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The Unique Contribution of CANDU Technology in the Battle against Climate Change

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ABSTRACT – The world faces a difficult challenge: reducing carbon dioxide emissions which contribute to climate change, while supporting the rapid economic growth of developing countries and the energy demand tied with it. To achieve this, numerous international jurisdictions are recognizing nuclear power for its low carbon emission merits and aggressively increasing their nuclear capacity. CANDU® reactors are not only a valuable option for nuclear capacity growth in their conventional high-efficiency, natural uranium-fuelled design, but also provide environmentally-friendly benefits through alternative fuel cycle designs. The inherent fuel flexibility of CANDU reactors allows the use of recycled uranium, underutilized thorium resources, and plutonium stockpiles.

Introduction

Rising populations and the rapid economic growth in emerging markets continue to increase the global demand for electricity. This results in additional pressure on resources and the need for more efficient and sustainable energy generating technologies. Some of the largest emerging and developing economies in the world include China, India, Brazil and Russia, which are also top electricity consumers and CO_2 emitters along with the United States, Japan and Canada [1]. China in particular, ranks as the world's largest greenhouse gas (GHG) emitter producing over 10 billion tonnes of equivalent CO_2 on a yearly basis, which represents about 25 % of total global carbon emissions [2].

On the climate change front, there is a revitalized global desire to reduce carbon emissions. The 2015 United Nations Climate Change Conference (COP 21) held in Paris negotiated a global agreement for the reduction of carbon emissions. This agreement, which was signed by all 196 parties present, set a global warming limit to less than 2 ^{O}C. The launch of Mission Innovation, a global partnership aimed at accelerating and increasing government and private investment in clean energy, was also announced at the conference. The initiative promotes clean energy that can help reduce GHG emissions and has been endorsed by multiple governments and private parties around the world.

This challenging international framework sets a promising stage for nuclear power to play a vital role. CANDU nuclear technology, in particular, with its fuel flexible applications that allow maximum resource utilization, is positioned to play a leading role in the climate change discussion.

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1. The Role of Nuclear Energy in Climate Change

Amongst all readily available low carbon electricity generating technologies, nuclear power sits at the top in terms of reliability and environmental friendliness. Nuclear energy generates zero GHG emissions and produces small indirect lifecycle emissions of ~10 tonnes equivalent CO_2 per GWh of electricity generated. According to the latest Intergovernmental Panel on Climate Change (IPCC) report, the full fuel cycle carbon emissions of nuclear energy are lower than those of solar and comparable to renewables such as hydro and wind [3]. As shown in Figure 1, this is significantly lower than the ~830 t/GWh and ~550 t/GWh produced by coal and gas fired plants, respectively [3].

Additionally, nuclear technology's inherent reliability allows it to achieve high capacity factors as it does not depend on fluctuating power sources like the wind or the sun to generate electricity. The world's average lifetime capacity factor of nuclear power plants hovers around 90%, while wind and solar sit at staggering 40% and 21%, respectively [4]. Therefore, it is conceived that an ideal *green* electricity mix would rely on nuclear and hydro for its base load, and include solar, wind and other renewables for resource diversification purposes.

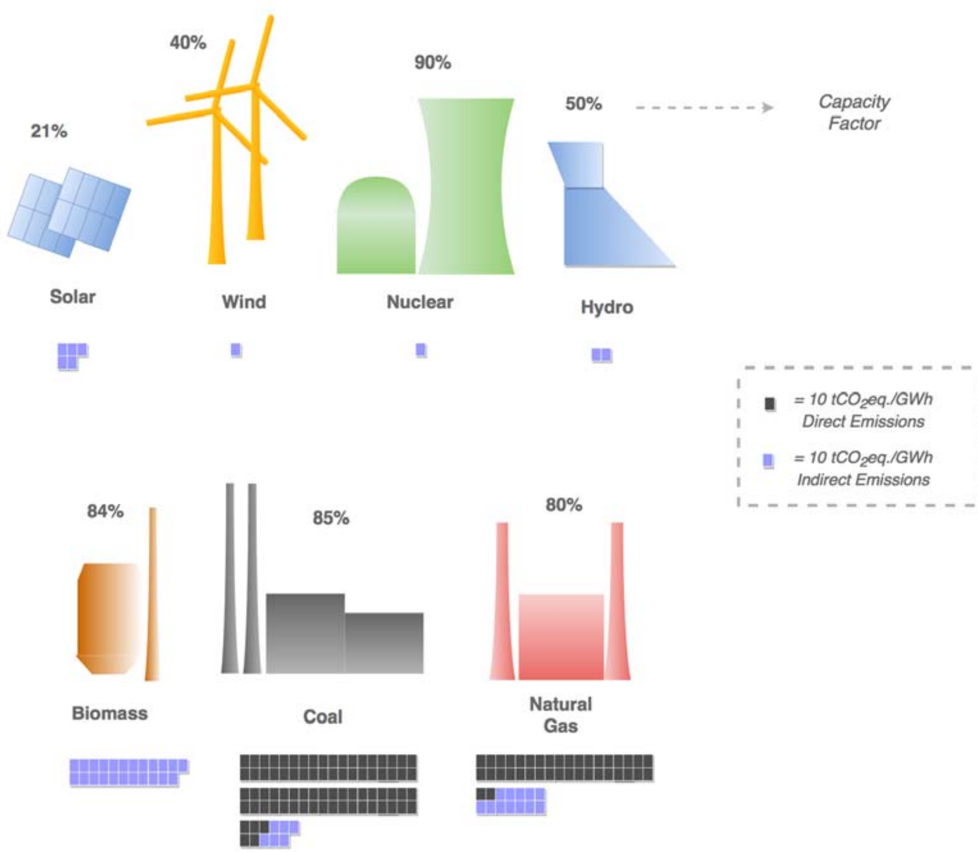

Figure 1 Capacity Factor & Carbon Emissions per Energy Source©

1.1 The Global Contribution of CANDU Technology

The international fleet of 28 CANDU reactors successfully operating in Canada, China, Korea, Romania and Argentina has a part to play in reducing global carbon emissions. These plants have operated safely for over 150 reactor-years and are ranked among the world's top performing nuclear reactors. Currently, the CANDU fleet saves over 200 million tonnes of CO_2 each year, when replacing traditional coal plants.

Ontario in particular, is one of the lowest carbon emitting jurisdictions in North America, with more than 60% of the province's electricity generated from nuclear [5]. The 2014 closure of its final coal power plant was a major accomplishment, made possible primarily through the restart of two CANDU nuclear units. This has significantly lowered Ontario's carbon emissions to one of the lowest in the world. Ontario has also successfully integrated renewable generation with its base load hydro and nuclear units, creating a model for a diverse and low carbon electricity system in Canada.

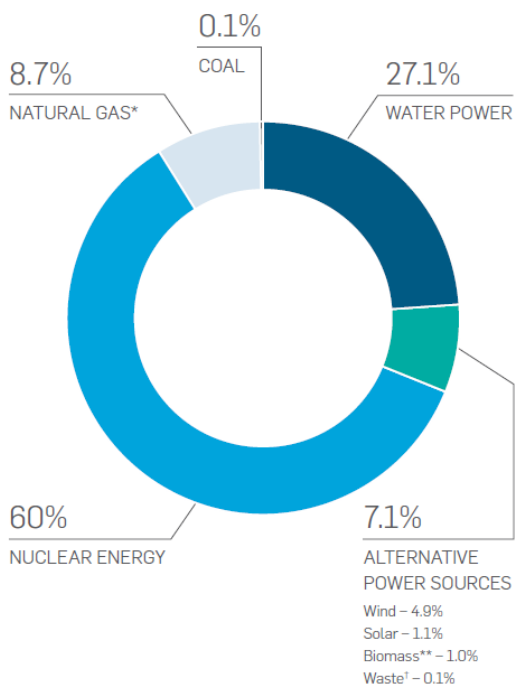

Figure 2 Ontario's Electricity Mix©

1.2 Nuclear Spent Fuel in Perspective

Even though nuclear power provides undeniable environmental benefits, the negative perception that the general public has of spent fuel poses a substantial barrier to its implementation. Nuclear spent fuel is typically criticized for its longevity and high radioactive content, which requires special disposal measures and extended monitoring. However, there are key features of nuclear spent fuel that are more environmentally friendly than its counterparts.

A twin unit 1,400 MWe CANDU nuclear station disposes about 10,000 fuel bundles each year. Given the small size of the fuel bundles, the two unit station's entire spent fuel disposal over 50 years would fill one Olympic swimming pool. Spent fuel is the only "waste" produced by nuclear, since no toxic air pollutants are released. It is worth noting that traditional CANDU reactors use natural uranium (NU) fuel, which doesn't require fuel enrichment that would otherwise generate additional by-products. Moreover, spent nuclear fuel contains unlocked energy that could be reprocessed and reused in more advanced technologies (like fast breeder reactors) in the future.

In comparison, a typical 500 MWe coal fired power station burns 1.4 million tonnes of coal each year and produces 3 million tonnes of CO_2. According to a study carried out by MIT, other combustion-related emissions are also released including sulfur dioxide (SO_2), nitrogen oxides (NO and NO_2), house gas and methane (CH_4) [6]. These are all leading causes of global warming, smog, acid rain and toxic air pollution. Other toxic releases including mercury, ammonia, sodium chloride, carbon and mineral dust are released during combustion causing serious lung diseases and deaths. All of these wastes are not carefully accounted for or monitored the way nuclear spent fuel is, but rather perpetually released into the atmosphere.

Alternatively, the manufacturing of photovoltaics for solar power, requires large quantities of many toxic chemicals (arsenic, cadmium, lead, selenium hydride, hydrofluoric acid, germane, etc.) and carcinogens (cadmium, chromium, indium phosphide, thiourea, arsine, carbon tetrachloride, etc.), while releasing several GHGs like, nitrogen trifluoride, hexafluoroethane and sulphur hexafluoride [7]. This serves to explain why the lifecycle GHG emissions of solar power are significantly higher than those of nuclear. In addition, typical solar panels have a 25 year lifespan, at which point they would need to be replaced to ensure electrical output is maintained. The waste produced from dismantling these panels is significant given their large size per energy output.

2. Advanced Fuel CANDU Technologies – Towards Closing the Fuel Cycle

In order to support the anticipated large-scale international nuclear power development and to reduce GHG emissions while preserving natural resources and minimizing waste, there is a global emphasis on technology advancements and improved efficiencies. To that end, CANDU technology is strategically positioned to further improve the sustainability of nuclear power by providing fuel flexible options.

The utilization of recycled fuels allows countries like China to reduce their dependency on natural uranium (NU) and reduce their spent fuel volumes, while providing significant performance and economic advantages.

Additionally, the utilization of alternative fuels such as thorium and plutonium further improves resource diversification. The world's thorium resources are estimated at 6.4 million tonnes, which are indigenous in several emerging and developing countries including India, Brazil and China [8]. Several tonnes of plutonium have been accumulated in countries like the USA, Russia, the UK and France in the form of separated civil plutonium and weapons-grade plutonium [9]. These stockpiles can be used to manufacture Mixed Oxide (MOX) fuels for reactor power generation.

3.1 Natural Uranium Equivalent

SNC-Lavalin and its Chinese partners: the Third Qinshan Nuclear Power Company (TQNPC), the China North Nuclear Fuel Corporation (CNNFC) and the Nuclear Power Institute of China (NPIC), have developed a recycled uranium-based fuel for use in CANDU reactors: Natural Uranium Equivalent (NUE) fuel.

This groundbreaking design is a mixture of ~70% Recycled Uranium (RU) and ~30% Depleted Uranium (DU) in the standard 37-element CANDU fuel bundle. RU in the mixture contains ~ 0.85 - 0.99 wt% U-235, while DU contains ~ 0.2 - 0.3 wt% U-235. The resulting NUE fuel has a U-235 content comparable to that of NU and thus behaves similarly in the CANDU reactor.

Figure 3 CANDU Standard 37-Element Fuel Bundle

NUE fuel makes effective use of the large global stockpiles of RU, which are mostly kept in storage. Reprocessed RU stockpiles from commercial power reactors are estimated at about 90,000 tonnes with a current global fuel recycling capacity of about 4,000 tonnes per year [10].
On the other hand, DU is an under-utilized nuclear fuel resource that is derived as a by-product of nuclear fuel enrichment processes. DU world stockpiles are estimated at 1.5 million tonnes [10], which are expected to grow further as nuclear capacity increases. Although there is some commercial use of DU for shielding purposes, most of it remains in storage and is considered a waste product.

Given the availability of DU and RU, and their minor commercial applications, they are generally priced less than NU and thus significant economic benefits can be achieved.
Recycled fuels utilization in CANDU reactors reduces the burden that recycling facilities face to manage the supply of RU that would otherwise require monitored storage and/or re-enrichment and handling for its reuse in LWRs.
A partnership between SNC-Lavalin and its Chinese partners was established in 2008 to demonstrate the use of NUE fuel in the Chinese Qinshan CANDU reactors. Several technical assessments were carried out to confirm that NUE fuel implementation in CANDU reactors behaved similar to NU fuel and to support the licensing requirements to perform a demonstration irradiation of NUE fuel bundles in the Qinshan reactors.

Irradiation testing began in March of 2010, where 24 NUE fuel bundles were inserted in two channels of Qinshan Unit 1. The conventional eight-bundle refueling scheme was followed and the fuel bundles were successfully removed from the reactor in the spring of 2011. The results from the demonstration irradiation showed that NUE fuel behaved as predicted in the reactor: no defects, sheath swelling or anomalies were observed in the extracted NUE fuel bundles during inspection and no non-homogeneity issues were found during the manufacturing process.

Further confirmation of NUE fuel performance was obtained through a Post Irradiation Examination (PIE). Twelve NUE fuel elements were extracted and shipped from the reactor to NPIC's hot-cell facility. The study confirmed that NUE fuel behaved similarly to NU fuel: consistent appearance, no sheath anomalies, normal strains on pellets and ridge heights, normal element elongation, no sheath failure, similar grain sizes, no thermal hot spots, consistent sheath microstructures and consistent burnup [11].

3.2 The Advanced Fuel CANDU Reactor

Based on the success of the NUE fuel irradiation in the Qinshan CANDU reactors, SNC-Lavalin and its Chinese partners started the development of the Advanced Fuel CANDU Reactor (AFCR™), a generation III reactor design that can use recycled uranium and thorium-based fuels. The heavy water moderated, heavy water cooled AFCR is a fuel flexible evolution of the proven CANDU 6 reactor. It is designed to use advanced fuel cycles: derivatives of recycled uranium (DRU) and low enriched uranium/thorium (LEU/Th) in a 43-element CANFLEX® fuel bundle.

DRU fuel is a mixture of dysprosium (a neutron absorber), and RU with a slightly higher U-235 content than NU. The burnup of DRU fuel (10,000 MWd/tHE) is higher than that of NU (7,500MWd/tHE). CANFLEX fuel bundles are compatible with all CANDU fuel handling components and fulfil safety requirements by providing reduced fuel-element linear power and enhanced critical heat flux (CHF) compared to the standard 37-element NU fuel bundle [12]. This ensures reduced risks for commercial implementation.

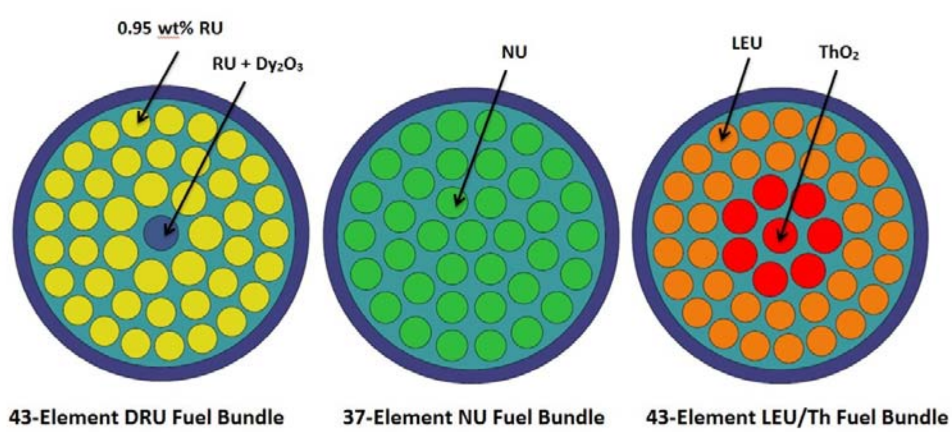

Figure 4 Comparison of AFCR and CANDU 6 fuels©

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The AFCR incorporates innovative features that enhance safety, operation and performance such as improved waste management systems, advanced control room design, significant fire protection system improvements, emergency power supply upgrades and improved buildings' robustness. Additional AFCR enhancements are also incorporated based on operational feedback, client requirements and post-Fukushima improvements [12].

Similar to NUE fuel, DRU and LEU/Th fuels reduce dependence on NU. A strategic synergy between CANDU technology and LWRs is formed through the use of recycled LWR spent fuel for manufacturing of DRU fuel. Four LWRs can fuel one AFCR, allowing improved uranium utilization and increased electricity production from otherwise unused resources.
LEU/Th fuel, on the other hand, further adds to the sustainability characteristics of the AFCR by making use of an underutilized, naturally abundant resource. Furthermore, the successful demonstration of LEU/Th can lead to more advanced applications, such as plutonium-thorium fuel, which have a larger potential for greater economic and resource utilization benefits.

DRU and LEU/Th fuels are expected to provide additional economic benefits with ~32% less costs than NU in the traditional CANDU design and ~128% less than enriched uranium in the typical Pressurized Water Reactor (PWR) [12].

For illustration purposes, if AFCRs were implemented in China in a 4:1 ratio at current capacity, uranium fuel utilization for nuclear electricity generation would increase by 20%, 2 billion MWh of additional energy would be produced from the same uranium resources each year, and 26 million tonnes of CO_2 would be displaced annually when replacing coal-fired power plants.

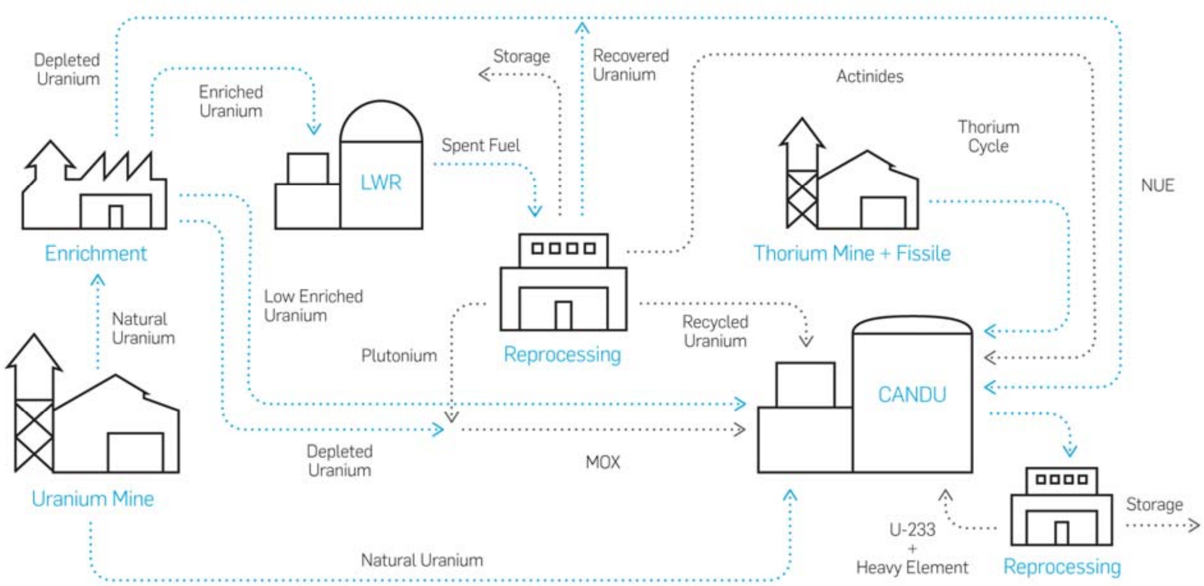

Figure 5 CANDU Fuel Cycles Map©

3.3 The CANMOX Enhanced CANDU 6 Reactor

SNC-Lavalin is developing the CANMOX™ EC6® Reactor capable of utilizing plutonium in the form of MOX fuel. This solution has been developed to address the UK's desire to dispose of their 140 tonnes of existing civil plutonium stockpiles through deployment in a nuclear reactor for electricity generation. CANMOX fuel consists of a mixture of plutonium and DU oxides in the CANFLEX 43-element fuel bundle, which is compatible with all traditional CANDU fuel handling components.

Similar to the AFCR, the CANMOX EC6 design is an incrementally upgraded generation III and post-Fukushima compliant version of the proven CANDU 6 reactor design. The utilization of plutonium stockpiles in the CANMOX EC6 reactor eliminates proliferation-related concerns, while also making use of otherwise waste products like DU.

A consortium led by SNC-Lavalin to construct 4 CANMOX EC6 units with a 2,800 MWe capacity in the UK includes the development and construction of a CANMOX Fuel Plant. The fuel plant design is led by GE-Hitachi Canada, which will be in charge of manufacturing CANMOX fuel pellets to be assembled into the CANFLEX fuel bundle.

Once again, the CANMOX design exemplifies the superior fuel flexibility of the CANDU reactor, which provides sustainable and environmentally friendly solutions for the disposition of unused resources in the near term.

3. Conclusions

The worldwide increased demand for electricity coupled with the strengthened interest in reducing global carbon emissions has created a niche position for CANDU technology to thrive.
The inherent fuel flexible characteristics of the CANDU reactor allow it to use RU, thorium and plutonium-based advanced fuels. This feature improves the sustainability of nuclear further and makes use of otherwise underutilized resources and waste products.

The availability of long-term resources for nuclear power plants is of critical importance to many countries with growing economies and shortage of domestic uranium resources. CANDU technology's superior flexible fuel utilization capabilities are thus an excellent solution that is ready for near-term implementation.

It is expected that the commercial implementation of NUE, DRU, LEU/Th and CANMOX fuels will result in improvements of associated recycling infrastructure as well as further technology advancements towards closing the fuel cycle. In this way, waste streams can be drastically reduced and strategic resource diversification attained, while generating GHG-free, reliable and economic electricity.

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4. Acknowledgments

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