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Non-electric Applications for Small Modular Reactors (SMRs)

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ABSTRACT

Nuclear energy is often linked exclusively to electrical power generation. However, it has the potential to increase worldwide energy and water security through non-electric applications, such as seawater desalination, hydrogen production, district heating, maritime propulsion and various industrial applications. These additional applications expand the prospects for nuclear energy and enhance the benefits that can be derived from it, such as reduced environmental impact and climate change mitigation. Currently, nuclear energy remains confined only to commodity markets where its competitiveness is uncertain. But new advanced nuclear systems can power a diverse portfolio of socially and economically valuable activities. In this paper, non-electric applications of small modular reactors are reviewed, including technological, environmental and economic issues of such applications as well as future prospects and benefits of non-electric applications of future advanced nuclear reactors.

Keywords: *small modular reactors, non-electric applications, electricity market, heat market*

1 INTRODUCTION

Today most people are aware of the important contribution nuclear energy makes in providing a significant proportion of the world's low-carbon electricity. However, the applications of nuclear technology outside of civil electricity production in power plants are less well known. [1]

Non-electric applications powered by nuclear energy could present sustainable solutions for a number of energy challenges current and future generations will have to face. Traditionally, electricity generation and management, and then meeting energy demands for industry and transportation, are considered independently. As we seek to achieve net-zero carbon emissions, we need to pause and reassess our energy demands. When we consider overall energy use, only one-third is in the form of electricity. Additional energy demands are in the form of heat or steam for industrial processes, as well as transportation. These sectors are much harder to abate, and electrification may not be the best option. The primary output from a nuclear plant is heat, and we should leverage that heat effectively as we seek to decarbonize industry and the primarily fossil-fuel dependent transportation sector. The non-grid applications of non-emitting nuclear energy are vast, including, but not limited to: [2]

- Seawater or brackish water desalination;
- District heating
- Clean hydrogen production via water and steam electrolysis;
- Synthetic fuel production for transportation systems;
- Production of heat and hydrogen for industrial processes, such as steel manufacturing;
- Maritime propulsion
- Ammonia production for fertilizer and chemical uses.

2 DESCRIPTION OF NON-ELECTRIC APPLICATIONS

Some applications of nuclear energy for non-electric uses have been understood for decades and, in cases like desalination and district heating, been demonstrated or implemented industrially. But such applications have been quite limited. [3]

Because traditional nuclear power plants operate 24/7, they are impacted by negative power prices, which occur when generation appears simultaneously with reduced electricity demand – something that is becoming more prevalent with increased deployment of variable renewables. [2]

This is where future SMRs can thrive.

2.1 Desalination

Water sits at the centre of the climate crisis. Rising sea levels, increasingly frequent flooding and droughts, and declining glacial and snow cover are all projected to frustrate access to sources of potable water. Without solutions to mitigate these and other effects of climate change, water scarcity will increasingly pose a threat to quality of life on a global scale. The demand for fresh water for drinking and industrial use is not limited to landlocked countries, but also affects small island developing states and countries with large coastal territories. Small modular reactors could offer a solution, while serving a dual purpose: producing low carbon electricity and turning seawater into fresh water. [4]

Addressing the world water problem has led to very creative solutions—the most common of which is seawater desalination, which is defined as the removal of salt and minerals from seawater. All desalination processes use energy in the form of heat and/or electricity, which, if generated by a nuclear reactor, will be referred to as nuclear desalination.

Desalination technologies can be broadly categorized as thermal and membrane desalination processes depending on the energy form (heat or electricity, respectively) that is used in the primary process for separating salt/minerals from water.

Over 150 reactor-years of nuclear desalination experience have been accumulated primarily in India, Pakistan, and Japan. Running nuclear power plants as base load plants is more economical and simpler than requiring them to follow load. Therefore, in a cogeneration mode and while grid load is low, reverse osmosis units run at full capacity even if their capacity exceeds water demands. Excess water produced during this period will, in turn, be stored for future use. This way excess energy (electricity) is stored as a final product (water) instead of requiring nuclear power plants to follow load.

A combination of a variety of desalination techniques (thermal or membrane in single or hybrid mode) have been shown to be successfully coupled with different types of nuclear power plants to produce water and electricity at different scales. The economics of nuclear desalination has been found to be competitive with other desalination techniques driven by other sources of energy. Nuclear desalination doesn’t require additional safety measures than those already existing for the nuclear power plant. Special consideration for potential water radiation contamination is achieved through insertion of additional physical barrier between the nuclear island and pathways of final water product. Marine, coastal, atmospheric, siting, and socioeconomic impacts of nuclear desalination have been shown to be either equivalent or (in some cases) better than those when other energy sources are used. Finally, efforts are under way to improve existing desalination techniques and invent new ones to increase the efficiency of nuclear desalination. Integrated solutions and systems have also been proposed to use multiple energy sources, including nuclear and renewable energies to meet multiple needs, including water desalination, industrial process steam, hydrogen production, electricity generation, and district heating. This will allow for resource optimization while minimizing the overall environmental impact of the proposed integrated solution. [5]

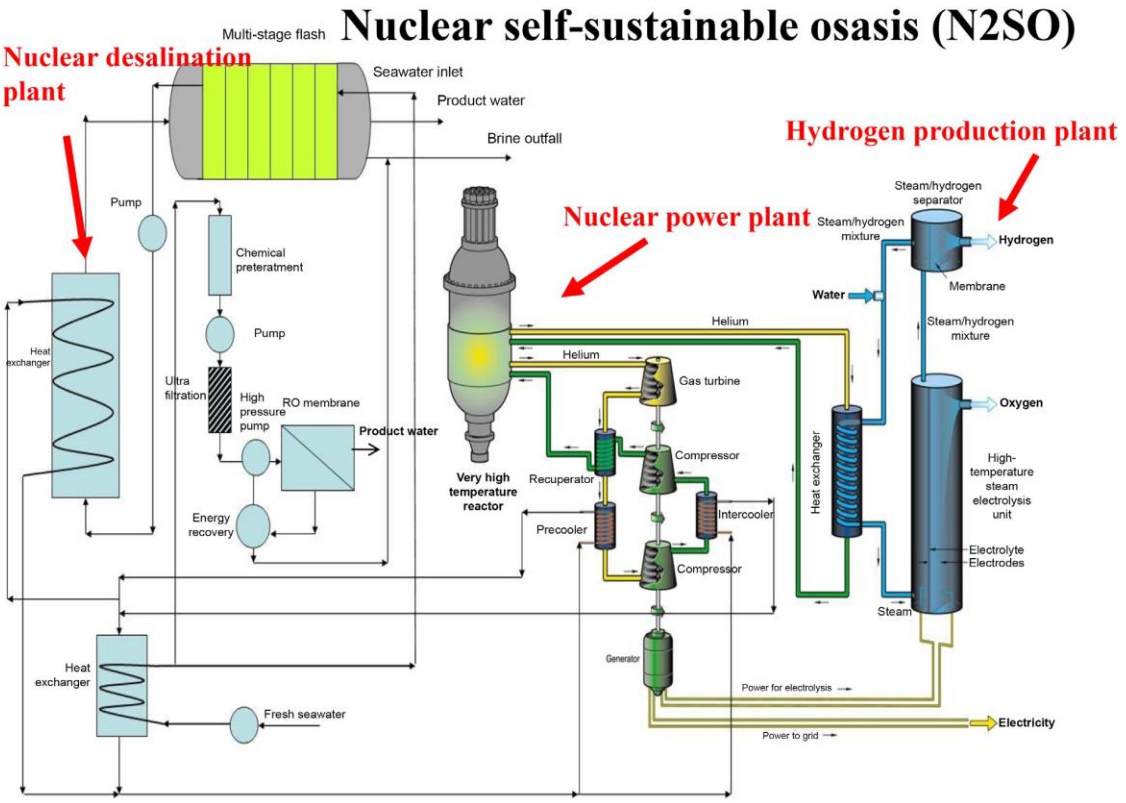

Figure 1: A very high temperature reactor self-sustainable oasis concept [5]

2.2 Nuclear hydrogen

Hydrogen is not found in free form (H_2) but must be liberated from molecules such as water or methane. It is therefore not an energy source and must be made, using energy. It is already a significant chemical product, about half of annual pure hydrogen production being used in making nitrogen fertilizers via the Haber process and about one-quarter to convert low-grade crude oils (especially those from tar sands) into liquid transport fuels. There is a lot of experience handling hydrogen on a large scale, though it is not as straightforward as natural gas.

Most hydrogen today is made by steam reforming of natural gas or coal gasification, both with carbon dioxide (CO2) emissions. Future demand will be mainly for zero-carbon hydrogen. Plans for increased hydrogen production are essentially based on electrolysis using electricity from intermittent renewable sources. Off-peak capacity of conventional nuclear reactors or other power plants can also be used. In future, a major possibility for zero-carbon hydrogen production is decomposition of water by direct use of heat from nuclear energy, using a thermochemical process enabled by high-temperature reactors. [6]

Water electrolysis operates at relatively low temperatures of less than 100 degrees Celsius, while steam electrolysis operates at much higher temperatures of around 700 degrees to 800 degrees Celsius and requires less electricity than water electrolysis. Water electrolysis is a process whereby electricity is used to separate the hydrogen from the oxygen in water. This type of technology has been commercially available for decades. High temperature electrolysis follows the same principle but uses water in the form of steam, thereby reducing the amount of electricity required. Advances in electrolyser technologies are making hydrogen production from conventional nuclear power reactors more efficient and cheaper. [4]

2.3 District heating

Nuclear energy is competitive for urban district heating applications. According to the International Atomic Energy Agency, about 43 nuclear reactors around the world—mostly in Eastern Europe and Russia—provide district heating in addition to generating electricity. Combined heat and power arrangements are more attractive for new small- and medium-sized nuclear reactors because these designs incorporate enhanced safety features, require smaller investments, pose fewer financial risks, and may be easier to site closer to end-users. [7]

Nuclear-based district heating appears promising for urban areas plagued with polluted air and greenhouse gases released from burning of fossil fuels. Advantages of nuclear heat supply are fuel conservation, improvement of the environment, and reduction of heat discharged to the atmosphere. Almost two-thirds of the heat generated in a conventional nuclear power plant is released to the environment. A well-designed CHP system could boost a nuclear plant's energy efficiency from about 33% to 80%. Nuclear heat in the form of hot water can be economically delivered up to 150 kilometres away at competitive cost and with a heat loss of 2% to 3%. When a nuclear district heating system replaces individual heating boilers, the combustion process emissions from thousands of small stacks are eliminated. Nuclear energy can be competitive for urban district heating applications (Figure 2). Therefore, it is justified to review the status of recent nuclear-based district heating technology.

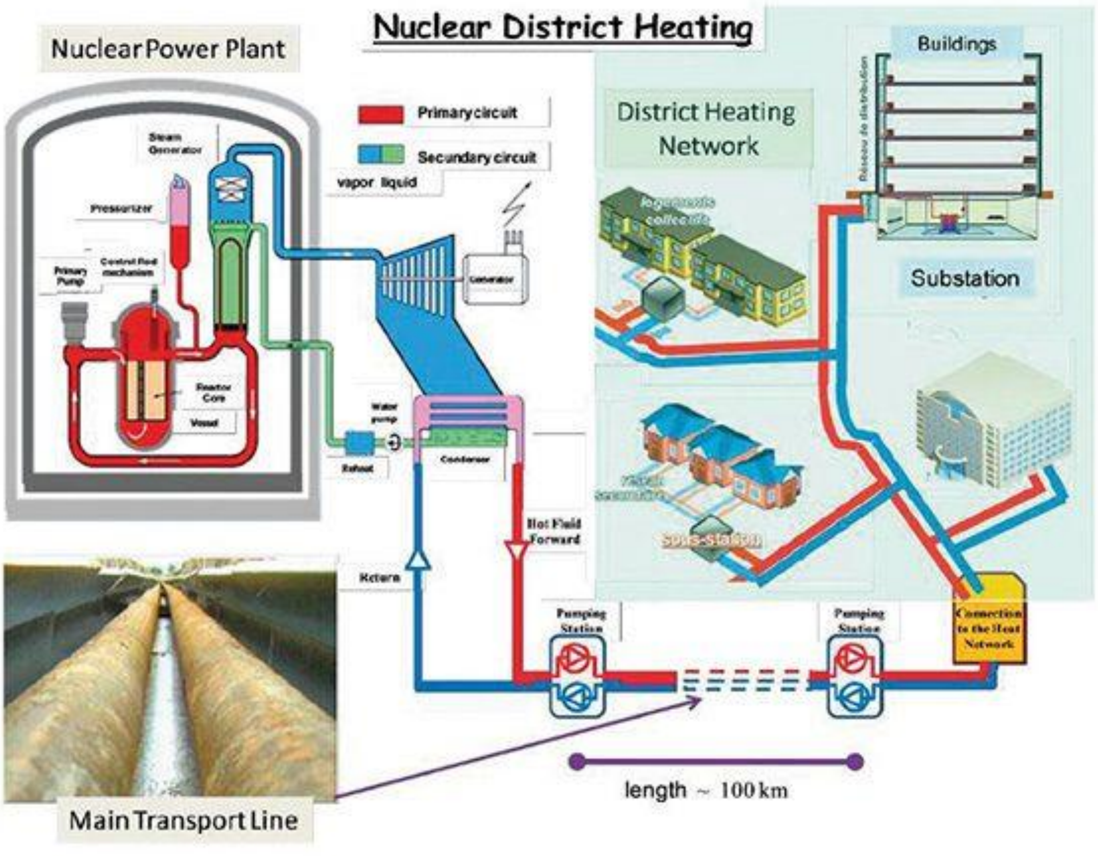

Figure 2: Typical nuclear-based district heating systems extract heat from the reactor plant's secondary circuit [7]

Issues to be resolved relative to the use of heat supplied by nuclear energy include public acceptance of nuclear plant sites in relative proximity to populated centers, development of economical heat transport methods, and availability of large dual-purpose turbines for production of electricity and extraction steam at suitable temperatures and pressures.

Although costs and technology status of nuclear-based district heating are favourable and there are environmental advantages, institutional barriers are deterrents to implementation. These barriers must be overcome before the energy conservation potential of this approach can be realized on a significant scale. [7]

2.4 Synthetic fuel production for transportation systems

Synthetic fuel is a carbon-neutral alternative to traditional fossil fuel that has significant potential in being the climate friendly choice of the transport sector in its Net Zero plans due to having similar energy densities to fossil fuels and ability to “drop in” to current fuel transportation systems (i.e. pipelines) and engines. There are two main types of synthetic fuels:

- Electrofuels, which are made when captured CO_2 reacts with H_2 made from the splitting of water powered by low-carbon electricity or heat
- Biofuels, which are made through the chemical or thermal treatment of biomass or biofuels

The clean electricity needed to create sustainable fuels can be supplied from low-carbon sources, such as nuclear power or renewables. Nuclear energy provides consistent, low-carbon power and can therefore be considered a more reliable feedstock.

Nuclear power can help produce synthetic fuels by:

1. Generating low carbon electricity and heat to enable hydrogen production through electrolytic and thermochemical processes;
2. Nuclear heat can drive Direct Air Capture (DAC) technology, which extracts CO2 directly from the atmosphere. This CO2 can be recycled from burning synthetic fuels and can be synthetised again to make more fuel
3. Low-carbon power from nuclear can be used to drive synthetic fuel production processes, such as Fischer-Troph, to make synthesise hydrocarbons. [8]

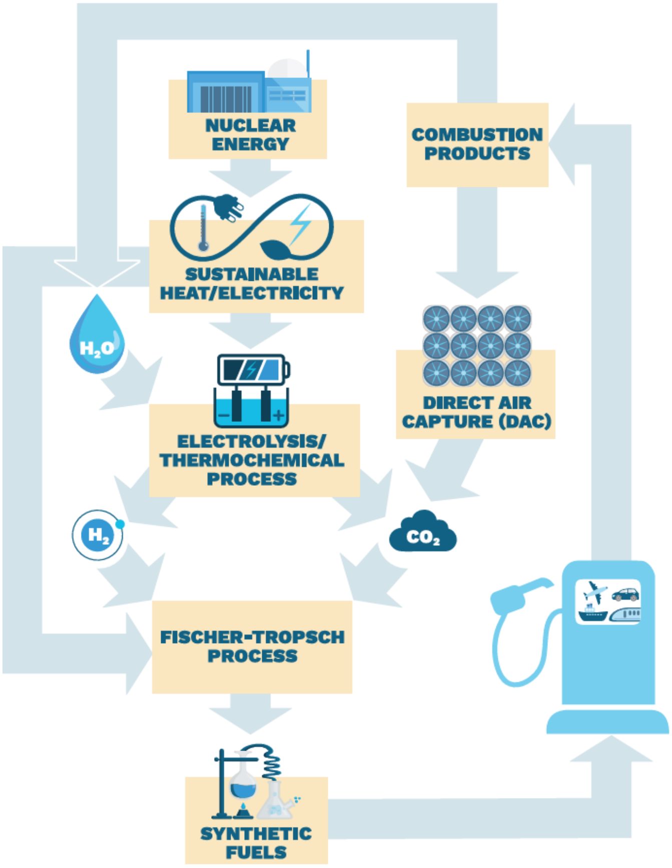

Figure 3: Production route for sustainable aviation fuel [8]

2.5 Maritime propulsion

More than 80% of the world’s traded goods spend time on large shipping vessels. This means most of the products you buy and the foods that you eat could come at a price. That’s because the maritime industry accounts for nearly 3% of global carbon emissions and it is not a sector that can be easily decarbonized.

Nuclear reactors have been cleanly propelling military vessels for more than 60 years and interest is growing in using new reactor technologies to dramatically scale back the maritime industry’s carbon footprint and lower operating costs.

According to the International Maritime Organization (IMO), maritime shipping emits more than 1 billion tons of carbon dioxide emissions each year. If treated as a country, international shipping would be the sixth largest CO_2 emitter in the world. These emissions are largely caused by the diesel engines and low-grade bunker fuel used to power shipping vessels—leading to higher levels of air pollution in nearby ports and surroundings communities. It's estimated that the world’s largest 17,000 ships account for roughly 80% of global shipping emissions. Replacing diesel engines in these vessels with nuclear propulsion systems could significantly clean up maritime emissions and put the industry well on its way to achieving the IMO’s carbon reduction goals.

The U.S. Navy, along with five of other military forces around the world, currently use nuclear-powered submarines and aircraft carriers. The United States, Germany, Japan, and Russia tried demonstrating commercial vessels in the 1950s but all of them proved to be too expensive to build and maintain. New start-up companies, supported by private-public partnerships, are using modern technology such as new simulations, higher-resolution modelling, and advanced construction techniques to optimize advanced reactor designs to power shipping vessels.

Many container and tanker ships require up to 50 megawatt systems, which is enough energy to power around 50,000 homes. This requires a lot of bunker fuel and constant refuelling that can lead to high operating costs. Nuclear reactors could allow these same ships to run longer and on less fuel. Existing nuclear-powered submarines and aircraft carriers use highly enriched uranium and light-water reactor systems to run for 30 years or more without refuelling. New advanced modular designs cooled by molten salts, liquid metal, or gas could serve a similar function using a lower-enriched uranium fuel that could be used for commercial purposes. [9]

2.6 Ammonia production

Widely used in agriculture, ammonia is among the top 10 most commonly produced industrial chemicals in the world. A gas at ambient temperature and pressure, ammonia can be compressed and liquefied at much lower pressures than hydrogen, making it significantly easier to store and transport. It also has an energy density almost double that of hydrogen.

Past interest in ammonia as a fuel has ranged from exotic applications to more down-to-earth research into ammonia's potential as a carbon-free alternative fuel for internal combustion engines. For example, NASA and the US Air Force broke records in the 1960s with the experimental X 15 aircraft powered by an ammonia-fuelled rocket engine. [10]

Nuclear-based ammonia production idea is to harness both unused generating capacity and waste heat to produce ammonia with a near-zero carbon footprint. The ideal for a nuclear plant is to produce electricity at a constant rate regardless of the time of day. However, nighttime demand is low relative to the day with the result that plant output often falls to 30 percent of rated capacity. This means that electricity can be generated incrementally in this period at very low cost. Incremental electricity can be used to produce hydrogen via electrolysis and then produce ammonia via Haber-Bosch synthesis.

Conventional nuclear plants produce waste heat with a temperature of approximately 300 °C. That is too low to provide significant thermal support for the ammonia synthesis reaction (which is typically conducted at 400 °C and above.). However, gas-cooled nuclear reactor technology, which is currently under development, would produce waste heat with a temperature as high as 800 °C.

Nuclear plants are such finely tuned systems that it would be cost-prohibitive to try to integrate an ammonia production module on a retrofit basis. It is therefore necessary to design new plants built for this purpose. [11]

3 CONCLUSION

Several non-electric applications for SMRs are reviewed in this article. These applications are significantly greater than electricity generation, including desalination, nuclear hydrogen production, district heating, synthetic fuel production, maritime transport and ammonia production. They expand the prospects and benefits of nuclear energy, such as reduced environmental impact and climate change mitigation.

There are certain challenges that need to be overcome, such as ample flexibility for dual electric and non-electric operation of future SMRs and economic challenges, however interest in non-electric applications of nuclear energy is growing and potential uses of nuclear energy beyond electricity generation and supply are likely to find increasing application in the future.

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