity production. Another potential utilization of hydrogen is to replace partly the fossil fuels consumption for transportation to reduce emissions. The hydrogen may be added to natural gas directly in the gas pipeline networks, forming a mixture of methane and hydrogen able to be transported according to present safety standards and it can be used for home heating purposes. A relatively low hydrogen concentration (5–15% by volume) is compliant with the target of low risks associated with the utilization of the gas blend in end-use devices (such as household appliances) [42].

Most of the hydrogen produced today comes from steam methane reforming alongside other fossil-based fuels, and a much lower percentage is generated through water electrolysis. These technologies have different requirements in terms of temperature and pressure [43].

Hydrogen can be produced using nuclear energy through the following processes: low temperature electrolysis, high temperature steam electrolysis (HTSE), thermochemical water splitting, and steam reforming with heat input from a nuclear reactor [44].

Low temperature electrolysis needs only electricity and water, whereas HTSE needs electricity, water and a significant amount of heat to provide the necessary steam. High temperature electrolysis operates at 750 to 950ºC [45, 46]. A high temperature nuclear reactor (HTR) satisfies directly the requests of temperatures for HTSE and could achieve a competitive thermal-to-hydrogen conversion efficiency of 45% to 55% [47]. Most of the current fleet of water-cooled reactors are designed to operate at lower temperatures (200–300°C) so that they can readily support low temperature electrolysis but also provide the thermal energy needed to vaporize the water for HTSE, and later combined with heat recuperators and topping heaters to increase the temperature up to the one required by higher temperature hydrogen production technologies.

Electrolysis at low temperature, using cheap off-peak electricity from currently operating NPPs may be economically approached, but in current market conditions, nuclear hydrogen produced by low temperature electrolysis method might not be competitive. An important window of opportunities is open by the new context of the systems with large penetration of variable renewable (especially dominated by wind and PV) where the fluctuations have introduced variability of the electricity price on the intraday market, even negative prices, in some cases.

Due to the need to shift away from fossil fuels, the electrolysis technology using low carbon energy sources is gaining more attention for hydrogen production. For example, a 40 GW electrolyser capacity is targeted in the EU by 2030 [48].

There are different types of electrolysers – alkaline, polymer electrolyte membrane (PEM), anion exchange membrane, and solid oxide-based [49]. Nowadays the most common electrolysers are of PEM and alkaline technologies. In countries such as Canada and the USA the test on ramping up and down the alkaline and PEM electrolysers capacity have started. anion exchange membrane and solid oxide electrolysers are currently under testing in laboratories but are sought to be commercially deployed.

Developments of the thermochemical water splitting processes, which consists of a series of chemical reactions that split water to hydrogen and by-product oxygen, aim to provide a way to produce hydrogen at high temperatures with higher efficiencies. A variety of combinations of chemical reactions and catalysts were investigated since the 1960s that can be generally divided into two broad types: high temperature two-step processes (with temperatures well above 1000°C) and low temperature multistep processes (which are designed to operate below 1000°C). The higher the temperature, the better it is for process thermal efficiency but for practical reasons the thermochemical cycles use of energy sources that can supply heat up to 1000°C were considered for development. This supports the use of advanced high temperature reactors – e.g., high temperature gas cooled reactor (HTGR), very high temperature reactor (VHTR), with outlet temperature in the range 750–950°C for hydrogen production via thermochemical cycles. While over 200 thermochemical cycles have been identified for water splitting, very few of them have progressed beyond theoretical calculations to working experimental demonstrations that establish the technical feasibility of these thermochemical processes [50].

One of the most studied thermochemical cycles is the Iodine-Sulphur (I-S), proposed initially by General Atomics in the 1970s and is currently advanced to the stage of a detailed pilot design plant. The HTGR coupled with the thermochemical hydrogen production process have been attracting increased attention as the method is believed to offer advantages in large scale operation. The reasons are the following: the temperature range of helium gas (up to 900°C) obtained from the HTGR coincides with the temperature range needed by the chemical reactions, the numbers of elements and reactions concerning the process are small, and the equipment and materials are feasible as the temperature stays below 1000°C. The I-S process consists simply of three essential chemical reactions and the high temperature of the process is the basis for high thermal efficiency which is estimated in the range of 40–50%. The Japan Atomic Energy Agency (JAEA) has conducted R&D on the I-S process, on long term stable hydrogen production, high thermal efficiency for hydrogen production, stable operation of components in corrosive environments, and safety in integration of the I-S process and the HTGR. A test facility of hydrogen production scale has been constructed with practical structural materials with test operations carried out that achieved 150 h of hydrogen production with a rate of 30 L/h in 2019 [51]. Safety demonstration tests using the High Temperature Engineering Test Reactor (HTTR), the 30 MW experimental HTGR of JAEA, were carried out following the restart of reactor operations in July 2021 [50].

Hybrid processes splits water molecules through a closed series of thermochemical and electrochemical reactions. In this type of cycle, the low temperature reaction, which has a low thermodynamic efficiency and is therefore not favourable, is forced electrochemically. The hybrid sulphur (HyS) cycle was originally developed by Westinghouse, and it is among the most studied hybrid processes. In the United States, the preconceptual reactor plant design of Next Generation Nuclear Plant project selected HyS and a nuclear heat supply system based on pebble bed modular reactor. The HyS was selected over HTSE because although having more technical challenges than HTSE, it is likely to have lower capital and hydrogen costs and thus be more commercially attractive.

Figure 9 gives an overview of possible hydrogen production methods using nuclear energy, by providing clean electricity and/or heat.

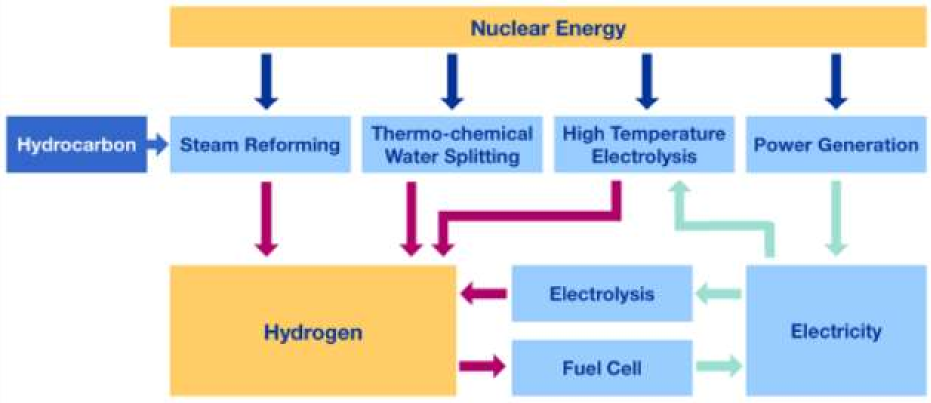


FIG. 9. Various hydrogen production methods using nuclear energy.

Nowadays many countries already included clean, reliable, and effective hydrogen production and usage in their national strategies for net zero. While the majority consider hydrogen production using renewable energy sources, some countries, such as Canada, China, Japan, Republic of Korea, the Russian Federation, UK, and USA [52] also see a great potential coming from using nuclear energy for hydrogen production.

In Canada, its hydrogen strategy includes hydrogen based clean fuel production and carbon dioxide utilization, safety solutions, storage, and techno-economic assessment of the hydrogen production technologies [53]. Canada investigates potential markets for nuclear hydrogen production (in Ontario, New Brunswick, Alberta, and Saskatchewan) with high and medium impact areas (considering natural gas grid injection and/or local iron and steel industries and/or repurpose natural gas plants or install carbon capture and storage systems in near-term) [53].

China has issued its Medium and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035) [54]. The High Temperature Gas-Cooled Reactor Pebble-bed Module (HTR-PM) reactor was connected to the grid and China conducted key activities for nuclear hydrogen production that include R&D on the intermediate heat exchanger, development of a pre-pilot facility of hydrogen production, and studies on the coupling of the HTR-PM with S-I thermochemical cycle for hydrogen production [55]. Fundamental studies on the technologies of nuclear hydrogen production, including the thermochemical water splitting process using S-I cycle and high-temperature steam electrolysis, have been performed [55]. An HTSE system for hydrogen production at a laboratory-scale has been designed and tested and a program for the long-term stable operation of HTSE has been realized [55]. In 2021, the Industry and Technology Alliance of HTR hydrogen production was established involving key organization in China including industrial partners interested in clean hydrogen like the China Steel Group.

Japan has its roadmap for Green Growth Strategies [56] and when it comes to nuclear industry it includes that by 2030, the technology development for clean hydrogen using high temperature heat from the HTTR will be achieved, and by 2040, the demonstration of coupling between hydrogen production plant and HTGR will be developed. There are 2 hydrogen production technologies considered to be coupled with the HTTR: the steam methane reforming and the S-I thermochemical cycle [52]. JAEA operates a test facility closed S-I cycle loop, with the hydrogen production capacity of 30 L/h in normal conditions. The loop has achieved up to 150 h continuous operation tests. JAEA has developed additional fluid flow monitor and control technologies with the goal to significantly extend the stable operation period of the loop [57].

Republic of Korea has issued a master plan for implementing the hydrogen economy, aiming to establish an ecosystem across its entire cycle, and focusing on building national infrastructure [58]. Korea Atomic Energy Research Institute (KAERI) develops key technologies for nuclear hydrogen production using VHTR, such as VHTR design codes, a He experimental loop, lab-scale TRISO fuel fabrication, lab-scale pressurized S-I process, coupling technology between VHTR and HTSE. An integral test facility for HTSE (30 kWe) is also developed by KAERI with a maximum 850°C of steam supply from the close He loop. A 100-h continuous operation test was performed on the 3 kWe solid oxide electrolysis cell (SOEC) stack and an integral test using 6 kWe SOEC modules is planned for 2024. Republic of Korea targets to develop hydrogen reduction steel making technology for full application by 2040 [59].

In Russian Federation, the development of a HTGR power plant coupled with a hydrogen plant is in the front-end engineering design phase. The hydrogen production would be through steam methane reforming and the HTGR would have a thermal capacity of 200 MWt. The hydrogen plant will be capable of producing 110 000 t of hydrogen annually. The NPP will have 4 HTGRs and, accordingly, 4 hydrogen plants. The design and licensing stages of the project are scheduled to be completed in 2028, followed by construction of the first unit, which is expected to be completed in 2032. The remaining units are planned to be built in 2035 [60].

The medium-term activities include R&D on the low temperature pyrolysis of methane using HTGR heat. The technology of high temperature solid oxide water electrolysis is being currently developed and the key points are the synthesis of new materials for SOEC and the development of pilot units [61].

3.4. SECTOR COUPLING – NUCLEAR POWER AND COGENERATION DRIVEN DECARBONIZATION OF THE SHIPPING SECTOR

Practically every nation depends, directly or indirectly, on trade and commerce facilitated by the shipping industry. Even though emissions from shipping have global geographical scope and characteristics, it is crucial that this sector and its emissions be also kept in mind by every national government and its international partners when planning their climate action strategies and their nationally determined contributions to the Paris Agreement of 2015 [9]. The role of nuclear power in decarbonizing this sector and the possible mechanisms of sector coupling therefore need to be considered by national strategies, in countries already equipped with nuclear reactors but also by countries that are looking into deployment of nuclear power.

The shipping or maritime sector uses enormous amounts of primarily hydrocarbon or fossil fuels such as distillate oils, diesel oils, and heavy fuel oils for its operations, which make it one of the most carbon intensive sectors today. About 3% of the total global CO_2 emissions (total 40 Gt/a) are attributed to its fuel use alone [62]. It is also considered as one of the hardest to abate industries. Nuclear power and cogeneration offer the following possibilities for maritime decarbonization:

- Electrification with the electricity being derived from land based nuclear reactors (located very close to major ports) and stored on board ships in batteries;
- Electrification with electricity supplied from an on-board micro or small, modular nuclear reactor;
- Consider possibly nuclear propulsion that can use both electricity and heat, as needed, provided by a nuclear reactor; up to now, nuclear propulsion has been applied only for navy applications, icebreakers and submarines;
- Nuclear assisted production of green hydrogen (stored on board) and its use as fuel via combustion engines or in specially designed marine fuel cell stacks;
- Nuclear assisted green ammonia production (using nuclear hydrogen from water electrolysis with nitrogen from nuclear assisted air separation plant) or green methanol (hydrogen produced using nuclear energy and CO_2 from direct air capture/post combustion capture from thermal power plants) as fuel in combustion engines or fuel cells;
- Production/upgradation of sustainable fuels/biofuels using nuclear heat, electricity and hydrogen in land based nuclear cogeneration plants.

Nuclear power plants can support cogeneration plants or conventional chemical production facilities which help produce these energy chemicals in bulk quantities at stable prices through relatively mature technologies, higher plant availability factors, significantly lower land area requirement compared to renewable heat and electricity systems and with very low life cycle CO_2 and other GHG emissions. This is an example of how apparently disparate sectors can be linked together for achieving net zero emissions. But it is evident that significant nuclear capacity would need to be added for this to be realized in practice along with widespread cogeneration project deployment, supported by new regulatory practices to support deployment within realistic timeframes. Some estimates are provided in Table 3, using a reference fossil fuel ship and the equivalent nuclear ship with on-board reactor or a ship working on nuclear derived hydrogen from a land-based reactor [62, 63].

TABLE 3. KEY TECHNO-ECONOMIC DIMENSIONS OF NUCLEAR ASSISTED SHIPPING DECARBONISATION PATHWAYS - SOME EXAMPLES

Reference ship and voyage using fossil fuel	**Equivalent ship with on-board nuclear reactor**	**Equivalent hydrogen powered ship working on nuclear hydrogen from land-based reactor**
Weight: 327 90 t, Speed: 20 knots[1], Fuel consumption: 63 t/d, Emissions: 200 t CO_2/d	Minimum on-board reactor power: 15 MWe, Million USD 73−117 for the reactor	H_2 consumption: 13.5 t/d H_2, Nuclear power (land based): 32 MWe Water electrolyser investment: Million USD 31 On-board fuel cell investment: Million USD 1.46

3.5. JET FUEL SECTOR DECARBONIZATION

Today the estimated emissions of only one hour flight are around 90 kg CO_2 per hour [64]. This brings into consideration the idea of decarbonizing jet fuel production industry. One of the major aircraft manufacturer Airbus is targeted to have its first climate-neutral, zero-emissions commercial airplanes up to cruising altitude within the two decades. But to be just powered by hydrogen is not enough as the actual emissions will depend on the source of the hydrogen and its production as assessed over the entire life cycle of the hydrogen production pathway [65].

Currently the renewable hydrocarbon fuels (green or drop-in biofuels which are made from sustainable and renewable sources) can be divided on the following types: renewable diesel and gasoline and sustainable aviation fuels [66, 67]. Sustainable aviation fuels made from renewables are currently available and used in limited quantities in the USA, while UK considers the deployment of sustainable aviation fuels where nuclear will play one of the most important roles [68]. For example, Rolls-Royce is exploring the issue if sustainable aviation fuels volumes can be boosted by using small modular reactors power for synthetic fuel production [69]. Synthetic fuels are produced by using CO_2 captured by a specific carbon dioxide removal system or from industrial processes and creating the fuel via electricity. An SMR can produce such fuels that meet the specifications of an aviation fuel, to decarbonize flight [69].

It is proposed in the UK to include nuclear power as a possible source of sustainable aviation fuels. It is suggested to treat nuclear produced fuel the same way as renewable fuels of nonbiological origins, which means that it will be necessary to consider fuel production process in the GHG emissions calculation methodology. The development of such a methodology is also currently an ongoing project in the UK [69].

3.6. OPERATING NUCLEAR POWER PLANTS FOR FURTHER DECARBONISATION

Operating NPPs contribute around 10% of the world's electricity [70]. This represents around one quarter of global low-carbon electricity generation. Today's nuclear capacity is 374.26 GWe (as of August 2023) as reported by the IAEA Power Reactor Information System [71]. The emissions from the entire worldwide power sector in the five years between 2015 and 2019 are roughly 70 Gt of carbon dioxide [15]. The same amount was collectively prevented from being released over the past five decades by nuclear power. Nuclear power continues to prevent

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[1] The knot is a unit of speed equal to one nautical mile per hour, exactly 1.852 km/h.

more than 1 Gt CO_2 yearly [15]. For comparison, the CO_2 emissions yearly by fuel and for the cement industry are presented in Fig. 10, for 2021 (based on data from Ref. [72]).

By 2050, the IAEA projects that nuclear power's current capability for producing electricity will have doubled. This depends on around 550 GW of new construction in addition to lifetime extensions of existing facilities [16]. However, in the worst-case scenario, a refusal to embrace nuclear could result in virtually no change in capacity by 2050, leaving the world well short of what is required to prevent a global disaster [16]. The production of electricity accounts for around 40% of the world's CO_2 emissions from the energy sector, with the other 60% or so coming mostly from the use of fossil fuels in transportation, industry, and building heating [16]. There is a need to switch to low carbon fuels like hydrogen in hard to abate sectors. Nuclear power is one of the few low carbon energy sources that can provide electricity, heat, and hydrogen. There are several choices available thanks to numerous cutting-edge nuclear technologies, including small modular reactors and advanced nuclear reactors.

A decrease in nuclear capacity could have a significant impact on the trajectory of carbon emissions [73]. The annual carbon emissions might increase by 2.9 Gt by 2050 if gas fired facilities virtually fill the nuclear capacity shortfall needed to satisfy net zero goals [74].

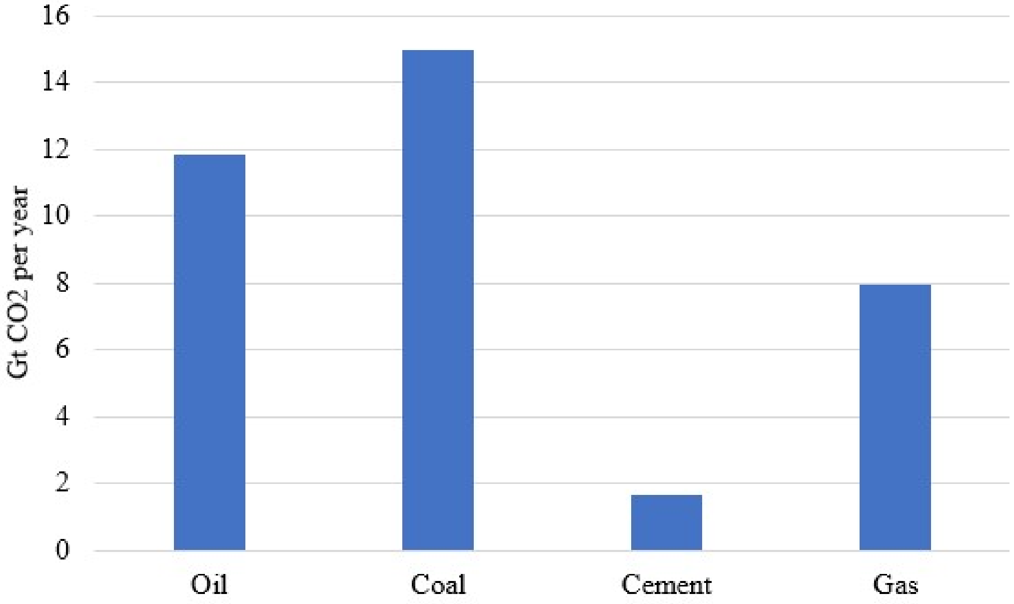

FIG. 10. The CO_2 emissions yearly by fuel and for the cement industry, for 2021.

3.7. ROLE OF THE SMALL MODULAR REACTOR TECHNOLOGY FOR NUCLEAR COGENERATION AND POTENTIAL CONTRIBUTION TO CLIMATE CHANGE MITIGATION

Nuclear cogeneration is a proven practice in operating nuclear plants combining more than 750 reactor-years of operation experience worldwide [75]. However, the practice of nuclear cogeneration is still very limited. The NPPs were designed in the past with the purpose for electricity generation only. Additionally, some uses of nuclear cogeneration (i.e. for applications that would need high temperature heat) are limited by the relatively low coolant temperature (~300°C) of the existing reactors, the existing reactors being mainly used, when operating in cogeneration, for district heating and thermal desalination via MED and MSF. Nuclear energy use for non-electric applications accounts for merely 1% of the nuclear energy produced worldwide [24, 75].

The SMRs based on existing nuclear reactor technologies, such as PWRs and boiling water reactors (BWRs), as well as based on advanced types (such as HTGR, sodium cooled fast reactor (SFR), lead cooled fast reactor (LFR), molten salt reactor (MSR)) promise to both enhance the traditional roles and support new roles of nuclear cogeneration due to several improved features over the large existing reactors, namely [76]:

- *Additional safety features*: Compared to existing reactors, SMR designs are simpler, and their safety concept relies more on passive systems and inherent safety characteristics of the reactor, such as low power and operating pressure. These increase safety margins and, in some cases, practically eliminate the risk of severe damage to the reactor core and thus the potential for large releases of radioactivity in case of an accident. Their safety concept may lead to simplified requirements, reduction in the cost of siting, and the possibility of coupling them to nearby industrial heat application plants. It may also permit deployment of electric and heat cogenerating reactors in or around cities or to remote communities.
- *Small size*: The SMR thermal ratings are about one-third or less of the large existing reactors. This would help lower investment requirement for the deployment and thus greatly improve the affordability to more countries, private investors, and industrial users. The modular sizes also make them readily scalable with the scale and increment of energy demand by most industrial heat process plants.
- *Modularity*. The SMRs bring the possibility to add modular units to the same site to supply various industrial processes. Some transportable turnkey systems are being developed to be completely built in a shipyard factory, delivered to remote sites, or exported to other countries as a marine plant for plug and play for electricity and heat supply.
- *Financial cost*. The SMRs are expected to reduce the capital requirement for the investment through reduced overnight cost, reduced construction times, and thus smaller interest payments during construction. Because of the modularity, the SMRs could be partially or completely built-in factory in streamlined production and avoid site specific uncertainty that often plague the construction projects of large existing nuclear reactors. The SMRs are expected to be financially more affordable and less risky than large reactors, attracting to a wider range of investors, industrial users, and countries. However, the costs of electricity produced with SMRs might be higher than in the case of large nuclear reactors. The current cost understanding is uncertain because of the early stage of development for the SMRs. The deployment of SMRs to not only conventional nuclear utilities but also all other markets including repowering fossil plants and hydrogen cogeneration is therefore hard to estimate. A systematic economic model for SMR needs to be developed and validated. In 2020, the IAEA launched a Coordinated Research Project, IAEA Coordinated Research Project (CRP) I12007, “Economic Appraisal of Small Modular Reactor Projects: Methodologies and Applications”, that focuses on the economics of SMRs, aiming to provide Member States with an economic appraisal framework for their development and deployment.
- *Higher temperature*: Some designs use coolants other than water and extend coolant temperatures to 500–950°C. This offers the SMRs up to additional high temperature heat applications such as production of hydrogen, carbon-neutral liquid fuel, and steelmaking. The high temperature also leads to a high level of thermal efficiency and in some cases

the cogeneration may be performed entirely by recovering the high temperature waste heat of the power conversion cycles.

— *Production flexibility*. Production flexibility is a measure for a nuclear plant to be able to adjust its output according to the demand or other indicators such as profitability of its production. When the product is electricity only, the adjustment is usually achieved by inserting nuclear reactor control rods to lessen the reactor fission power below the rated thermal level. This operation would marginalize the profit as the power generating cost of the nuclear plant usually depends little on fuel but substantially on load factor. The alternative is to maintain the reactor full fission power and be able to dispatch it between generating power and cogenerating heat. In other words, the nuclear reactor is operated to be flexible electricity and heat producers at the full reactor base load. The output of heat may be stored and used when needed to raise short-term heat output for district heating and steam supply or to generate peak electricity to compensate intermittent wind and solar power. Still alternative, the heat may be taken to adjacent industrial heat application processes such as HTSE and sulphur-iodine cycles for hydrogen production.
— *Advanced fuel cycle*: Some SMRs are designed to be fuelled by not just low enriched uranium but high assay enriched uranium, thorium, surplus plutonium, recycled spent fuel, with the hope of making nuclear fuel supply more abundant and sustainable to support new capacity or new markets including non-electric applications and cogeneration markets.

As a future choice of nuclear energy, the SMRs offer additional major advantages while facing development challenges to realize the broad potential for cogeneration of heat applications.

The major advantages that a SMR can offer are additional safety features, modularity, affordability, operating temperature, production flexibility, and fuel cycle sustainability, the areas that have limited the deployment of the existing large reactors for traditional cogeneration as well as for new applications. While these advantages are significant as detailed before, technical and performance issues exist, and R&D is required to achieve successful deployment for a great number of the SMR concepts proposed worldwide. The heat storage technologies and the heat application processes permitting frequent load following also requires substantial development and demonstration with integrated system operations [76, 77].

The United States' Idaho National Laboratory operates the Dynamic Energy Transport and Integration Laboratory, known as DETAIL. The laboratory incorporates simulated nuclear reactor, connecting heat, hydrogen and electricity producers, heat and electrical storage, and multiple heat and electricity customers through a thermal and electrical network. Each subsystem will be able to operate either independently or in response to the needs of the other systems. The objective is to demonstrate simultaneous, coordinated, controlled and efficient production and multidirectional distribution of electricity and heat for power generation, energy and hydrogen storages and industrial end uses.

In 2021, Japan's Ministry of Economy, Trade and Industry launched a multi-year national development project for an experimental integrated energy facility (Fig. 11) [78]. Led by JAEA with cooperation of vendors for nuclear reactors and industrial process plants, the project will build the 2 MWt scale plant that includes an electric-heated nuclear reactor simulator, cogeneration system of power, heat, hydrogen, and energy storage. A digital twin monitors component conditions and performance to facilitate the control of the plant according to not only demand but environmental, economic, and maintenance indicators.

A high-speed connectivity enabling Internet of Things connects the onsite system to renewable energy systems remotely and provides production coordination capabilities to heat and electricity producers in remote sites [25, 79].

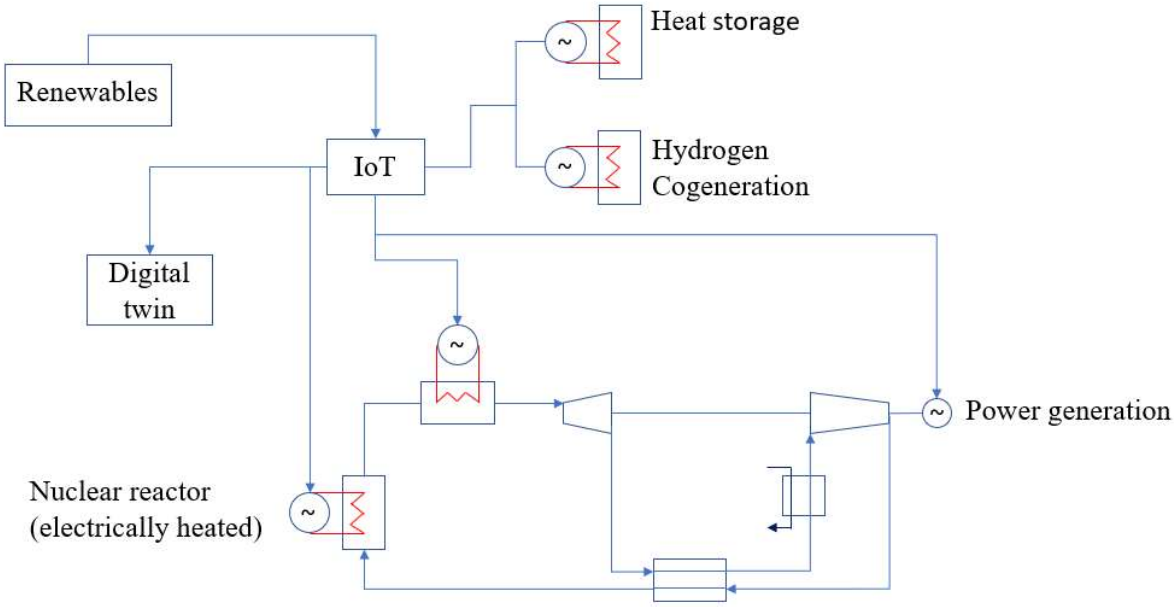

FIG. 11. SMR and renewable energy test system for electricity and heat cogeneration.

4. GENERALISED ASSESSMENT FRAMEWORK FOR INTEGRATED NUCLEAR COGENERATION PLANTS

Clean, low-carbon energy supply, ensuring long-term energy security and management of water stress due to growing population and impact of climate change are some of the biggest challenges, especially for developing nations. This is why some countries are working towards indigenous nuclear power program granting it a very important role in overcoming these challenges reliably and sustainably. For example, in India, the scope of the national nuclear power program has been extended from electricity supply alone to encompass nuclear-assisted sea water desalination and low-carbon or green hydrogen production as well. The present share of nuclear energy in India's energy portfolio is about 2% (mainly in the form of 7 GW of electricity exported to the national grid) and it is poised to grow further (to about 22 GW) by the middle of the 2030s. To quantify the multiple roles nuclear cogeneration plants can play in climate change mitigation and adaptation efforts, it is necessary to create a holistic, systems engineering based mathematical framework to perform these assessments on a whole life or life cycle basis. Selection of technology combinations for cogeneration, the scenarios to be evaluated, development of mathematical models to assess energy, economics and environmental aspects, and multi-criteria metrics based on thermodynamics, process engineering and engineering economics for evaluation and parametric studies are essential components of such an evaluation. The framework is suitable for rapidly assessing the multiple dimensions of these systems in a holistic manner and for ranking various options based on a proposed sustainability score or an index value.

Bhabha Atomic Research Centre (BARC) and Homi Bhabha National Institute developed jointly an analysis framework inspired by the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles methodology for sustainability assessment of nuclear power programs. The framework is simplified for application to nuclear cogeneration. It is combined with multi-criteria decision analysis and utilized in the present work for evaluating nuclear cogeneration projects using typical technical, economic, and environmental features of each technology option [80]. An application to the Indian context is provided further in this section.

The development and deployment of nuclear cogeneration processes has to be based on considerations other than only cost, and it has to include all the relevant dimensions and advantages offered when it comes to technology selection and deployment. It is important to keep in mind who the beneficiaries of the cogeneration project would be and treat the cost aspect as a carbon abatement cost for the beneficiary. This would highlight the true benefits with respect to climate action. It is important to understand the resource consumption and carbon emissions associated with a particular nuclear power project in a given country. This is going to be different for each country and will change with time as well as the national energy mix changes. These would also be essential inputs to certify nuclear heat or electricity or hydrogen as low carbon, provide a guarantee of origin to the service or product, ensure that purchase quotas or obligations are created for them like other forms of green or low carbon heat, electricity, or hydrogen. The impact of possible climate change pathways, manifested in ocean or air temperature rise and how that affects operation of a power plant, influences the power-water nexus and propagates and influences the behavior of coupled cogeneration plants in a feedback loop, has to be also studied. The feedback loop between climate and cogeneration is important to understand their long-term behavior. Creating new business propositions based on nuclear cogeneration would mean demonstrating its resilience or vulnerability to climate change (both chronic and acute events), so these assessments are important.

4.1. AIMS OF FRAMEWORK DEVELOPMENT

The process is only meant to facilitate a preliminary evaluation of the alternatives considering multiple facets of coupling a process plant with different energy sources. It is not a replacement for detailed due diligence process or decision support system that has to necessarily accompany every new technology implementation decision, particularly in nations planning their first cogeneration project (e.g., the detailed steps for planning and initiating a nuclear power programme are outlined in the IAEA Nuclear Energy Series No. NG-G-3.1 (Rev. 1) "Milestones in the Development of a National Infrastructure for Nuclear Power" [81]).

The broad objectives of this analysis aim to arrive at a preliminary decision regarding some or all of the following themes:

- Most suitable type of cogeneration program (i.e., high temperature process heat supply/district heating/desalination/hydrogen/other fuels or vectors/cooling services, etc.) – this depends primarily on the on-site requirements or in-house requirements of the power plant and the off-take industries which require one or more of the products or services stated above;
- Most suitable nuclear reactor technology to support the cogeneration program (i.e., light water/heavy water cooled reactors, advanced reactors, large scale reactors or SMRs) – assuming that more than one kind of NPP is available to support the chosen cogeneration program, this is determined by factors such as: the maximum temperature of the heat carrying stream on the power plant's secondary side, its nature (i.e., gas, vapor, liquid) and quantity available for cogeneration, the specific characteristics of the off-take application, the nature of coupling required (i.e., thermal, electrical, material, etc.);
- Most suitable site of implementation of the cogeneration program (i.e., co-located with NPP or closer to user site);
- Identification of techno-commercially most feasible cogeneration technology for a given objective/end use (i.e., hybrid or single desalination technology, alkaline or PEM water electrolyser for hydrogen production);
- Evaluating environmental impacts of using a certain cogeneration technology (e.g., avoided CO_2 emissions, land use considerations, fuel requirement, heat rejection to environment, water consumption, requirement for critical minerals including nuclear fuel and structural materials and their availability through sustainable supply chains);
- Comparison with alternate energy source/conversion technology that can support the same cogeneration program, rating and ranking of different alternatives (e.g., fossil fuels, different renewable energy options);
- Evaluating the sensitivity of the decision-making process to the input parameter values.

Some examples of factors that can be integrated into the framework are:

- Cogeneration plant overnight capital cost, costs of integration with nuclear power reactor;
- Cogeneration plant operation and maintenance cost including energy, raw materials/feed stock, manpower/labor cost, project overheads, land cost (rent/lease), costs of externalities;
- Cost of financing the project (debt, equity, mixed);
- Environmental benefits and other life cycle impact of the NPP and cogeneration facility.

4.2. REPRESENTATIVE SET OF INDICATORS IN THE ASSESSMENT MODEL

This section describes some of the quantitative indicators and metrics that can be used in the decision support system for deployment of cogeneration projects using different energy sources (nuclear, renewable, fossil fuel power plant) to support them. The list is provided in Table 4 and the calculations may be performed in a spreadsheet-based environment. The list is not exhaustive, and more parameters may be incorporated.

TABLE 4. REPRESENTATIVE SET OF INDICATORS FOR INTEGRATED ASSESSMENT OF NUCLEAR COGENERATION PROCESSES

Indicator category	**Specific quantitative metric**	**Method of evaluation**
Climate change and environmental factors	Life cycle CO_2 emissions per unit of production	Energy required per unit of production × CO_2 emissions per unit of energy form used
	Other pollutant (SO_x, NO_x, particulate matter, etc) life cycle emissions per unit of production	Energy required per unit of production × pollutant emissions per unit of energy form used
	Global warming potential	∑(Pollutant with global warming potential emitted per unit of production × Global warming potential value relative to CO_2)
	Ozone depletion potential	∑(Species with ozone depletion potential emitted per unit of production × Global warming potential value relative to CFC-11)
	Thermal discharge	Energy required per unit of production × (thermal to electrical conversion efficiency)
Energy usage	Energy consumption per unit of production	kWh (electrical or equivalent) of energy required per unit of product, depending on process conditions during operation
	Fuel consumption per unit of production	Gram fuel required per unit of production depending on fuel energy content and conversion efficiency
Land usage	Land area footprint per unit of production	Energy required per unit of production × area needed per unit energy produced
Resource consumption	Metals (e.g., structural materials such as steel, aluminium, zirconium alloys, etc used in the power plant)	Energy required per unit of production × metal required per unit of energy form used
	Non-metals (e.g., fuels (fossil or nuclear), coolants, moderators, cement, etc)	Energy required per unit of production × energy released per unit of energy form/fuel used
Levelized cost of production	Cost of heat, freshwater, hydrogen, or other service provided	Annualized life cycle cost of the cogeneration plant is calculated by annualizing the initial capital cost based on lifetime of the cogeneration plant and an assumed value of discount rate and adding annual operating cost to it (e.g., cost of energy from the nuclear/fossil/renewable plant, O&M, etc). This is divided by annual output from the plant to obtain a levelized cost of production.

4.3. DESCRIPTION OF THE FRAMEWORK AND USE OF SELECTED INDICATORS

The mathematical basis of the generalized framework is described in this subsection, using the example of an electrolytic hydrogen production facility working on nuclear electricity. A limited number of indicators are used in this example for simplification and for the purpose of demonstration.

Let the overnight capital cost of the cogeneration plant be C_P and let its design life in years be n_p. For a discount rate of $d\%$ per annum, the annualized life cycle capital investment for the integrated plant is given by:

$$C_{plant} = \sum C_p \times CRF_p \tag{1}$$

where the capital recovery factor is:

$$CRF_p = \frac{d(1+d)^{n_p}}{(1+d)^{n_p} - 1} \tag{2}$$

For a water electrolysis plant capacity of Q m^3/h of hydrogen (in normal conditions) at specific energy consumption of $E_{specific}$, the annual energy/electricity consumption (in kWh) can be expressed as:

$$E = Q \times E_{specific} \times 8760 \left(\frac{hours}{year}\right) \times AF \tag{3}$$

where AF is the annual capacity factor of the electrolyser plant (which is less than or equal to the load factor of the NPP). If nuclear electricity cost is C_{energy}, the annual energy cost for the integrated cogeneration facility is:

$$E_{cost} = E \times C_{energy} \tag{4}$$

Therefore, levelized production cost is calculated as:

$$LCOP = \frac{C_{plant} + E_{cost} + OM + F}{Q \times 8760 \times AF} \tag{5}$$

where the term OM represents annual expenditure on plant maintenance and other overheads and F represents the feedstock cost. From reaction stoichiometry of water splitting, an amount of 9 kg of fresh water has to be electrolyzed for the production of one kg hydrogen.

The cost of freshwater from desalination plant is used as an input to the calculation of the cost of electrolytic hydrogen.

The net CO_2 emissions, N_{CO2}, in this hydrogen production process by using an NPP with life cycle emissions intensity of X_n t CO_2 eq/unit electrical power is (in t CO_2/a).

$$N_{CO2} = Q \times E_{specific} \times 8760 \times AF \times X_n \tag{6}$$

This parameter thus takes into the account the environmental benefit of using a low carbon energy form to produce hydrogen as opposed to a fossil energy source.

If the thermal efficiency of the power plant is η_p, then the amount of waste heat released to the environment is directly proportional to (1- η_p), for every unit of electricity produced or used to support the cogeneration plant.

The above calculations and values of other indicators in Table 4 may be determined for every energy source being considered for supporting the same cogeneration plant.

A dimensionless multi-criteria index S_i is defined for a given nuclear cogeneration project that accounts for specific characteristics of the NPP, the cogeneration plant(s) and the CO_2 emissions avoided while producing hydrogen. The lowest cost of the product of cogeneration (i.e., hydrogen in this case), the lowest CO_2 emissions on a life cycle basis, and lowest thermal discharge (i.e., from the cycle with the highest thermal efficiency) are used as normalizing factors to obtain dimensionless ratios representing the various aspects of decision making for technology selection. These are then combined additively to form an integrated weighted multi-criteria metric or index for the cogeneration plant. From this definition in Equation 7, the reactor-cogeneration technology combination with the best business and environmental sustainability characteristics will have the largest value of S_i.

Let different weightages (w_i) be given to each of the three ratios used to define S_i. Thus, S_i may be expressed as:

$$S_i = w_1\left(\frac{CO_2}{CO_{2r}}\right) + w_2(\frac{1-\eta_p}{1-\eta_{pr}}) + w_3\frac{LCOP}{LCOP_r} \tag{7}$$

It is also possible to define S_i in product form, using the same sub-indicators but with the weightage factors appearing as exponents, i.e.:

$$S_i = \left(\frac{CO_2}{CO_{2r}}\right)^{w_1} \times \left(\frac{1-\eta_p}{1-\eta_{pr}}\right)^{w_2} \times \left(\frac{LCOP}{LCOP_r}\right)^{-w_3} \tag{8}$$

In this form too, a higher value of S_i represents a more feasible choice of technology/technology combination.

In the example described above, the impacts associated with the raw material extraction, manufacture, transportation, and installation of the cogeneration plant itself are ignored because for a plant of given design manufactured at the same location, these impacts would be very similar irrespective of the energy source used for the cogeneration operation. The characteristics of the energy source and the most significant impacts arising out of the choice of energy source used for a given scale of cogeneration is the focus of this assessment. Other factors may be easily included into the framework by defining more dimensionless ratios and suitably redistributing the weightage factors. Depending on data availability and depth of analysis required, it is also possible to define multiple S_i values representing different classes of indicators, i.e., S_1 for the climate change and environmental factors in Table 4, S_2 for the energy usage factors and so on and then combine them into one weighted average indicator for the purpose of comparing and ranking alternatives.

4.4. APPLICATION OF THE FRAMEWORK

The framework is simplified for application to nuclear cogeneration and is illustrated below in case of Indian context.

The technology combinations considered are indicated in Table 5. Focus is on hydrogen production using nuclear heat and/or electricity for water or steam electrolysis alongside nuclear desalination that ensures adequate water supply to the hydrogen plant and for cooling applications in the power plant's secondary cycle. Typical nuclear reactors already available or under development in India are used for analysis. Each of these combinations (denoted by cases 1 to 6 in Table 5 [80, 82]) can provide identical services but with different energy-economics-environmental characteristics.

TABLE 5. NUCLEAR REACTOR-COGENERATION PLANT COMBINATIONS

Type of nuclear reactor (typical example)	**Reactor considered in this study and related data**	**Cogeneration plant configuration**
Light water-cooled reactor (e.g., AP 1000 or VVER 1000)	VVER 1000, LCOE = 0.054 USD/kWh, PLF = 81%, efficiency = 35%	Case 1: RO─electro-deionization + PEM water Electrolysis Case 2: MED + PEM water Electrolysis
Heavy water-cooled reactor (e.g., CANDU 6 or PHWR-540 MWe)	PHWR-540 MWe, LCOE = 0.045 USD/kWh, PLF = 87.5%, efficiency = 30%	Case 3: RO─electro-deionization + PEM water Electrolysis Case 4: MED + PEM water Electrolysis
High temperature reactor (e.g., Xe-100 or HTR-PM)	Xe-100, LCOE = 0.09 USD/kWh, PLF = 80%, efficiency = 45%	Case 5: RO─electro-deionization + Solid oxide steam electrolysis Case 6: MED + Solid oxide steam electrolysis

** LCOE = Levelised cost of electricity, PLF = Plant load factor.*

Representative techno-commercial data for the cogeneration plants are available elsewhere [80]. For comparison, a typical coal based thermal power plant is used as a reference case and considered to support each cogeneration option at identical scale and operating conditions.

For each of the cogeneration cases 1 to 6 described in Table 5, the cost of hydrogen, the CO_2 emissions during life cycle operation of the facility and the waste heat discharge (represented by power plant efficiency) corresponding to the cogeneration plant capacity (here, a 1 MWe water electrolyser unit and associated freshwater requirement for hydrogen production are taken) are first evaluated at the baseline conditions. A sample result is shown in Fig. 12 for all the criteria equally prioritized and weighted i.e., $w_1 = 0.33$, $w_2 = 0.33$ and $w_3 = 0.33$.

It is observed that for hydrogen, Case 6 provides the highest value of $S_i = 0.966$ for high temperature steam electrolysis-based hydrogen production, with Case 4 providing the second-best alternative for hydrogen via water electrolysis with $S_i = 0.960$. Desalination by RO–electro-deionization proves to be a better alternative than thermal desalination owing to its lower energy consumption and upfront capital costs compared to thermal desalination. For hydrogen, the lower electricity consumption in high temperature steam electrolysis (compared to water electrolysis) is counter-balanced by higher capital cost and potentially lower useful life of steam electrolyser stacks, thus there is a smaller variation in these options for hydrogen production. Thus, the value of S_i can enable preliminary decision making and technology selection based on a few salient characteristics of the nuclear reactors and processes.

Figure 12 provides the multi-criteria index values for the integrated nuclear cogeneration plants with all criteria equally weighted.

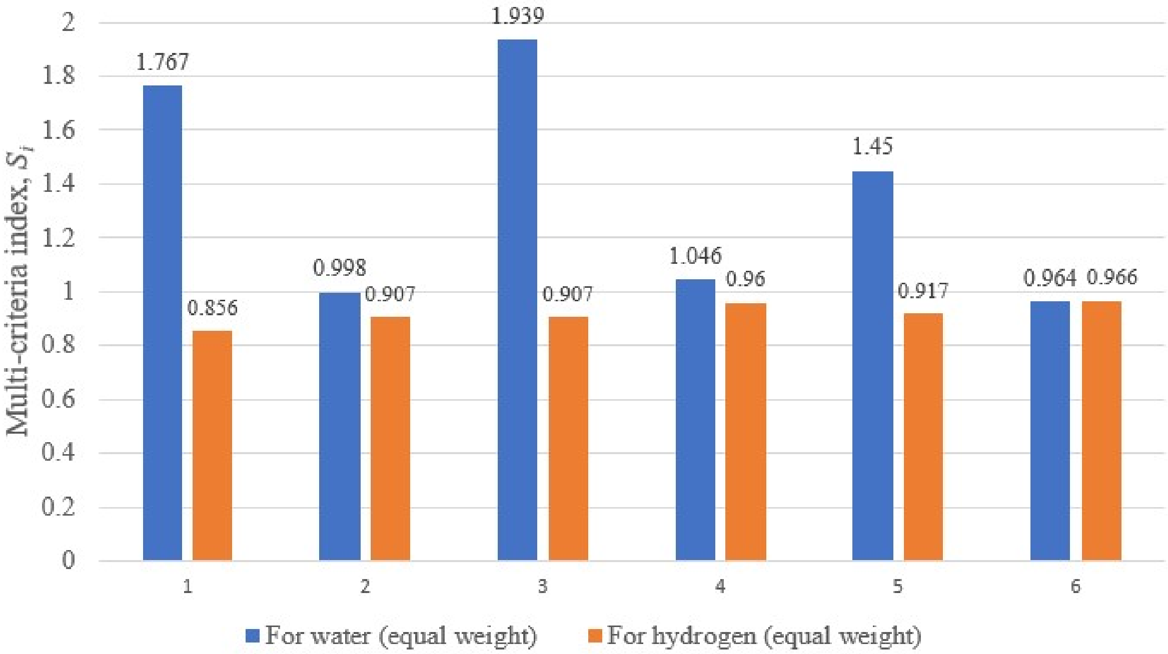

FIG. 12. Multi-criteria index values for integrated nuclear cogeneration plants with all criteria equally weighted.

5. CASE STUDIES

This section presents case studies to highlight the current or planned use of nuclear reactors in cogeneration mode for district heating, hydrogen production or other applications, based on the experience provided by the following Member States, with the occasion of IAEA Technical Meetings included at the end of this publication: Canada, China, Finland, India, Japan, Romania, the Russian Federation, the United Kingdom of Great Britain and Northern Ireland and the United States of America.

5.1. CANADA: NUCLEAR COGENERATION FOR HYDROGEN PRODUCTION

Canada has a long history with hydrogen, hydrogen production, hydrogen storage and distribution. Two of the Canadian ‘hydrogen firsts’ include the first patent for electrolysis technology in 1915 and the first breakthrough in PEM fuel cell power density reported in the early 1990s [83]. Therefore, the transition to a hydrogen economy in Canada is the natural step forward with significant economic and environmental benefits to the country.

The Canadian Hydrogen Strategy [84] lays out an ambitious framework for action that is intended to cement hydrogen as a tool to achieve Canada’s goal of net-zero emissions by 2050 and, at the same time, position Canada as a global, industrial leader for clean renewable fuels. Canada has all the ingredients necessary to develop a competitive and sustainable hydrogen economy: rich in feedstocks, a strong industry position led by innovation, a strong energy sector, an established record of international collaborations with multiple countries and regions around the world, established trade relationships for different commodities and proximity to important hydrogen markets.

5.1.1. Hydrogen process research at Canadian Nuclear Laboratories

Canadian Nuclear Laboratories (CNL) is Canada’s premier nuclear science and technology organization. In Canada, Atomic Energy of Canada Limited (AECL) manages and oversees the Federal Nuclear Science and Technology (FNST) Work Plan, which leverages the experience and expertise at CNL to contribute to government health, science, innovation, and climate change objectives. Through the FNST Work Plan, CNL performs nuclear-related science and technology that serves the collective interests of 14 federal departments and agencies within four research themes [85]:

- Development of biological applications and understanding the implications of radiation on life;
- Environmental stewardship and radioactive waste management;
- National and global security, nuclear preparedness, and emergency response;
- Safe, secure and responsible use and development of nuclear technologies.

As Canada’s national laboratory for nuclear science and technology, CNL strives to develop fundamental research concepts through the development phase to advance the technology readiness level for deployment. This paper and presentation highlights research programs of interest and in-progress at CNL with respect to clean energy and nuclear cogeneration – i.e., hydrogen production and nuclear heat applications within the FNST Work Plan.

At CNL, two main technologies have been selected for development with respect to hydrogen production and carbon dioxide utilization: the hybrid copper-chlorine thermochemical cycle (trademarked as HCuTEC^{TM}) and high temperature steam electrolysis/co-electrolysis (HTSE/HTCE). Some of the main characteristics of these two processes are:

- HCuTEC^{TM} is a hybrid thermochemical process to split water into hydrogen and oxygen. The inputs to the process are electricity, heat and water, and the chemical outputs are only hydrogen and oxygen; all other chemical species in the cycle are not consumed but internally recycled. The four main steps of the process are: electrolysis, separation, hydrolysis, and thermolysis. Hydrogen is produced at the cathode while cuprous chloride (CuCl) is oxidized to cupric chloride ($CuCl_2$) at the anode during Electrolysis. The anode stream is transferred to the separation step where solid CuCl and $CuCl_2$ are produced, and hydrochloric acid (HCl) is removed. The solid copper species are then transferred to the hydrolysis step where $CuCl_2$ reacts with steam (H_2O) to form copper oxychloride (Cu_2OCl_2) and HCl. The products of hydrolysis go through the thermolysis step to produce CuCl and O_2. The CuCl from the thermolysis step and the HCl from separation and hydrolysis are then fed back into the electrolysis step to close the cycle.
- In the HTSE with oxygen ion-conducting solid oxide electrolysis cells, the entering steam contacts the cathode in the solid oxide electrolytic cell. Here, the water splits into hydrogen and oxide ions (O^{2-}) using thermal and electrical energy. Operating the process at high temperature helps reduce the cathodic and anodic over voltages, which cause power loss in the electrolysis process. Thus, the HTSE process can produce hydrogen with lower electric power requirements than conventional water electrolysis. The typical operating temperature for the HTSE is in the range of 800 to 1000°C; therefore, it is possible to integrate the HTSE process with advanced nuclear reactors, such as VHTR designs and the Canadian supercritical water-cooled reactor (SCWR). In the case of the SCWR, with an outlet temperature of 600°C and pressure of 25 MPa, CNL studies showed that HTSE can be integrated before the second stage of the intermediate pressure turbine with a net thermal efficiency of about 46%. In the case of the HTCE, carbon dioxide can be fed with the steam to the cathode side of the cell to produce synthesis gas (i.e., a mixture of hydrogen and carbon monoxide), which can be used as the building block for products such as fuels and chemicals.

The current CNL focus on the process to develop these two technologies can be summarized as follows:

- A HCuTEC^{TM} laboratory-scale demonstration for the 100 g/d hydrogen production has been completed at CNL. Besides demonstrating the operation of the four steps of the process, a process and feasibility study was completed (in collaboration with Hatch Ltd.) not only to identify areas for improvement, but also looking at alternative unit operations for a 200 t/d plant. Although the preliminary levelized cost of hydrogen for the 200 t/d hydrogen seems to be unfavorable with respect to other technologies, process improvement and optimization could help to bring the overall cost down.
- Most of the HTSE/HTCE effort is focused on three main aspects – reduce capital cost, improve efficiency and increase the economic lifetime of the process. The R&D on materials development (e.g., anode, cathode and electrolytes for electrolytic cells) aim to identify efficient production methods and improved materials for the process. Furthermore, CNL is increasing its capabilities to conduct further materials and process studies.
- A clean fuel production concept where advanced hydrogen production technologies (e.g., HTSE/HTCE) are used to produce a variety of clean fuels such as ammonia, ethanol, etc, is under development.

Besides hydrogen production, CNL is also intensively working in areas related to hydrogen safety (e.g., catalyst development for the recombination of hydrogen and oxygen, hydrogen hazard assessments, ventilation systems) and hydrogen storage for a variety of applications (e.g., underground storage).

In Canada, there is ongoing research on testing electrolysers for ramping up their capacity. This is an essential step for achieving hydrogen economy, together with coupling NPPs with the hydrogen production facility.

5.1.2. Canadian roadmap for small modular reactors

The Canadian SMR Roadmap [86] defines a national path forward for SMR development in Canada. The roadmap, completed in 2018, represents a one-year, multi-stakeholder effort that identified three major areas of application for SMR technology in Canada:

- On-grid power generation for utilities to replace end-of-life coal plants with non-emitting base-load plants of similar size (SMRs);
- On-and off-grid combined heat and power for heavy industry, such as oil sands producers and remote mines (SMRs and microreactors);
- Off-grid power, district heating, and desalination in remote communities that currently rely almost exclusively on diesel fuel (micro-reactors).

The roadmap stresses that key players have to act in concert – i.e., federal, provincial and territorial governments, the regulator (Canadian Nuclear Safety Commission), the Crown corporation (AECL), CNL, and many others in the public and private sectors such as energy utilities, technology developers, universities and laboratories. Furthermore, the roadmap details recommendations for each essential enabling partner with specific recommendations for AECL and CNL to continue to work toward siting for SMR demonstration projects, to consider federal priorities around SMR as part of the FNST Work Plan, and to advance international collaborations on SMRs.

5.1.3. Research at Canadian Nuclear Laboratories on small modular reactors and hybrid energy systems

CNL's vision to serve the world as a global hub for SMR and energy research and technology includes the siting of a demonstration project on a CNL managed site and research into integrated energy systems with nuclear technologies to advance clean energy objectives for Canada. At present, CNL has:

- Implemented a staged invitation process for vendors interested in siting their demonstration unit on a CNL site with four project proponents: Terrestrial Energy's 190 MWe integral molten salt reactor, and high temperature gas reactors proposed by U-Battery Canada Ltd (4 MWe), StarCore Nuclear (14 MWe), and Global First Power (5 MWe) [87];
- Established the Canadian Nuclear Research Initiative program to accelerate the deployment of SMR and advanced reactor designs, including next generation on-grid reactors and fusion technologies, by allowing participants to optimize resources, share technical knowledge and gain access to CNL's expertise and unique facilities in advanced fuels, materials and chemistry, reactor safety, and component development and testing;
- Developed a Clean Energy Demonstration, Innovation and Research Park concept aimed to advance the technological readiness of low-carbon hybrid energy systems enabled by

an SMR as a demonstration platform of clean energy technologies that showcases the implementation of low-carbon solutions to stakeholders, advances the technology readiness level of nuclear-renewable hybrid energy systems; and demonstrates the operation of licensed, coexisting low-carbon technologies;
- Included research into hybrid integrated energy systems within its FNST Work Plan.

In addition to research targeting advancement of SMR technologies, CNL researchers have developed a techno-economic model to assess feasibility and benefits of integrated energy systems employing SMRs with other forms of energy generation and energy storage technologies to meet various heat and electricity demand scenarios. The CNL's Hybrid Energy System Optimization model minimizes cost or greenhouse gas emissions subject to emissions targets, technical limitations or constraints, and hourly energy (electrical and/or heat) demand. Using the Hybrid Energy System Optimization model, CNL has completed several conceptual case studies:

- Deployment of SMR for a representative remote mine site [88];
- Increased renewable generation in Ontario, Canada;
- Electrification of space and water heating in Ontario, Canada;
- Generation of electricity and heat for a Canadian remote community.

The remote community case study illustrates the impact to the energy demand when considering thermal demands in addition to electricity requirements for a community in northern Canada. In this case, the optimal energy generation mix and installed capacity, considering both cost and greenhouse gas emissions, varies significantly when considering provision of electricity only or electricity in addition to electric space heating or district heating demands via renewable, nuclear and fossil fuel sources.

As CNL continues to investigate feasibility and benefits of nuclear hybrid energy systems, particularly in the areas of thermal energy and cogeneration, research interests are turning toward lower-level analyses to feed the higher-level optimization model inputs and to technically evaluate the operational flexibility or limitations, and enhancements in efficiency that may be possible with more detailed modelling and investigations. Areas currently being investigated include: SMR cogeneration optimization, energy storage selection methodology, power cycle transient thermodynamic simulations, thermo-electrical microgrid architecture and control system design, simulation and hardware-in-loop testing of microgrid operation, thermal storage and heat transfer studies, and considerations for colocation and interconnection of industrial systems. The majority of these technical projects are currently in development stages or under consideration in projects recently started within the FNST Work Plan.

Canada is well positioned to advance SMR technologies and their potential use for cogeneration of energy and hydrogen production. There is a pressing domestic market need, a robust regulatory framework that is open to consideration of new designs, a capable supply chain, and a national laboratory with relevant established expertise in nuclear science and technology. The current activities with CNL research programs are driving innovation in hydrogen production technologies and integration of SMR in systems capable of meeting cogeneration needs for Canada and the world.

5.2. CHINA: NUCLEAR COGENERATION TO ACHIEVE CLIMATE CHANGE MITIGATION AND SUSTAINABLE DEVELOPMENT GOALS

5.2.1. China's policies on energy and carbon reduction

The Chinese government attaches great importance to addressing climate change. At the 75th Session of the United Nations General Assembly in 2020, a solemn commitment was made by the Chinese government to the world that China would increase its contribution and adopt more effective policies and measures to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. The white paper "Responding to Climate Change: China's Policies and Actions" [89], published in 2021, further expounded China's commitment, stating that China has incorporated "carbon emission peak and carbon neutrality" into its overall economic and social development plan, and will focus on green and low-carbon development of the energy sector, and fully commits to high-quality development that prioritize eco-environmental protection and green and low-carbon way of life.

In the Action Plan for Carbon Peaking Before 2030 [90] published by the Chinese Government, energy is pointed out to be the major source of carbon emissions. Building a clean, low-carbon, safe and efficient energy system is needed to speed up. The role of all kinds of energy in the system are repositioned, while clean and low-carbon energy will become the main body of increment. For fossil energy such as coal, the policy is put forward to transforming it to a basic guarantee and systematic regulating power. For renewable energy, such as wind, solar, hydropower, biomass etc., the policy of active development has been sustained. For nuclear power, active and orderly development while ensuring safety has been made clear. In addition, policies of supporting pumped storage and new type of energy storage facilities will be further increased, with the purpose to improve the comprehensive regulation capability of power systems and speed up the building of power system with the proportion of renewable energy gradually increasing.

5.2.2. Addressing climate change in China

To optimize the energy structure, the situation of the complementary development of stable and baseload energy represented by nuclear power with the intermittent and distributed renewable energy is forming at an accelerating pace. Compared with other energy sources, nuclear power can operate in a steady and reliable manner with long refuelling cycle. It is suitable for carrying the basic load of power grid and necessary load following and could replace fossil energy as the base-load power source on a large scale.

By the end of 2021, 51 nuclear power units have been in commercial operation in China, with installed capacity of 53 486 MWe, distributing from north to south in Liaoning, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi and Hainan, while generating 406 TWh of electricity in the whole year [91]. It is equivalent to reducing the consumption of standard coal by 120 million t, carbon dioxide by 4.33 billion t, sulphur dioxide by 1.09 million t, and nitrogen and oxygen waste by 940,000 t [91].

On the other hand, diversified application of nuclear energy is accelerating. The utilization of nuclear energy has gradually expanded from power generation to a series of multi-purpose forms such as heating and cooling, steam supply, seawater desalination and hydrogen production etc.

The district heating and cooling project of Zhejiang Qinshan NPP and the heating project of Shandong Haiyang NPP have been put into operation and achieved good social and economic benefits. Steady progress is being made in using nuclear energy for seawater desalination, industrial steam supply and hydrogen production, and demonstration projects will be launched soon.

5.2.3. Case studies of China National Nuclear Corporation for comprehensive utilization of nuclear energy

As the nuclear power investment and operation management platform under the backbone entity of China's nuclear industry - China National Nuclear Corporation (CNNC), China National Nuclear Power (CNNP) is committed to the efficient use of advanced nuclear energy technology and high-quality supply of clean and low-carbon energy. By the end of 2021, it was in holding position for 24 nuclear power units in operation, with installed capacity of 22.549 GW. In CNNP's Strategic Development Outline (2020–2050) and the 14th Five Year Development Plan (2021–2025), the comprehensive utilization of nuclear energy has been taken as an important direction. Moreover, CNNP will develop the nuclear power for industry, and actively explore the use of combined nuclear power and heat for heating and cooling of buildings, seawater desalination, steam supply and hydrogen production. In addition, CNNP has conducted research on technologies related to the coupling application of nuclear energy with renewable energy and applications of pool-type low temperature heating reactor and other SMRs. Some of the results will have been implemented or soon be implemented with demonstration projects. Figure 13 introduces schematically the comprehensive utilization system of electricity and thermal centred on nuclear power.

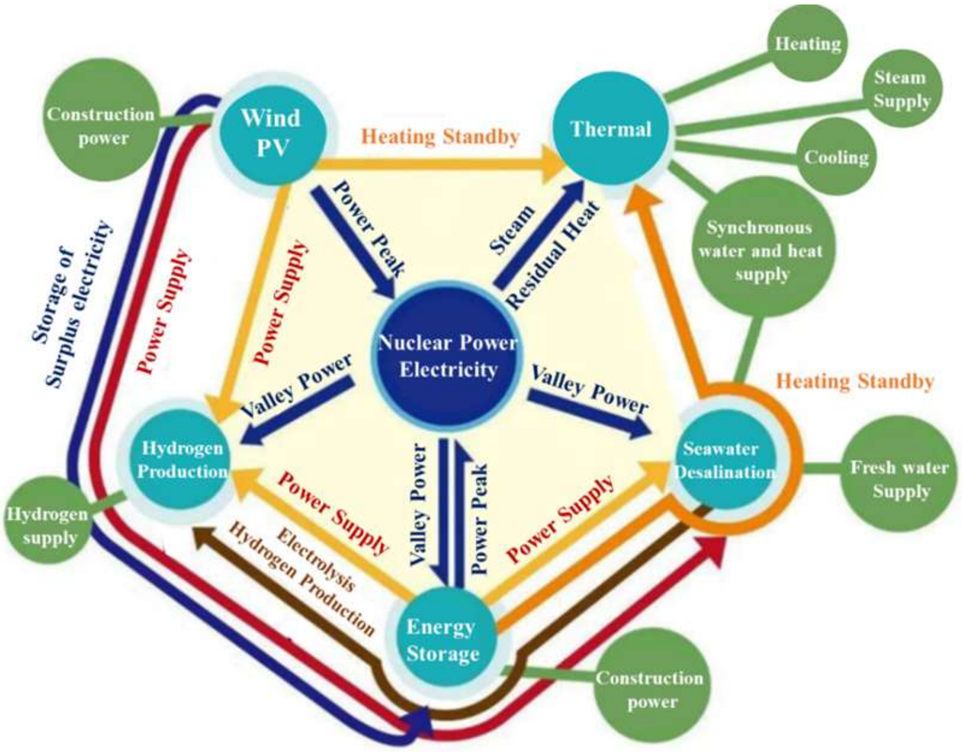

FIG. 13. Schematic of comprehensive utilization system of electricity and thermal centred on nuclear power.

5.2.3.1. Case of district heat supply with nuclear energy

Qinshan Nuclear Power Site is located in Haiyan County, Jiaxing City of Zhejiang Province in China, being in the load centre of the East China power grid. It has 9 units in operation, with a total installed capacity of 6620 MW, generating about 52 billion kWh of electricity a year, making it the nuclear power site in China with the largest number of nuclear power units, most diversified reactor types and the biggest installed capacity.

Through the cogeneration technical modification, this district heating project successfully realized the external heating by utilizing the surplus thermal power of Qinshan nuclear power units in winter, supplying hot water at 130℃ and returning cold water at 70℃, and it achieved nuclear energy heating for public facilities, residential communities, and industrial parks in Haiyan County. On December 3, 2021, the Phase I demonstration project was officially put into operation, with a heating area of 464,000 m^2. After the completion of the whole project, the heating area will reach 4 million m^2.

The source of heating steam to the primary station in the plant is taken from the auxiliary steam system of the conventional island, and it is used to heat the circulating water of the heating network through the primary heat exchanger. Then, the circulating water undergoes secondary heat exchanger at the secondary station with the user side through the pipe network. The heating system can realize multiple stages of isolation, such as the isolation between the primary circuit from secondary circuit in the NPP, the auxiliary steam from the circulating water circuit of heating network, and the circulating water circuit from the user side circuit, to ensure the safety and reliability of nuclear energy heating. The technical scheme used in the project is shown in Fig. 14. To ensure that radionuclides can be prevented from migrating from the NPP to the district heating installations under normal operation or accidental conditions of NPP, this project adopts the concept of multiple loop isolation, differential pressure protection and control of steam and water, radioactive monitoring and protection in steam and water loops, and membrane deaeration and water makeup, to effectively avoid the risk of radionuclide migration to the environment.

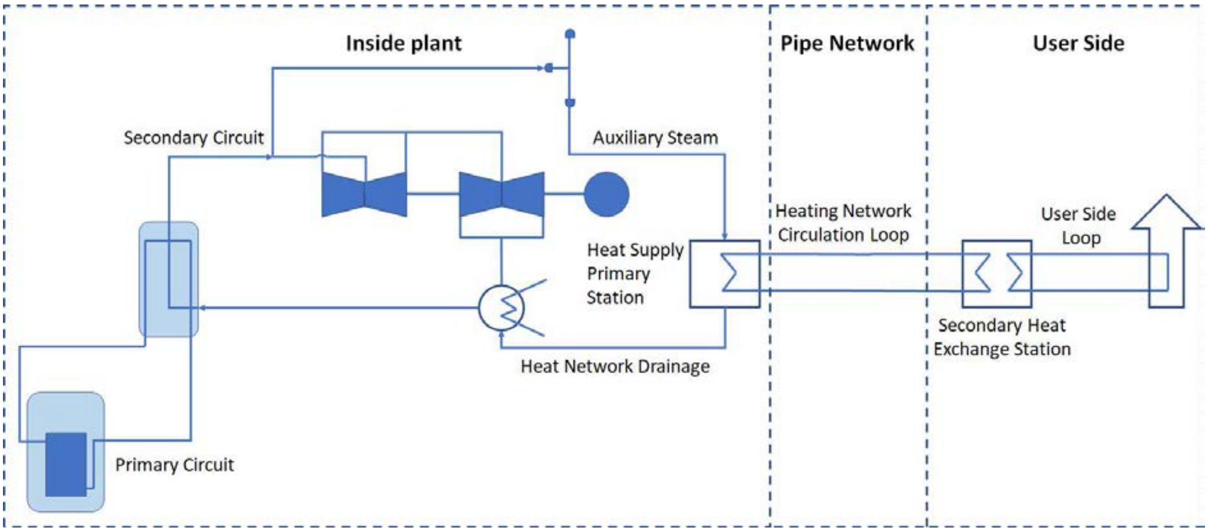

FIG. 14. Technical cogeneration scheme used in Qinshan Nuclear Energy Heating Project.

The performance results of this project can be summarized as it follows:

- *Economic performance*. The actual operation shows that, based on the current cost level of nuclear energy heating, and comparing with the traditional heating methods such as the air conditioner and gas fired floor heating in South China area, the cost could be reduced to a certain extent. In Haiyan County, where gas boilers are used for central heating, for a house of 100 m^2 (with heating period of 100 days), the annual heating cost of the resident can be reduced by about 33% after this technology is adopted.
- *Climate change related*. After the project is fully completed and put into operation, the heating capacity is expected to be 704,000 GJ/a, which can save 196 million kWh of electricity consumption comparing with the electric heating. Comparing with coal-fired thermal power units, it can reduce the burning of standard coal by about 24,600 t annually, and correspondingly reduce annual emission of sulphur dioxide by 1817 t, nitrogen oxide by 908 t and carbon dioxide by 59,000 t.
- *The influence on NPP operation and thermal efficiency to the condenser vacuum*. When circulating water temperature drops in winter, the condenser vacuum increases accordingly, and the plant's thermal efficiency increases. But some NPPs are restricted by the maximum output of turbine-generator, and the reactors could not reach the design rated power level. In this project, the surplus thermal power is fully exploited and utilized in winter for district heating, so there is no need to reduce the output of turbine-generator in operation, and the power of the reactors is kept within the design value. Taking a nuclear power unit with rated reactor power of 1930 MW and rated electric power of 650 MW as an example, the maximum power generation capacity can reach 670 MW with the condenser vacuum condition in winter, and under this condition, the reactor has not reached its design value, and each unit can supply an extra heating capacity of about 37.5 MW by average. This capacity can power the nuclear energy heating installation and the thermal efficiency of the unit can be increased by about 1.3%, with considerable economic benefit.

Some good practices derived from the deployment of the district heating project include:

- *Adoption of a fully modular construction plan of the primary station*. The fully modular design and construction technology is adopted in this project. The installation integrates the functions of process system, power configuration, control and protection, building structure, ventilation and fire protection, and radiation monitoring. It is assembled by several independent sub-modules and manufactured in the factory, so there is no need to construct a building, but being directly installed on the outdoor concrete foundation, meeting the requirements of rapid and convenient transport, installation and removal. The installations can operate either independently, or in combination via power line communication. This makes possible to build the installations according to the heat source capacity or the heating load demand.
- *Flexible utilization of visual analysis and digital simulation technologies*. Bentley 3D modelling code and Applied Flow Technology Arrow hydraulic calculation code were adopted in this project, and combining with the secondary development of these codes, visualization analysis and application of heating pipeline construction process was realized. Meanwhile, the best route of heating pipeline was finally determined through digital simulation of underground pipeline construction process in complex area.
- *Building a smart heat network management platform*. A smart heat network management platform was built up by incorporating the 5G, Internet of Things, Big Data, as well as the numerical modelling and intelligent analysis technologies, etc. The geographic

information system was utilized to open up user side data, reshaping the heat-network management architecture, and achieving accurate location of pipeline fault points. Therefore, the visualized handling and auxiliary decision-making proposals for any anomalies and emergencies could be realized. The construction of the smart heat network management platform improves the digital supervision capacity on the nuclear energy heating source, heating pipe-network and heat exchange stations, having the functions of intelligent dispatching, tour inspection and maintenance, and achieving the goal of optimal management and safe operation.

5.2.3.2. Case of industrial steam supply and seawater desalination

Tianwan NPP is located in the coastal area of Jiangsu Province, China. It is planned to build eight 1000 MW PWR nuclear power units. As of 2022, units 1–6 are in operation, and units 7 and 8 are under construction. After completion of the whole project, the site will become the world's largest nuclear power site in terms of total installed capacity. Tianwan NPP actively promotes the comprehensive utilization of nuclear energy and is committed to build itself into a world class nuclear multi-reactor comprehensive utilization industrial group and multi-energy complementary zero-carbon demonstration energy base.

Through the nuclear energy cogeneration technology, 600 t/h of low-pressure steam from Tianwan NPP was provided to the petrochemical industry users nearby. The NPP will provide water for own use by seawater desalination. The project started preliminary work in 2019.

The technical modifications are implemented on the conventional island of Units 3 and 4, establishing a heat exchange isolation loop with the steam conversion technology, and producing steam for industrial use. The specific scheme is to extract about 670 t/h of main steam, to heat up the demineralized water stage by stage with the preheater, heater, steam generator and superheater to produce steam, and then heat up the steam condensate returning to the steam-water circulation system of the conventional island of the unit.

Based on the overall consideration of safety and economy, the seawater desalination project of Tianwan NPP adopts membrane process (reverse osmosis) seawater desalination technology, and the power of the desalination facilities is taken from the plant auxiliary power system.

The new seawater desalination project will have a total capacity of 1520 t/h, based on the water demand for producing steam for industrial use in cogeneration and for operation of the units. The seawater desalination and demineralized water system adopts the following processes: coagulation clarification→ filtration→ ultrafiltration→ two-stage reverse osmosis→ one-stage desalinization→ mix bed. The actual process flow is as shown in Fig. 15.

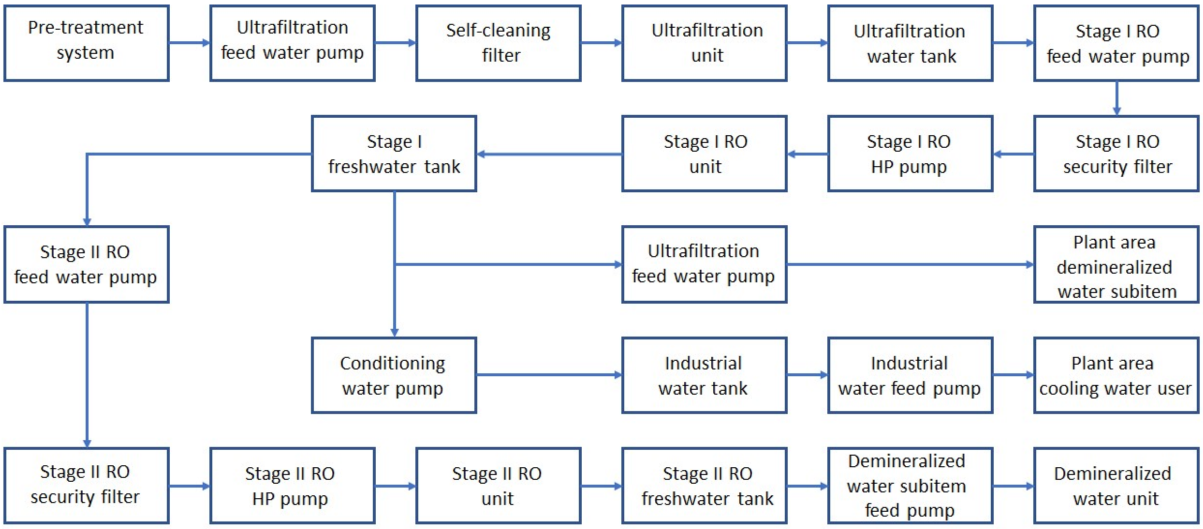

FIG. 15. Process flow chart of seawater desalination of Tian'wan NPP.

After completion of the project, Tianwan NPP will realize cogeneration of heat, power and fresh water with nuclear power. The NPP provides electricity to desalinate the seawater for industrial use. Part of high temperature steam is extracted from the main steam system of the secondary circuit as a heating steam source to produce steam for industrial use. This project will provide obvious environmental benefits after implementation. At the capacity of 600 t/h, it will supply about 4.8 million t steam annually, reducing consumption of standard coal by 400,000 t, and correspondingly reducing the emission of carbon dioxide (1.07 million t), and other pollutants, such as sulphur dioxide (184 t) and nitrogen oxide (263 t).

5.2.3.3. Other cases

Hainan Nuclear Power, a subsidy of CNNP group, has started breeding of silver-lipped pearl oyster with the residual heat of warm water discharged from the NPP. Silver-lipped pearl oyster is a shell living in subtropics and is a Grade II protected species in China. Breeding silver-lipped pearl oyster with the warm water discharged from the NPP can not only protect this species, but also inhibit the extensive breeding of planktonic algae, ensure the safe operation of the units and prevent water eutrophication, to achieve a win-win situation for the protection of ecological environment.

Fuqing NPP, a subsidy of CNNP group, actively explores the construction of an integrated energy station demonstration project for steam supply, heating, water supply, cooling, hydrogen production, photovoltaic and energy storage based on nuclear power. Fuqing city government and Fuqing NPP have signed a Cooperation Agreement, jointly investing to build the Clean Steam Supply Project - Phase I, using the mature steam-steam heat exchange technology, so that the NPP can supply the local industrial park with clean steam for industrial use, with annual supply of 6–10 million t. Based on the Phase I project, Fuqing NPP has signed the Comprehensive Energy Cooperation Agreement with Mintai (Fuzhou) Blue Economy Industrial Park. Fuqing NPP will build the Comprehensive Energy Station Project - Phase II. The project plans to build an integrated infrastructure of steam supply, heating, water supply, cooling, hydrogen supply, photovoltaic and energy storage in this industrial park, to form an integrated intelligent energy system to realize the coupling production, conversion, storage, and consumption of a variety of energy sources.

5.2.4. Prospects of comprehensive nuclear energy utilization

In addition to the comprehensive utilization of nuclear energy using the traditional PWR reactors, CNNP actively promotes the comprehensive utilization of new type of reactors for various applications.

5.2.4.1. Yanlong pool-type low temperature heating reactor

The Yanlong nuclear reactor is developed for heating purposes, based on long safe and stable operation of swimming pool type research reactor conducted by CNNC Group. The reactor core is placed deep in a water pool at atmospheric pressure, and the static pressure of the water layer is used to raise the water temperature at the core outlet to meet the heating requirements. Heat is transferred to the heating loop via two-stage exchange, and then to the users through the heating grid. The Yanlong reactor is characterized by no core melting in case of accident, zero discharge, easy decommissioning and low investment.

An isolation loop with high pressure is added to ensure the isolation of radioactivity from the heating grid. In 2017, CNNC started the Yanlong pool type low-temperature heating reactor heating demonstration project in Beijing, realizing safe heating for 168 h. At present, the demonstration project with this type of reactor is progressing smoothly in Jilin Province, China and is expected to be put into operation in 2025.

5.2.4.2. Multiple utilization of small modular reactor

The ACP100 is a multi-functional small modular PWR reactor independently developed by CNNC Group with independent intellectual property rights. It has the characteristics of high safety, flexible application, and modular construction.

In the offshore, island and other special areas, it will have broad application prospects for power supply, heating, industrial steam supply, offshore oil and gas exploitation, seawater desalination and hydrogen production. In July 2021, a demonstration project was officially started at Hainan Site, and it is expected to be operation in 2026.

5.2.4.3. High temperature gas-cooled reactor for steam supply and hydrogen production

The HTGR is an advanced nuclear reactor technology, featuring inherent safety, high outlet temperature and wide applications. At present, the reactor outlet temperature of the HTGR demonstration project can reach 750°C.

It can meet the single or multiple needs in chemical and metallurgical fields for heat (direct heat source), steam (steam for industrial use), electricity (power generation). In the future, the reactor outlet temperature can be over 950°C, well matching with the thermochemical cycle hydrogen production technology suitable for large-scale hydrogen production.

China has continually carried out research on hydrogen production with HTGR and is expected to complete large-scale research and development of HTGR technology by 2030.

5.3. FINLAND: DISTRICT HEATING REACTOR DEVELOPMENT

The most common form of heating in Finland is district heating, which covers almost 50% of houses and residential and commercial buildings.

5.3.1. The energy context in Finland

In 2019, the Government of Finland decided to phase out coal in energy production in a period of 10 years. Similar decisions aiming to reduce reliance on peat and other fossil fuels are expected to be taken within the near future. Long-term plans also include considerable reductions in the utilization of biomass, eventually extending the climate actions to all burnable fuels. The CO_2 emissions from the Finnish energy sector are divided between electricity production, heating, industrial use and transportation. Some 80% of domestic electricity is already generated using low-carbon technologies, but coal and other fossil fuels are still used for the co-generation of heat and power. This coupling also poses one of the major challenges in the energy transition. Cogeneration plants cannot be simply replaced with traditional nuclear, wind or solar power without compromising the supply of heat.

The transition from local boilers to centralized heating networks occurred in the aftermath of the oil crises of the 1970's, and considerable investments have since then been put to maintaining this infrastructure. Even though heat pumps and other more local solutions are gaining popularity, district heating is likely to remain in a major role, especially in larger cities and other densely populated areas. Short-term plans rely on biomass as the alternative heating fuel, but in recent years, also the possibility of using nuclear energy for district heating has been frequently brought up in public discussion.

5.3.2. The nuclear option

The idea of using nuclear reactors for district heating is not new. Nuclear reactors have been used for cogeneration of heat and power at least in Bulgaria, China, Hungary, Romania, Russia, Slovenia, Switzerland, Sweden and the Ukraine. District heating reactor technology has been actively developed especially in China. In Finland, the first comprehensive studies were carried out in 1971–1973, by evaluating the cost of nuclear-based district heating with existing technology and engineering standards. It was concluded that nuclear energy could become a competitive and technologically viable heating option by the 1980's [92]. The plans were eventually abandoned for political reasons, and coal was chosen as the primary heating fuel for large cities. The same power plants are now being phased out.

The nuclear option was re-evaluated in a recent techno-economical case study, in which various scenarios relying on low-carbon heating options were considered after the coal phase-out of 2029 [93]. Two reactor technologies were selected for the study: the NuScale SMR in co-generation mode and the Chinese DHR-400 pool-type district heating reactor. The nuclear options were compared to conventional technologies (biomass, waste heat, heat pumps, storages, etc.). The study showed that nuclear energy could provide a cost-effective district heating option for Helsinki, with somewhat conservative margins.

One of the identified issues with existing SMR concepts is that the unit size is generally too large for most Finnish district heating networks. The overall annual heat demand is around 40 TWh, but the consumption is divided between 166 separate local networks. The 400 MW output of the DHR-400 reactor, for example, would be suitable for the capital region, but in addition there are more than 100 municipal district heating networks where the total capacity is 50–200 MW. Satisfying the customer needs therefore calls for even smaller unit size. These numbers also emphasize the fundamental differences between the heat and the electricity market. In Finland, electricity is traded in the European Nord Pool power exchange, but heat is always both produced and consumed at the local level[2].

5.3.3. District heating reactor technology

District heating networks are typically designed for a temperature range of 65–120°C, depending on season and weather. Heat supply is provided by large base-load stations, with additional peak load units to compensate for the difference between production and demand during the coldest winter days. Base load generation in a typical Finnish district heating network covers 80–90% of operating time. The largest heat demand falls on the months from September to May, leading to approximately 75% utilization rate for base-load operation.

The operating regime of district heating networks can be achieved with any reactor technology, including conventional LWRs operating in cogeneration mode. There are, however, some considerable advantages in designing a reactor exclusively for low-temperature heat production without any turbine cycle. The inlet temperature of the district heating network can be reached at much lower pressure compared to what is required for running a steam turbine. Low temperature reactors can be operated below 1 MPa pressure, compared to 7 MPa for BWRs and 12–15 MPa for PWRs. The pressure vessel wall thickness can be reduced to 10–30 mm, which is a fraction of what is used in conventional LWRs. This leads to lower manufacturing costs, simplified quality control and broader supply chain.

Low operating temperature also means that the amount of energy stored in the primary circuit as latent heat is considerably lower compared to conventional LWRs. This is directly reflected in the design pressure of the reactor containment. Decay heat removal in most modern SMR concepts relies on natural convection. Lower operating temperature and pressure may considerably simplify the design of passive systems. Since district heating reactors are not bound by the limitations of thermodynamical efficiency, the unit size is typically smaller compared to reactors designed for electricity production. Small unit size is directly reflected in the amount of decay heat.

Many of the design challenges of district heating reactors are common to all SMRs and next-generation technologies. Regulatory guidelines in most countries were written for Gen-II LWRs, in which the safety design is based on active systems. Interpreting how the principles of redundancy and diversity have be applied to passive systems is not straightforward. There are also unique challenges related to, for example, emergency planning zones. Heat, unlike electricity, cannot be transferred cost-effectively over large distances, so the production needs to be brought close to consumption. Urban siting challenges not only licensing, but also public acceptance.

5.3.4. The district heating reactor concept

Development of a new SMR for the purpose of district heating and other low temperature applications was launched at VTT Technical Research Centre of Finland (VTT) in March 2020. To mitigate the technology risks later, it was decided that the reactor design has to mostly rely

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[2] There is considerable demand for low-carbon heat also in other countries with cold winter climate. District heating networks are common especially in the Eastern Central Europe. The combined volume of European district heating markets is 300–400 TWh/a, with most of the supply currently provided by burning fossil fuels.

on conservative well-established solutions, without unconventional features, materials, or manufacturing techniques. Apart from open questions related to urban siting, emergency planning zones and challenges common to all SMRs relying on passive safety, the licensing of the reactor is expected to not require any additional effort or new expertise from the regulator. Finally, the technology has to be compatible with the Finnish nuclear waste management strategy relying on deep geological disposal.

The pre-conceptual design phase was completed by the end of 2020. The main results were published in papers presented at international conferences [94–96]. The technology was later named the "Low-Temperature District Heating and Desalination Reactor" (LDR). Even though the main emphasis was put to district heating, it was recognized that the reactor could also be used for desalination and production of industrial heat. Potential industrial applications include hydrogen production by low-temperature steam electrolysis and regeneration of sorbent compounds used for carbon capture and storage.

The technology is based on modular design. The district heating plant may be constructed of one or several LDR-50 reactor units, each capable of supplying 50 MW of heat into the network at 65–120°C temperature. Several siting options are being considered. In addition to above ground heating plant, the reactors may be sited in an underground rock cavern or retrofitted into a decommissioned fossil power plant.

The nuclear design of the LDR-50 reactor relies on conservative LWR technology. The core is comprised of 37 PWR type fuel assemblies, truncated to 100 cm active length. The fuel enrichment is around 2–3% ^{235}U. Reactivity control is managed by movable control rods and burnable absorber. Soluble boron is not used for active reactivity control, but boron injection can be used as a secondary diverse shut-down mechanism in the case of failed scram.

Thermal hydraulic design is based on natural convection. The primary circuit is fully enclosed inside the reactor vessel, which eliminates the possibility of large break loss of coolant accident. The primary circuit is separated from the district heating network by a secondary circuit and two sets of heat exchangers. Water in the secondary side is circulated by electric pumps. The reactor is designed to be operated in steady-state and load-follow modes. The primary circuit is pre-pressurized with inert gas, and the operating pressure follows coolant temperature. At 120°C core outlet temperature the pressure inside the reactor vessel is around 0.5 MPa. The reactor vessel is enclosed inside a larger containment vessel, which is further submerged in a pool of water acting as the final heat sink (Fig. 16). Decay heat removal from the reactor core is achieved by passive convection without any mechanical moving parts. The intermediate space between the reactor vessel and the containment vessel is partially filled with water. In normal operation, water flows in the lower part of the reactor vessel at 80–100°C temperature. Water in the intermediate space remains below boiling point, effectively isolating the reactor from the pool. When the primary heat transfer route is compromised, temperatures begin to rise, eventually leading to boiling in the intermediate space. Evaporation and condensation on the cooler outer wall of the containment vessel forms an efficient passive heat transfer route into the final heat sink.

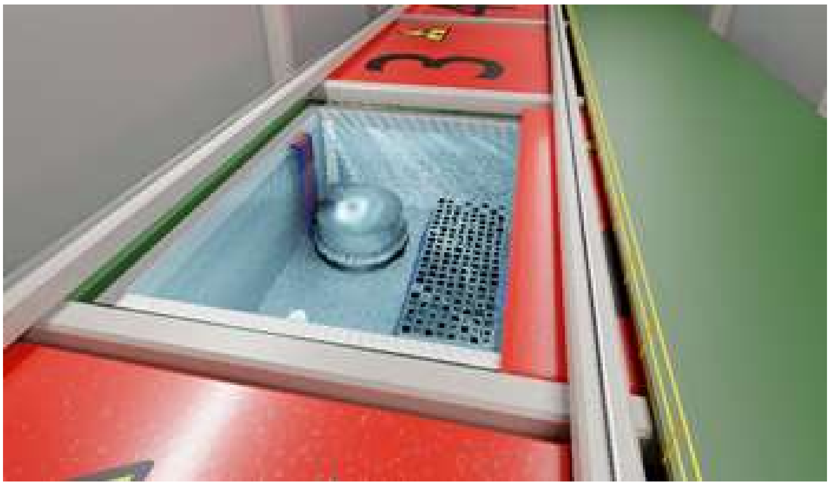

FIG. 16. Visualization of the reactor hall inside a district heating plant comprised of four LDR-50 reactor modules. The open cover of unit 2 shows the top part of the reactor containment vessel in the pool acting as the final heat sink. In this design variation the spent fuel rack is placed in the same pool (reproduced courtesy of VTT, Finland).

Various performance and safety analyses have been carried out for the LDR-50 reactor module using state-of-the art computer codes developed at VTT. Core design analyses have been performed using the Kraken computational framework, which solves the coupled multi-physics problem between neutronics, thermal hydraulics and fuel behavior. Fuel cycle simulations have been carried out for initial and equilibrium cores. Design boundary conditions include various safety-related parameters, such as shut-down margins, reactivity coefficients and peaking factors. The current core design enables 2–3 year refueling interval for an operating cycle with 75% load factor. Reactor performance in normal operation and transient conditions has been evaluated using the Apros power plant simulator. The computational model includes the reactor core and primary circuit, heat exchangers and secondary circuit, with the inlet and outlet temperatures of the district heating network as the boundary conditions. Reactor start-up, shut-down and operation in steady-state and load-follow modes has been demonstrated by Apros simulations.

The passive safety functions have been evaluated in various scenarios, including full-scale station black-out, reactivity transients and primary coolant leak. The analyses have shown that the cooling functions of the reactor core are not seriously compromised in any of the mentioned scenarios. The passive safety features provide a considerable grace period before active measures from the plant staff would be required for returning the reactor to a safe shut-down state. This is largely credited to the small unit size and low operating temperature and pressure in the primary circuit.

5.3.5. The national ecosystem

Currently, VTT collaborates with Lappeenranta-Lahti University of Technology (LUT) on the design optimization of heat exchangers for the LDR-50 reactor module[3]. VTT is also coordinating the national EcoSMR project [97], established to support Finnish industry, enhance national expertise on SMRs, and create an international innovation and business ecosystem that promotes networking and enables Finnish companies to participate in the

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[3] LUT University is also developing a small channel-type LWR concept “LUTHER” for district heating. This is a separate project from VTT’s LDR-50.

emerging SMR markets. The project partners include VTT and LUT, reactor operators (Fortum and Teollisuuden Voima Oyj), energy companies (Helen and Vantaan energia), and engineering companies (such as EnviroCase, Platom, Refinec and Rockplan). In addition to the project partners, members of the ecosystem include Finnish and international companies, such as UPM Energy, Ensa, GE-Hitachi and Westinghouse.

The ecosystem was not exclusively established to promote nuclear energy for district heating, but the national reactor design efforts have gained considerable attention among the members. For the LDR-50 project this provides the opportunity to establish contacts with both technology suppliers and end users. Research topics under the EcoSMR project deal with questions related to licensing and siting issues of SMRs in general, specific challenges of heating reactors, and new business models for the novel applications of nuclear energy.

5.4. INDIA: ACTIVITIES AND CURRENT STAUS RELATED TO NUCLEAR COGENERATION

The current Indian primary energy mix is mainly based on fossil fuels such as coal and petroleum products. Despite the lower per capita energy consumption and carbon emissions (1.8 t of CO_2 per capita per year) compared to global averages (4.8 t of CO_2 per capita per year), India accounts for about 7% of total global GHG emissions at present [98]. GHG emissions originate from electricity production using coal, industrial activities (production of iron and steel, cement, ammonia, petrochemicals, etc.), transportation (liquid and gaseous hydrocarbon use) and from the agriculture sector. Electricity makes up about 18% of final energy consumption in the country and more than 70% of this electricity today is sourced from coal-fired thermal power plants. The transportation sector is mainly dependent on imported petroleum products (of which 90% is petrol and diesel and 10% is aviation turbine fuel) as well as some share of natural gas. This constitutes more than 30% of India’s final energy usage [98]. Given India’s ever growing energy needs in its quest to become a developed economy with sustained and inclusive growth for all, its commitments to climate action and decarbonization of energy and industrial sectors for a net zero nation by 2070 and its urgent need to attain energy security and significant reduction in energy imports, massive expansion of its clean energy portfolio (made up of nuclear, renewables) and clean energy based services such as hydrogen and synthetic energy vector production including biofuels, carbon capture technologies and hydrogen production is imperative and need to be urgently scaled up.

5.4.1. India’s nuclear power

India currently has about 7 GWe of installed nuclear power capacity. The present share of nuclear energy in India’s electricity portfolio is about 2%. Installed capacity is poised to grow further in the coming years, with programs to almost triple it by mid-2030s. Like many other nuclear equipped nations, NPPs in India have also served primarily as baseload suppliers of electricity to the national grid, with present electricity tariffs ranging from 0.032 USD/kWh to 0.06 USD/kWh [99]. Nuclear cogeneration using nuclear heat and/or electricity thus has the potential of diversifying the use of nuclear power, makes its utilization more efficient and providing opportunities for foraying into partnerships with industries and sectors beyond the electricity market alone. With a growing nuclear fleet, the potential impact of nuclear cogeneration activities in India is also expected to be far reaching.

India’s current nuclear fleet consists of pressurized heavy water reactors, pressurized water reactors and boiling water reactors, which all work with primary coolant temperature of about 300–320°C. The steam generated in the secondary cycle is at a maximum temperature of about 250°C [100]. Therefore, these process conditions can be suitably utilized for water desalination by thermal (multi-stage flash, multi-effect distillation, low temperature distillation) and membrane techniques (reverse osmosis). Hydrogen production in a carbon-free manner can also be accomplished by low temperature water electrolysis using a part of the desalinated water and nuclear electricity as the inputs. Such a combined cogeneration scheme is best implemented at coastal NPPs, though cogeneration of hydrogen alone can also be achieved at any in-land power plant site where freshwater availability is not a bottleneck. Demonstration and pilot scale facilities for these processes have already been set up and operational experience has been gained in India.

5.4.2. Nuclear desalination

Development of sea and brackish water desalination technologies using energy from NPPs was initiated in India in the 1970s. Indigenous expertise has been built up in numerous technologies such as multiple effect distillation with or without thermo-vapour compression, multistage flash separation, reverse osmosis, low temperature evaporation, advanced low temperature distillation etc. Development of innovative heat exchange devices, corrosion resistant materials, reverse osmosis membranes, novel routes to achieving enhanced energy recovery and economy while operating the desalination plants have naturally progressed in parallel. A program of phase wise improvement of the nuclear desalination technologies has been adopted. India has set up and has been operating a hybrid multi-stage flash distillation (4.5 million L/d) and seawater reverse osmosis (1.8 million L/d) desalination plant at Kalpakkam, coupled to the 220 MWe PHWR of Madras Atomic Power Station. Currently this is the world’s largest operating nuclear desalination plant. From feed seawater containing 35,000 ppm dissolved salts, it produces desalinated and demineralized water having 25–400 ppm dissolved salts. Total power consumption of this plant is about 4 MW, including steam and electricity which are obtained from Madras Atomic Power Station.

The wealth of experience gained from in-house design and deployment of this plant has been successfully applied to the design of another hybrid desalination plant being built at Odisha on the eastern coast of the country and this project is currently in the construction phase. This plant has a proposed capacity of 5 million L/d and will be based on seawater reverse osmosis (4.5 million L/d) + MED (0.5 million L/d) technologies. While this plant is not directly coupled to an NPP, it will leverage the interdisciplinary capabilities and knowledge acquired by units under the Department of Atomic Energy, India and will add to the indigenous nuclear desalination experience. Theoretical studies and practical demonstrations of specially designed low temperature evaporation processes and the advanced low temperature distillation processes have been carried out to establish feasibility of utilizing waste heat available at temperatures of about 60°C in the moderator circuits of PHWRs.

The conceptual design of the desalination plant that can be coupled to the 300 MWe Advanced Heavy Water Reactor, also designated as Indian BWR, capable of producing up to 3000 m^3/d of demineralized water using hybrid desalination technology is currently being analysed. Several process schematics including standalone Multiple effect distillation (with and without thermo-vapour compression), sea water reverse osmosis and hybrid configurations using combinations of these schemes have been considered and their techno-commercial analysis has been performed using the IAEA Desalination Economic Evaluation Program to arrive at the optimal scheme under the current Indian scenario.

Multiple barriers and engineered safety features have been included in these schematics to prevent radioactive contamination of the desalinated water when the plant is thermally and electrically coupled with the nuclear power station. The levelized cost of water produced by nuclear desalination in India is estimated about 1–2 USD/m^3 depending on the type of desalination process technology adopted, which is at par with internationally reported figures and competitive with other technologies for obtaining potable or demineralized water starting from raw water. India has also embarked upon technology development for management of the concentrated brine that is generally the reject from thermal and membrane-based desalination. Brine can be considered as a resource, rather than a waste since it is the source of several valuable inorganic salts and ultimately metals which have commercial and industrial applications. Brine concentration by evaporation and subsequent fractional crystallization can enable separation and recovery of individual salts. Yet another direction in which India is directing its efforts currently is the on-site management of spent reverse osmosis membrane modules. These membranes are polymeric materials which can be chemically treated after their useful service life is over to recover the monomers or they may be used to produce important products like porous carbon by pyrolysis or other high temperature processing operations.

5.4.3. Nuclear hydrogen

Nuclear hydrogen production via commercially mature water electrolysis technology is a promising, low-carbon route to obtaining bulk quantities of hydrogen for industrial decarbonization. This has very relevance to all countries like India who need to also reduce dependence on imported fossil fuels and chemical feed stock like natural gas. The first phase of a National Hydrogen Mission has recently been announced, which emphasizes low carbon hydrogen production for domestic consumption using renewable and bio-resources. Accordingly, India has been carrying out research and development activities on various aspects of nuclear hydrogen production. According to a recent study, India's existing, upcoming and planned nuclear reactors can power modular water electrolysers to produce 1.8–4.0 million metric t hydrogen per year at annualized production costs competitive with current renewable hydrogen costs. Nuclear hydrogen can meet between 6–15% of the current green hydrogen demand of priority sectors in India. Switching to green hydrogen in these sectors can avoid CO_2 emissions of up to 570 million metric tons per year, which is about 15% of India's current total GHG emissions [99]. This will make it possible for the nuclear industry to support the decarbonization of more than the Indian electricity sector. It also creates a stronger case for further expansion of India's nuclear power capacity, which would help overcome this current 85% green hydrogen supply deficit, which would further increase when new end-use sectors for hydrogen open up.

At present, research and development initiatives in India in the field of nuclear hydrogen production are based on several electro- and thermo-chemical technologies. This includes water and steam electrolysis process development, intermediate temperature (550°C) thermochemical cycles (e.g., Cu-Cl cycle and high temperature (850–950°C) thermochemical cycles (e.g., I-S process and its variants. Advanced nuclear reactor technologies (molten salt reactors, high temperature reactors, fast breeders) to support high temperature hydrogen production are also being developed indigenously, particularly with a view towards efficient utilization of India's large domestic thorium reserves. At BARC, India has indigenously developed highly compact, skid mounted, modular alkaline water electrolysers using advanced porous nickel electrodes in a zero-gap filter-press type construction, capable of producing up to 10 m^3/h of high purity (99.9%) hydrogen from 30% KOH in demineralized water feed solution. The specific power consumption is about 5 kWh/m^3 hydrogen and water consumption is about 1 L/m^3 hydrogen. Owing to its modular construction, the plant capacity can be scaled up by adding more electrolysis cells in series and stacks in parallel [101]. The technology has been transferred to private and public sector industries in India for scale up and deployment. Based on the relative maturities of the various hydrogen technologies, for near-term implementation in India, a program based on water electrolysers and ancillary technologies coupled to indigenous water-cooled nuclear reactors is likely to be adopted as the entry point for the nuclear industry into the hydrogen domain.

Nuclear cogeneration has been and will continue to be an important segment of the Indian nuclear power program, contributing to climate change mitigation, adaptation, and sustainable development of the country.

5.5. JAPAN: ROLE OF HIGH TEMPERATURE GAS-COOLED REACTOR TECHNOLOGIES TO ATTAIN CARBON NEUTRALITY

5.5.1. Commitment to attain carbon neutrality

On October 26, 2020, Former Prime Minister Suga declared in a key policy speech to the National Diet that Japan aims to become a carbon-neutral, decarbonized society by 2050. In response to the declaration, the Ministry of Economy, Trade and Industry, in collaboration with other ministries and agencies, formulated the “Green Growth Strategy through Achieving Carbon Neutrality in 2050.” Japan upholds an ambitious goal while showing realistic pathways toward it wherever possible. The strategy specifies 14 promising fields that are expected to grow and provides them with action plans from the viewpoints of both industrial and energy policies. The strategy directs all available policies to supporting positive efforts by companies toward this goal. The 14 fields include nuclear industry with HTGR.

5.5.2. Challenges to attain carbon neutrality

The Japan’s approach to attain carbon neutrality in 2050 consists of four pillars:

- Promotion of energy conservation;
- Decarbonization of electricity sector;
- Promotion of electrification and reduction of CO_2 emission intensity for non-electricity sector;
- Utilization of negative emission technologies.

The challenges in the decarbonization of electricity sector and reduction of CO_2 emission intensity for non-electricity sector are discussed below.

5.5.2.1. Challenges in decarbonisation of electric sectors

Today, our electricity power sector highly depends on fossil fuels due to low capacity in carbon-free power generators. Towards the decarbonization, the Green Growth Strategy sets a target of renewables’ share of power generation as 50% to 60% in 2050. To enable such high renewable penetration levels on electric grid, the imbalance between generation of the intermittent renewable sources, e.g., wind power and solar photovoltaic dispatchable generators and demands have to be managed.

One of the challenges to maintain a power gird stability is to secure carbon-free flexibility in exchange for fossil fuel fired power plants. The priority dispatch rule in Japan designates an order of dispatching control as follows when power generation exceed the demand:

- Control of generations in fossil fuel fired power plants, utilization of pumped storage hydropower plants;
- Power transmission to other area;
- Control of generation in biomass power generation plant;
- Curtailments of solar and wind power generation plants;
- Control of generations in base load power plants.

An important consideration for the energy systems with a high share of renewables is the rate of curtailment. For example, the curtailment rate of renewables may rise more than 30% of their generated energy when the penetration rate of intermittent renewables reaches 46% in the energy mix [102]. Curtailment of renewables involves energy wasted and economic penalties. Another challenge is to ensure a grid inertia that will help to mitigate drop of grid frequency against a loss of dispatched generator. The reduction of inertia will be caused by the reduction of synchronous generators due to the displacement of renewables that are connected to the grid by power electric devices. Insufficient system inertia may result in blackout due to immediate frequency decay initiated by grid emergency events. Simulations performed indicated that the rate of frequency change will exceed 2.0 Hz/s (this is the value to limit the power plant tripping) if penetration level of intermittent renewables reaches 30% to 40% [102].

5.5.2.2. Challenges in decarbonisation of non-electric sectors

The CO_2 emission from non-electricity sector accounts for 60% of the carbon footprint in Japan and all of the heat is produced by burning fossil fuels. Main contributors to the emission are industrial sectors such as steel making, chemical, petroleum, and transport sectors. Hydrogen is expected to play a key role in the decarbonization of the field. Particularly, the use of hydrogen as a substitute of coke as reducing agent is considered to be promising to reduce CO_2 emission in the steel making sector. In November 2018, the Japan Iron and Steel Federation formulated the “Long term vision for climate change mitigation: A challenge towards zero carbon steel”. The vision outlines a roadmap setting a goal to establish a hydrogen-based ironmaking technology which can eliminate CO_2 emission from the process by external hydrogen supply.

To realize the “zero-carbon steel” technology, high hurdles have to be cleared: continuous supply of carbon-free external heat to sustain reduction reaction, stable supply of large amount of carbon-free hydrogen with a competitive cost, etc. 7 million t hydrogen is required to maintain the current annual production rate of pig iron in Japan. The cost parity of hydrogen with competing coal is 8 m^3/JPY if environmental cost is not considered [103].

5.5.3. Potential roles of high temperature reactor technologies

High temperature reactors are expected to take an important role to attain carbon neutrality in 2050 due to the inherent safety characteristics and high temperature heat supply capability. The HTGR safety characteristics comes from the use of ceramic coated fuel particle, graphite moderator and helium coolant. Coated fuel particle has excellent heat resistant property, and the coating will not fail even at 1900°C. Graphite moderator has high heat capacity and large thermal conductivity, and capable to remove heat passively from the reactor pressure vessel outside. Helium coolant is chemically inert and does not change phase and will not invite explosions of hydrogen or vapor. As a result, radionuclides can be retained within plant by autonomous reactor shutdown and core cooling with no reliance on active equipment and/or immediate operator actions against loss-of-core cooling accidents. The high temperature supply capability offers high thermal efficiency of 50% in electricity and carbon-free hydrogen generation with the use of helium gas turbine power conversion system and thermochemical I-S process. The heat can also be supplied to multi-purpose applications such as district heating, seawater desalination and so on.

Figure 17 shows a plant layout of Gas Turbine High Temperature Reactor (GTHTR300C) [104], a JAEA's HTGR cogeneration plant design. Table 6 shows the major specifications of the GTHTR300C. The GTHTR300C is an advanced system, and the design was developed with a cooperative work of JAEA and domestic industries. The design has unique features such as multiple applications, passive safety, compelling economics, flexible plant siting, etc. The features of HTGR cogeneration plant will contribute to overcome the challenges that are raised in the previous chapter.

Firstly, the HTGR cogeneration plant can be used to compensate the intermittent and perturbating performance of the renewable resources on power system stability. FIG. 18 illustrates the concept of a HTGR renewable hybrid energy system. Numerical simulations indicated that the HTGR cogeneration plant can follow the daily and hourly load variation of the renewable energy with constant reactor power and power generation efficiency by allocating of heat generated in the reactor to gas turbine and hydrogen production plant. In addition, the plant is also able to accommodate generator load variations in the minute time scale by fully utilizing heat storage capability in the reactor without sacrificing reactor availability and efficiency. Furthermore, the plant accommodates the second time scale variation mainly by inertia of the gas turbine [105]. Table 6 includes the major specifications of the GTHTR300 system.

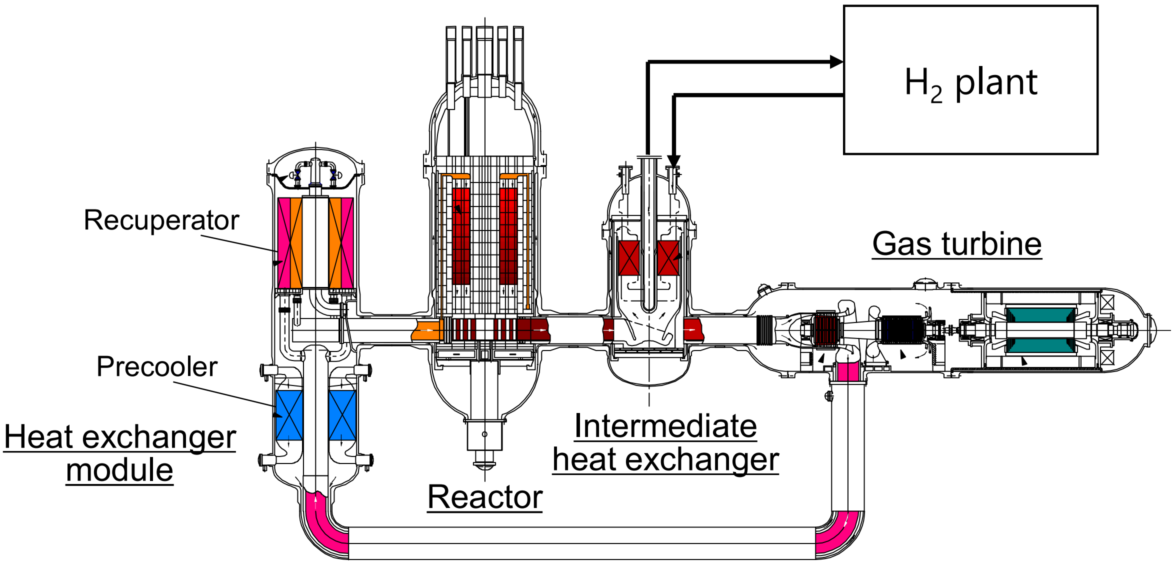

FIG. 17. Plant layout of GTHTR300C.

TABLE 6. MAJOR SPECIFICATIONS OF GTHTR300

	Power and hydrogen cogeneration	**Higher hydrogen production capacity**
Reactor power	600 MWt	600 MWt
Reactor temperature (out/in)	950°C /594°C	950°C/594°C
Power output (efficiency)	202 MWe (47%)	87 MWe (37%)
Hydrogen production rate	1.9–2.4 t/h	4.1–5.2 t/h
Average fuel burnup	120 GWd/t	120 GWd/t
Refuelling interval (months)	18	18

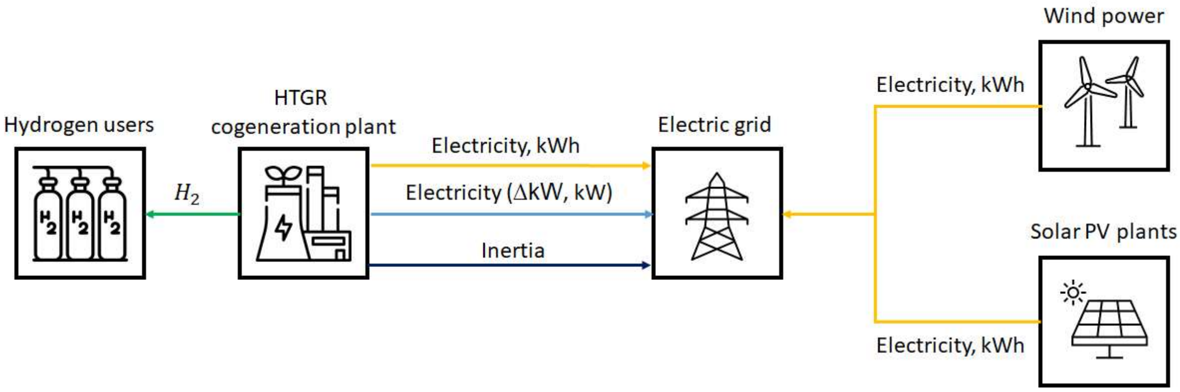

FIG. 18. HTGR renewable hybrid energy system concept.

The HTGR cogeneration plant has a potential to supply large-scale, stable and cost-competitive carbon-free hydrogen. Figure 19 depicts a schematic of HTGR energy supplying a steel making system with hydrogen produced via I-S process. The energy and material balance of a system to produce steel (capacity of 10,000 t/d) was estimated as shown in Fig. 19 [106]. A study showed that 5 units of HTGR cogeneration plants were required for a standard steel plant in Japan, associated CO_2 emissions from the steel plant being thus eliminated. The cost of hydrogen is estimated as 25 JPY/m^3 [107].

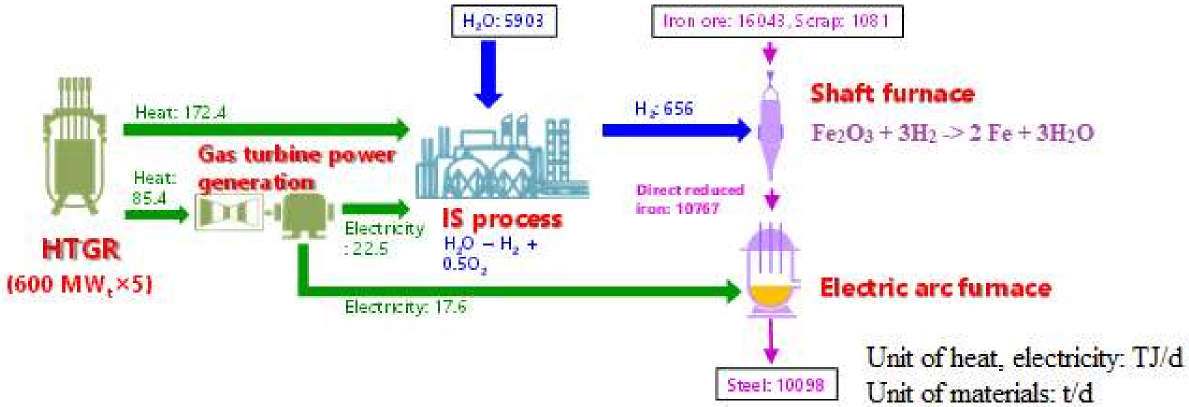

FIG. 19. HTGR energy supplied steel making system.

5.5.4. Deployment of a cogeneration plant

Table 7 shows a roadmap towards HTGR commercial deployment proposed by JAEA. Private sectors are exploring several concepts for commercial HTGR plants cooperating with JAEA on design and analysis codes and new developments on component technologies. HTGR steam turbine power generation plant concept is planned to be commercialized in the beginning of 2040. A cogeneration concept with a helium gas turbine and a steam methane reforming hydrogen production plant is expected to be deployed around the same time. A concept with a helium gas turbine and a hydrogen production plant will be demonstrated in the latter half of the 2040s. Regulatory authority will establish safety standards for HTGR commercial plant through the licensing. To support activities in private sectors, JAEA plans heat application test with the HTTR, to develop coupling technologies of hydrogen production plant to HTGR by 2030.

Figure 20 shows a sketch of the HTTR heat application test facility. The objective of the test is to establish a safety design for coupling HTGR and hydrogen production plant and demonstrate performance of components required for coupling between HTGR and hydrogen production plant e.g., high temperature isolation valves using the HTTR. To complete development of the coupling technologies, we will obtain a license for change of reactor instalment by Nuclear Regulatory Authority, construct a steam methane reforming hydrogen production plant and connect the plant to the HTTR. JAEA will also conduct a continuous hydrogen production test and plant dynamic tests.

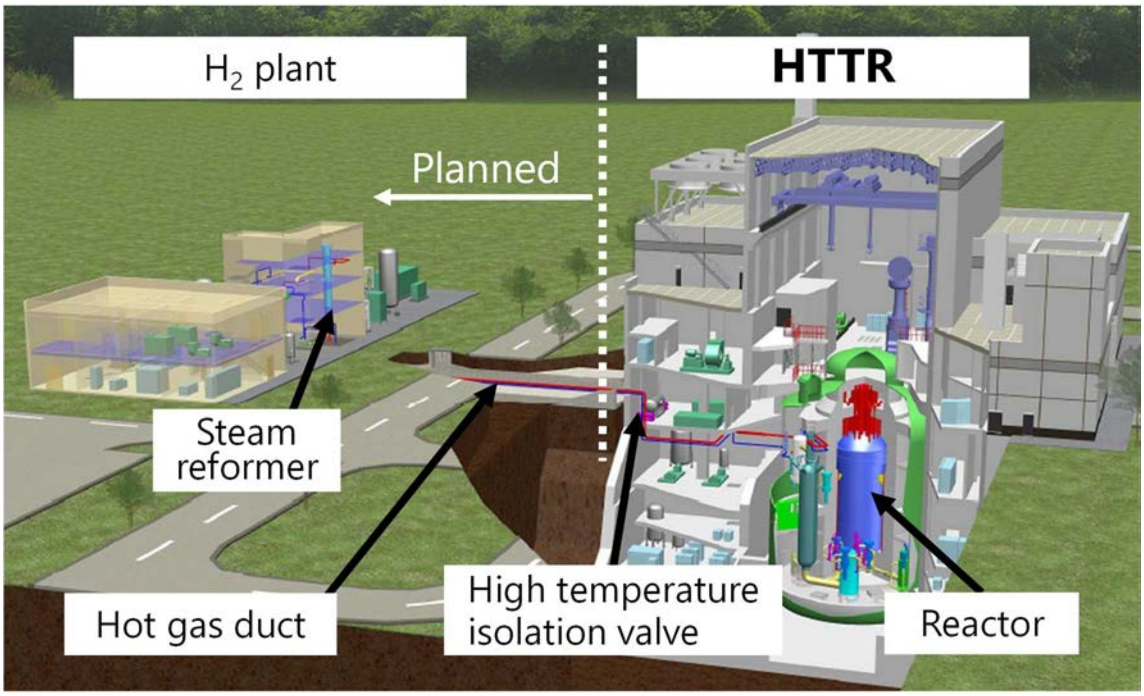

FIG. 20. HTTR heat application test.

TABLE 7. ROADMAP TOWARDS HTGR DEPLOYMENT – JAEA PLAN

Time	Private sector	JAEA		Regulatory authority
2020-2030	• Demonstration of key technologies (gas turbine/steam reformer) • Demonstration plant (gas turbine/steam reformer, steam turbine) - Conceptual study - Basic design - Safety analysis - Licensing - Procurement	International collaboration with private sector (Poland, UK, etc) in design and analysis codes, know-how - Demonstration of component technologies	• Design & construction of HTTR heat application test facility • Qualification of fuel and material under commercial condition • Establishment of design & material standards • Development of hydrogen plant coupling technologies • Development of the key technologies (I-S)	• Development of review capability • Safety review of HTTR for coupling hydrogen plant • Safety standard development for commercial HTGR
2030-2040	• Demonstration of key technologies • Demonstration plant (gas turbine/steam reformer, steam turbine) - Construction and operation • Demonstration plant (clean hydrogen) - Conceptual study - Basic design - Safety analysis - Licensing - Procurement		• HTTR heat application test • Qualification of fuel & material under commercial condition	Safety review of demonstration plant (gas turbine/steam reformer, steam turbine)
2030-2040	• Demonstration plant (clean hydrogen) - Construction & operation • Commercial plant (gas turbine/steam reformer, steam turbine) - Conceptual study - Basic design - Safety analysis - Licensing - Procurement	**HTTR heat application test** Development of coupling technologies between HTGR and hydrogen plant including: - establishment of safety design for coupling hydrogen plant to nuclear reactor - development of unique components that are required for coupling		• Safety review of demonstration plant (clean hydrogen) • Safety review of commercial plant (gas turbine/steam reformer, steam turbine)

5.5.5. Distributed carbon neutral hybrid systems based on small modular reactors

During the most recent decade, Japan has experienced some of the severest power outages on record. They caused by extreme natural conditions including earthquakes and extreme weather conditions damaging equipment of the regional utility power grids. They affected several prefectures at a time and metropolis including Tokyo, large number of households (hundreds of thousands to millions). They impaired critical infrastructure such as communication, transportation, gas stations, water supply, shops, hospitals, and businesses for as long as weeks. The rapid introduction of wind and solar energy may aggravate the problem further because of the intermittent nature of the renewable energy power sources.

Aiming to improve reliability and resilience of supply system, Japan started a 4-year national project to study distributed energy systems in October 2020. The study participants include the University of Tokyo (national grid systems), the Institute of Energy Economics Japan (energy and fuel demand and supply), JAEA (SMR developer), Mitsubishi Heavy Industries (nuclear reactor vendor), and JGC Holdings Corporation (industrial process plant developer). Two concepts are being investigated – micro system and regional system.

The concept of micro energy system (Fig. 21) aims to improve resilience of energy supply for critical infrastructure and major commercial districts by avoiding the risk associated the supply failures encountered with large grids and supply networks. The system is based on building an innovative SMR nuclear cogeneration system that excludes the release of radioactive materials from the plant in the event of an accident through the development of fully inherent safety technology. It provides all low carbon energy demand for power, heat, hydrogen fuel. It serves critical infrastructure for commercial, finance, health, and research.

The microreactor will be designed for autonomous operation with infrequent or no refueling over the lifetime. It can be standardized, factory manufactured in series, and transported to a site to plug in and play. It would require small footprint and support systems. The variants of the system may be used to supply remote areas installations with reliable, resilient, and carbon-free energy. The study is examining compatibility and integration issues of the micro energy system with critical infrastructures in terms of energy supply conditions, operation and safety requirements, security considerations, cost relative to other energy operations, and reliability and resilience performance.

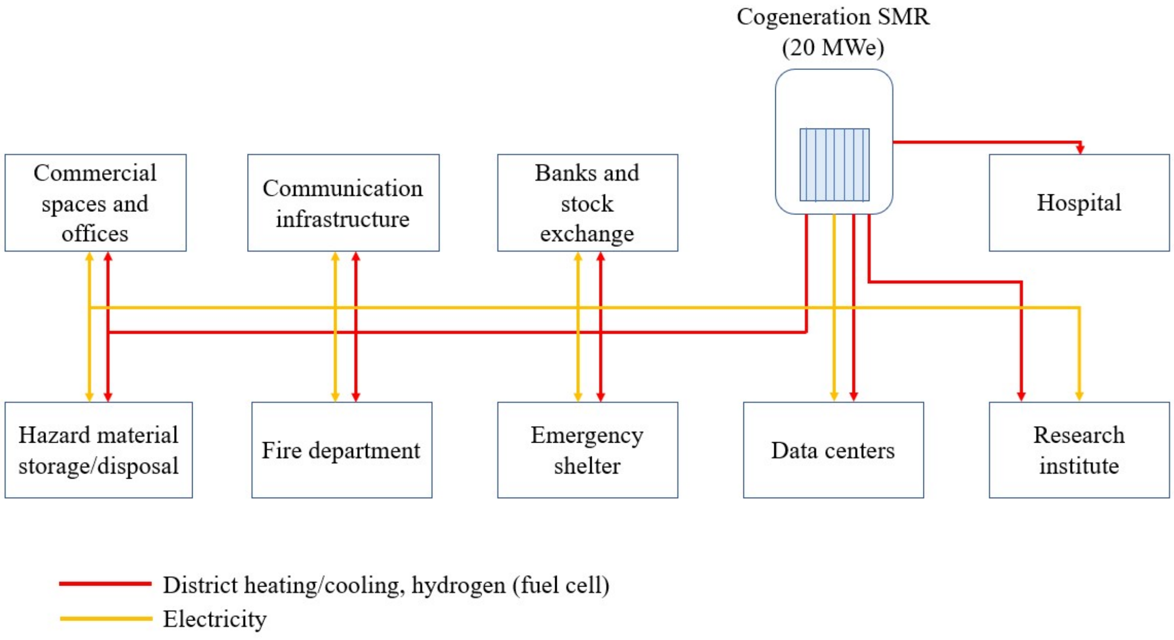

FIG. 21. Micro nuclear reactor cogeneration system for critical infrastructure.

On the other hand, the regional energy system (Fig. 22) aims to model a distributed energy system to supply areas in the same prefecture. Japan has 47 prefectures, which are presently served independently by 10 electric utilities. The smaller regional energy system is expected to be able to strengthen energy supply resilience, respond to the demand needs of local economics, and relate closer to their economic and environment interests such as cost of energy and CO_2 reduction.

The project has developed an integrated simulation method that can derive the optimum introduction scenario considering the regional characteristics of energy demand mix (electricity, fuel for transportation, heat and hydrogen for industries), performance and economic characteristics of energy supply mix including various types (LWR, HTGR, SFR), roles (base and variable electricity, and heat and hydrogen cogeneration), deployment schedule of the various SMRs and cogeneration technologies, system resilience and cost.

In the system, hydrogen is produced from the SMRs. Hydrogen is supplied as fuel to gas turbine power generation and as material to industries, for which carbon free steel manufacturing process is being investigated. Since hydrogen is difficult to transport, various hydrogen carriers (synthesized ammonia, methane, and methanol) are being studied from production through air capture, CO_2 recycle, and hydrogen produced from the SMR.

When nuclear reactors produce more electricity than the grid needs, some of their surplus thermal heat and/or electricity is diverted via cogeneration to produce materials for clean hydrogen, clean liquid fuel got transportation and industry sectors. Doing so can allow for operational and production flexibility while increasing the resilience of electricity grids containing large shares of wind and solar power, generating additional revenue for the nuclear plants, lowering total hybrid system costs, and delivering a zero or negative emission system.

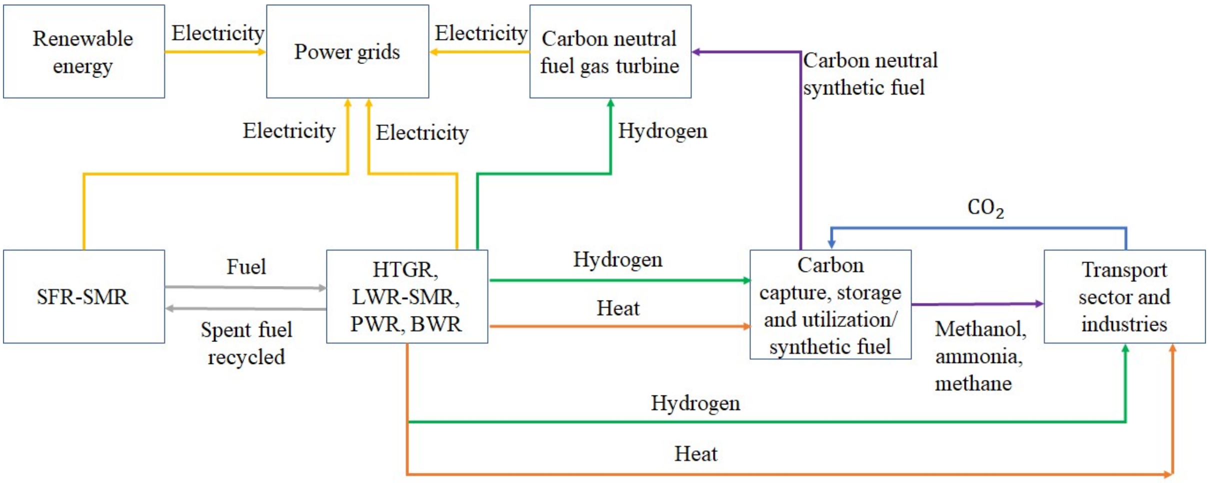

FIG. 22. Regional energy system using SMRs for cogeneration of power, heat and hydrogen.

5.6. ROMANIA: NUCLEAR COGENERATION - EXISTING EXPERIENCE, THE POTENTIAL AND THE CHALLENGES IN THE CONTEXT OF FUTURE ENERGY MARKET AND CLIMATE CHANGE POLICIES

Since ‘90s, Romania has been using a small fraction of wasted heat from its Cernavoda NPP to supply the local district heating system (DHS).

5.6.1. Romanian experience in nuclear cogeneration

The funds for the interface, backup and networks for nuclear cogeneration were included in the Cernavoda Socio-Economic Programme combined with other local investments, offering a set of benefits for the community with the aim to increase the public acceptance and to prevent possible delays or blockages. The Socio-Economic Programme initially consisted of a set of investments defined as complementary works for the planned Cernavoda NPP (5 units of 700 MWe each) [108]: district heating; hospital, schools, high schools; water supply plant; new bridges.

The heating was considered as an important driving factor since most of the inhabitants were targeted for the benefits. The most important message of the Socio-Economic Programme was “to provide the cheapest heating for all the inhabitants of Cernavoda town”. After the implementation, the results of investments were planned to be transferred without any payment to the local community. An extension of the Socio-Economic Programme was produced in 2003 by a socio-cultural investment, including modernization of the town road infrastructure, construction of new kindergartens, a wastewater treatment plant, a youth center for education and entertainment, public fountains, and residential buildings.

The nuclear based DHS for Cernavoda town is a classical vertical type with a main source (the Cernavoda NPP) and a single backup. The distribution of the heat is in the responsibility of a local utility that owns the network and the local heat exchangers. The heating power generation consisting of two heat exchangers with a total thermal power of 46.51 MW [109]. The incomes obtained due to heat generation and electricity generation are mentioned in Ref. [110]. However, the heating has a great value for the local community. The price paid for the heating by the final consumer from Cernavoda town is among the lowest in the country [111]. A set of good practices may be noted:

- Good quality of the service (amount of heat, temperature, stability, functionality in extreme weather conditions);
- Excellent price according with the market;
- No public concerns on nuclear heating;
- Good cooperation of the stakeholders (NPP owner, NPP operator, local utility company, local regulators, local authorities, consumers).

5.6.2. Market potential for nuclear district heating

An investigation on the extension of the nuclear DHS based on a retrofitting approach was performed by the Institute for Nuclear Research, RATEN ICN (2018–2019) and produced the following conclusive elements:

- For Cernavoda town the potential for extension is reduced (as DHS is almost completed to all buildings, and there are limited chances for an economic boom);

- There are some potential urban agglomerations that may be appropriate for the nuclear heating (Medgidia, Constanta, Fetesti, Slobozia, Calarasi);
- Bucharest, with 2.2 million inhabitants, located 230 km far away from Cernavoda, may be considered, based on the technical performances of the pipelines.

Due to its size and distance to Cernavoda, Constanta metropolitan area seems to have the most important potential for the extension of nuclear cogeneration. However, some critical points were identified:

- The distance (50 km) involves the use of modern pipes (with losses < 5%);
- Large investment needed for the transport system;
- Different interests of the stakeholders (local utilities, local authorities, NPP owner, NPP operator).

Technically, the investment is possible by using modern pipes with insulator conductivity less than 0.04 W/(m·K), that would lead to a loss of heat no more than 120 W/m (meaning the reduction of the total heat loss to no more than 2% of the transported power).

From the decision-making process point of view, it has to be noted that the stakeholders have a relatively broad spectrum of interests in the DHS business. The NPP owner may be interested to increase the plant overall efficiency by selling a part of the wasted heat, but technically, the heat extraction will produce an impact on the amount of electricity production. Normally, the NPP owner will not be interested in the investment for the transport pipes, and the DHS owner cannot support such investment for long distance transport. Other stakeholders, such as the local authorities or local utilities, may have interest in supporting other heating systems and/or different business models. Development of a national programme to support the heat transport network can be a practical approach. Also, the public money for modernization, improvement of the energy efficiency, measures of the national plan for climate changes may be a valuable and practical resource for funding. However, the decision-making process is complex and quite long due to the diversity of the stakeholders' interests and also to the differences in understandings of the technical aspects, the business models, the outcomes, and the benefits and their sharing.

In case of the retrofitting approach, there are difficulties generated by the need for technical adaptation of the existing configuration to one allowing the extraction of the wasted heat. In case of new plants, the concept of cogeneration readiness is recommended to be used during the design phase. It is defined as the anticipating of the additional space requirements for pipelines and heat exchangers to allow the upgrading of the plant for a future use.

Currently, the cogeneration readiness has a cost representing approximately 10% of the total capital costs required for retrofitting adaptation. Based on such design, the NPP may be operated in the electricity-only mode until the market, business and institutional conditions will be favorable for the cogeneration mode contributing to a significant reduction of the investment risks.

In case of Romania, the district heating has a great potential due to:

- High density of households in the urban areas, characterized by the dominance of block of flats, grouped into quartiers;
- Existing networks for heating in many of the urban areas, based on combined heat and power conventional units;

- Long tradition of DHS in the country;
- Optimal size of the county's capitals (medium towns, with 200 000–400 000 inhabitants).

An important drawback consists of the tendency of the last decade to close the DHS in some towns or to reduce their share in the heating. In 1989 there were operational 315 DHS and as of 2022, there are less than 50 [112]. Moreover, the total number of households connected to DHS drastically decreased from 2.7 million (in 1990s) to 1.08 million (in 2022) [112].

A set of socio-economic factors (such as the prices, the evolution of the new technologies, trends in the quality of life) have generated a process of closing of many DHSs and/or to reduce their activity.

From the point of view of the heating needs, typical conditions of climate in Romania were used for an average town in Romania (like the capital of a county). Based on the dominance of block of flats in the urban area and considering a typical distribution of the flats according to their sizes and consumption, a total heat demand was estimated around 525 GWh/a. In such conditions a SMR system is appropriate to cover the winter needs for heating in the case of the considered typical town. Some open issues are:

- The licensing aspects such as the size of emergency planning zone and the isolation of the loops;
- The optimal backup solution;
- The efficiency in the context of the seasonal variation of heating needs.

Also, the seasonal variation is important in Romania. Winters are usually cold, and summers are very hot. The heating season usually lasts for 5 months (from the end of October to the beginning of April) in the year. An increasing of electricity consumption during summer arose due to the increasing of the cooling needs supported by the improvement of the life quality. Therefore, the use of SMR to produce dominantly heat in the winter and electricity in the summer seems to be practical. On the other hand, the development of SMR exclusively oriented to heating has a great market potential.

5.6.3. Market potential for process heat

In the 1990s, the Romanian industry suffered a complex process of restructuring of the economy, stimulated by privatization and liberalization of the market. The process has determined the closure of many large industrial platforms. A lot of abandoned sites have resulted, with vast contaminated lands. Most of them have a large potential for the reconversion due to the value of lands (nearby urban areas), existing networks, roads, and buildings.

There are some barriers (such as the cost of the remediation, the availability of quite very cheap lands nearby the main routes of transport). However, the reconversion of the abandoned platforms is expected in the next decade, after the exhausting of the profitable sites.

An integrated solution for the energy approach was proposed:

- Using the synergy between nuclear and renewables;
- Start the activity by installing PV panels on a significant area, before the remediation process;
- Start the remediation for the nuclear site;
- Modernization and reconversion of the buildings to host new business;

- Install a SMR in cogeneration mode;
- Continue the site remediation and expand the activities (new buildings, new business);
- Finalize the remediation on the area occupied by PV panels.

The proposed solution has some advantages such as:

- A progressive investment, including a progressive remediation;
- The use a large part of the energy on the site and improve the efficiency by reducing the transport losses;
- Contribution to the balancing of the variability (especially day-night) of the PV production;
- Create the conditions for smart micro-grid implementation;
- Reduce the impact of PV on the agriculture.

Two SMRs were selected as representative for Romania regarding the investigation of the integrated approach feasibility to convert a representative brownfield: integrated PWR, and a lead cooled fast reactor.

5.6.4. Nuclear hydrogen deployment perspectives

Romania today is making the research into the possibility of coupling the current fleet with the hydrogen production facility, as hydrogen is of the great interest for the country industries decarbonization policy. Nuclear hydrogen is considered to be produced either at the current fleet (two CANDU reactors) or with the help of future fleet (SMRs or additional CANDU units).

5.7. RUSSIAN FEDERATION: NUCLEAR ENERGY FOR DECARBONIZATION

The Rosatom State Corporation (Rosatom) makes a considerable contribution to the decarbonization of the Russian energy sector by commissioning new nuclear power units of high capacity, using nuclear reactors to provide energy to remote regions, and replacing diesel and gas generation with floating power units. The use of nuclear-powered ships instead of traditional hydrocarbon-fueled ones makes it possible to reduce carbon dioxide emissions and human impact in the Arctic regions.

5.7.1. Nuclear cogeneration using high temperature gas cooled reactors

In 2018, the Rosatom State Corporation included hydrogen energy into the priority areas of the technology development. Nuclear hydrogen production opens additional possibilities for decarbonizing the industry, power engineering and transportation.

To implement the adopted decision, research was carried out on hydrogen production using nuclear energy and the following processes: steam methane reforming, methane pyrolysis, traditional and high-temperature water electrolysis. Steam methane reforming and traditional water electrolysis have been chosen for the nuclear hydrogen production in the near term.

The nuclear hydrogen energy in Russian Federation has gained support on the state level which is detailed in several government decrees:

- The Energy Strategy of the Russian Federation until 2035 (Government resolution No 1523-p, June 2020);
- Plan of Measures on the Development of Hydrogen Energy in the Russian Federation until 2024 (Government resolution No 2634-p, October 2020);
- Russia’s Hydrogen Energy Development Concept (Government resolution No 2162- p, August 2021).

The concept calls for creating hydrogen industrial clusters and implementing pilot projects contributing to hydrogen production for export and domestic market:

- Northwest Cluster, focused on hydrogen supply of domestic industrial enterprises;
- Eastern Cluster, focused on export to Asia and on the development of hydrogen infrastructure in energy and transportation in the Russian Federation;
- Arctic Cluster, focused on the development of low-carbon energy supply systems for the Arctic region of Russian Federation, as well as on export of hydrogen and hydrogen-based energy mixtures.

Rosenergoatom, JSC has launched an investment project aimed at developing nuclear hydrogen energy technologies targeted at:

- Large-scale and local nuclear hydrogen production, including Front End Engineering Design and technologies development of a NPP with high-temperature gas-cooled reactors and chemical-process part, and hydrogen production via water electrolysis using the power produced by an NPP;
- Development of the hydrogen power industry infrastructure for hydrogen storage, transportation and application;
- Integration into national economy and international business.

These areas are planned to be developed simultaneously in three phases:

- Phase 1, up to 2025: R&D, development of technologies, design documentation with testing of pilot commercial modules of the main production components and of hydrogen consumption;
- Phase 2, up to 2031: Construction of a first commercial NPP, development of the hydrogen energy infrastructure components, strategic partnerships and large-scale deliveries to consumers;
- Phase 3, after 2031: Deployment of the hydrogen supply system, hydrogen infrastructure development and technology commercialization; implementation of large-scale environmentally friendly hydrogen production; integration into national economy and international business.

Within the investment project, nuclear hydrogen production is being developed considering water electrolysers supplied by energy from existing NPPs and steam methane reforming supplied by energy provided by HTGR. The main technical characteristics of hydrogen production by steam methane reforming coupled with a HTGR are presented in Table 8.

TABLE 8. MAIN TECHNICAL CHARACTERISTICS.

Parameter	Value
Application	Hydrogen production using steam methane reforming
Type of reactor	coupled with HTGR, with block-type core
Primary helium temperature	330°C/850°C
Secondary helium temperature	800°C/275°C
Number of reactor units	4
Thermal power	800 MW
Hydrogen capacity	440 000 t/a
Hydrogen purity	>99.99%
NPP operating mode	100% baseload
Capacity factor	*0.9*
Steam-methane mixture temperature	*750°C*
Natural gas consumption (for steam methane reforming)	0.53 billion m^3/a (normal conditions)

The features of such a nuclear cogeneration project are the following:

- Mature industrial technologies for steam methane reforming (Russian Federation has a sufficient amount of the necessary raw materials, catalysts, equipment and technologies);
- Helium cooled HTGR is the heat source for the chemical process. It implements inherent safety characteristics and residual heat removal;
- Heat exchange between HTGR and chemical-process part is achieved via the helium intermediate circuit;
- Carbon dioxide released in the chemical process is considered for recycling for the intensification of oil production, and the production of by-products (e.g., fertilizers such as urea and ammonium bicarbonate, and building materials).

The safety of the coupled NPP with the chemical plant is ensured by physical separation of the nuclear island from the chemical-process part and engineering solutions to mitigate the consequences of possible explosions in the segments associated with the chemical plant. The safety level of HTGR reactor plant corresponds to the safety level of Generation IV reactor systems. The radiation purity of hydrogen is ensured by helium coolant clean-up systems for primary and intermediate circuits, as well as by control of the composition of impurities in helium circuits.

The flowchart of the hydrogen production using a nuclear reactor and a chemical plant includes three main parts:

- The nuclear island with a HTGR, intermediate heat-exchanger, main circulating compressor, shutdown cooling system, helium purification systems, emergency cooling system, and fuel storage systems;
- The heat transfer intermediate circuit with heat-exchangers, compressor, system for cleaning and correcting the composition of the helium coolant;
- The chemical-process part for steam methane reforming.

Equipping the reactor circuit, intermediate circuit and chemical engineering circuit with specific valves ensure safety is provided against any leakage in the heat exchangers between the circuits. Figure 23 presents the flowchart of the pilot demonstration for hydrogen production using a high temperature reactor and a chemical plant.

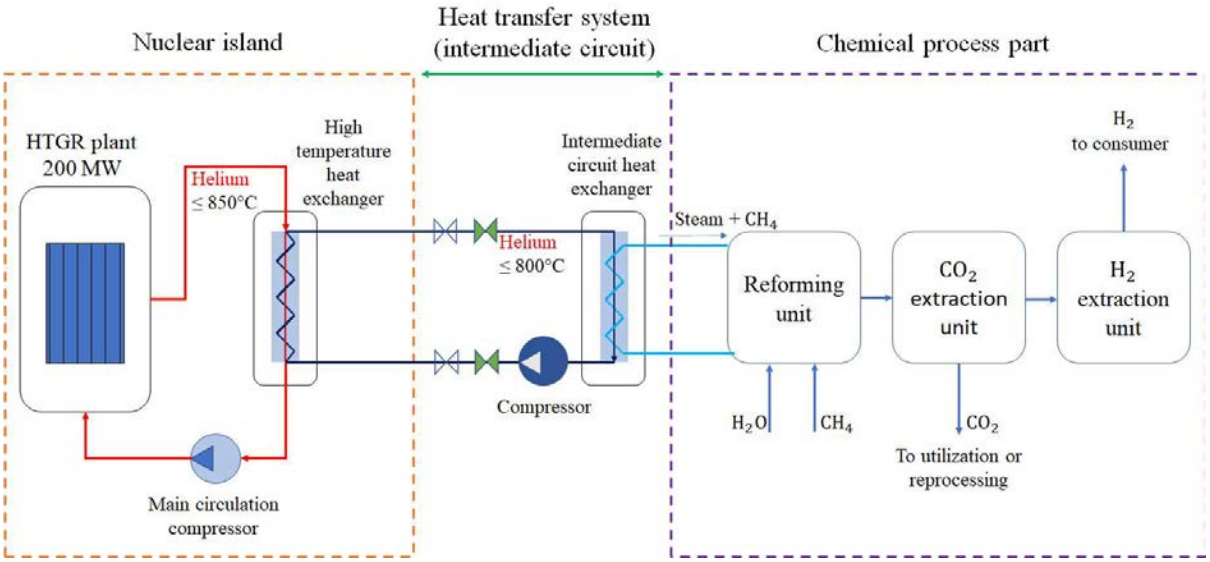

FIG. 23. Flowchart of pilot demonstration for hydrogen production using a high temperature reactor and a chemical plant.

Using HTGRs coupled with steam methane reforming can provide large scale hydrogen production.

The concept of hydrogen energy development in the Russian Federation considers pipeline transport and other types of transport of hydrogen in a liquefied state, in a chemically bound form and in a compressed state as priority methods. Currently, the possible allocations for the nuclear cogeneration plants are being considered, considering provision of natural gas, water, logistics of supplies, removal of carbon dioxide, requirements of regulations for the location of nuclear installations, availability of human resources.

The R&D program on the key areas of the hydrogen production using nuclear reactors coupled with steam methane reforming involves:

- Verification of the codes based on the existing calculation and experimental data;
- HTGR fuel development and qualification (manufacturing technology restoration);
- Development and verification of the main components of the reactor, compressors, safety systems, fuel handling systems, etc.;
- Graphite qualification based on all types of testing of the available graphite grades;
- Irradiation testing of the existing materials for high temperatures and updating of the norms applied for the strength analysis of the reactor plant components;
- Development of a general mathematical model of the chemical process segment and its experimental verification;
- Development of codes for simulation of various processes associated with the nuclear cogeneration system;
- Creation of regulatory structure.

Based on the Russian experience in the development of nuclear-hydrogen facilities in the 1970s and 1980s, the best option considered is to integrate the nuclear cogeneration system for hydrogen production with a large hydrogen consumer. For example, a VG-400 nuclear reactor can provide for up to 2720 t of hydrogen per day to be supplied to the Kirovo-Chepetsk Chemical Combine for ammonia synthesis.

The introduction of hydrogen into the Russian economy is planned through pilot projects:

- Rosatom’s project to create a center of competence for hydrogen energy and hydrogen production by water electrolysis at the Kola NPP in order to develop technologies for electrolysis production, storage, transportation and consumption of hydrogen;
- Projects for the introduction of hydrogen buses in large cities and rail transport based on hydrogen fuel cells.

5.7.2. Heat supply using nuclear heat plant

AST-500 is a nuclear heat plant that has two 500 MWt pressurized water-cooled water moderated reactors, to provide residential and industrial facilities with hot water and heat.

During the design development, the economic feasibility of introducing the nuclear energy sources into the heat supply sector was substantiated by ensuring significant savings in gas and fuel oil, improving the environmental situation in cities, and solving the problems of hydrocarbon fuel transportation. Various options for profiles of nuclear cogeneration plants and nuclear heat plants were elaborated and optimal solutions for the equipment design and layout were recommended.

By 1983, the plant’s detailed design, working design documentation, and R&D for the reactor plant were developed. The sites were selected, and construction began in the city of Gorky (now Nizhny Novgorod) and Voronezh. In the city of Gorky, two sets of reactor plant equipment were manufactured and delivered to the plant. Two reactor cores were manufactured. The total construction readiness for the buildings of the two units by the end of the 1980s was 85–90%, and the installation readiness of the equipment was about 70%. The construction and installation work on the start-up complex of the first power unit were near completion. The operational personnel were recruited and trained. The commissioning and operational documentation was developed. However, the project was not completed due to the changed political and difficult economic situation.

The design of building structures considered a whole range of exceptional loads, such as: extreme wind and snow, maximum temperature, aircraft impact, blast wave, tornado, earthquake with a magnitude of 6, as well as internal design basis accident, including overpressure of 30 t/m^2 due to rupture of a pipe with a diameter of 150 mm.

For the reactor vessel and safety vessel, a large amount of strength calculations was performed. These were validated by stress measurements, in which both vessels (on a scale of 1:4) were subjected to significant horizontal and vertical dynamic loads. Figure 24 shows a schematic diagram of an AST-500 nuclear heat plant.

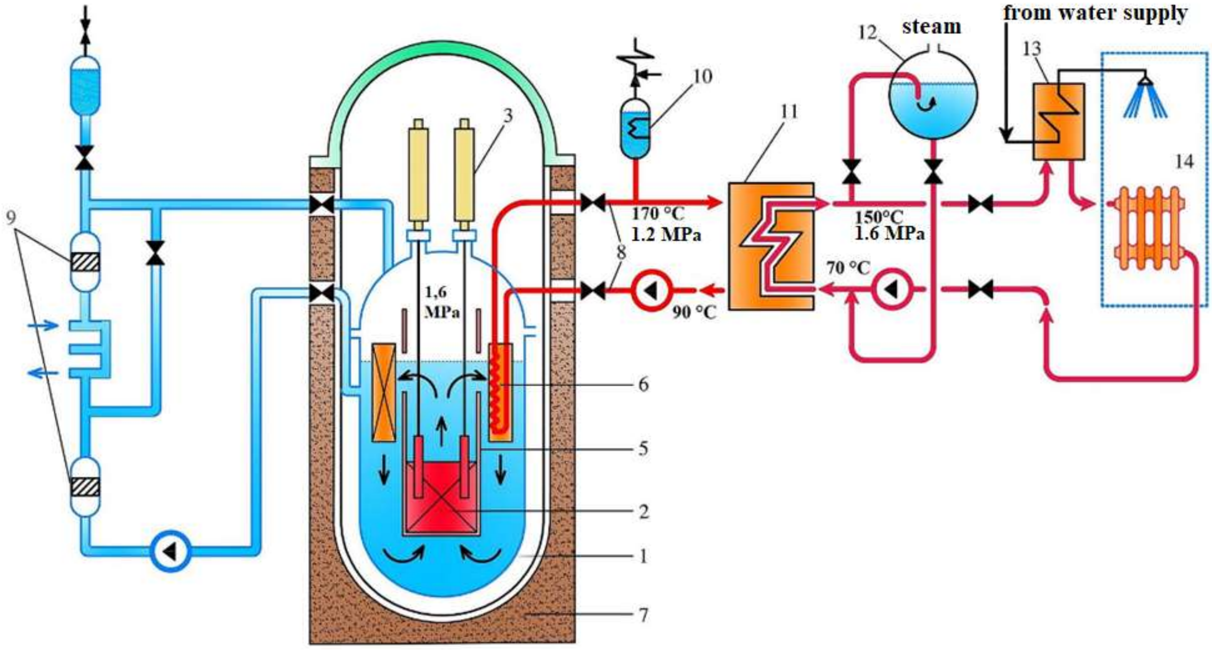

FIG. 24. Schematic diagram of AST-500 nuclear heat plant. 1 — reactor vessel, 2 — core, 3 — control rods, 5 — internal safety vessel, 6 — heat exchanger, 7 — reactor cavity, 8 — secondary circuit pipelines, 9 — secondary circuit auxiliary systems, 10 — pressurizer, 11 — system water heat exchanger, 12 — emergency core cooling system, 13 — cooldown heat exchanger, 14 — heat sink.

The fuel assembly reloading equipment is designed to prevent unintentional fall of the assembly or shipping container. Each step of the reloading process is controlled automatically. An accidental drop of assembly and container was analysed to prove that no release of radioactivity was occurring.

5.7.3. Heat supply of remote coastal regions and isolated territories

The Akademik Lomonosov NPP [113] is a flagship design of a series of small transportable power units. It represents a new class of energy sources based on Russian nuclear shipbuilding technologies. The Akademik Lomonosov NPP (Fig. 25) is equipped with two KLT-40S reactor systems (each with a 35 MWe capacity).

FIG. 25. The Akademik Lomonosow Floating Power Unit (reproduced courtesy of Rosatom State Corporation).

The main characteristics of the Akademik Lomonosov NPP:

- Length according to design waterline is 140.0 m;
- Length overall is 144.2 m;
- Beam overall is 30.0 m;
- Depth to upper deck is 10.0 m;
- Displacement is approx. 21 560 t.

The project is developed for reliable year-round heat and power supply to remote areas of the Arctic and the Far East. It solves two problems: the first one is to replace the retired capacities of the Bilibino NPP, which has been operating since 1974, and the Chaunskaya Cogeneration Plant, which is already 70 years old; the second one is to provide energy to the main mining companies located in Western Chukotka in the Chaun-Bilibino energy hub.

The electric power supplied to the shore-based network without heat energy consumption by the shore is about 70 MW. In the mode of generating the maximum thermal power of about 168 MW, the electric power supplied to the shore-based network is about 30 MW. The Akademik Lomonosov NPP will be able to provide electricity to a settlement with a population of about 100,000 people. It may also be used for desalination of seawater (estimated from 40,000 to 240,000 m^3 of fresh water per day).

5.7.4. Use of nuclear energy for ship propulsion

Currently, the Russian Federation is the only country in the world with a civilian nuclear sea fleet. The use of nuclear generation can significantly reduce emissions from the combustion of fossil fuels used in the conventional civil fleet, which is especially important under the operation conditions of ships in areas with a fragile ecosystem, such as the Arctic.

5.7.4.1. Nuclear icebreakers

The nuclear icebreakers are used to facilitate the transport of cargo ships and other vessels along the Northern Sea Route. The first nuclear icebreaker was put into operation in 1959. It was a world’s first nuclear powered surface ship, which was unparalleled in power among icebreakers of the entire world. As a source of energy, the OK-150 nuclear steam supply system was accepted. It was a reactor plant with a loop type layout, i.e., the main equipment of the circuit was in separate vessels connected by long pipelines.

The Russian Federation has been operating two types of nuclear icebreakers: in deep water areas, caravans are escorted by linear icebreakers, and in shallow water areas, by icebreakers with limited draft of the Taimyr type. At the same time, it is necessary to transfer caravans from a linear icebreaker to a shallow draft one and vice versa, which leads to downtime of the caravan and icebreakers and negatively affects the economic efficiency of cargo transportation.

Currently, Russian enterprises are developing a new generation versatile nuclear icebreaker equipped with RITM-200 reactors with an integrated steam generating unit. The double draft makes the icebreaker universal, i.e., capable of operating both in deep water and in shallow water areas, combining the properties of both a linear and a shallow draft icebreaker. For such icebreakers, Afrikantov OKBM JSC has developed new generation reactors of the RITM type.

On October 21, 2020, the Arktika lead nuclear icebreaker with a RITM-200 reactor officially went into operation. The nuclear-powered ship of the new design is the largest and most powerful in the world. Due to the increased beam, the universal nuclear-powered icebreaker is capable of navigating tankers with a displacement of up to 70,000 t alone in the Arctic. The icebreaker can pave the way for ships through ice up to three meters thick. Figure 26 shows a typical nuclear icebreaker [114].

FIG. 26. Nuclear icebreaker (reproduced courtesy of Rosatom State Corporation).

The main characteristics of a nuclear icebreaker with RITM-200 are the following:

- Length according to design waterline is 160.0 m;
- Length overall is 172.7 m;
- Beam overall is 34.0 m;
- Depth to upper deck is 15.2 m;
- Displacement is 33,540 t.

In 2022, two more Arktika class universal nuclear icebreakers, the Sibir and the Ural, will be added to the nuclear fleet. Until 2027, it is planned to build five more Arktika class icebreakers of this design. At present, the RITM-400 has already been developed for the latest Lider nuclear icebreaker. The RITM-400 reactor plant has a thermal power increased to a record 315 MW, which exceeds all available ship reactors and will enable the Lider nuclear icebreaker to have improved operational characteristics. It will be able to break through ice more than four meters thick and lay a channel up to 50 m wide. This will result in year-round navigation along the Northern Sea Route, including for large-capacity vessels.

5.7.4.2. Sevmorput carrier

The Sevmorput nuclear container, the only operating cargo ship with nuclear propulsion plant, was built on December 31, 1988. Since the start of operation, the Sevmorput container ship (Fig. 27) has travelled 486,000 km, transported more than 1.5 million t of cargo, having carried out only one nuclear reactor refuelling during this time [114].

FIG. 27. Sevmorput lighter aboard ship carrier (reproduced courtesy of Rosatomflot).

The main characteristics of the carrier are the following:

- Length is 260.1 m;
- Beam overall is 32.2 m;
- Depth to upper deck is 18.3 m;
- Displacement is 61,880 t.

The ship is designed to carry 74 units of lighters (barges) in the holds and on the upper deck with their loading and unloading by the ship's lighter crane. It is possible to transport in the holds and on the upper deck 1324 ISO containers. The ship is capable of sailing independently in solid, even ice fields up to one meter thick at a speed of about two knots[4]. The hull is divided by 11 transverse watertight bulkheads into 12 compartments, including 6 cargo holds. The nuclear propulsion plant of the ship does not limit the cruising range. The lines and strength of the hull make it possible to use the ship in the Arctic basin under the assistance of an icebreaker, as well as for independent navigation in ice fields.

5.8. UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND: COGENERATION TO SUPPORT SIZEWELL C ENERGY HUB

Sizewell C is a proposed new nuclear power station in Suffolk, UK. Once operational, Sizewell C will be able to generate enough electricity to supply approximately 6 million (or about 20%) of Britain's homes. It could also be the center of an energy hub, by diverting some of the low-carbon heat generated by the plant to other technologies such as direct air capture or hydrogen production to accelerate progress towards net-zero target. For the UK to reach its net zero target for greenhouse gas emissions by 2050, the decarbonization of electricity alone is not enough, and the UK has to also decarbonize its heat, transport and industrial processes. Sizewell C energy hub aims to facilitate decarbonization beyond electricity, through the supply of low-carbon heat to drive innovative processes.

Sizewell C has been studying the feasibility of cogeneration in relation to the UK EPR design to support the project's energy hub ambitions and utilize the plant's primary source of energy (heat) before any efficiency losses are incurred through the conversion of heat to electricity. In

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[4] The knot is a unit of speed equal to one nautical mile per hour, exactly 1.852 km/h.

its current design as a plant configured to export only electrical energy, each unit at Sizewell C will produce 4.5 GWt of heat, which is then converted into 1.76 GWe of electrical energy resulting in an efficiency loss of 60% (equivalent to 2.8 GWt of heat energy) through the conversion process as illustrated in Fig. 28.

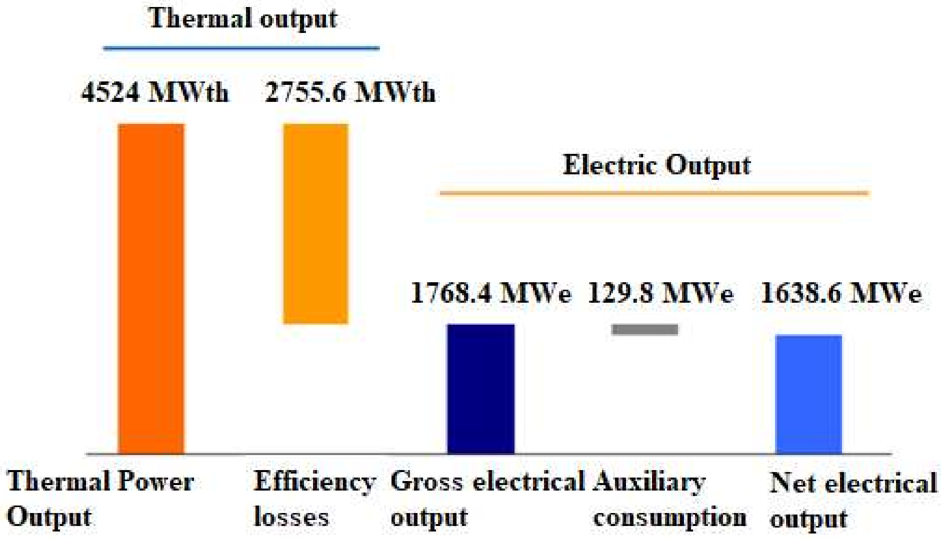

FIG. 28. Sizewell C thermal and electrical output (per unit), if configured as an electricity only plant.

Assuming that the turbine is working at 100% turbine maximum continuous rating 2600 kg of pressurized water at 230°C is turned into 290°C high pressure steam at 7.52 MPa in the reactor's steam generators every second. The high-pressure steam is then first led through a small high-pressure turbine, and then reheated in the moisture separator reheaters, before entering an intermediate pressure turbine, after which it enters multiple identical large low-pressure turbines.

To enable cogeneration, a fraction of the steam produced could in principle be extracted at certain points of the steam cycle and be led to a heat exchanger to produce secondary steam or hot water for an external consumer. The fluid supplied to the user of the heat will always be kept separate from the water-steam cycle in the EPR. When there is a steam/hot water exchange, this equipment will resemble a conventional condenser or reheater. The extracted steam would then be returned as water at a lower temperature to an appropriate point in the cycle. The extraction of steam produces an opportunity cost in respect of the foregone electricity production and Fig. 29 illustrates how the opportunity cost varies depending on the point at which heat is extracted from the steam cycle.

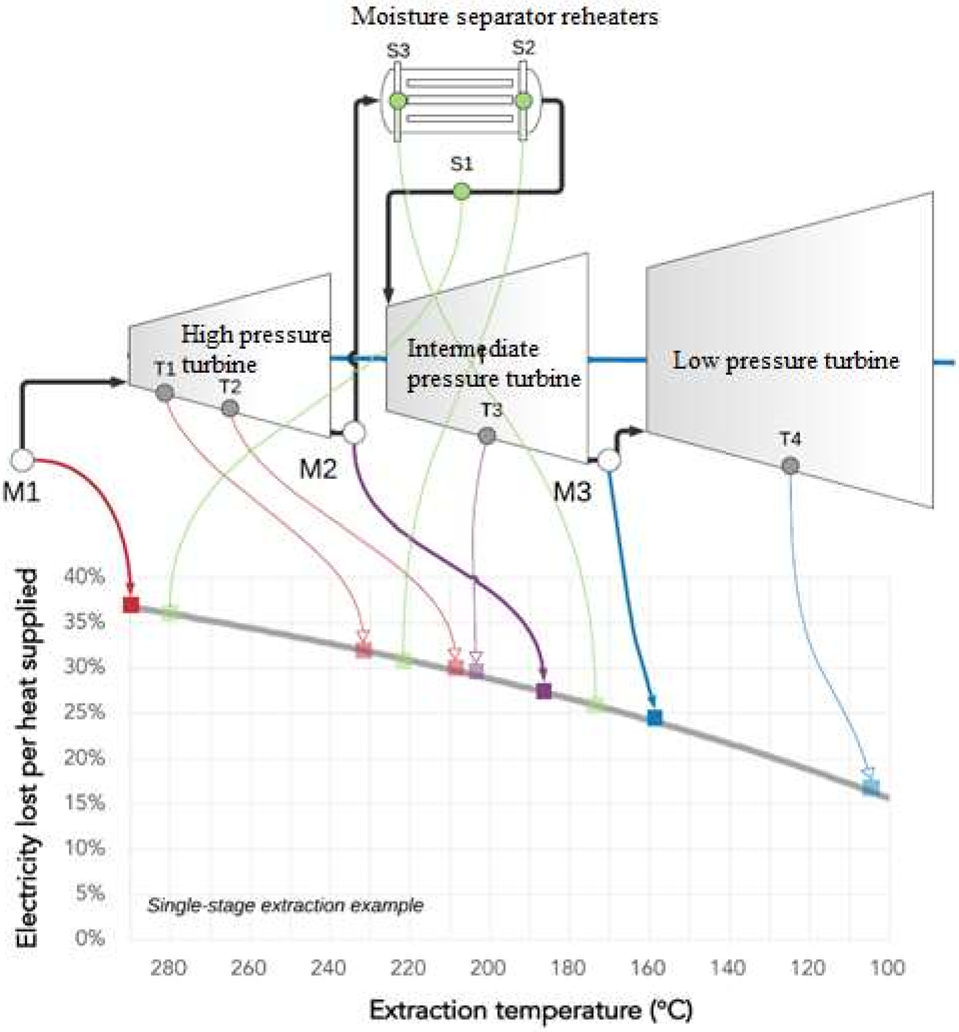

FIG. 29. Variance of opportunity cost of foregone electricity production with point of heat extraction from the EPR's steam cycle.

As part of Sizewell C's studies on cogeneration the project had identified four potential extraction locations as indicated in Fig. 30 by solutions A, B C and D. Location A refers to the high-pressure turbine steam header, Location B refers to the high-pressure turbine discharge while location C indicates the moisture separator reheater discharge and location D refers to the intermediate pressure crossover line.

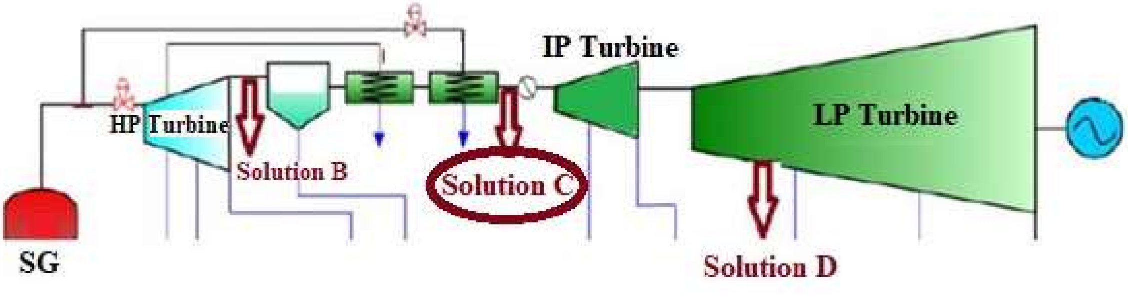

FIG. 30. Potential steam extraction points from the EPR's steam cycle.

A key strategy for the Sizewell C business case is to replicate both the design and the safety case of Hinkley Point C in order to provide cost savings through a fleet effect. Therefore, a key constraint in evaluating the potential for cogeneration at Sizewell C is therefore, for any proposed modifications to be minor. An analysis of the potential opportunities to extract steam at locations A to D, concluded that the moisture separator reheaters discharge (location C) could enable Sizewell C to extract 200 MWt of heat at a temperature of 276°C and a pressure of 1.14 MPa from each unit and is the preferred extraction location. The quality of the heat extracted at the moisture separator reheaters discharge would suit several heat-powered applications that Sizewell C could pursue in the future such as direct air capture, hydrogen production and district heating.

Sizewell C has the potential to be much more than a nuclear power station and act as an exemplar for what nuclear power stations of the future may look like, i.e., capable of not only providing reliable, stable baseload low carbon electricity but also driving forward technologies of the future which will have a key role to play in the world achieving its net zero ambitions. Sizewell C has been considering other applications as well such as thermal or cryogenic storage, synthetic fuel production, and agricultural processes such as greenhouses. At Sizewell C, nuclear energy will have a defining role to play in achieving the net zero future and if the energy hub plans currently explored are implemented, Sizewell C will be able to make a positive contribution to shaping that vision.

Sizewell C operator intents to construct a demonstrator for a direct air capture process. The UK government granted USD 3.7 million in 2022 for the project, to create a demonstration facility that can absorb 100 t/a of CO_2. If the demonstrator is successful, a large-scale direct air capture plant will be built near to the Sizewell C NPP and pipe heat there through underground pipelines to fuel the collection of 1.5 million t of CO_2 each year [115].

5.9. UNITED STATES OF AMERICA: GENERAL COGENERATION APPLICATIONS AND PLANS

Future clean energy systems are considered for production of biofuels, new chemical processes, clean water, industry, electricity, and hydrogen vehicles. The USA is also considering the use of SMRs and microreactors for cogeneration. The MARVEL microreactor is intended to produce combined heat and power to a functional microgrid (expected construction in 2023 and criticality in 2024). The reactor size has to be aligned with the needs of each application.

Heat augmentation can be applied, if needed, to match process temperature demands. A special laboratory called DETAIL was developed for electrically heated testing of integrated systems. This is an essential step to investigate coupling opportunities of low-temperature and high-temperature electrolysers with NPPs. The USA has current studies looking into hydrogen production through electrolysis of water, thermochemical water splitting, photochemical cells, and biological pathways [116].

Electrolysis of water and thermochemical water splitting for hydrogen production have the potential to be powered and heated by nuclear reactors. The current light water reactors fleet is considered as a possible source for hydrogen production, and special simulators and training programs on such coupling process are under development.

According to the Department of Energy, a 1000 MW nuclear reactor has the potential to produce 150,000 t of hydrogen per year [117]. The USA government is highly supporting the development of clean hydrogen production through electrolysis research, development and demonstration, R&D dedicated to clean hydrogen manufacturing and recycling, and development of regional clean hydrogen hubs. In 2021, the USA launched the Hydrogen Energy Earthshot, aiming to achieve a cost of USD 1 for 1 kg of clean hydrogen in one decade [118]. The results of a comprehensive assessment of the USA hydrogen supply and demand is included in Refs. [119] and [120].

There are currently five projects which were selected for demonstrations of hydrogen generation at current operating NPPs in the USA, aiming the following:

- Hydrogen production using direct electrical power offtake;
- Develop monitoring and controls procedures for scaleup to large commercial-scale hydrogen plants;
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations;
- Produce hydrogen for captive use by NPPs and clean hydrogen markets.

Nuclear hydrogen would be eligible for tax credits of up to 3 USD/kg under the newly approved Inflation Reduction Act, which might make it a desirable option for reactor owners [121]. The nuclear hydrogen demonstrations projects selected are the following [121]:

- At Nine Mile Point NPP (consisting of 2 BWRs and operated by Constellation Energy Corp.), using a 1 MWe PEM electrolyser;
- At Davis-Besse NPP (operated by Energy Harbor), through a partnership between Idaho National Laboratory, Xcel Energy and Arizona Public Service, using a 1–2 MWe PEM electrolyser. Davis-Besse is situated close to key hydrogen consumers in the manufacturing and transportation sectors of the market;
- At Prairie Island NPP (operated by Xcel Energy), using a 150 kWe HTSE/SOEC electrolyser. Beginning in early 2024, this project will generate hydrogen using solid oxide electrolysers, with the intention of scaling up further.
- At Palo Verde Generating Station (operated by Arizona Public Service), using a 15–20 MWe PEM electrolyser.

Currently a big number of tests on electrolysers capacity ramping is taking place in the United States. This is an essential issue to investigate coupling opportunities of low temperature and high temperature electrolysers with NPPs.

The R&D on hydrogen production using LWRs is ongoing with a set of primary and secondary interfacing organizations and industry advisory committees (such as the Hydrogen Regulator Research and Review Group). The USA is developing currently a generic probabilistic risk assessment for licensing considerations and identification of the most important potential hazards.

Nuclear hydrogen production systems studied in the USA have been focused on the use of nuclear power for I-S thermochemical cycles, hybrid sulphur thermochemical cycles, and high-temperature water electrolysis. The Department of Energy's Nuclear Hydrogen Initiative has been investigating the use of a Next Generation Nuclear Plants for heating and powering I-S thermochemical cycles with a maximum temperature of 900°C needed for the reactions [122].

The HyS thermochemical cycle consists of the breakdown of H_2SO_4 at 830–900°C and an electrolytical cell that produces hydrogen at 20–100°C and 0.17 V [43]. The high-temperature electrolysis of water is accomplished using an electrolytic cell with a solid electrolyte. Steam in the temperature range of 750–950°C enters the cell and is electrified to separate the steam into oxygen and hydrogen [123].

The Nuclear Energy Research Initiative brought about two designs for nuclear powered hydrogen production systems. The design known as H2-MHR consists of a modular helium reactor with a maximum coolant exit temperature of 950°C, an intermediate heat exchanger with helium in both its primary and secondary loop, and an I-S thermochemical cycle [44]. The second design is the Secure Transportable Autonomous Reactor Hydrogen project which is a heavy liquid metal cooled reactor combined with a U-nitride fueled fast reactor that has a maximum exit coolant temperature of 800°C. The reactor is lead cooled, with lead transferring heat to molten salt that heats a calcium-iron-bromide thermochemical cycle that requires temperatures of 700–750°C to run [44].

Another design for nuclear hydrogen production in the USA is a molten-salt cooled advanced high-temperature reactor. The advanced high temperature reactors are designed to reach outlet coolant temperatures of 1000°C and have liquid fluoride salt as the chosen coolant with an intermediate heat exchanger used for heat transfer to a secondary loop also consisting of a liquid salt coolant [43].

The USA has also experience on the water desalination by using NPPs. The Diablo Canyon power plant in USA uses reverse osmosis to produce water from ocean water. Produced water is used for Diablo Canyon NPP needs, such as primary coolant system, power conversion cycle, emergency core cooling system, make up water, and potable water. Produced water from the desalination facility is stored in two water reservoirs. The capacity of these reservoirs is twenty million litres. The desalination facility based on reserve osmosis has 4500 m^3/d in two parallel units. After the salt is separated from the ocean water, pH adjustment and chlorination in chemical treatment are performed for makeup water or drinking usage. The facility has a pre-treatment stage for adding chemicals of ferric sulphate and polyelectrolyte and ultra filtering the particles from the fluid and using ultraviolent lights to kill bacteria. The high operating pressure of the pumps is 5.5 MPa. The salt separation rate of the facility is 99%. The energy of the facility for producing the water is ~4.5 kWh/m^3.

Several private SMR deployment projects with cogeneration missions are mentioned below.

TerraPower and GE Hitachi Nuclear Energy are developing an integrated and flexible energy system based on the Natrium reactor – 345 MWe (slightly beyond the 300 MWe for typical SMR systems) sodium fast reactor. The system is based on SFR and features a molten salt energy storage that can boost peak electricity generation to 500 MWe for several hours and supports cogeneration of industrial process heat applications when demands for electricity is low than the rated power [124]. In October 2020, TerraPower was selected by the Department of Energy to construct and operate a demonstration system within 5 to 7 years [125]. In June 2021, TerraPower and PacifiCorp announced a plan to build a demonstration system in Wyoming. The project, which will be sited to repower a retiring coal plant, seeks to validate the design, construction, and operational features of the Natrium technology [126].

NuScale Power is another SMR developer. Its PWR design generates 77 MWe of electricity per module and features natural circulation of coolants for safer, simpler operation and can scale to meet various output levels by adding up to 12 units in a plant [127]. The NuScale system variants can provide clean, affordable, and reliable process heat applications. One module can produce 250 MWt of steam for industrial applications such as chemical processing or use in producing synthetic fuels, such as nearly 50 metric tonnes of hydrogen per day. In addition, this heat can be used in a range of low temperature, low pressure applications such as water desalination and district heating. The multi-module plant system permits a high degree of flexibility for a wide range of simultaneous cogenerating applications. For example, some modules can be dedicated to electricity production, while others provide heat to support industrial processes or produce hydrogen. This makes the NuScale design especially well-suited for hybrid energy applications in which multiple energy sources are integrated with multiple energy consumption processes to form a highly optimized and efficient system. In August 2020, NuScale Power received design approval for the first and only SMR from the U.S. Nuclear Regulatory Commission. The company aims to commercialize the technology by the end of this decade. In May 2021, NuScale Power and Prodigy Clean Energy, a Canadian company that designs and develops marine nuclear plants, announced a Memorandum of Understanding to collaborate on business development opportunities for a marine-deployable NuScale, as a turnkey clean energy system for customers along the shorelines including remote coastal locations and island nations [128].

6. INTERNATIONAL ORGANIZATIONS INVOLVEMENT IN SUPPORTING VARIOUS ASPECTS OF NUCLEAR COGENERATION

Established in 2001, the Generation IV International Forum was created as a co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by 2030. In 2021, the Generation IV International Forum established a Task Force on Non-Electric Applications of Nuclear Heat aiming to identify specific benefits the Generation IV reactor technologies could bring into the nuclear heat sector in the context of future energy markets. Considering the complexity and variety of boundary conditions (such as local/global economy, geopolitics, national strategies) that have to be taken into account to determine the optimal combination of reactor technology, power level, and non-electric applications to fulfill specific requirements, this Task Force aims at providing decision makers with the tools for pursuing optimal solution depending on their specific needs rather than suggesting a technology down-selection. The lead of this Task Force is carried out by OECD Nuclear Energy Agency.

The International Atomic Energy Agency has been developing various resources dedicated to non-electric applications of nuclear power, such as:

- Tools, that are free to download, easy to install and use and regularly updated:
  - Hydrogen Economic Evaluation Programme (HEEP) that supports an integrated assessment of hydrogen production cost using different energy sources, hydrogen generation processes, including also important aspects of hydrogen economy like storage, transportation, and distribution. Users have the option to use case studies embedded in a default library or develop specific assessments based on relevant input data. HEEP was validated and benchmarked with 2 other tools for hydrogen cost assessment (G4-ECONS and H2A codes) in the framework of a dedicated IAEA Coordinated Research Project entitled “Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software”.
  - Desalination Economic Evaluation Program (DEEP) that can be used for performance and cost evaluation of various power cogeneration configurations for desalination.
  - Desalination Thermodynamic Optimization Program (DE-TOP) that can be used for the thermodynamic analysis and optimization of nuclear cogeneration systems.
- Dedicated toolkits that facilitate easy finding of any of the Agency’s activities on nuclear hydrogen production and water desalination. These includes links to IAEA tools, highlights on IAEA topical publications, news on IAEA topical activities and a newsletter.
- Comprehensive publications on non-electric applications of nuclear power. Most recent publication are included in Table 9.
- A range of technical exchange forums and associated events, from technical and consultancy meetings, to training workshops and research coordination meetings. The research coordination meetings are dedicated to gather the progress on the Coordinated Research Projects that are conducted through the dedicated IAEA mechanism.

TABLE 9. MOST RECENT IAEA PUBLICATIONS DEDICATED TO NUCLEAR HYDROGEN AND NUCLEAR DESALINATION

Reference	Scope
Nuclear hydrogen	
International Atomic Energy Agency, Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software, TECDOC No. 1859, IAEA, Vienna (2018).	This publication includes the results obtained by participant Member States in the IAEA CRP on the hydrogen production using nuclear energy. One of the major objectives of the project was to validate and benchmark HEEP with some other similar codes for assessment of hydrogen production cost. The publication includes relevant data, as well as technology-based case studies.
International Atomic Energy Agency, Hydrogen Production using Nuclear Power, Nuclear Energy Series NP-T-4.2, IAEA, Vienna (2012).	This publication offers a comprehensive overview in the nuclear hydrogen production, encompassing dedicated national and regional programmes, highlights of the technologies, issues related to coupling a nuclear reactor with a hydrogen generation plant, safety aspects, as well as insight into hydrogen infrastructure and economics.
International Atomic Energy Agency, Advances in Nuclear Power Process Heat Applications, TECDOC No. 1682, IAEA, Vienna (2012).	While not specifically dedicated to nuclear hydrogen production, this publication gathers some relevant aspects connected to the use of high temperature gas reactors in the production of hydrogen.
International Atomic Energy Agency, Role of Nuclear Based Techniques in Development and Characterization of Materials for Hydrogen Storage and Fuel Cells, TECDOC No. 1676, IAEA, Vienna (2012).	This publication gathers the insights of a topical IAEA technical meeting and aims to provide the status in performance testing and characterization of existent and potential materials for fuel cells and hydrogen storage.
International Atomic Energy Agency, Design and Evaluation of Heat Utilization Systems for the High Temperature Engineering Test Reactor, TECDOC Series No. 1236, IAEA, Vienna (2001).	This publication gathers the results of the IAEA CRP on Design and Evaluation of Heat Utilization Systems for the High Temperature Engineering Test Reactor, covering aspects related to the reactor technology and to hydrogen production using this technology.
International Atomic Energy Agency, Safety related design and economic aspects of HTGRs, TECDOC Series No. 1210, IAEA, Vienna (2001).	This publication reviewed the status (as of the time of drafting) of international development activities associated with the safety related design and economic aspects of the HTGR including aspects related to nuclear hydrogen production using HTGR.
International Atomic Energy Agency, Hydrogen as an Energy Carrier and its production by Nuclear Power, TECDOC Series No. 1085, IAEA, Vienna (1999).	This publication includes an overview on relevant aspects related to conventional and advanced hydrogen production methods, storage and transport of hydrogen, as well as safety risks of large-scale hydrogen applications.
Nuclear desalination	
International Atomic Energy Agency, New Technologies for Seawater Desalination Using Nuclear Energy, IAEA-TECDOC-1753, IAEA, Vienna (2015).	This publication compiles the findings of research and development activities related to seawater desalination using nuclear energy. The publication also provides information on competitiveness and sustainability of seawater desalination using nuclear energy and a techno-economic feasibility study of nuclear desalination.
International Atomic Energy Agency, Environmental Impact Assessment of Nuclear Desalination, IAEA-TECDOC-1642, IAEA, Vienna (2010).	This publication addresses environmental concerns of nuclear desalination, including experimental data and the experience gained in operating nuclear desalination projects, as well as the risks perceived by the public.

The Nuclear Energy Agency (NEA/OECD) established an Expert Group on the Role and Economics of Nuclear Co-generation in a Low-carbon Energy Future with the objective of developing a dedicated methodology for assessing the technical and economic aspects of nuclear cogeneration. The most recent topical reports published in 2022 are: “Beyond Electricity: The Economics of Nuclear Cogeneration” [129] and “High-temperature Gas-cooled Reactors and Industrial Heat Applications” [130].

7. CONCLUSIONS

Nuclear cogeneration introduces some important advantages in terms of decarbonization, and improvement of the overall efficiency of the NPPs. Policy makers need to recognize and consider the NPPs potential to generate large amounts of clean heat and have to find realistic solutions to use it for non-electric applications. These would provide sustainable solutions for several energy challenges while also contributing to achieving the climate goals.

Governmental support is needed for the use of nuclear energy together with the other low carbon energy sources and to ensure a level playing field. There is an imperative to incentivize pilot projects to allow shifting to commercial deployment, while also looking into accelerating technology demonstration and deployment for more efficient technologies currently under R&D.

Moreover, developing specific regulatory frameworks to ensure licensability of tailored systems considering nuclear energy for non-electric applications, developing techno-economic assessment and business case for considering nuclear as an option for the various non-electric applications (and this can include considering nuclear in hybrid energy systems) and ensuring optimization of NPPs operating in cogeneration mode are needed in order to boost the use of nuclear energy beyond electricity generation. The real implementation may be achieved only after a large process of consultation with the participation of all stakeholders (including national authorities, local authorities, NPP owner, NPP operator, interface owners, network owners, householders, and public).

A set of benefits need to be highlighted to attract stakeholders and investors to finance the nuclear cogeneration project and to create a high interest for the end-users. Also, the discussion on the drawbacks and barriers has to be stimulated to clarify all the difficulties and pave the way from the ideas to the implementation.

Member States interested in nuclear cogeneration might:

- When applicable, consider nuclear cogeneration option in the first phase of developing a nuclear power programme, thus ensuring optimization of the system for non-electric applications;
- Consider non-electric applications and system optimization in the context of deployment of SMR technologies;
- Assess competitiveness of nuclear energy with other energy sources;
- Ensure sound stakeholder engagement for a successful deployment of nuclear cogeneration project.

APPENDIX 1. NUCLEAR HYDROGEN PROJECTS WORLDWIDE.

Country	Status	Vendors/ stakeholders/ owner	Description (hydrogen production technology, hydrogen output, type of the reactor)	Ref.
Canada	R&D	Canadian Nuclear Laboratories, Ontario Tech University	*Technology:* Cu-Cl thermochemical cycle. *Type of the reactor:* SCWR, LWR The integrated lab-scale Cu-Cl cycle being developed by Canadian Nuclear Laboratories and Ontario Tech University conducts experimentation, modelling, simulation, advanced materials, thermochemistry, safety, reliability, and economics. Additionally, off-peak electrolysis as well as the integration of hydrogen plants with Canadian NPPs are studied.	[24], [131]
China	R&D	The Institute of Nuclear and New Energy Technology	*Technology:* I-S thermochemical process *Type of the reactor:* HTR-PM R&D on the I-S cycle with financial support of the Government of China. The objectives are the construction of an integrated, bench scaled I-S facility and the achievement of a long term, continuous closed cycle operation and coupling with the HTR-PM. Up to now, a hydrogen production capacity of 100 L/h (normal conditions) was achieved.	[24]
India	R&D	Bhabha Atomic Research Centre	*Technology:* Water/ steam electrolysis; thermochemical water splitting *Type of reactor*: PHWR, Innovative High Temperature Reactor Demonstration projects on water electrolysers coupled to currently operational nuclear power reactors planned at select sites – vendor selection and techno-commercial analyses in progress. In order to supply high temperature process heat for the thermochemical water splitting necessary to produce hydrogen, BARC is also developing the Innovative High Temperature Reactor. This reactor is a pebble bed type with molten salt cooling.	[132]
Japan	R&D	Japan Atomic Energy Agency, Mitsubishi Heavy Industries, Ltd.	*Technology:* Steam methane reforming; thermochemical water splitting *Type of the reactor:* HTTR According to Japan's Basic Energy Plan, which was authorized by the government in October 2021, hydrogen will be produced using high-temperature gas reactors. Furthermore, the Green Growth Strategy for 2050 Carbon Neutral (published in June 2021) states that by 2030, it will be necessary to use the HTTR to manufacture significant amounts of carbon emissions free hydrogen. Steam methane reforming, as well as I-S hydrogen production facility are investigated for coupling with the HTTR. Deployment target: 2040.	[133]
Korea, Republic of	R&D	Hyundai, SK Group, USNC, GS Energy, NuScale, Korea Atomic Energy Research Institute	*Technology*: High temperature steam electrolysis; thermochemical water splitting. *Type of the reactor*: Microreactor, SMR, Very High Temperature Reactor In 2023, a memorandum of understanding to conduct joint R&D was signed by Hyundai, SK Group, and USNC in order to develop a hydrogen micro hub employing solid oxide electrolysers. The USNC Micro Modular Reactor will provide high-temperature steam and electricity for the micro hub in order to power a solid oxide electrolyser. In 2023, Uljin County in North Gyeongsang Province, South Korea, and the Korean private company GS Energy have signed a memorandum of understanding to discuss the possibility of using NuScale Power's SMR technology to supply heat and	[134], [135], [136]

Country	Status	Vendors/ stakeholders/ owner	Description (hydrogen production technology, hydrogen output, type of the reactor)	Ref.
			power to the envisaged Uljin Nuclear Hydrogen National Industrial Complex. At KAERI, researchers are investigating a VHTR-based process of producing hydrogen, by coupling the reactor with I-S thermochemical cycle, hybrid sulphur cycle, and high temperature steam electrolysis methods, respectively.	
Russia	R&D	Rosatom	*Technology***:** Water electrolysis *Type of the reactor***:** VVER-440 reactor (440 MWe). According to Russia's energy strategy, by 2035, hydrogen will be developed and consumed domestically, as well as produced for export on the global markets. The Plan of Measures on "Development of Hydrogen Energy in the Russian Federation until 2024" was approved by the Russian government in October 2020. Since 2018, ROSATOM has prioritized the scientific and technical development of hydrogen energy. A demonstration project for hydrogen production by water electrolysis is undergoing at Kola NPP. A brand-new electrolysis unit with Russian design has generated its first hydrogen in 2023. The plant's turbogenerators, which produce power, are cooled using hydrogen. This hydrogen was formerly produced by alkaline electrolysis and the new technology used is PEM, producing hydrogen with a purity of 99.99%.	[137], [138]
Russia	R&D	Rosatom	*Technology:* Steam methane reforming *Type of the reactor:* HTGR Russia intends to use steam methane reforming and a domestically designed high temperature gas cooled reactor to produce clean hydrogen commercially after 2030. The project is currently under preparatory stage.	[139]
UK	R&D	EDF Hynamics, Lancaster University, EIFER, Atkins	*Technology*: Water/ steam electrolysis. *Type of the reactor*: PWR To produce hydrogen by electrolysis utilizing electricity directly from Heysham NPP, EDF Energy's Hydrogen to Heysham (H2H) project looked at the viability of this method. In conjunction with EDF Hynamics, Lancaster University, EIFER, and Atkins, a concept design for a 2 MW electrolyser system—1 MW each from a PEM and an Alkaline electrolyser—was developed as part of the feasibility study. The study supported the technical viability of hydrogen production in conjunction with nuclear power. The UK government confirmed in September 2023 that EDF will receive GBP 6.1 million in financing as part of the “Industrial Hydrogen Accelerator Programme” for the ground-breaking Bay Hydrogen Hub project. This research, in collaboration with Hanson Cement, Vulcan Burners, the National Nuclear Laboratory, and EDF, will show how HTSE can be used at a Heysham NPP.	[140], [141]
UK	R&D	Sizewell C	*Technology:* Water electrolysis *Type of the reactor*: PWR Sizewell C issued (November 2020) an Expression of Interest seeking partners to develop its hydrogen demonstrator project, which may be powered by Sizewell B.	[140]
USA	R&D	H2@Scale initiative, US utilities, US Department of Energy	*Technology:* Water/ steam electrolysis *Type of the reactor*: PWR Demonstration projects: (1) Constellation: Nine-Mile Point NPP (~ 1 MWe PEM); (2) Energy Harbor: Davis-Besse NPP (~ 1-2 MWe PEM); (3) Xcel Energy: Prairie Island or Monticello NPP (~ 150 kWe HTSE); (4) APS/Pinnacle West Hydrogen: Palo Verde Generating Station (~ 15-20 MWe PEM).	[121]

APPENDIX 2. NUCLEAR DESALINATION PROJECTS WORLDWIDE.

Country	Status	Site	Start of operation	End of operation	Description (desalination technology, water output, type of the reactor)	Ref.
China	In operation	Haiyang NPP	2021	-	*Technology:* reverse osmosis and thermal desalination *Reactor*: LWR Shandong Nuclear Power Co. reported in May 2021 that Haiyang NPP had produced fresh water at a temperature of 95°C. Using heat produced by the NPP, a two-stage reverse osmosis and evaporation system is used in the process. The "Shandong Haiyang Nuclear Energy Heating Project" could generate 30 million t of fresh water annually.	[142]
India	In operation	Kudankulam	2012	-	*Technology:* MVC MED *Reactor:* VVER (1000 MWe) The full MVC plant was commissioned in mid-2012, with a total capacity of 7680 m^3/d to supply the plant's primary and secondary coolant and the local town.	[35]
India	In operation	Madras Atomic Power Station, Kalpakkam	2002	-	*Technology:* RO + MSF *Reactor:* PHWR Hybrid Nuclear Desalination Demonstration Project comprising of a RO unit with 1800 m^3/d capacity and a MSF plant unit of 4500 m^3/d, plus a recently-added barge-mounted RO unit. This is the largest nuclear desalination plant based on hybrid MSF-RO technology using low-pressure steam from a nuclear power station and seawater. The loss in power incurred by the NPP due to the desalination plant is 4 MWe.	[35]
Japan	Closed	Ehime, Ikata-1,2	1975	2018	*Technology*: MSF *Reactor*: PWR *Capacity:* 2000 m^3/d desalinated water	[143, 144]
Japan	In operation	Ehime, Ikata-3	1994	-	*Technology:* RO *Reactor:* PWR *Capacity:* 2000 m^3/d desalinated water	[143, 144]
Japan	Closed	Fukui, Ohi-1,2	1976	2017	*Technology:* MSF *Reactor:* PWR *Capacity:* 3900 m^3/d desalinated water	[143]
Japan	In operation	Fukui, Ohi-4	1989	-	*Technology:* RO *Reactor*: PWR *Capacity:* 2600 m^3/d desalinated water	[143, 144]
Japan	In operation	Fukuoka, Genkai-4	1992	-	*Technology:* MED *Reactor:* PWR *Capacity:* 1000 m^3/d desalinated water	[143, 144]

Country	**Status**	**Site**	**Start of operation**	**End of operation**	**Description (desalination technology, water output, type of the reactor)**	**Ref.**
Japan	In operation	Fukuoka, Genkai-3	1988	-	*Technology:* RO *Reactor*: PWR *Capacity:* 1000 m^3/d desalinated water	[143, 144]
Japan	In operation	Fukui, Takahama-3,4	1983	-	*Technology:* MED *Reactor:* PWR *Capacity:* 1000 m^3/d desalinated water	[143, 144]
Japan	Suspended operation	Kashiwazaki, Kariwa-1	1985	2011	*Technology:* MSF *Reactor:* BWR *Capacity:* 1000 m^3/d desalinated water	[143]
Jordan	R&D	Amra Site	-	-	*Technology:* RO, MED, MSF *Reactor:* Choosing of SMR technology is undergoing The cooling water source is As-Samra Wastewater Treatment Plant (Red Sea), 60 km far.	[38]
Kazakhstan	Closed	Aktau	1972	1999	*Technology:* MED *Reactor:* BN-350 fast reactor (350 MWe) The nuclear reactor supplied up to 135 MWe of electric power while producing 80 000 m^3/d of potable water, about 60% of its power being used for heat and desalination.	[35]
Pakistan	In operation	Karachi NPP (KANUPP-1)	2009	-	*Technology:* MED. *Reactor:* PHWR Pakistan completed a 1600 m^3/d MED desalination facility in 2009, connected to the nearby 125 MWe PHWR Karachi NPP (KANUPP-1) through an intermediate coupling loop. For internal use, it has been running a 454 m^3/d RO plant.	[35]
USA	In operation	San Luis Obispo, Diablo Canyon NPP	1985	-	*Technology:* RO *Reactor:* LWR *Capacity:* 2450 m^3/d desalinated water.	[145]

APPENDIX 3. NUCLEAR DISTRICT HEATING PROJECTS WORLDWIDE.

Country	Status	Start of operation	End of operation	Description	Ref.
Bulgaria	In operation	1987	-	*Site:* Kozloduy NPP (VVER-1000) *District heating*: 20 MWth to Kozloduy town, 150-170°C Kozloduy town is located 5 km away from Kozloduy NPP, with nearly 15 000 people.	[146]
Canada	Closed	1972	2006	*Site:* Bruce A NPP (PHWR) *Capacity:* 5350 MWt delivered through piping of more than 6 km length. The secondary heat transport system of Bruce A NPP diverted high pressure steam via a steam transformer plant to the Bruce bulk steam system. A portion of around 15 MWt was supplied for heating buildings on-site.	[24]
China	In operation	2020	-	*Site:* Haiyang NPP, Shandong (AP1000) The Haiyang NPP officially started providing district heat to the surrounding area in November 2020. When phase 2 started operation in 2021, it replaced the 10 coal-fired boilers in Haiyang. This saved annually 100 000 t of raw coal and reduced CO_2 emissions by about 180 000 t in each heating season. In 2023, China started its first long-distance nuclear energy heat supply pipeline network project across prefecture level cities. The long distance pipeline will provide heat to a 13 million square metre area and meeting the needs of 1 million residents. This will replace the consumption of some 900 000 t of coal, reducing carbon dioxide emissions by 1.65 million t.	[147]
China	In operation	2021	-	*Site:* Qinshan NPP, Zhejiang In December 2021, the Qinshan NPP began operating a district heating demonstration project, composed of three phases. Currently, the initial phase delivers central heating powered by nuclear energy to 460 000 square meters of housing spread across three residential areas and 5000 square meters of apartments for almost 4000 Haiyan County people. By 2025, the whole Shupu Town region as well as Haiyan County's main metropolitan area are to be covered by a 4 million m^2 nuclear heating area.	[147]
Czech Republic	In operation	2022	-	*Site*: Temelin NPP (VVER-1000) The nuclear district heating currently supplies heat energy to the nearest Tynn and Vltavou cities, through a 5 km long pipe. ČEZ began building a 26 km long hot water pipeline between the Temelín NPP and České Budějovice city (~25 km away, nearly 100 000 citizens), to deliver 750 TJ of heat per year (~30 MWt on average).	[148], [149]
Czech Republic	Planned	-	-	*Site*: Dukovany NPP (VVER-440) A pipeline is to be built from the Czech Republic's Dukovany NPP to provide district heating to Brno, the country's second largest city almost 50 km away.	[150]
Czech Republic	R&D	-	-	*Site:* TEPLATOR TEPLATOR is a demonstration designed unit with 55 VVER-440 fuel assemblies with output capacity 50 MWt, temperature of output coolant is designed to 98°C. Several versions of TEPLATOR with variable capacity and temperature output are proposed, from 50	[149]

Country	Status	Start of operation	End of operation	Description	Ref.
				MWt for TEPLATOR DEMO up to 150 MWt with TEPLATOR FULL. TEPLATOR is a concept of a reactor producing heat only, developed by a team of researchers from the University of West Bohemia in Pilsen and Czech Technical University in Prague. This unit is sufficient for heating a large city with more than 100 000 citizens due to production more than 1 PJ per year.	
Hungary	In operation	-	-	*Site*: Paks NPP (VVER-440) Paks town is 5 km away from Paks NPP, with a population of nearly 20 000 people. The NPP provides 40 MWt for district heating of Paks town.	[146]
Romania	In operation	-	-	*Site:* Cernavoda NPP (CANDU) *Capacity:* A steam flow rate of about 80 t/h is extracted for district heating from the main steam line, which is enough to provide 60% of the necessary heating for Cernavoda town (approx. 30 000 inhabitants). Heat demand in winter: 46 MW, water temperature 150°C/70°C; in summer: 7 MW, water temperature 75°C/40°C.	[151]
Russia	In operation	2020	-	*Site:* Akademik Lomonosov floating NPP (KLT-4S) The 2 KLT-40S reactors of Akademik Lomonosov floating NPP, located in Pevek, Chukotka, Russia's Far East, are variants of the KLT-40 designs that were developed to power icebreakers. The floating NPP provides 70 MW for space heating and domestic hot water supplied to the Russian port of Pevek on the East Siberian Sea.	[152]
Russia	In operation	1975	-	*Site*: Bilibino NPP (EGP-6) Bilibino NPP comprises 3 EGP-6 units (units 2-4) with total net output 164.8 MWt and it is located in Chukotka region, 4.5 km away from the Bilibino town. Unit 1 of Bilibino NPP was shutdown in 2019. The maximum heat output in winter months (when the air temperature can drop to -50°C) may reach 116 MW in the heating mode only. Bilibino-3 started to provide district heating in 1975 and Bilibino-4 in 1976.	[153]
Russia	In operation	1973	-	*Site*: Kola NPP (VVER-440) Kola NPP (4 VVER-440 units, all in operation) is located 11 km away from Polyarnye Zori town and provides district heating up to 232 MW. Kola-1 started to provide district heating in 1973, unit 2 in 1974, Kola-3 in 1981 and Kola-4 in 1984.	[144, 153]
Russia	In operation	1984	-	*Site*: Kalinin NPP (VVER-1000) The Kalinin NPP VVER-1000 (4 units, all in operation) is located 4 km away from Udomlya town and provides up to 700 MW for district heating (as of 2013). Kalinin-4 started to provide district heating in 2011, Kalinin-3 in 2004, Kalinin-2 in 1986 and Kalinin-1 in 1984.	[144, 153]
Russia	In operation	1982	-	*Site*: Smolensk NPP (RBMK-1000) Smolensk NPP (3 units RBMK-1000, all in operation) is located 4.5 km away from the Desnogorsk town. Currently, the heating plants in operation provide up to 520 MW, supplying the heated water for heating and hot water supply of Desnogorsk town. Smolensk-1 started to provide district heating in 1982, Smolensk-2 in 1985 and Smolensk-3 in 1990.	[153]
Russia	In operation	1972	-	*Site*: Novovoronezh NPP (VVER) The Novovoronezh NPP (3 units closed, 2 VVER units in operation: 1 VVER-400 and 1 VVER-1000), is located 3.5 km away from the Novovoronezh town and provides up to 350 MW for district heating, which is	[144, 153]

Country	Status	Start of operation	End of operation	Description	Ref.
				91% of the entire Novovoronezh town heat supply. Unit 4 started to provide district heating in 1972 and unit-5 in 1980.	
Russia	In operation	1980	-	*Site*: Beloyarsk NPP (BN-600, BN-800) The Beloyarsk NPP (2 units closed, 2 units in operation: BN-600 and BN-800) is located in Sverdlovsk region, 3.5 km away from the Zarechny town. BN-600 provides up to 66 MW (since 1980).	[144, 153]
Switzerland	In operation	1984	-	*Site:* Beznau NPP. Beznau NPP (2 PWR, 365 MWe each) provides up to 150 GWh heat per year. The heat is extracted at a supply temperature from 125°C in winter down to 80°C in summer. Beznau supplies 80 MWt of heat to homes and industry over an 80-mile network serving 11 towns. In 2009 separate water/steam circuit was built for another paper factory.	[24], [152, 154]

APPENDIX 4. NUCLEAR COGENERATION FOR INDUSTRIAL APPLICATIONS WORLDWIDE.

Country	Status	Start of operation	End of operation	Description	Ref.
Canada	Closed	1972	2006	Bruce NPP, Bruce bulk steam system (BBSS) project The secondary heat transport system of Bruce A diverted high pressure steam via a steam transformer plant to the Bruce bulk steam system. It produced medium pressure process steam for the heavy water plants (~750 MWt). 72 MWt of steam from BBSS was delivered to the Bruce energy centre industrial park, supplying a plastic film manufacturer, a greenhouse, an ethanol plant, an alfalfa plant, an apple juice concentration plant and an agricultural research facility.	[24]
Canada	Closed	1973	1997	Bruce NPP, Bruce bulk steam system (BBSS) project BBSS directed 750 MWt to the Bruce Heavy water plant, 15 MWt to building heating and 72 MWt to Bruce energy centre. Bruce NPP A, supplying heat for the Bruce Heavy Water Plant with a design capacity of 100.6 kg/h heavy water, 99.75% purity. Heavy water production stopped in 1997 and steam system was dismantled in early 2000s.	[24]
Germany	Closed	1984	2003	Stade PWR The project supplied a salt refinery with 60 t/h of process steam at a pressure of 0.8 MPa and a temperature of 270°C. About 95% of the steam transported by pipeline over approximately 1.5 km returned in the form of condensate. The salt production was based on solution mining where water is brought into an underground salt bed, with the brine pumped to the surface, heated and evaporated in pressure vessels (vacuum evaporation). The external steam decoupling resulted in a reduction of the net electricity production by around 10 MW.	[129]
Germany	R&D			HTR-Modul HTR-Modul design has an output of 170 MWt per unit. A four-module plant with 680 MWt can produce 2530 t/d of methanol at a coal throughput of 2690 t/d. In addition, 1050 t/d of charcoal can be produced. The reactor was designed for industrial applications, such as coal gasification and methanol synthesis. Coal is gasified with hydrogen at 920°C and 8 MPa to provide synthesis gas for the methanol synthesis.	[24]
Japan	R&D			GTHTR300C Japan Atomic Energy Agency studied a steel making system based on the nuclear plant concept GTHTR300C.	[155]
Korea, Republic of	R&D			Very High Temperature Reactor VHTR was studied for opportunities in steel production. POSCO steel company estimates that 1300 MWt thermal power from about twin units of VHTR is required to produce 2 Mt/y of hot compacted iron. The reactor can be used for hydrogen production through electrolysis or using thermochemical cycles. The Nuclear Hydrogen Development and Demonstration project develops VHTR reactor technologies and thermochemical hydrogen production applying the I-S thermochemical process. The sulphur–iodine process development, planned for a period of six years with equal share of government and private funding, has completed a laboratory scale experiment and is currently demonstrating operation of an integrated system at a production rate of 50 L/h of hydrogen.	[24]
Norway	Closed	1964	2018	Halden BWR The reactor provided 20 MWt heat/steam for industrial application, supplying a paper mill.	[24]

Country	**Status**	**Start of operation**	**End of operation**	**Description**	**Ref.**
Switzerland	In operation	1979	-	Gösgen NPP Gösgen NPP (1010 MWe PWR) provides an equivalent of 45 MWt heat. About 1% of the steam is diverted from the live steam system to heat a water/steam circuit that runs through a 1.8 km long steam line to the cardboard factory. The line has a maximum capacity of 70 t/h of steam, operating at a pressure of ~1.2 MPa and a temperature higher than 200°C.	[24]
Switzerland	In operation	2009	-	Beznau NPP Beznau NPP (2 PWRs, 365 MWe each) supplies 80 MWt of heat to homes and industry over an 80-mile network serving 11 towns. Separate water/steam circuit was built for another paper factory designed for a maximum throughput of 10 t/h of steam at a pressure of 1.5 MPa.	[24]
United Kingdom	Closed	1956	2003	Calder Hall Magnox reactor The steam generated at Calder Hall Magnox reactor was mainly used in a turbine for electricity production or as process heat in the nearby Windscale fuel works. The reactors were also used to sterilize hypodermic syringes and to produce radioactive cobalt, used in the treatment of cancer.	[24]

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ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
BARC	Bhabha Atomic Research Centre
BWR	Boiling water reactor
CANDU	Canada Deuterium Uranium reactor
CNL	Canadian Nuclear Laboratories
CNNC	China National Nuclear Corporation
CNNP	China National Nuclear Power Co Ltd
COP	Conference of Parties
CRP	Coordinated Research Project
DEEP	Desalination Economic Evaluation Program
DE-TOP	Desalination Thermodynamic Optimization Program
DHS	District heating systems
EU	European Union
FNST	Federal Nuclear Science and Technology
GHG	Greenhouse gas
GTHTR300C	Gas Turbine High Temperature Reactor
HEEP	Hydrogen Economic Evaluation Programme
HP	High pressure turbine
HTCE	High temperature co-electrolysis
HTGR	High temperature gas cooled reactor
HTR	High temperature reactor
HTR-PM	High Temperature Gas-Cooled Reactor Pebble-bed Module
HTSE	High temperature steam electrolysis
HTTR	High Temperature Engineering Test Reactor
HyS	Hybrid sulphur
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
I-S	Iodine-Sulphur thermochemical cycle

JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
LCOE	Levelized cost of electricity
LWR	Light water reactor
LDR	Low temperature district heating and desalination reactor
LFR	Lead cooled fast reactor
LUT	Lappeenranta-Lahti University of Technology
MED	Multi-effect distillation
MSF	Multi-stage flash
MSR	Molten salt reactor
NDC	Nationally determined contributions
NEA/OECD	Nuclear Energy Agency/ Organization for Economic Cooperation and Development
NPP	Nuclear power plant
PEM	Polymer electrolyte membrane
PHWR	Pressurized heavy water reactors
PWR	Pressure water reactor
PV	Photovoltaic
R&D	Research and development
RO	Reverse osmosis
SCWR	Supercritical water-cooled reactor
SDG	Sustainable development goal
SFR	Sodium cooled fast reactor
SMR	Small modular reactor
SOEC	Solid oxide electrolysis cell
TVC	Thermal vapor compression
UNFCC	United Nations' Framework Convention on Climate Change
VHTR	Very High Temperature Reactor
VTT	Technical Research Centre of Finland

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