The Clean Energy Research Centre (CERC)

Xiaotao (Tony) Bi* and Junnan Chao

Clean Energy Research Centre, University of British Columbia, 2360 East Mall, Vancouver, Canada, V6T 1Z3

*Corresponding author. E-mail: tonybi@mail.ubc.ca

Graphical Abstract

Introduction

The Clean Energy Research Centre (CERC) is a multidisciplinary research hub dedicated to undertaking world-class clean-energy research, training, development and demonstrations. Our ‘future today’ research adds to the outstanding research endeavours and sterling reputation of the University of British Columbia (UBC) within Canada and globally. Our goal is to become a world leader and a research–development–demonstration powerhouse for innovative clean-energy solutions to climate change and sustainability problems.

1 History of the centre

CERC was officially opened in 2006 with the completion of a new 400-square-metre research laboratory with an investment in $9 million worth of state-of-the-art research equipment. It is supported by the Canada Foundation for Innovation (CFI) and the British Columbia Knowledge Development Fund (BCKDF). Initially, CERC primarily involved researchers from the Departments of Chemical and Biological Engineering and Mechanical Engineering, with participation from Materials Engineering and Electrical and Computing Engineering researchers. CERC has since expanded its membership to include a broader range of disciplines within Applied Science. Its faculties and schools are active in energy research at UBC Vancouver and UBC Okanagan. Currently, there are >70 faculty members and 200 graduate students participating actively in CERC activities. CERC welcomes collaboration with partners from industry, academic institutions and various levels of government, both inside and outside of Canada.
2 Research themes

Providing safe, widespread and equitable access to sustainable energy is one of the key challenges of our time. CERC hosts top-tier researchers who view this challenge as an opportunity to help future generations to inherit a better world. The specialty areas of CERC researchers are clustered within six main research themes, as shown in Fig. 1.

2.1 Bioenergy systems and biorefinery

There are an estimated 30 million tonnes of forest residues available each year in British Columbia (BC), which can be converted to high-value biofuels or biochemicals. To support a bioenergy and bioproduct sector in the province and in Canada, the ’Bioenergy systems and biorefinery’ theme was established in CERC to focus on:

- Research, development, scale-up, demonstration and deployment of key clean technologies (e.g. gasification, torrefaction, pyrolysis, fermentation, methanation, etc.) for the production of renewable bioenergy and biofuels from forest, agricultural and municipal biomass wastes via thermochemical and biological routes.
- Promotion of joint research, innovation, development and demonstration of bioenergy products and technologies with partners from industry and academia worldwide.

Novel technologies have been developed and demonstrated in recent years for the production of low-carbon renewable biofuels and bioproducts. These include a dual fluidized-bed gasifier for biomass steam gasification and a two-stage fluidized-bed gasifier for biomass oxygen-steam gasification for the production of syngas and renewable natural gas that is created from forest residues. CERC also has a microwave-assisted pulsed fluidized bed for the catalytic pyrolysis of biomass residues for high-quality bio-oil and biochar production. Programmes, such as the China-Canada Bioenergy Centre, BC-SMART Consortium and the Natural Gas and renewable natural gas that is created from forest residues. programs, such as the China-Canada Bioenergy Centre, BC-SMART Consortium and the Natural Gas and renewable natural gas that is created from forest residues. With strong support from the Canadian government and industry, the ’Electro- and photo-chemical energy system’ theme is committed to overcoming both short- and long-term challenges associated with these systems. Although photo- and electro-chemical systems can provide cleaner and sustainable energy solutions, the engineering challenges and the costs associated with these systems prevent them from entering the market in a profitable form. With the recent development in the cost-effective production of solar-cells technology as well as the optimization of battery and electrolyser operations, it is possible that these renewable-energy systems will replace conventional fossil-fuel-based energy systems soon.

The electro- and photochemical energy systems provide efficient ways of harvesting energy from the renewables (sun and wind) and storing the energy to resolve intermittency supply issues (batteries) as well as transforming the energy for household and portable energy applications, and for generating useful chemicals or fuels (green H2, etc.). At CERC, our research aims at addressing universal problems. Our research team is involved in discovering advanced photo and electroactive materials, designing new devices and systems, and developing mathematical models to predict the real-time scenarios utilizing tools that range from computational to experimental.

2.3 Urban energy systems: transportation/buildings

Transportation connects communities and supports Canada’s economy. It facilitates the distribution of trillions of dollars in goods each year in Canada alone. To continue supporting the movement of goods across a vast country like Canada, cutting-edge solutions must be developed to increase trade. The transportation sector must also innovate to mitigate its environmental impact.

The ’Urban energy systems: Transportation/buildings’ theme is at the forefront of this transformation. Its focus is on solutions at every level, from a provincial level down to the performance of an engine cylinder in a vehicle. It will attain these goals by working on:

- Developing strategies that decarbonize long-distance transportation to reduce province-wide emissions.
- Investigating the feasibility of mobile energy hubs by using electric vehicles as energy-storage systems to stabilize the electric grid in urban communities.
- Developing new ways to measure emissions more accurately in marine vessels that use natural gas and developing strategies to mitigate the emissions.
- Creating a portable emissions measurement system to understand the real-world emissions of a semi-truck that uses diesel and hydrogen co-combustion.
- Developing optical sensors that help to characterize the in-cylinder combustion properties in novel fuel systems that inject natural gas directly into the engine cylinder.

2.4 Carbon capture and decarbonization of energy systems

Worldwide climate-action plans are focusing on keeping the global temperature rise to ≤2°C. This requires bold actions to reduce...
The current research under this theme demonstrates a commitment with an intense awareness of market and policy implications. There are tremendous opportunities for technological innovation. The ‘Carbon capture and decarbonization of energy systems’ theme conducts future-focused research on CO2 capture, storage and conversion coupled with an intense awareness of market and policy implications.

The current research under this theme demonstrates a commitment to:

- Build a set of tools for integrative policy towards decarbonizing Canada’s maritime shipping industry
- Use liquid heterogeneous catalysts to enable the production of fuels and chemicals without producing carbon dioxide.
- Reduce GHG emissions by turning solid waste into energy and fertilizers in BC’s Lower Mainland.
- Create a smart, personalized carbon dashboard to visually connect a carbon footprint to climate-positive actions.
- Develop combustors of gas turbine engines that can burn a cleaner fuel—hydrogen-enriched natural gas.
- Educate and grow the carbon capture, conversion and sequestration sectors.

2.5 Data analytics and optimization

The influence of data science in the clean-energy sector continues to expand with major algorithmic developments in machine learning, relentless growth in computing power, advancements in sensor technology and Internet of Things capabilities. However, in most manufacturing sites, ‘mountains’ of industrial data are often underutilized when they are actually ripe for value extraction. These incredible volumes of data, when combined with expert domain knowledge and advanced analytics capabilities, are poised to produce valuable insights never before realized in the clean-energy sector. Facing these challenges and opportunities, research under the ‘Data analytics and optimization’ theme focuses on:

- Using advanced analytics for extracting and exploiting knowledge from large, complex, heterogeneous energy data sets including time series, images and text documents.
- Building sophisticated predictive models and answering complex energy questions using causal inference and machine learning.
- Developing optimization tools to help organizations to manage energy assets and improve decision-making through data-driven insights.

2.6 Policy analyses of clean-energy systems

The United Nation’s Sustainable Development Goal 7 focuses on affordable and clean energy. This includes ensuring access to affordable and sustainable energy for all. In recent decades, there has been a rapid transition to clean and renewable energy. While technological innovation has been at the heart of this transition, policies enabling easy access, continued adoption and affordability are essential.

The CERC ‘Policy analysis for clean energy’ theme is an interdisciplinary group that conducts leading research on public policy, energy security, sustainable energy systems and technological innovation. There are also tremendous opportunities for policy-driven, just and equitable transition to clean energy.

3 Key technologies

3.1 Steam-oxygen two-stage fluidized-bed biomass gasification

Biomass gasification is a high-temperature thermal chemical process converting biomass residues to bio-syngas for the production of power, biohydrogen, biofuels and biochemicals. The quality of the syngas is crucial for the downstream conversion. Low-tar syngas is required for successful combined heat and power (CHP) generation. N₂-free and tar-free syngas is needed for the production of biohydrogen, biomethane and liquid biofuels/chemicals.

To meet those requirements, a novel steam-oxygen two-stage fluidized-bed gasification technology has been explored.

In the two-stage gasification system (Fig. 2), by applying a bubbling fluidized-bed pyrolyser (Stage 1) before the circulating fluidized-bed riser gasifier (Stage 2), the heavy hydrocarbons (tar) are mostly released in the gas phase in the first stage prior to entering the riser. It significantly extends their time in the system and, consequently, allows most of the tar content to be cracked in the dense phase and the freeboard of the riser, which greatly lowers the tar concentration in the gas product.

The air-blown version of this technology has been demonstrated by CERC’s partner, the Chinese Academy of Sciences, on a 10-kt/a Chinese herb-residue treatment demonstration plant for >2 years. The operation results showed that for feedstock containing high moisture and volatile contents, the tar concentration in the gas product could be controlled at <50 mg/Nm³.

A new pilot unit has been designed and commissioned at CERC (Fig. 3) to evaluate the performance using steam and oxygen as gasification agents to reduce N₂ content in the bio-syngas. This research is supported financially by Western Economic Diversification Canada (WD), Nature Resources Canada’s Clean Growth programme and BC Bioalliance, a BC pulp and paper industrial consortium. The low-tar and low-N₂ high-heating-value syngas will be a promising alternative to natural gas for CHPs and lime kilns, and an ideal feedstock for the production of renewable natural gas (RNG) to meet the 15% RNG blending target of BC by 2030.

3.2 Microwave-assisted fluidized-bed catalytic pyrolysis

Pyrolysis is a promising pathway for converting biomass residues to biofuels (diesel and jet fuel) and biochemicals (e.g. carbon, alcohol). The low quality of bio-oil and biochar, however, imposes challenges to upgrading and application.

To improve the quality of bio-oil and biochar, researchers at CERC, since 2010, have been exploring the in situ catalytic pyrolysis incorporated with microwave heating in a bench microwave reactor system. Microwave-assisted fluidized-bed catalytic pyrolysis (MACP) technology has been developed by integrating microwave heating, in situ catalysis and horizontal gas-pulsating fluidization technologies. As well, a pilot-scale unit (Fig. 4), sponsored by CFI, has been built up in the Biorefinery Research and Innovation Centre (BRIC), which is a new research and demonstration facility of CERC funded by CFI, BCKDF (BC Knowledge Development Fund) and WD.

In the MACP reactor, in situ microwave-assisted catalytic cracking of organic vapours on a hot catalyst surface improves bio-oil quality significantly, as is reflected by low oxygen content, low acidity and viscosity. The unique internal microwave heating of biomass particles also results in a very porous structure of biochar particles and thus a high specific surface area, which in conjunction with remaining natural catalysts as nutrients serves...
as a high-value carbon-based fertilizer with high water- and nutrient-holding capacity.

3.3 Torrefaction in a pulsed fluidized bed with heat recovery

Torrefaction is a promising approach to improve the quality of biomass pellets. Due to its high heating value and hydrophobicity, torrefied pellets have been considered as a premium substitute fuel for existing coal-fired power plants to meet the GHG-emission-reduction targets. However, nowadays, dedicated high-efficiency and scalable reactors tailored for torrefaction are still not available.

With CERC researchers’ extensive knowledge of fluidization, a novel fluidized-bed process with a pulsed gas flow has been developed for torrefaction over recent years. The novel process is able to take full advantage of the fast heat and mass transfer rate of fluidized beds to shorten the reaction time, thus reducing the reactor volume and improving the heating efficiency. The optimized pulsation enables the system to achieve good fluidization quality with irregular sawdust particles. A horizontal shallow fluidized-bed design is implemented to allow uniform product quality, which has always been a challenge for conventional fluidized-bed systems.

A small pilot horizontal pulsed fluidized-bed reactor has been developed for continuous sawdust torrefaction at a biomass feed rate of 1–4 kg/hr (Fig. 5). A fixed-bed catalytic reactor was included to combust the volatiles released from the torrefaction reaction. The effects of operating conditions on solids mixing and torrefied sawdust properties were investigated. The prototype unit successfully produced sufficient torrefied biomass materials for making torrefied pellets in a continuous pelleting machine. Solids back mixing was significantly lower in the reactor compared to that in the conventional fluidized beds.

3.4 ‘Mangrove’ technology

It is recognized by the global community that water shortages and climate change are two of the biggest challenges for this century. Solutions for the sustainable use of water, and to reduce CO2 and other GHG emissions are urgently needed. Wastewater treatment and the reduction of CO2 emissions have long been a challenge for the oil and gas industry. In the past, however, they were always seen as two separate problems.

The process begins with gas-phase CO2, which is fed into an electrochemical cell along with wastewater contaminated by salt or other dissolved solids. An electrochemical process then simultaneously converts the CO2 and separates the salts present in the brine. The result is a series of high-value chemicals that can be used on the industrial site, sold or used to create other chemical products. This technology can directly process industrial CO2 and, as a bonus, other pollutants in the gas such as SOx and NOx can also be handled. Instead of adding costs to the industry, Mangrove’s innovative approach is able to use CO2 to turn waste gases and saline water into valuable chemicals and to also reduce water use in oil and gas operations. Over the past few years, Mangrove’s electrochemical process has been further designed to produce lithium hydroxide from all lithium sources, including...
brine, hard rock and clay. This not only removes the geographical constraints for the lithium hydroxide production, but also significantly lowers the production cost.

It is estimated that there will be an annual market of $450 million for this technology across the oil sands mining industry, with a GHG reduction potential of 1.4 million tonnes of carbon dioxide equivalent (CO₂-eq) per year by 2030.

Since 2013, a $15 million grant and investor funding have been received to support the development of the technology. Between 2016 and 2018, the Mangrove team broadened out from UBC as Mangrove Water Technologies Ltd. Over the past few years, one lab-scale and two commercial-scale demonstrations were completed by the team, and the first commercial module was designed and built in 2020.

3.5 Fluidized membrane reactor technology (MRT)
Canada’s hydrogen demand for upgrading fuel cells, ammonia production and other chemical purposes is growing rapidly. However, there are many challenges in hydrogen production from methane reforming with high-temperature fixed-bed catalyst tubes. There is, for example, a need for expensive metal alloys to withstand high temperature, large catalyst particle size for minimizing pressure drop, carbon formation, catalyst deactivation and limited chemical conversion due to thermodynamic equilibrium. To overcome these disadvantages, novel fluidized-bed membrane reactor (FBMR) technology was developed. The FBMR incorporates perm-selective membranes for in situ removal of pure hydrogen from the reactor, thus shifting the equilibrium of reversible reforming reactions forward. This improves methane conversion and hydrogen yield as well as allowing the reactor to be operated at a lower temperature (~600°C). Besides, technologies have also been developed for depositing Pd and Ru on porous stainless-steel disks and tubular ceramic supports to form a thin pinhole-free Pd–Ru composite membrane. These membranes show excellent hydrogen flux, >99.9% hydrogen purity and higher thermal stability. The FBMR reactor technology was demonstrated by MRT, a UBC spin-off company to facilitate high-purity hydrogen production for fuel-cell applications. The current research is focused on how to improve the durability of the membrane tubes with thinner-coated metal films.

3.6 CO₂ redox flow battery for large-scale energy storage
For >200 years, starting with Volta’s pile, most battery innovations have focused on diverse metals or metallic species. Due to the unprecedented growth in battery demand for diverse applications (electronics, mobility and grid-scale energy storage all dominated presently by a single technology: Li-ion), there are increasing challenges regarding the supply chain and prices of metals used in batteries. In order to tackle these challenges, a novel class of non-metal flow batteries, the CO₂ redox flow battery (CRB), has been developed. It is now patented globally in 52 countries. The idea behind this battery is to combine energy storage and CO₂ utilization in one device. The fundamental principles, first-generation catalysts and results with gas-diffusion electrodes in batch mode of operation were published in J Power Sources 495 (2021) 229752.

The CRB at the negative electrode in the charging stage consumes...
CO₂ (e.g. captured from industrial emission sources such as cement, petrochemical, coal power generation, waste incineration, etc.) to produce a formate salt (e.g. HCOONa) solution. In the discharge stage (i.e. power generation), the formate salt is oxidized to produce a carbonate solution (e.g. Na₂CO₃). Thus, the battery acts as a net CO₂ sink, leading to the mineralization of CO₂. As a rule of thumb, 1 tonne of CO₂ consumed could provide ≤1.6 MWh of energy. At the positive electrode, in the present form, the Br₂/Br⁻ redox couple is used. The battery open circuit voltage is 1.6 V and peak power densities of ≤120 mW cm⁻² have been obtained thus far, with research continuing at a fast pace. The CRB technology has been recognized by a number of major competitive awards including the Keeling Curve Prize for 2021 and the NRC Impact Canada Charging the Future.

3.7 Novel wavelength-modulated spectroscopy (WMS) methane sensor

Gaseous fuels for internal combustion engines provide a route to the decarbonization of applications that are not suitable for electrification in the near term. This includes large energy consumers with high duty cycles such as marine engines and heavy-duty trucks. RNG and other bio-derived gaseous fuels are suitable for these applications. However, such renewable gaseous fuels often contain significant amounts of methane, which has a very high global-warming potential and requires unique combustion strategies to ensure complete combustion to prevent methane emissions. The Thermochemical Energy Conversion Laboratory at the UBC Clean Energy Research Centre has developed a WMS methane sensor, which is suitable for measuring the methane concentration in the raw exhaust of in-use internal combustion engines. Relative to existing technologies, the WMS methane sensor is portable, significantly less expensive than commercial options, highly specific to methane and demonstrates a low signal drift. The WMS sensor is based on tunable laser diode (1651 nm) ex situ absorption measurement. The WMS sensor has been implemented on a liquefied natural-gas-fuelled marine vessel to quantify the methane emissions under real-world operating conditions and to develop GHG-mitigation strategies. Under typical operations, methane emissions were observed to increase at lower engine loads due to the lean air-fuel ratio. To mitigate these emissions, a combination of technical measures (cylinder deactivation) and operational measures (optimal load scheduling, implementation of shore power) were implemented. These measures resulted in a >60% reduction in GHG emissions—the equivalent GHG emissions of ~750 cars per year of vessel operation. This research demonstrates the need for in-use characterization of low-carbon strategies, as well as the potential for GHG reduction through optimal operation.

4 Key programmes

CERC researchers have created and led several programmes and networks nationally and internationally to bring government, industry and academia together for collaborative efforts to develop, demonstrate and deploy clean-energy technologies.

4.1 China-Canada Bioenergy Centre (C-CBC)

C-CBC is jointly initiated and hosted by the UBC in Canada and Beijing University of Chemical Technology in China. It is a platform to foster bioenergy technology R&D, demonstration and commercialization in both Canada and China. Its work covers all of the major areas in the bioenergy field: biomass feedstock logistics and pretreatment; thermal chemical and biological conversion to produce bioenergy, bioenergy and biofuels upgrading; and biomass and bioenergy utilization. Since its opening in August 2015 (Fig. 6), C-CBC has recruited 41 partner organizations including academic institutions, not-for-profit organizations and companies. It has 77 faculty/researcher members from the two countries and has hosted dozens of postdoctoral fellows, visiting scholars and visiting students from member universities.

Over the past 6 years, C-CBC members have been awarded significant research grants from provincial and federal programmes in both countries. Major achievements include but are not limited to the construction of the BRIC at UBC, a 250-m² pilot test facility funded by the CFI in 2017. The project on synthesis gas and RNG production from forest residues, mainly funded by the WD and Natural Resource Canada (NRCan) Clean Growth Program, is making good progress.

C-CBC has also co-organized a number of international conferences on bioenergy, such as the 6th Asia-Pacific Forum on Renewable Energy (AFORE 2016), the 6th International Conference on Biomass Energy (ICBE 2018) in October 2018 and the 2nd International Conference on Sustainable Biofuels with Mission Innovation in April 2019. It also initiated and led the
Bioenergy Dialogue of the Canada-China Track II Energy Dialogue and hosted the first meeting in Beijing in January 2019.

Bioenergy plays a pivotal role in energy transition and GHG mitigation. Its research, development and deployment will remain a high priority for Canada and China to reach carbon-neutral targets in 2050 and 2060, respectively. Therefore, the collaboration between Canada and China on bioenergy should be further strengthened.

4.2 BC-SMART biofuels consortium

The origins of the BC-SMART initiative (Fig. 7) date back to 2012 when studies by the International Energy Agency Bioenergy Task 39 working group recognized the potential of drop-in biofuels. After further work, the Task 39 group published its report in 2014 identifying the opportunities and challenges of drop-in biofuels along with recommendations to enhance their commercial viability.

The BC-SMART initiative was officially launched in 2017 under the auspices of the BC Ministry of Energy, Mines and Petroleum Resources with the goal of developing a roadmap to decarbonize transportation fuels, in particular fuel for the long-distance sectors. The consortium is co-chaired by senior government and industry representatives supported by a jointly funded secretariat led by Prof. Jack Saddler, an outstanding scientist of CERC and a former dean of Forestry Faculty.

BC-SMART drives coalition building and information sharing to explore technology development and deployment (hardware) and policy tools (software) to encourage the production and use of low-carbon fuels as sustainable, affordable and commercially viable solutions to decarbonize long-distance transport.

The key values of BC-SMART:

- Provides a vehicle for committed industry, government and academic institutions and organizations to contribute to BC’s decarbonizing efforts.
- Establishes an action plan with clear goals and timelines that support the goals of the Clean BC Plan.
- Identifies the funding required to develop a co-processing strategy at BC’s refineries while encouraging the supply of bio-based feedstocks/intermediates.
- Establishes robust low-carbon fuel-supply chains for the marine, aviation, rail and trucking sectors.

4.3 The BRIC

The BRIC opened its door at the UBC in the autumn of 2021 (Fig. 8). The centre is a research and demonstration facility aimed at accelerating the development of low-carbon, market-ready bioenergy products and carbon-negative energy systems. The $8 million BRIC project is supported by the CFI, the BC Knowledge Development Fund, WD and the UBC Faculty of Applied Science.

Companies are invited to take a leadership position by developing novel prototypes and market-ready bioproducts that are more cost-effective and environmentally sustainable than their fossil-based counterparts.
Building on work conducted at CERC over the past 15 years, the BRIC will bring together top academic researchers and industry partners to create leading-edge technologies that could significantly reduce our reliance on carbon-intensive fossil fuels.

### 4.4 Transportation Futures

Transportation Futures is a multidisciplinary research project hosted by UBC led by Dr Walter Mérida, the previous CERC director, which supports research and innovation in transportation. The project started in 2014 supported by the Pacific Institute for Climate Solutions. The original goal of the project is to investigate big-picture technology pathways for reducing BC’s transport GHG emissions alongside social readiness and market support for changing transportation systems.

This project identifies the expansion potential in BC for low-to-zero carbon, renewable-energy use and generation within the transport sector that includes public transit, personal vehicles and commercial freight. The project has three themes:

- **Theme 1:** Consumer behaviour and response to zero-emission vehicles.
- **Theme 2:** Deployment strategies for charging infrastructure and hydrogen refuelling stations.
- **Theme 3:** Electrification (from bicycles to buses).

Over the years, the Transportation Futures cluster has expanded to different universities and has received support from industry and both the provincial and federal governments. In 2018, the cluster was awarded $11 million by the CFI. The research spans from energy, to policy, to the impacts on health and well-being. The Transportation Future’s research team utilizes UBC’s city-scale test bed for clean, safe and connected transportation.

### 5 Education

Beyond science and technology, CERC also sees educating next-generation researchers as key to the sustainable development of the clean-energy research community.

Besides the regular research master’s and Ph.D. students, CERC launched the first Master of Engineering in Clean Energy Engineering (CEEN) programme in Canada in 2009. This professional 1-year programme is designed for qualified engineering graduates and selected science graduates seeking training in engineering science, and in management and leadership in clean energy. The CEEN programme has trained >200 clean-energy specialists and most of them are playing leading roles in both the Canadian clean-energy sector and in government organizations in promoting clean-energy deployment and improving energy efficiency. CEEN is now part of the UBC Master of Engineering Leadership programme.

CERC also hosts monthly research seminars with invited speakers around the world to provide a global outlook on clean energy to our researchers and students.

### 6 Perspective

As a Canada-based multidisciplinary research hub for clean energy, CERC always considered supporting Canada’s energy transition to meet its 2030 and 2050 GHG-mitigation targets as its top priority. The current research undertaken by the CERC researchers spans all aspects of GHG-mitigation areas from clean and renewable-energy development to emissions control.

#### 6.1 Clean and renewable energy generation

Clean and renewable alternatives for fossil fuels have always been considered essential for reducing GHG emissions. At CERC, extensive work has been done on technology development on converting abundant biomass waste in BC to renewable energy and biofuels and exploitation of the potential biomass as a carbon-neutral or carbon-negative energy source. Currently, developments of novel technologies such as biomass gasification, torrefaction, pyrolysis, fermentation and methanation are in progress. They show promising results from various demonstration projects. Besides, the world-leading researchers at CERC on electro- and photochemical systems for renewable-energy
storage and transformation offer promising options as zero-carbon-emission energy systems.

6.2 Transportation and power-grid optimization
Carbon emission from the transportation sector accounts for more than a quarter of the total GHG emissions in Canada. The researchers at CERC span all aspects of the transportation sector, from technology development to policy analysis, aiming to bring viable, cost-effective solutions to the market. Some of those researchers even go beyond the transportation sector. One recent innovative project at CERC designed a system that combined urban transportation with power-grid optimization. A new concept for mobile energy hubs (MEHs) was proposed in which parked and plugged-in electric vehicles are used as power banks that can transfer energy back to the electric grid to help balance peak loads and integrate renewable energy. The deployment of MEHs could significantly lower the peak demand of the power grid, consequently lowering GHG emissions from the peak power generation. The feasibility of the MEHs is now being carefully studied by CERC researchers.

6.3 Carbon capture, storage and utilization (CCSU)
Compared with clean-energy production and utilization, CCSU is also important for achieving carbon neutrality. At CERC, technologies like pre- and post-combustion CO₂ capturing with solid sorbents and CO₂ capture from chemical looping combustion, as well as carbon sequestration with biochar, are being investigated for further decarbonizing the energy system. Besides, to offset the current high bioenergy production cost to make it economically viable, studies on a variety of value-added carbon-utilization options are being examined. This includes electrochemical conversion of CO₂ for the production of valuable chemicals and fuels, co-polymerization of CO₂ as well as utilizing a biochar by-product as a high-value carbon material, benefitting agricultural and forest soil, and the remediation of heavy-metal and pollutant-contaminated mining-site soil and water.

The ‘Carbon negative energy system’ (CNES) research cluster is currently under development in CERC. The cluster aims to bring together the expertise of many disciplines at UBC for research and the development of novel conversion technologies embedded with carbon and carbon-dioxide capture, utilization and storage (BECCUS). By leveraging our existing industrial partnerships and networks, extensive environmental, techno-economic and policy analyses are also conducted to quantify the potential carbon negativity of the energy system. The ultimate goal of the cluster is to help to provide technically feasible and economically viable CNES pathways to achieve deep GHG reduction in BC and Canada to meet the 2030 and 2050 GHG targets.