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Innovations in Clean Energy Technologies: A Comprehensive Exploration of Research at the Clean Energy Technologies Research Institute, University of Regina †

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Abstract: The Clean Energy Technology Research Institute (CETRI) at the University of Regina, Canada, serves as a collaborative hub where a dynamic team of researchers, industry leaders, innovators, and educators come together to tackle the urgent challenges of climate change and the advancement of clean energy technologies. Specializing in low-carbon and carbon-free clean energy research, CETRI adopts a unique approach that encompasses feasibility studies, bench-scale and pilot-plant testing, and pre-commercial demonstrations, all consolidated under one roof. This holistic model distinguishes CETRI, fostering a diverse and inclusive environment for technical, scientific, and hands-on learning experiences. With a CAD 3.3 million pre-commercial carbon capture demonstration plant capable of capturing 1 tonne of CO_2 per day, and a feed-flexible hydrogen demonstration pilot plant producing 6 kg of hydrogen daily, CETRI emerges as a pivotal force in advancing innovative, reliable, and cost-competitive clean energy solutions, essential for a safe, prolific, and sustainable world. This paper provides a comprehensive overview of the diverse and impactful research carried out in the center, spanning various areas including decarbonization, zero-emission hydrogen technologies, carbon (CO_2) capture utilization and storage, the conversion of waste into renewable fuels and chemicals, and emerging technologies such as small modular nuclear reactors and microgrids.

Keywords: clean energy; carbon capture and utilization; hydrogen production; small modular nuclear reactors; microgrid testbed; pilot plant; zero-emission technologies

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1. Introduction

The escalating global demand for energy, coupled with ever-increasing concerns over climate change and environmental sustainability, has prompted a critical re-evaluation of our reliance on conventional energy sources [1–3]. The depletion of finite fossil fuel reserves, along with the associated greenhouse gas emissions, underscores the urgent need for a transition towards cleaner and more sustainable energy technologies [4]. This has led to a paradigm shift in the energy landscape, focusing on the development and deployment of innovative solutions that minimize environmental impact while meeting the rising energy needs of a growing world population [5]. Conventional energy sources, primarily reliant on fossil fuels such as coal, oil, and natural gas, have played a pivotal role in powering economic development over the past century. However, the deleterious consequences of these energy sources, manifested in air pollution, climate change, and geopolitical conflicts over resource access, necessitate a fundamental shift towards cleaner alternatives [6,7]. The urgent need for clean energy technologies is underscored by the alarming rise in global temperatures, extreme weather events, and the consequential impacts on ecosystems and human societies. Clean energy technologies from renewable sources such as solar, wind, hydropower, and bioenergy, offer a sustainable pathway to address these pressing challenges [8]. In this context, renewable energy sources emerge as a promising solution, providing a means to decouple economic growth from environmental degradation [9–11]. Moreover, the development and widespread adoption of clean energy technologies can foster energy security, mitigate geopolitical tensions related to resource access, and stimulate economic growth through the creation of innovative industries and job opportunities. Positioned at the forefront of innovation, reliability, and cost-competitive clean energy solutions, the Clean Energy Technology Research Institute (CETRI) plays a pivotal role in facilitating the transition toward a safe, prosperous, and sustainable world. CETRI, formerly known as the International Test Center for CO_2 Capture (ITC), is located within the greenhouse gas technology center building (Figure 1) at the University of Regina [12].

Figure 1. Greenhouse gas technology Center.

This institute serves as a nexus, bringing together a diverse and dynamic team comprising researchers, industry leaders, innovators, and educators, all dedicated to addressing the interrelated challenges of climate change and the evolution of clean energy technologies. Distinguished for its focus on low-carbon and carbon-free clean energy research, CETRI engages in multifaceted activities encompassing decarbonization, zero-emission hydrogen (H_2) technologies, carbon capture and utilization, the transformation of waste into renewable fuels and chemicals, and modular nuclear reactors and microgrids [13]. What distinguishes CETRI is its comprehensive approach to clean energy research. The institute integrates various stages, including feasibility and proof-of-concept studies, bench-scale and pilot-plant testing, process simulation and optimization, and pre-commercial demonstration, into its research framework. CETRI's commitment to addressing these global challenges positions it as a trailblazer in advancing sustainable solutions and fostering innovation within the realm of clean energy. By convening experts and resources, CETRI contributes significantly to the collective effort aimed at mitigating climate change impacts and propelling the development of cleaner and more efficient energy technologies. Implementing a research center embedded within an academic institution, proficient in orchestrating a unified hub for a myriad of diverse research activities under a single roof, is an extraordinary and seldom-achieved accomplishment. The center holds several patents related to inhibiting amine degradation during CO_2 capture from gas streams, reactive extraction processes for regenerating amine-based solvents used in carbon dioxide capture, sulfur-tolerant catalysts for hydrogen production via the carbon dioxide reforming of methane-rich gas, catalysts for hydrogen production, and methods of capturing CO_2 from streams, among others. Beyond this remarkable capacity, the center unfolds a vast spectrum of learning experiences for researchers, both present and prospective. It not only emphasizes technical and scientific pursuits but also provides hands-on learning opportunities, cultivating an environment that thrives on diversity and inclusivity. Moreover, the research institute boasts state-of-the-art laboratories and facilities that are meticulously designed and strategically leveraged to not only facilitate groundbreaking research but also extend their capabilities to provide valuable analytical services to external clients. This strategic utilization of resources not only enhances the institute's research output but also strengthens its collaborative efforts with industry partners and stakeholders, further solidifying its position as a leading center of excellence in the field.

2. Carbon Capture Utilization and Storage

In terms of carbon capture, utilization, and storage (CCUS) technology, CETRI has a CAD 3.3 million pre-commercial (indoor) carbon capture demonstration plant. Established more than two decades ago, this carbon capture demonstration plant occupies a two-storey building within the greenhouse gas technology center. This facility is equipped with a gas turbine, gas boiler, and state-of-the-art monitoring and control systems. The carbon capture demonstration plant, illustrated in Figure 2, can capture one tonne of CO_2 per day.

Figure 2. Pre-commercial carbon capture demonstration plant housed inside the greenhouse gas technology center building, which spans a two-storey building.

As depicted in Figure 2, the carbon capture plant features three absorber towers dedicated to CO_2 capture and one desorber tower responsible for regenerating the catalyst solvent. The highly effective solvent catalyst, developed and patented at CETRI laboratories, utilizes an active amine-based solvent blend. This innovative blend demonstrates remarkable efficacy in capturing CO_2 from flue gases. The solvent catalyst blends can be regenerated without requiring a substantial amount of energy. A distinctive feature of this CO_2 capture pilot plant is its utilization of hot water instead of steam, eliminating the need to divert steam or energy from the facility's primary functions. This innovative process not only decreases the cost of post-combustion capture but also lowers the energy requirements and equipment size typically associated with an amine-based CO_2 capture plant. As an exemplar of CCUS initiatives, CETRI has conducted pioneering research as part of SaskPower's Boundary Dam Carbon Capture and Storage Project. This endeavor introduced an innovative technology harnessing amine-based catalysts, which has proven pivotal in significantly reducing the energy penalty associated with carbon capture, utilization, and storage. Beyond the carbon capture demonstration pilot plant, CETRI has a diverse array of laboratory-scale carbon capture modules (see Figure 3). These modules serve as integral components of the research infrastructure, allowing for a nuanced and in-depth exploration of carbon capture technologies. The various laboratory-scale setups enable the systematic investigation of diverse capture methodologies, fostering a comprehensive understanding of their performance, efficiency, and scalability. This multifaceted approach ensures that research endeavors span from large-scale applications to intricate, controlled laboratory experiments, facilitating the development and optimization of carbon capture solutions across a spectrum of operational scales. In the realm of carbon dioxide utilization, CETRI is proactively developing intelligent methodologies to seamlessly integrate CO_2 into various industries, particularly in applications such as making concrete, chemicals, and synthetic fuels. Moreover, CETRI provides support to industries involved in coal, oil, and gas sectors, aiding them in achieving their greenhouse gas (GHG) emissions targets though carbon capture. This collaborative endeavor is geared towards bolstering sustainability and fostering the adoption of eco-friendly practices across these sectors.

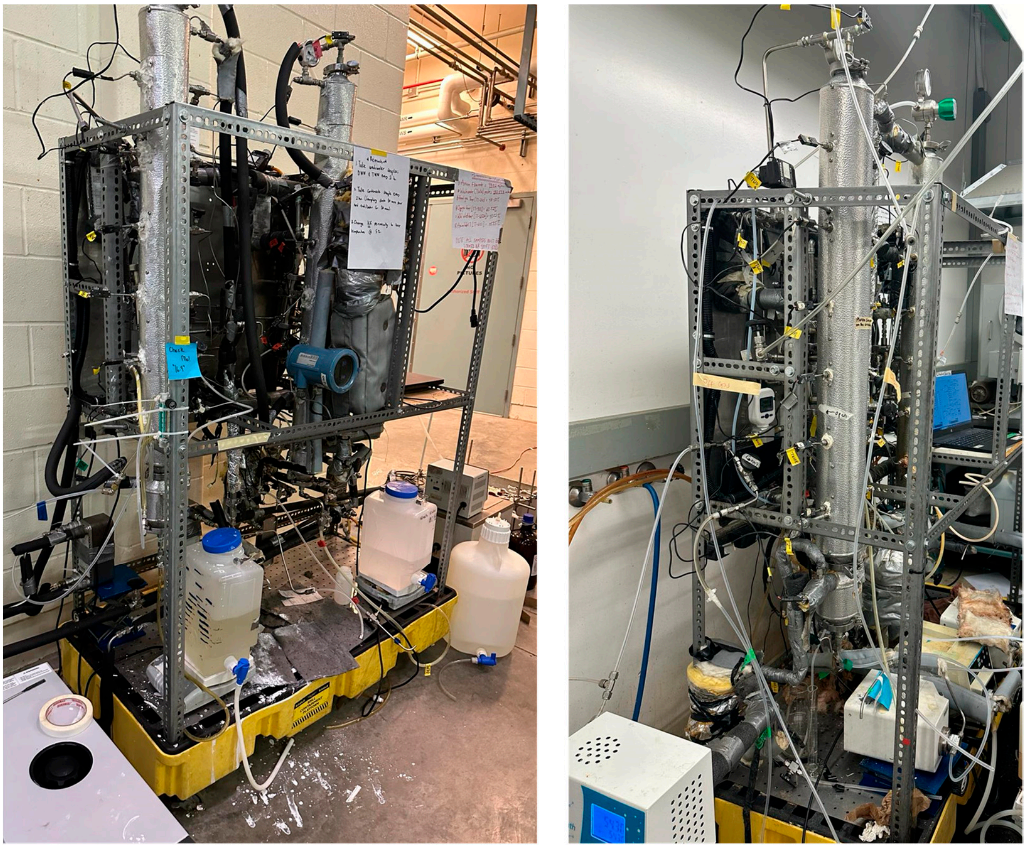

Figure 3. Photos of two laboratory-scale carbon capture modular reactors.

3. Zero-Emission Hydrogen Technologies

In addition to the CO_2 capture pilot plant, CETRI operates a well-established hydrogen demonstration pilot plant, as illustrated in Figure 4, which has been working for over two decades. The hydrogen pilot plant represents a significant investment of CAD 2.7 million from various stakeholders, including the Canadian government and provincial and federal entities, as well as industrial partners.

Figure 4. Hydrogen demonstration pilot plant. On the left is a side view of the hydrogen demonstration plant, and on the right is the front view of the hydrogen demonstration plant.

The catalyst-aided hydrogen demonstration pilot plant can produce 6 kg of hydrogen per day. A notable aspect of this hydrogen demonstration pilot plant is its feed flexibility, accommodating solid, liquid, and gas feeds. Furthermore, it offers process flexibility, allowing for the implementation of various methods to produce hydrogen. Some of the CO_2 produced as a by-product by the hydrogen plant can be recycled, while the remainder can be stored or repurposed for various applications, such as enhanced oil recovery. The hydrogen produced can be efficiently separated from the other product compositions using membrane reactors within the hydrogen demonstration pilot plant. Similar to the carbon capture pilot plant, the catalysts employed in generating blue hydrogen are both developed and patented by CETRI. These catalysts exhibit the capability to convert various feedstocks into environmentally friendly, clean-burning hydrogen. The hydrogen pilot plant currently utilizes a diverse range of feeds for hydrogen production, including biofuels, biogas, low-grade natural gas, and certain industrial biproducts. The utilization of renewable bioenergy sources for producing clean blue hydrogen, in conjunction with carbon capture and storage, presents a promising pathway towards achieving Canada's goal of reaching net-zero emissions by 2050. The Clean Energy Technologies Research Institute at the University of Regina offers the necessary expertise and infrastructure to support these initiatives. In addition to the hydrogen demonstration pilot plant, CETRI has laboratory-scale packed-bed reactors (see Figure 5) that play a pivotal role in the advancement of hydrogen generation, particularly through processes like water gas shift reactions and various reforming processes. These catalysts are intricately crafted to enable the conversion of various hydrocarbons through techniques such as dry reforming, steam reforming, and autothermal reforming, ultimately resulting in hydrogen production. Leveraging these versatile catalytic reactions within packed-bed reactors, researchers can investigate efficient pathways for sustainable hydrogen production, thereby making significant contributions to the advancement of clean energy technologies.

Figure 5. Laboratory-scale packed-bed reactors employed in the generation of hydrogen from different hydrocarbons.

4. Energy from Waste

In tandem with its focus on CCUS and zero-emission hydrogen technologies, CETRI is deeply engaged in research and development initiatives aimed at unleashing the potential of agricultural, forestry, and municipal solid waste. Simultaneously, the institute is actively exploring the efficient utilization of plastic waste to propel sustainable energy solutions forward. These multifaceted initiatives encompass the exploration of cutting-edge technologies and processes aimed at converting a wide range of waste streams into valuable resources, including energy, fuels, and chemicals. CETRI researchers concentrate on extracting the organic content from agricultural and forestry residues, as well as leveraging the varied components within municipal solid waste, with a clear objective of developing methods that are both highly efficient and environmentally friendly. Moreover, by addressing the challenge of plastic waste through advanced recycling technologies, CETRI contributes significantly to the principles of the circular economy. These comprehensive efforts not only alleviate the environmental impact of waste but also play a pivotal role in diversifying energy sources and reducing dependence on traditional fossil fuels. The ongoing research underscores CETRI's commitment to addressing waste management challenges, paving the way for a future marked by sustainability and resource efficiency. Moreover, CETRI plays an active role in advancing process development capabilities for a diverse range of products, including bioethanol, renewable diesel, methanol, hydrogen, and carbon black, as well as various commodity and specialty items.

5. Emerging Technologies: Modular Nuclear Reactors and Microgrids

The research performed at CETRI centers on the safety and licensing of small modular reactors. The primary focus is on addressing challenges related to the corrosion or corrosiveness of nuclear fuel proposed for use in various small designs. In one area of concentration, the research investigates the corrosion and hydrogen absorption of accident-tolerant fuel (ATF) cladding materials. ATF cladding, designed to be more corrosion-resistant than standard Zr-based cladding, plays a crucial role in providing valuable time during severe accident scenarios, such as those encountered during incidents like Fukushima. In order to carry out these studies, CITRI is equipped with a high-temperature tube furnace capable of simulating the high-temperature steam conditions prevalent in severe accidents. Additionally, a custom pressure vessel has been developed to allow neutron reflectometry (NR) measurements while exposing a sample to the pressurized water environment present during reactor operations. Another area of focus is the corrosion mitigation of steel and nickel alloys in molten salts for use in molten salt reactors (MSRs). MSRs, a broad class of small modular reactor designs, can achieve higher temperatures than traditional water-cooled designs, necessitating the development of corrosion mitigation strategies. The dedicated radioactive substances lab at CETRI features a glovebox with reactor wells designed for molten salt experiments, along with a Raman microscope equipped with a fiber-optic probe for measuring the conditions of the molten salt during the experiment. This glovebox is versatile, accommodating other air-sensitive materials and fluids, such as molten sodium-containing heat pipes. The third focus area is the incorporation of small modular reactor waste into Canada's broader radioactive waste strategy. Canada's plan for the long-term management of used CANDU fuel is to place it in an engineered barrier system within a deep geological repository (DGR). However, many small modular reactor designs will generate used fuel and other waste streams differently from Canada's current CANDU fleet, which requires research into how the waste and the materials that will store them will behave in a simulated DGR environment. This focus area involves the operation of multiple electrochemical workstations and equipment for synthesizing new simulated radioactive wasteforms for testing.

Furthermore, CETRI researchers at the University of Regina secured CAD 976,000 from PrairiesCan through their Regional Innovation Ecosystems Program to establish a microgrid research lab and testbed. The funding spans fiscal years 2022–2023 and 2023–2024, with the project concluding in March 2025. Collaborating with Siemens Canada Ltd., the University of Regina successfully developed a research-based microgrid lab featuring a variety of energy assets, including photovoltaic generation, grid-compliant battery storage, loads, and a control center. The system was successfully commissioned in December 2023.

6. Summary

The present work outlines the comprehensive research and development initiatives of the Clean Energy Technology Research Institute (CETRI) across various clean energy domains. In carbon capture utilization and storage (CCUS), CETRI operates a CAD 3.3 million pre-commercial carbon capture demonstration plant, showcasing innovative technologies, such as amine-based solvent blends, that significantly reduce the energy penalty associated with CCUS. The institute's laboratory-scale carbon capture modules further facilitate a nuanced exploration of diverse methodologies for large-scale applications. In the realm of zero-emission hydrogen technologies, CETRI manages a well-established hydrogen demonstration pilot plant, which is both feed- and process-flexible. This plant, operational for over two decades, aligns with Canada's net-zero emissions goal and contributes to renewable bioenergy sources. The institute actively develops and patents catalysts for generating clean-burning hydrogen. Furthermore, CETRI is actively engaged in Energy from Waste initiatives, exploring the potential of agricultural, forestry, municipal solid waste, and plastic waste for sustainable energy solutions. Researchers focus on developing environmentally friendly methods for extracting organic content from residues and utilizing advanced recycling technologies, contributing to the circular economy and diversifying energy sources. Finally, this work discusses CETRI's involvement in emerging technologies, particularly in small modular nuclear reactors and microgrids. It focuses on the safety and licensing of small modular reactors, particularly addressing corrosion challenges in nuclear fuel for various small modular reactor designs. Research includes ATF cladding's corrosion and hydrogen absorption, crucial for severe accidents. Furthermore, with CAD 976,000 funding and collaboration with Siemens, a microgrid lab featuring diverse energy assets, was successfully commissioned in December 2023. Overall, CETRI's multi-faceted efforts underscore a commitment to sustainability, resource efficiency, and innovative solutions in the clean energy landscape.

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