Canadian Nuclear Laboratories: Canada's Past Experience and Future Goals for Nuclear Flexibility

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Canadian Nuclear Laboratories (CNL) is Canada's premier nuclear science and technology organization. CNL has a dual mission to support the needs of the federal government through the Federal Nuclear Science and Technology Work Plan, which is managed by Atomic Energy Canada Limited, while also competing to provide commercial services both nationally and globally. CNL develops peaceful and innovative applications of nuclear technology for the existing nuclear fleet (CANDU® and light water reactors, LWRs) and for future advanced reactors, including SMR technologies.

CNL's long-term plans and mission include demonstrating the commercial viability of advanced reactor designs/SMRs and providing the world with sustainable energy solutions. For example, the extension of reactor operating lifetimes (e.g., refurbishment), hydrogen energy technologies, and advanced fuel development for the reactor designs of tomorrow. The following research areas will be discussed in this chapter.

- Hybrid energy system models to couple various clean technologies and to assess the associated economic benefits of those systems
- Clean hydrogen technologies (i.e., production, storage, safety) to provide clean energy alternatives to support a national hydrogen economy
- A Clean Energy Demonstration Innovation and Research park to demonstrate the integration of renewable energy and other clean technologies with the flexible operation of an SMR at the Chalk River site.

These research areas led by CNL support the Flexible Nuclear Campaign for the CEM NICE Future initiative. Natural Resources Canada is the federal department in Canada responsible for nuclear energy policy and leads Canada's engagement at the CEM. Natural Resources Canada (NRCan) draws upon scientific expertise at CNL to support Canada's participation.

1.1 Hybrid Energy System Background

In Canada, the energy landscape is changing, creating opportunities for many provinces to transition to low-carbon energy sources. The changes include:

- Target reduction of greenhouse gas (GHG) emissions related to energy production toward net-zero emissions by 2050 (Wilkinson 2019);
- Transition of Indigenous communities from reliance on diesel-fueled power to clean, renewable, and reliable energy by 2030 (Trudeau 2019);

- Increased focus on maintaining grid reliability and minimizing system costs while increasing the penetration of VRE sources

- Increasing energy demands expected from disruptive changes in other areas, such as transportation and manufacturing (e.g., vehicle electrification) ("Pan-Canadian Framework on Clean Growth and Climate Change" 2016).

Clean energy systems of the future will need to include all sources of clean energy to be viable and sustainable. The traditional base load electricity production from nuclear reactors is necessarily affected with increased penetration of variable renewable technologies (such as wind and solar). This results in de-rating of reactors in order to give preference to the production from variable renewable technologies. However, nuclear and renewable technologies are preferred over GHG-emitting technologies. For this reason, nuclear reactors and variable renewable technologies are no longer perceived to be at odds with each other. Instead, an energy system is required that leverages the unique capabilities of each technology to create an "all of the above" clean solution that is reliable and cost-effective.

In 2018, CNL initiated a research project under Atomic Energy of Canada Limited's Federal Nuclear Science and Technology Work Plan to develop a hybrid energy system optimization model. This model was developed to study the interactions between different supply and demand sources in hourly, seasonal, and annual timeframes, to better understand the trade-offs of different energy systems and what is required to transition to a cost-effective low-carbon energy system in different regions across Canada. With an objective to identify the lowest-cost energy system that meets GHG target emissions, the hybrid energy system optimization model highlights how different technologies can be combined to complement each other, as shown in Figure 1.

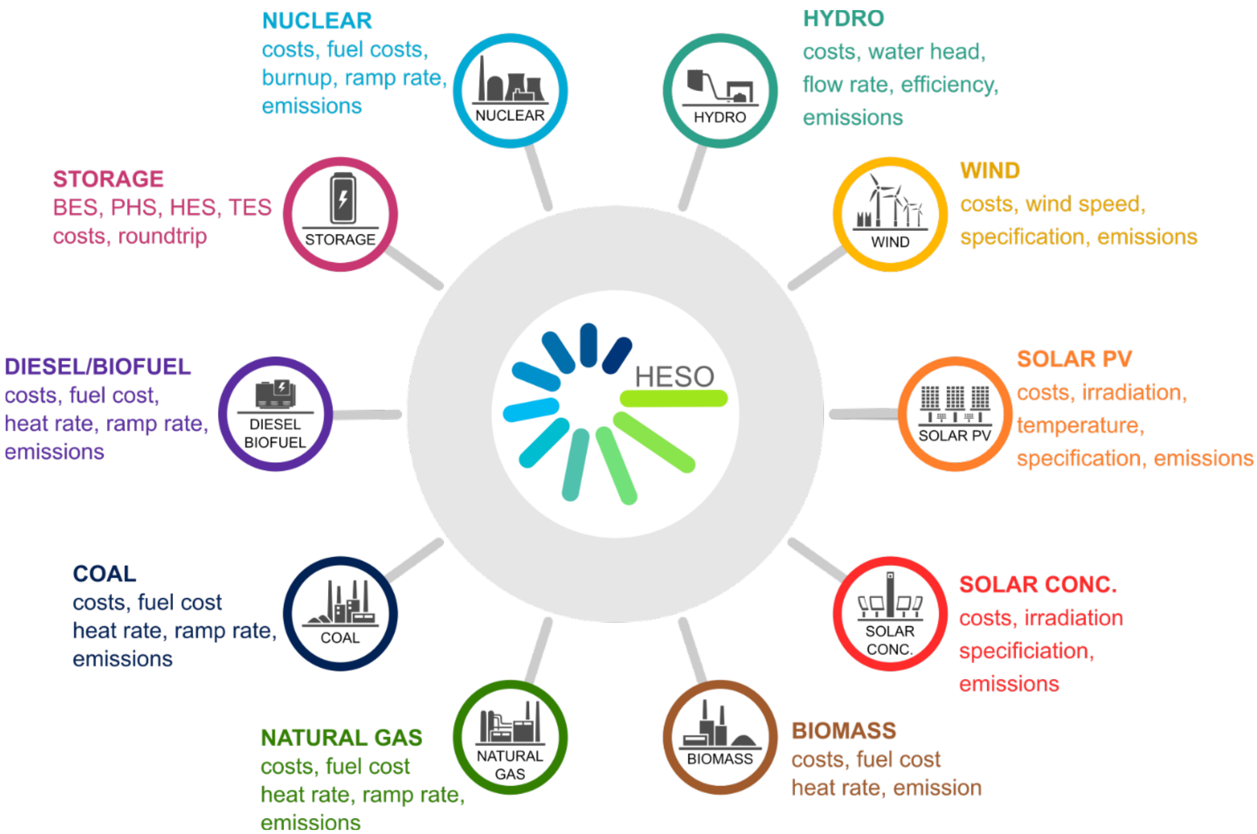

Figure 1. Hybrid energy system optimization model inputs

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In 2020, a number of cases were evaluated using this model, including one that studied the impact of electrifying residential water heating.

1.2 Residential Water Heating Electrification Case Study

The two main methods for heating water in Canada are electric or fossil-fueled (most commonly natural gas). A case study was performed to understand the impact of converting fossil-fueled water heaters to electric water heaters in a given region. It is expected that low-carbon electricity sources, such as nuclear, could displace the natural gas through electrification and reduce overall emissions.

The scenario assumed just over 42 TWh of thermal energy is currently supplied by natural gas to heat water, emitting just under 21 megatonnes (MT) of GHG annually. The electricity grid currently produces 135 TWh of electricity, emitting only 2.65 MT of GHG. Several alternate scenarios were studied where a portion of the fossil-fuel water heaters were to converted electric water heaters, ranging from 25% penetration to 100% penetration.

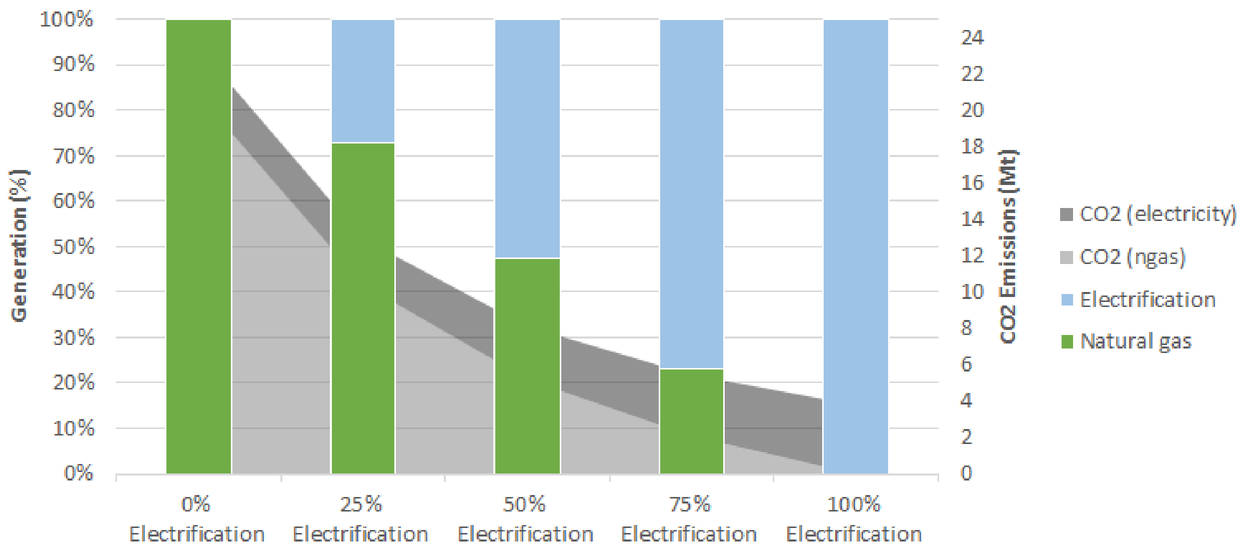

Figure 2. Reduction of GHG emissions by electrification of water heating

Source: CNL used with permissions.

Figure 2 shows that electrification will result in a significant decrease in GHG emissions from water heaters, with only a slight increase in GHG emissions from electricity production. This was achieved, while keeping the cost of electricity constant, by increasing generation from wind, solar and conventional nuclear power plants to maintain the same total percentage of generation, while also increasing electricity generation from natural gas to address the increased variability in the system as shown in Figure 3. It is expected that advanced nuclear reactors will have improved load following capabilities that could further reduce GHG emissions by displacing natural gas electricity generation and allow for a higher penetration of wind and solar.

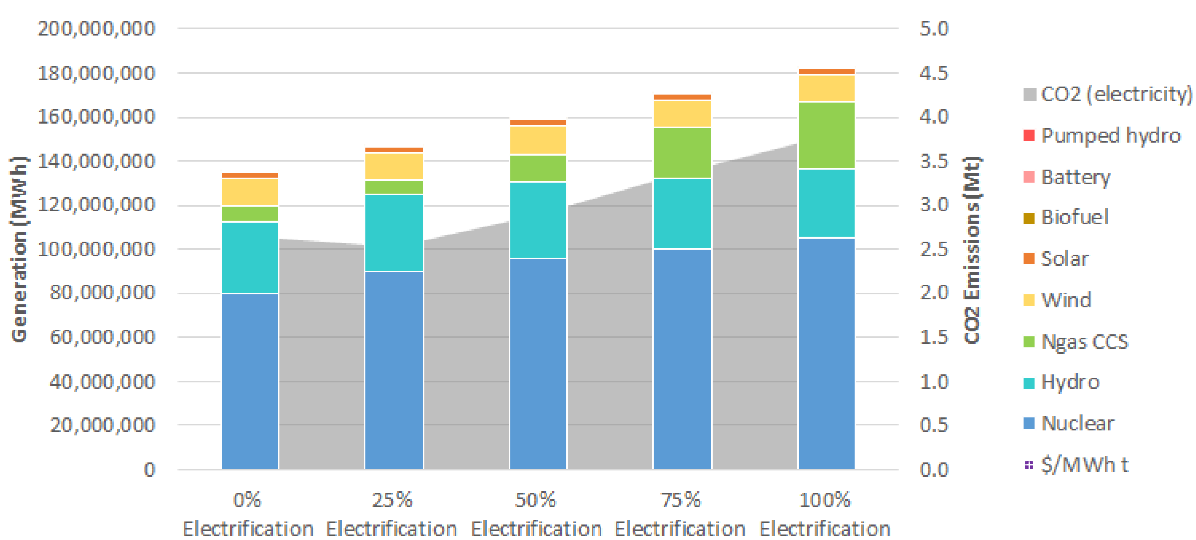

Figure 3. Ontario electricity generation by source based on electrification level (energy generation)

Source: CNL Used with permissions.

Although promising, additional work is required to improve the cost-competitiveness of electric heat. The poor roundtrip efficiency compared to direct heat with fossil fuels and North America's abundance of low-priced natural gas makes electric heat prohibitively expensive in many parts of Canada. While natural gas prices remain low, alternative products, such as clean hydrogen, may be better for this application.

1.3 Coupling of Nuclear to Industrial Processes for Greater Flexibility

One of a nuclear reactors greatest strength in a flexible energy system is its ability to provide both heat and electricity. Historically, most nuclear reactors have focused on electricity production to meet base load demand. When electricity demand dropped below base load levels, generation is reduced, which also reduced the revenues earned during that period. However, by leveraging the heat produced by a nuclear reactor, nuclear energy can enable several opportunities to improve flexible operations as part of a clean energy system, while also increasing revenues.

One approach to flexible operations requires coupling the nuclear reactor to an industrial process that can utilize the high temperature heat from a reactor (e.g., hydrogen production). Operation can be shifted between products in response to variability in electricity demand by changing the pathway of the steam. When electricity demand is high, all steam is sent through the turbine set to generate electricity. During periods of low demand, some (or all) of the steam is diverted to the industrial process.

To support product flexibility, CNL is advancing research into aspects of the hydrogen economy to ensure hydrogen production and storage can be used safely as part of the flexible energy solutions of tomorrow.

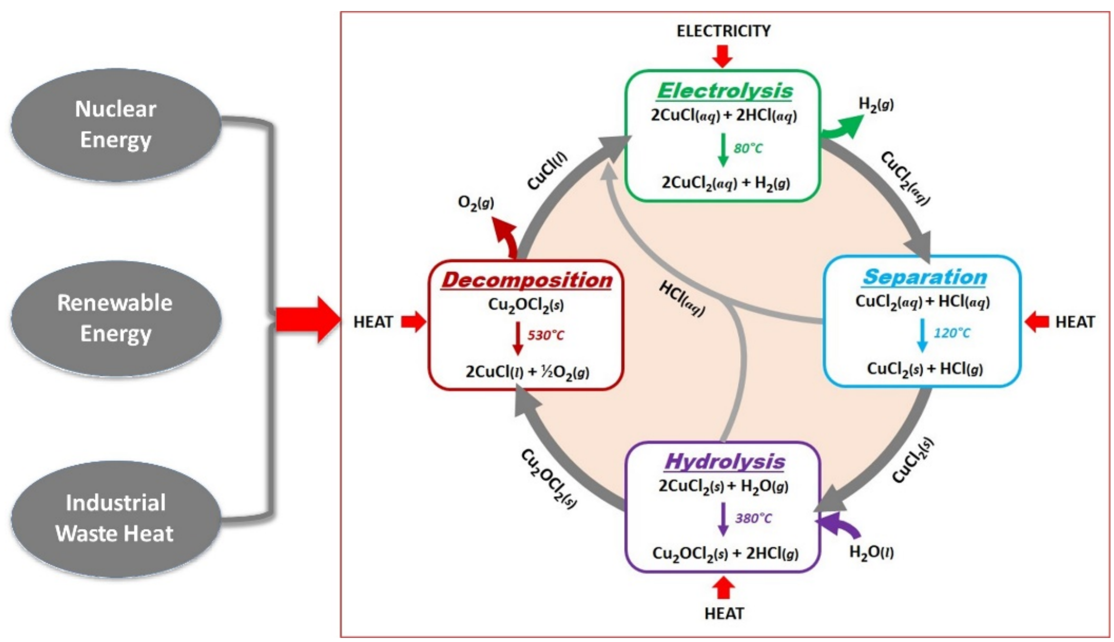

Figure 4. Hybrid Cu-Cl thermochemical hydrogen production

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CNL is leveraging a long history of hydrogen research as applied to the CANDU industry in heavy water production, hydrogen safety and tritium management, and, most recently, hydrogen production and fuel cell research. CNL is presently demonstrating the full copper-chlorine (Cu-Cl) process, a hybrid thermochemical cycle using heat and electricity to produce hydrogen at the lab scale (shown in Figure 4), progressing toward large-scale hydrogen production without GHG emissions. Thermochemical cycles have an advantage for large scales, and potentially higher efficiency, than electrolysis, owing to direct use of thermal energy. The Cu-Cl cycle consists of three chemical reaction steps (electrolysis, hydrolysis, and decomposition) and auxiliary physical processes (water removal by drying/crystallization, species separation, and heat recovery). The overall reaction of the cycle is the splitting of water into hydrogen and oxygen:

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

In simplest terms, the CuCl thermochemical cycle uses water, heat, and electricity as inputs to produce hydrogen and oxygen. The copper containing compounds are circulated throughout the process and are not consumed. The attractive features of the Cu-Cl process, compared to other thermochemical cycles, are the lower operating temperatures (highest temperature for the cycle is 530 C, well-suited for coupling to many Gen IV technologies. Therefore, corrosion issues are more tractable than for other higher-temperature cycles. The main technical challenges of the Cu-Cl process are related to the complex reactions associated with some steps and the difficulty with solid material transfer (particularly at elevated temperatures). CNL is working to address these challenges and to generate data for scaling up the process from laboratory scale, to pilot scale, and ultimately to industrial production scale.

CNL is also developing technologies to store hydrogen in metal alloys, liquid organics, and underground hydrogen locations. CNL has contributed to the development of conventional hydrogen safety applications to advance the safe use of hydrogen as an energy storage medium and as a fuel in the broader economy leveraging hydrogen safety expertise derived from nuclear sector applications. Recently, CNL expanded its capability to model the entire hydrogen system network required for fuel cell powered passenger trains (e.g., rail (CH2M, EY, and CNL 2018)). The modeling capability can also be applied to demonstrate the viability of coupling nuclear reactors to other industrial processes for greater system-wide flexibility.

1.4 Other Initiatives

The Government of Canada provided an investment of $1.2 billion over 10 years, beginning in 2016, to revitalize the Chalk River Laboratories. This investment on new and renewed science infrastructure will support the nuclear research needs of the Canadian Government and the evolving science and technology needs of the Canadian and global nuclear industry. It will build a world-class nuclear science and technology campus and position the organization as a global leader in nuclear science and technology, growing its commercial business and building a modern, efficient and collaborative campus environment at the Chalk River Laboratories.

This investment will support CNL's long-term goals in to demonstrate the commercial viability of advanced reactors, including the small and very small modular designs. The ability to demonstrate the flexibility of nuclear power using SMRs coupled with other technologies and energy sources requires an operating demonstration unit. Accordingly, CNL is pursuing initiatives, in addition to those identified above, to advance the deployment of SMRs in Canada. CNL has a strategic goal to deploy a SMR at one of our managed sites by 2026. To date, several SMR vendors have expressed an interest in siting a demonstration reactor project through CNL's SMR Siting Invitation Process while, in parallel, working on aspects of licensing with the Canadian Nuclear Safety Commission, the national regulator. In 2019, CNL launched the Canadian Nuclear Research Initiative to help advance research and development needs of SMR technologies. In the Canadian Nuclear Research Initiative program, CNL and SMR vendors pursue joint research projects, to be executed at CNL, focused on accelerating the deployment of SMRs in Canada and developing innovative solutions for the SMR industry.

The deployment of SMRs is a major milestone toward flexible nuclear operation in Canada, as their smaller size and advanced reactor technology will enable clean nuclear to be leveraged in some of the harder to decarbonize areas such as remote communities or industrial sites. In conjunction with siting an SMR at CNL, the Clean Energy Demonstration Innovation and Research park concept is being developed. The intent of this Clean Energy Demonstration Innovation and Research Park is to bring industrial partners and technology developers together with SMR vendors to demonstrate the ability to couple SMRs with other technologies, thereby increasing the flexibility of the system. The park will be a venue to showcase the technologies for interested stakeholders, resolve technical issues (e.g., licensing) and demonstrate integration of technologies (e.g., hydrogen production, district heating, desalination) to inform optimal energy usage during all times of the day and periods of the year.

Today, CNL continues its commitment to ensure Canadians and the world receive clean energy, health, and environmental benefits from nuclear science and technology with confidence that nuclear safety and security are assured.

1.5 References

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