

WISE

Waterloo
Institute for
Sustainable
Energy

2022-2023

Annual Report



UNIVERSITY OF
WATERLOO



WISE
WATERLOO INSTITUTE
FOR SUSTAINABLE ENERGY

Waterloo Institute for Sustainable Energy





IMPROVE
conventional
generation methods



DELIVER
energy more
intelligently

VISION

Energy challenges command our world's attention. A healthy energy system requires balance amongst energy resources we know and those we have yet to bring to fruition.

Building a globally sustainable energy future requires us to rethink and then re-fashion the way we produce and use energy. In this critical endeavor, we wish to engage emerging science and technologies to unlock the previously unimagined pathways for the evolution of the energy system. At WISE, we focus on integration of social, environmental and economic innovation that can enable rapid diffusion of transformative technologies.

OUR VISION: CLEAN ENERGY, ACCESSIBLE AND AFFORDABLE FOR ALL



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MISSION

Conduct original research and develop innovative solutions and policies to help transform the energy system for long-term sustainability.

STRATEGIC OBJECTIVES



COLLABORATE

Expand opportunities for multi-disciplinary energy research at Waterloo, improve research productivity – share facilities and resources and develop HQP through research and education.



REACH OUT

Promote engagement of external partners and advance energy research through partnerships and greater access to research funding.



INFLUENCE

Establish WISE as the authoritative source of energy insights and analysis, and translate important scientific discoveries for a wide audience, informing energy policy both here and around the globe.



A NOTE FROM THE EXECUTIVE DIRECTOR

Our efforts have been dedicated to support our members' R&D activities in advancing clean and sustainable energy solutions. As an institute, one of our main goals is to promote industry-academic-government collaborations regarding the adoption of appropriate net-zero technologies, use of energy-efficient innovations, and development of sustainable communities and infrastructure. Our focus is to catalyze new partnerships that will unlock solutions for comprehensive impact and provide a more holistic approach to achieving the United Nation's Sustainable Development Goals (UNSDGs) in Canada and elsewhere.

We have organized several relevant workshops with significant multisector participation and supported various research initiatives and partnerships to harmonize pathways towards a low-carbon energy future, including the Sustainable Futures Initiative (SFI), to make the University of Waterloo a global leader in sustainability research, education, and innovation for the benefit of the local and global environment, economy, and society. The SFI is a significant part of Waterloo's strategic plan for the future of our institution, predicated on the premise of elevating multiple activities taking place within

and across three of Waterloo's research institutes: the Waterloo Institute for Sustainable Energy (WISE), the Waterloo Climate Institute (WCI), and the Water Institute (WI).

WISE has also successfully participated in programs that will help to develop renewable-energy-based solutions for remote Indigenous communities in the Canadian North. Thus, under the umbrella of our Affordable Energy for Humanity (AE4H), a Global Change Initiative, we have secured and allocated funds to support multiple international internships, hosted innovation labs, and joined hands with several organizations and entrepreneurs to empower and build human capacity to allow the energy sector in underprivileged economies to thrive, especially drawing on the strength of community members to deliver solutions through education, training, and networking. I am proud to mention that WISE has advocated, supported and implemented Equity, Diversity, Inclusion & Anti-racism (EDI-R) policies since its inception and as part of its mandate. We have always promoted and encouraged multidisciplinary-interdisciplinary-transdisciplinary initiatives to ensure EDI-R opportunities in our day-to-day operating activities.

It is with pleasure that I submit the WISE Annual Report 2022-2023 and sincerely thank our membership for their commitment and contributions to having significant societal, technological, environmental, and economic impact by progressing the local and global energy research agenda to transition to a prosperous Net-Zero future. I am also very thankful for the tireless dedication of WISE staff in full support of our members and strategic goals.

CLAUDIO CAÑIZARES, Executive Director

NOTE FROM THE VICE PRESIDENT, RESEARCH AND INTERNATIONAL

The Waterloo Institute for Sustainable Energy (WISE) has launched the Sustainability Futures Initiative (SFI) in collaboration with the Waterloo Climate Institute (WCI) and Water Institute (WI) to address the global challenges of energy security, affordability and accessibility. This initiative will catalyze new collaborations that will unlock solutions for greater impact and provide a more holistic approach to achieving the United Nation's Sustainable Development Goals with a focus on the interconnections between energy, climate and water. The goal is to shape the future of sustainability for the benefit of the environment, economy, and society. Advancing sustainable futures for the world is a complex problem that links these three domains, alongside societal needs, and inequities, and is driven by global challenges such as extreme weather events, food insecurity and poverty, and endangered ecosystem. SFI is a unique approach that draws upon Waterloo's expertise in interdisciplinary research to provide innovative solutions to address these challenges for a better world.

WISE has successfully supported multiple R&D projects under the leadership of the Executive Director Professor Claudio Cañizares, forming key collaborations both at the national and international level, and providing strategic direction in developing innovative solutions in clean and sustainable energy applications.

The WISE 2022-2023 annual report provides a comprehensive overview and advancements in the five thematic areas of net-zero technologies; power systems; energy-climate nexus; energy-water nexus; and a global change initiative – Affordable Energy for Humanity (AE4H).



CHARMAINE DEAN
Vice-President, Research and International



RESEARCH LABS

From renewable energy technology to smarter demand management, economic modelling to carbon capture and storage, we're solving immediate problems in a timely way and providing leadership to shape the long-term evolution of sustainable energy systems.



BRIDGE:

SUPPLY AND DEMAND WITH BETTER STORAGE

Applied Nanomaterials and Clean Energy Lab
Carbon Nanomaterials Lab
Fuel Cell and Green Energy Lab
Giga-to-Nano Centre
Nazar Research Group



CONSERVE:

ENERGY THROUGH GREATER EFFICIENCY

Advanced Systems Glazing Lab
Information Systems and Science for Energy Lab (ISS4E)
Sustainable Energy Policy Group



DELIVER:

ENERGY MORE INTELLIGENTLY

Electricity Market Simulation and Optimization Lab
High Voltage Energy Lab
Information Systems and Science for Energy Lab (ISS4E)
Non-destructive Testing Lab



ENABLE:

SMART POLICIES AND PLANNING

Sustainable Energy Policy Group



IMPROVE:

CONVENTIONAL GENERATION

Center for Pavement and Transportation Technology Lab
Mechatronics Vehicle Lab
Non-destructive testing Lab
Qing-Bin Lu's Lab
Solar Thermal Research Center



TRANSFORM:

ENERGY SYSTEMS THROUGH GAME-CHANGING TECHNOLOGIES

Center for Advanced Photovoltaic Devices and Systems
Center for Advanced Materials Joining
Fluid Mechanics Research Lab
UW Live Fire Research Facility
Wind Energy Lab

Harvesting Lab
Kleinke Research Centre
Fuel Cell and Green Energy Lab
Giga 2 Nano Centre
Mechatronics Vehicle Lab
Solar Thermal Research Center
Advanced Glazing System Lab
Laboratory for Research in Thermochemical Process and Green Energy

COLLABORATE

At WISE, we believe the biggest breakthroughs come from uniting leading researchers from dozens of disciplines. That's why our membership spans 19 departments and encompasses every faculty at the University of Waterloo.

19

departments

6

faculties



MESSAGE FROM THE DEPARTMENT CHAIR, ELECTRICAL AND COMPUTER ENGINEERING



The genesis and origins of the Waterloo Institute for Sustainable Energy (WISE) are genuinely inspiring. An institute that was founded to advance the R&D activities centered on de-carbonization of sectors such as power & energy, transportation, buildings, construction and others. To achieve the objective it brought together disciplines including engineering, science, mathematics, arts, environment, energy policy, climate change, and Indigenous communities. The primary focus of WISE has always been on renewable and sustainable energy. The students, faculty, staff, alumni, industry partners, governmental organizations and the community have driven the institute's rich history and helped shape its foundation in the development of clean and environmentally friendly energy solutions.

WISE has played a significant role in supporting research, project development, and entrepreneurial based ventures for the Department of Electrical and Computer Engineering (ECE). Several of the ECE faculty members including Professors Cañizares, myself (Bhattacharya), Jayaram, Azad, El-Shatshat, Salama, Kazerani, Shen, Sivoththaman, Zhuang, El-Hag, Aziz, Ramahi and Golab have benefitted over the years, in many different ways, from various research resources and initiatives, facilitated by WISE.

The ECE Department is home to more than 2,500 talented undergraduate students enrolled in our world-renowned co-operative education programs in Electrical Engineering and Computer Engineering. We also jointly offer collaborative undergraduate programs in Software, Mechatronics, Nanotechnology and Biomedical Engineering. Our department is also home to more than 750 innovative and highly dedicated graduate students with inquisitive minds seeking to advance the state of the art, and develop expertise in their fields of research. We offer highly-regarded and unique Master of Engineering (Co-op and Regular) programs, with various specializations to opt for, a research-based Master of Applied Science program, and a Doctor of Philosophy program, all designed to prepare our students for careers in academic, government, or corporate environments.

We are one of the largest ECE departments in North America, with a faculty complement of more than 95 talented faculty members who cover a range of 14 recognized research areas. Of our world-class faculty, 20 are active Fellows of the IEEE, 9 are active Fellows of Canadian Academy of Engineering, and 6 are active Fellows of the Royal Society of Canada. Our department is home to world-class research labs, such as the High Voltage Engineering Lab, Giga-to-Nano (G2N) Centre, Centre for Intelligent Antenna and Radio Systems (CIARS), and Centre for Integrated RF Engineering (CIRFE), among others. The research activities in the ECE Department covers a wide range of fields, from electric power engineering to breakthroughs in wireless technology that will enhance communications across our global society.

WISE has always provided substantial support to ECE faculty members to advance their research and facilitate collaboration for national and global impact, and developing human capital. The Affordable Energy for Humanity (AE4H) is a global change initiative by WISE and a stellar example of leveraging our global employer network to power international and interdisciplinary innovations as our students and faculty build relationships with policymakers, community members and businesses from around the world. Internationalization has brought distinct talent to our campus while providing students and researchers more opportunities globally in the energy sector. Innovation, international collaborations and multi-disciplinarity has helped University of Waterloo take a more prominent role in developing state-of-the-art energy solutions for the under-privileged economies on the world stage.

On behalf of the ECE Department, I wish WISE all success over the next years and look forward to more initiatives and collaboration with ECE faculty members in the important areas of sustainable energy provisions for the world.

KANKAR BHATTACHARYA

Chair, Department of Electrical and Computer Engineering, University Research Chair, Professor



EDUCATION AND TRAINING

QUEEN ELIZABETH SCHOLARSHIPS

As an institute committed to growing clean energy development at home and abroad, we take pride in collaborating with Universities Canada, Global Affairs Canada, the Rideau Hall Foundation, and the Steele Family Foundation to deliver work-integrated learning opportunities. Within these partnerships, WISE/AE4H has been able to assist with clean energy development in nations lacking adequate energy infrastructure, as well as continuing the cycle of new, innovative learning and opportunity for Waterloo students. As representatives of the University of Waterloo and WISE/AE4H, these students have done extraordinary work with some of our member organizations, helping to actualize clean energy development abroad. This year's students worked primarily in East Africa and India putting their technical and interdisciplinary skills to the test during in-field placements for their co-op semesters. These partnerships are an important way WISE/AE4H works to fulfil the United Nations Social Development Goals (SD7).



CO-OP STUDENT PROGRAMMING

The Energy Access Internship Program is a international internship program that facilitates remote and in-person co-op and field placements with AE4H partners around the world. Students can work remotely from their homes for AE4H employers abroad or work in-country in positions such as Hardware Engineering Intern, Strategic Communications Intern, Business Development Intern, and more.

WISE is grateful for the support of the Clean Technology Hub Nigeria, Green Growth Africa, the ENventure program at New Energy Nexus Uganda, the United Nations Development Program Fiji, Avani Bio Energy, and The Nelson Mandela African Institution of Science and Technology for hosting students through the Energy Access Internship Program in 2022-2023.

STUDENTS

The fifteen amazing students from five faculties who participated in the Energy Access Internship Program used their skills and hard work to create meaningful impact at AE4H institutions to promote access to energy.

- › Aryaman Chaturani, Mechanical and Mechatronics Engineering
- › Matthew Lloyd, Mechanical and Mechatronics Engineering
- › Nickie Senthil Kumar, Environment and Business
- › Srishti Singh, Systems Design Engineering
- › Mackenzie White, Master of Arts in Global Governance
- › Shaza Ahmed, Master of Arts in Global Governance
- › Emaad Alam, Chemical Engineering
- › Renée Hinton, Architectural Engineering
- › Amanda Donofrio, Environment and Business
- › Jessica Bona, Environment, Resources and Sustainability
- › Samantha Kremer, Science and Business
- › Tatum Soward, Physics and Astronomy
- › Sydney Buis, Environmental Engineering
- › Terissa Zhang, Planning
- › Samantha Kaiser, Accounting and Financial Management



CLEAN TECH HUB, NIGERIA

Clean Tech Hub is a pioneering hybrid hub for the research, development, demonstration and incubation of clean energy ideas, technologies, and resources for clean energy organizations and environment and climate friendly initiatives across Africa.



AVANI BIO ENERGY, INDIA

Avani Bio Energy is a social enterprise that develops sustainable livelihood solutions in the rural, developing region of Uttarakhand, India. Avani has developed and implemented several biomass gasification power plants in villages across Uttarakhand. These plants, which are fueled by pine needles, produce electricity which is sold to the state power company, generating revenue for the villages. This initiative provides employment opportunities for community members who operate the power plants and who collect and deliver pine needles for the biomass fuel. The power plant project also helps address forest fire problems in the region, as collecting the pine needles from the forests around the villages and power plants helps reduce the spread of fires.



GREEN GROWTH AFRICA

Green Growth Africa is a nonprofit organization based in Nigeria that is committed to raising global and multi-stakeholder support for greener and climate-resilient organization Africa through various programmes and initiatives including Mentoring for Research and the Environmental Education Program. The organisation operates a multidisciplinary network of about 1,500 professionals, researchers, students, and youth from 140 countries across the globe who are committed to green growth in Africa. Headquartered in Ibadan, Nigeria, Green Growth Africa has team members in 10 countries across five continents of the world, and has projects in 22 African countries.



ENVENTURE, UGANDA

The ENventure program powered by New Energy Nexus empowers rural CBOs in Uganda to start clean energy enterprises. Through our Seed Incubator, we invest small amounts in a large number of CBOs. Over a 1-year period of monitoring their energy sales and loan repayments, the best performers are selected for our Growth Accelerator which offers larger debt, financial management support, and investment-readiness.



UNITED NATIONS DEVELOPMENT PROGRAMME

UNDP is the United Nations development agency, working in about 170 countries and territories, helping to eradicate poverty, reduce inequalities and exclusion, and build resilience so countries can sustain progress. UNDP plays a critical role in helping countries achieve the Sustainable Development Goals. UNDP Fiji is part of UNDP's Pacific Office, which provides support to fifteen countries together with a total population of 2.4 million, and works on effective governance, inclusive growth as well as resilience and sustainable development.



NELSON MANDELA AFRICAN INSTITUTION OF SCIENCE AND TECHNOLOGY, TANZANIA

The Nelson Mandela African Institution of Science and Technology (NM-AIST) in Arusha is one in a network of Pan-African Institutions of Science and Technology located across Sub-Saharan Africa (SSA). These institutions, which are the proud brainchild of the late Nelson Mandela, envision training and developing the next generation of African scientists and engineers with a view to impacting profoundly on the continent's development through the application of Science, Engineering and Technology and Innovation (SETI). Professor Askwar Hilonga of NM-AIST invented Nanofilter®, a low-cost and sustainable water purification system particularly suited to the needs of local people in Tanzania.

STUDENT TESTIMONIALS

"As an intern for WISE's international partners in the renewable energy sector, my co-op term has been a very beneficial and inspiring experience. In the virtual work-from-home setting, I have the opportunity to collaborate with individuals across the world on meaningful and impactful tasks for companies who are working to provide electricity and improve lives in remote villages, most of whom are gaining access to electricity for the first time in history. This memorable experience introduced me to the field of sustainable energy, widening my career perspective and motivating me to pursue similar positions in the future."

YELDA SAFI

"This was my first international co-op term facilitated through WISE and it was an incredible learning experience. Not only did I get to learn more about sustainable energy and apply the skills I have developed through my undergrad, but I also got to learn more about energy initiatives in developing regions. Working with team members from different countries was really interesting as I got to learn about practices and policies that I was previously unfamiliar with."

AYESHA ASIM



REACH OUT



Change requires many partners. That is why we actively engage with the world beyond our hallways. We're working closely with industry, government and the non-profit sector in Canada and abroad to create sustainable energy solutions. We foster connections, establish formal partnerships and pursue major initiatives with external organizations.

IN THIS ANNUAL REPORT WE HIGHLIGHT FIVE ENERGY RESEARCH THEMES OF OUR INSTITUTE'S MEMBERS:

- › Net-Zero Technologies
- › Power Systems
- › Energy-Climate Nexus
- › Energy-Water Nexus
- › A Global Change Initiative – Affordable Energy for Humanity (AE4H)

1 NET-ZERO TECHNOLOGIES

Net-Zero is a concept gaining momentum in the Canadian environment and energy landscape. In 2021 the Government of Canada launched the Canadian Net-Zero Emissions Accountability Act which outlines Canada's commitment to achieve net-zero emissions by the year 2050. The 2030 Emissions Reduction Plan, launched in 2022, is another federal level policy that guides net-zero initiatives until 2030. Net-Zero means no greenhouse gas emissions are generated, or emissions are offset through methods such as tree planting, carbon capture and storage, or purchasing carbon offsets. There are many aspects of Net-Zero. Advances in renewable energy technologies such as wind, solar, geothermal, hydrogen, electric vehicles, and microgrids are making it easier than ever to achieve net-zero in the energy sector. Communities are enacting policies to achieve net-zero targets and are implementing programs to achieve net-zero in sectors including utilities, buildings, and transportation. Multiple companies across the utilities landscape are exploring different options to partner with right stakeholders and other industries to move toward energy transition, maximizing investments, building capability, and mitigating risk. These entities are working on their strategic planning and business models to explore new and emerging market opportunities. A Net-Zero Energy (NZE) building can generate as much clean energy as it consumes. They are expected to be highly energy efficient as opposed to a new building constructed to today's building code minimum. NZE utilizes on-site clean and



CLAUDIO CAÑIZARES
Professor, Electrical and
Computer Engineering

sustainable energy systems to produce the remaining energy they require. Transportation is a significant contributor to greenhouse gas emissions; innovations such as electric vehicles and sustainable aeronautics are contributing to net-zero in the transportation industry.

Over the last decades, Ground Source Heat Pump (GSHP) systems have grown in popularity and acceptance worldwide, having the potential to bring about significant benefits, especially if these systems participate in electricity markets through a load aggregator to optimize their operations and provide services such as load shifting and demand reduction, as proposed here.

In this context, GSHP systems can be considered as an economically viable and attractive alternative to existing Heating Ventilation and Air Conditioning (HVAC) systems for space heating/cooling in buildings and houses from an aggregator point of view. Hence, a study by **Professor Cañizares** (Electrical and Computer Engineering) and **Professor Bhattacharya** (Electrical and Computer Engineering) presented



KANKAR BHATTACHARYA
Professor, Electrical and
Computer Engineering

a detailed mathematical model for a GSHP with a vertical U-pipe Ground Heat eXchanger (GHX) configuration to provide residential space heating/cooling, integrating several such GSHPs into a load aggregator model. Then, a two-stage

operational strategy for the GSHP price-taker aggregator participating in day-ahead and real-time electricity markets was proposed, to determine the optimal annual heating/cooling load dispatch to control the temperatures for a community of houses that minimized the aggregator's cost. Detailed numerical studies and comparisons with HVAC systems were carried out to

demonstrate the feasibility and benefits of the proposed aggregated operation of GSHPs in electricity markets.



JATIN NATHWANI
Professor, Management Sciences

Professor Nathwani (Management Sciences) and **Professor Wen** (Mechanical & Mechatronics Engineering) have explored on how



JOHN WEN
Professor, Mechanical
and Mechatronics
Engineering

the trade-off between the incident solar irradiance and conversion efficiency of a photovoltaic panel affects its power production. A neural network was developed through statistical analysis and a data-driven approach to accurately calculate the photovoltaic panel's power output. Although the incident beam irradiance at a specified location directly related to the tilt angle, the diffusion irradiance and energy conversion efficiency were nonlinearly dependent on a number of operating parameters, including cell temperature, wind speed, humidity, etc. A mathematical model was implemented to examine and cross-validate the physics of the neural network. Through simulation and comparison of the optimized results for different time horizons, it was found that hourly optimization can increase the energy generated from the photovoltaic panel by up to 42.07%. Additionally, compared to the base scenario, annually, monthly, and hourly optimization can result in 9.7%, 12.74%, and 24.78% more power, respectively. This study confirmed the data-driven approach was an effective tool for optimizing solar power. It recommended adjusting the tilt angle of photovoltaic panels hourly, during the daily operation of maximizing the energy output and reducing solar costs.



FUE-SANG LIEN
Professor, Mechanical
and Mechatronics
Engineering

The presence of power augmentation effects, or synergy, in vertical-axis wind turbines (VAWTs) offers unique opportunities for enhancing wind-farm performance. **Professor Lien** (Mechanical & Mechatronics Engineering) used an open-source actuator-line-method (ALM) code library for OpenFOAM (turbinesFoam) to conduct an investigation into the synergy patterns within two- and three-turbine VAWT arrays. The application of ALM greatly reduced the computational cost of simulating VAWTs by modelling turbines as momentum source terms in the Navier-Stokes equations.

In conjunction with an unsteady Reynolds-Averaged Navier-Stokes (URANS) approach using the k -shear stress transport (SST) turbulence model, the ALM has proven capable of predicting VAWT synergy. The synergy of multi-turbine cases was characterized using the power ratio which was defined as the power coefficient of the turbine cluster normalized by that for turbines in isolated operation. The variation of the power ratio was characterized with respect to the array layout parameters, and connections were drawn with previous investigations, showing good agreement. The results from 108 two-turbine and 40 three-turbine configurations obtained using ALM were visualized and analyzed to augment the understanding of the VAWT synergy landscape, demonstrating the effectiveness of various layouts. A novel synergy superposition scheme was proposed for approximating three-turbine synergy using pairwise interactions, and it was shown to be remarkably accurate. The results obtained from this study could be enhanced by future work in the following ways. First, the isolated turbine performance could be more rigorously validated. This may be achieved by obtaining a high-fidelity airfoil coefficient dataset (possibly driven by full-order URANS CFD simulations), exploring various additional correction models (e.g., for dynamic stall), and testing different Gaussian kernel formulations. It is recommended that multi-turbine full-order blade-resolved CFD simulations be performed to thoroughly and systematically evaluate the accuracy of ALM simulations in predicting VAWT power-generation performance. Furthermore, it would be valuable to extend the present investigation to larger turbine groups (four or more turbines in the array), to more diverse turbine geometries or heterogeneous wind farms, and to different Tip-Speed Ratios (TSRs). The current model is also suitable for extension towards the evaluation of synergy in complex terrain situations, for which a different lower-boundary condition can be imposed to represent the complex terrain. The virtual turbines can also be freely arranged both in the horizontal plane and the vertical direction, using the ALM technique, in order to capture the synergy in sophisticated cases such as an urban siting. The use of a low-cost, effective reduced-order approach such as an ALM simulation is expected to be invaluable to the optimal design of large-scale VAWT farms—involving, as such, the leveraging of the unique opportunities provided by turbine synergistic interactions.

2 POWER SYSTEMS

A power system is a network of multiple elements and components that work together to process and deliver electrical power. The electrical grid is an example of such a system, which consists of generation, transmission, and distribution. The electric power systems have a progressively fundamental role to play as the energy backbone of a net zero future. In traditional power systems, large fossil-based power plants (coal, oil, and natural gas) have provided balancing in the network parameters and its exchanges. Also, the priority is to make sure that power flows and dynamics are within bounds and stable (for the angle, voltage, and frequency) in normal and after events (faults, failures). The standardized conventional planning and control models are now challenged by the new concepts and modernized structures. Current distribution networks are going through a series of changes due to various interrelated factors such as greenhouse gas (GHG) reduction targets, digitization (data analytics and internet of energy), supply & demand management, power congestion, system stability and security, power quality requirements, mixing of renewables, and network growth and reliability. The clean energy sources such as wind and solar produce electrical energy which gets managed by power grids across the globe are intermittent and variable, which means they are non-dispatchable (cannot be controlled by the grid operators) and require storage. Other types of sustainable and renewable energy sources that are dispatchable and can provide base-load power without energy storage are bioenergy, geothermal, hydrogen, hydroelectric, and marine/ocean thermal energy technologies.

In terms of energy access, microgrids are an expanding segment of the power system engineering, which signifies a paradigm shift from large central station power plants toward more localized, distributed generation in communities. The capability for flexible operation to deliver electrical energy services makes microgrids applications resilient and competitive both in rural and urban settings. Microgrids have been shown to efficiently integrate distributed generation resources and loads, using centralized and decentralized controls that compensate the variability of renewables to deliver stable and reliable electricity.

A project by **Professor Cañizares** (Electrical and Computer Engineering) and **Professor Bhattacharya** (Electrical and Computer Engineering) presented a Frequency Regulation (FR) model of a large interconnected power system including Energy Storage Systems (ESSs) such as Battery Energy Storage Systems (BESSs) and Flywheel Energy Storage Systems (FESSs), considering all relevant stages in the frequency control process. Communication delays were considered in the transmission of the signals in the FR control loop and ESSs, and their State of Charge (SoC) management model was considered. The system, ESSs and SoC components were modelled in detail from a FR perspective. The model was validated using real system and ESSs data, based on a practical transient stability model of the North American Eastern Interconnection (NAEI), and the results showed that the proposed model accurately represented the FR process of a large interconnected power network including ESS, and could be used for long-term FR studies. The impact of communication delays and SoC management of ESS facilities in the Area Control Error (ACE) was also studied and discussed, as well as the computational efficiency of the proposed FR model.

Optimal Power Flow (OPF) is one of the most important problems in power system operation. Independent system operators (ISOs) should run OPF problem to find generation setpoints, considering variations in demand. Due to the nonlinear and non-convex attributes of the optimization problems in power systems such as OPF, traditional iterative optimization algorithms require significant amount of time to converge for large electric networks. Therefore, power system operators seek other methods such as DC Optimal Power Flow (DC-OPF) to obtain faster results, to obtain the state

of the system. However, DC-OPF provides approximated results, neglecting important features of the system such as voltages and reactive power. Fortunately, recent

developments in machine learning have led to new approaches for solving such problems faster, more flexible, and more accurate. **Professor Pirnia** (Management Sciences) has implemented a Deep Neural Network-based Optimal Power Flow (DNN-OPF) algorithm on small to large case studies to show the accuracy



MEHRDAD PIRNIA
Professor, Management Sciences

and efficiency of the ML-based algorithms. His study provided a novel approach to classify the feasible and infeasible AC-OPF problems, and suggested a constraint-guided method, based on normalizing outputs and using particular activation functions to respect the limits of generators. Furthermore, the proposed post-processing approach guaranteed the feasibility of the solutions. The suggested method was applied on IEEE24-bus, IEEE 300 bus, and PEGASE 1354 bus systems and the results showed significant improvement on accuracy of the results and execution time, comparing to traditional gradient-based methods, such as Newton-Raphson and Gauss-Seidel methods.

Integration of converter-interfaced renewable energy sources (RESs) into the power system and the transfer of power from RESs to remote load centres over high-voltage direct current (HVDC) lines may require connecting multiple voltage-sourced converters (VSCs) to a



NASSER LASHGARIAN AZAD
Professor, Electrical and Computer Engineering

common alternating current (AC) system. Because of this connection, control loops of various converters will interact through the AC grid, leading to instability and an undesirable transient response. A project led by **Professor Azad** (Electrical and Computer Engineering) focused on the system-level integration of multi-VSC

systems for the integration of RESs. μ analysis was used to determine under which control modes the independently stabilized VSCs connected to a common AC system ensured the multi-VSC system stability. Furthermore, a sufficient criterion was proposed for the design of the converters' outer control loops independently to ensure the stability of the interconnected multi-VSC system. For cases of severe interactions, where the interconnected multi-VSC system may become unstable even if individual VSCs were stable, a joint controller design for converters was proposed to stabilize the multi-VSC system. The interaction analysis indicated that employing AC voltage control mode by all the converters caused the highest interaction level, and having more converters in reactive power control mode reduced the impact of interactions on the interconnected system stability.

Interconnected Microgrids (IMGs) are considered a futuristic paradigm of power grids that offer modularity, resilience, and independence with energy exchangeability. In this context, each MG is accountable to its own citizens

(i.e., generators or loads) and can participate in a market with its neighbours, if this enhances the benefits of its citizens.

Thus, greedy behaviour is assumed to be rational for MGs participating in such a market. In a study by



MAGDY SALAMA
Professor, Electrical and Computer Engineering

Professor Salama (Electrical and Computer Engineering),

a novel decentralized platform to facilitate energy trading between IMGs was developed. The platform would allow interested MGs to participate and gain benefits assuming self-benefit-driven (SBD) actions from participating MGs. The proposed platform provided a market-clearing approach based on sequential rounds. In each round, the MG with the cheapest energy price was privileged to export its surplus energy and maximize its own benefits. In order to identify the round champ, a decentralized ranking algorithm was developed to determine the MG with the cheapest energy price. The effectiveness of the proposed platform was validated using various case studies.

3 ENERGY-CLIMATE NEXUS

According to the International Energy Agency (IEA), energy is responsible for two-thirds of total greenhouse gas. Therefore, the energy sector is the key player in efforts to reduce emissions and mitigate climate change. Sustainable energy plays a vital role in providing support to climate change mitigation by reducing greenhouse gas emissions, and climate change adaptation by facilitating communities build resilience across key sectors. The Government of Canada has made many domestic and international commitments to address climate change, including commitments to reduce its greenhouse gas emissions and reach net-zero emissions by 2050. The 2016 Pan-Canadian Framework on Clean Growth and Climate Change (PCF) was Canada's first-ever national climate plan, which was launched in collaboration with the ten provinces and three territories, and in discussion with the Indigenous peoples. It was a key initiative for Canada to accomplish its Paris Agreement target, which was to cut pollution in a feasible, practical, accessible and affordable way than any other climate plan in Canadian history.

Limiting global warming to 1.5–2.0°C in line with our climate commitments will require decarbonization of residential buildings. The traditional approach starts with major energy efficiency upgrades to the building envelope followed by switching to low-carbon fuel sources for space and water heating. Building envelope retrofits have been a policy goal for over two decades in Canada and elsewhere, yet historical rates and associated emission reductions fall far short of what is required if we are to meet our climate

targets. Alternatively, **Professor Parker** (School of Environment, Enterprise and Development) proposed direct fuel switching to electric heat



PAUL PARKER
Professor, School of
Environment, Enterprise
and Development

pumps for space and water heating in regions with low-carbon electricity. Using a database of 44,463 home energy profiles in Waterloo Region, Canada, he modeled the energy efficiency and greenhouse

gas emission impacts of building envelope retrofits and direct electrification. While all retrofit plans achieved significant energy efficiency gains (17–40%), so did direct electrification (70%) and building envelope retrofits plus electrification combined (70–80%). Only plans that included electric heat pumps achieved greenhouse gas emission reductions of 90% or more. Compared to the conventional approach, direct electrification with heat pumps may be a simpler, more effective, and more realistic approach for policies aiming to decarbonize the residential sector.

In order to reach global reduction targets for greenhouse gas (GHG) emissions, cities and urban areas will be at the forefront of deep decarbonization practices. As the urgency for climate action heightens, local governments and stakeholders are developing pathways towards deep decarbonization at the local level and committing to community-wide greenhouse gas reductions of 80–100% by 2050 or earlier. Urban areas are the largest place-based source of greenhouse gas emissions, accounting for 71%–76% of global emissions. Local governments have direct and indirect control of over a significant proportion of emissions that occur within their municipalities. However, there remains a gap in

knowledge about the local technical and policy pathways that are being developed in order to



AMELIA CLARKE
Professor, School of
Environment, Enterprise
and Development

achieve deep decarbonization

and how these pathways

vary for different size

cities. **Professor**

Clarke (School

of Environment,

Enterprise and

Development) did a

study that qualitatively

analyzes eight local government

deep decarbonization plans of cities that range in size from eight thousand to nine million people.

The eight cities were: (1) Bridgeport (Canada), (2)

Park City (USA), (3) Guelph (Canada), (4) Lahti

(Finland), (5) Vancouver (Canada), (6) Oslo

(Norway), (7) Toronto (Canada), and (8) New York

(USA). She analyzed emerging patterns among

the cities, while also considering the impacts of the population size and the national context. Each city

has unique circumstances and priorities when it

comes to decarbonization, and not all cities prioritized

their highest emitting sectors for decarbonization.

She found that emerging technical pathways to deep decarbonization focus on five priority sectors

(electricity, buildings, transportation, waste, and

carbon sinks and storage), but also that several

local governments were developing innovative

strategies beyond what is described in the literature

for decarbonizing the priority sectors within their

jurisdiction and were expanding the scope of their

plans to include emerging areas in GHG mitigation

such as scope 3 and embodied greenhouse gas

emissions. Electricity is one of the priority sectors, and

decarbonization can be done by removing unabated

fossil fuels entirely from the electricity grid. It was

found out that local governments have limited control

over this sector, but they can utilize building scale

and district energy solutions. Also, sometimes they

own local utilities. The elimination of unabated fossil fuels from the electricity sector is needed to address

ambitious climate goals in cities. In this study, the

empirical results validated the literature; all of the case

cities have targets to significantly increase the capacity

of renewable electricity.

With the rising level of atmospheric CO₂ worsening climate

change, a promising global movement toward carbon

neutrality is forming. Sustainable CO₂ management

based on carbon capture and utilization (CCU) has

garnered considerable interest due to its critical role in

resolving emission-control and energy-

supply challenges. A study done

by **Professor Chen** (Chemical

Engineering) summarized the

state-of-the-art progress

in developing promising

materials for sustainable CO₂

management in terms of not

only capture, catalytic conversion

(thermochemistry, electrochemistry,

photochemistry, and possible

combinations), and direct utilization, but also emerging

integrated capture and in situ conversion as well as

artificial-intelligence-driven smart material. In particular,

insights that span multiple scopes of material research

are offered, ranging from mechanistic comprehension

of reactions, rational design and precise manipulation

of key materials (e.g., carbon nanomaterials, metal-

organic frameworks, covalent organic frameworks,

zeolites, ionic liquids), to industrial implementation. This

review concluded with a summary and new perspectives,

especially from multiple aspects of society, which

summarized major difficulties and future potential for

implementing advanced materials and technologies in

sustainable CO₂ management. This work may serve as

a guideline and road map for developing CCU material

systems, benefiting both scientists and engineers working

in this growing and potentially game-changing area.



ZHONGWEI CHEN
Professor, Chemical
Engineering

4 ENERGY-WATER NEXUS

Water and energy are interconnected and interdependent. Water plays a crucial role during the extraction, processing, refining and conversion stages of energy production for both renewables and non-renewables. On the other hand, drinking water and wastewater plants are considered to be one of the largest energy users, often accounting for a major share of total energy consumed. High savings and a quick payback period could result by incorporating energy efficiency practices in the engineering processes for drinking water and wastewater treatment plants.

Introducing sustainable energy resources is a promising technique to overcome the growing demands for environmentally friendly and low-priced energy. A project by **Professor Jatin Nathwani** (Management Sciences) carried out the design, analysis, and optimization process of an original multigeneration facility to produce power, cooling, heating, freshwater, and hydrogen. Energy, exergy, exergoeconomic, exergoenvironmental, and environmental assessments were conducted to investigate essential performance indicators. The multi-objective particle swarm optimization algorithm was applied to determine the most optimal conditions for system operation. Obtained results from the exergy study revealed that the solar cycle contributed the most to exergy destruction around 39.5 % of overall value. Also, the exergoenvironmental assessment identified

that the exergoenvironment factor, exergy stability factor and environmental damage effectiveness are 1.35, 0.82, and 3.67, respectively. Also, obtained results from the optimization showed that the optimum condition for system operation leads to economic and technical parameters improvement. The total unit cost of the product, the exergy efficiency, work output, and Levelized costs of water, hydrogen, and electricity were 61.2 US\$/GJ, 41.07 %, 48.32 kW, 5.58 US\$/m³, 2.99 US\$/kg, and 6.32 cent/kWh. Also, the system avoided the emission of 2,965.45 tons of CO₂.

Hydrogen is a promising energy carrier to provide sustainable energy use throughout the world. Researchers and policy-makers have focused on investigations in three areas of hydrogen-related technologies in the energy market: (1) alternative fuel production based on hydrogen and carbon dioxide; (2) hydrogen injection to the natural gas pipeline networks; (3) usage of hydrogen in transportation applications. One of the most important challenges facing hydrogen technology development is the production of green hydrogen, which can be achieved through water electrolysis coupled with renewable power generation. Although many studies have been conducted, there is still a need for further development, which requires open-source big data and models and standardization of the processes to compare different renewable-based hydrogen production systems. To fill this research gap, the performance of a grid-connected hybrid wind turbine and solar photovoltaic-based water electrolysis systems for large-scale green hydrogen production were investigated by **Professor Wen** (Mechanical and Mechatronics Engineering). The objective was to propose an accurate methodology to compare wind and solar systems, or hybrid ones, for green hydrogen production worldwide. A large dataset describing the hybrid wind turbine-photovoltaic hydrogen production in various locations was created



by performing dynamic simulations using TRNSYS and analyzed using MATLAB and Excel. Several dimensionless indicators were employed and assessed for standardizing the performance evaluation procedure of renewable-based hydrogen production systems, including the electrolyser load portion satisfied by the wind turbine and photovoltaic, the generated wind turbine and photovoltaic energy portion supplied to the electrolyser load and the quantity of energy exported to and imported from the grid. The annual and monthly values of these indicators together with the total amount of green hydrogen production were estimated for 28 global locations. The procedure applied can be easily used to test small-scale applications like residential users or large-scale applications like industrial users, as well as for any hydrogen demand and climatic conditions.

Gas hydrates are a type of crystalline compounds that consists of water and small gas molecules. A wide range of applications of gas hydrates in storing natural gas in the form of artificially created solid hydrates, known as solidified natural gas technology, gas separation



YURI LEONENKO
Professor, Earth and
Environmental Sciences

processes, and seawater desalination technology, has attracted great interest in scientific and practical studies. Gas hydrate formation may also cause deleterious effects such as blockage of gas pipelines. Therefore, accurate prediction of equilibrium conditions for gas hydrates is of great interest. A study led by **Professor Leonenko** (Earth and Environmental Sciences) proposed machine learning based models to predict methane-hydrate formation temperature for a wide range of brines. In this regard, firstly, a comprehensive database including 987 data samples covering 15 different brines was gathered from the literature. After data cleaning and preparation, three different models of multilayer perceptron, decision tree, and extremely randomized trees were used and tested. The results showed that the extremely randomized trees were capable of predicting methane-hydrate formation temperature with good accuracy. The root mean squared error for this model for the testing dataset was acquired as 0.6248, which showed its great accuracy. The findings of this study could be used as a reliable tool to predict the methane-hydrate formation PT curve in the pure water, single-salt brines, and multi-salt brines.

5 A GLOBAL CHANGE INITIATIVE – AFFORDABLE ENERGY FOR HUMANITY (AE4H)



Created by Dr. Jatin Nathwani and Dr. Joachim Knebel in 2015, the Affordable Energy for Humanity global change initiative is a consortium of over 150 energy access researchers and practitioners from over 37 countries. AE4H members represent some of the leading energy access institutions and experts from around the world, and have an incredible cumulative impact.

There remain over 2.5 billion people around the world without access to reliable electricity and clean cooking services, approximately 800 million of whom have no access to electricity. Access to energy is a catalyst of at least 13 of the 17 Sustainable Development Goals, and as such should be a priority in global sustainable development. For example, access to

150
members

37
countries



clean cooking services can reduce mortality and disease due to indoor air pollution, access to reliable lighting can help improve the quality of medical care and the quality of education, and access to electricity can provide the opportunity for the creation of microbusinesses and other income-generating opportunities.

AE4H members work together to promote research, education, and projects regarding global access to energy. In 2022-23, this included remote and in-person international co-op placements for UW students, AE4H and student Innovation Labs, energy mentorship for University of Waterloo students, and several new or completed partnership initiatives with AE4H members.

AE4H PARTNERSHIP INITIATIVES

The greatest strength of the Affordable Energy for Humanity Initiative is its diverse and impactful partners. We are pleased to partner with AE4H members on initiatives that promote awareness, capacity, and research regarding access to energy. Here are two partnership initiatives that were either initiated or completed in 2022-23.



1. AE4H Innovation Lab

On April 26, 2023, at the 4th International Conference on Solar Technologies & Hybrid Mini Grids to Improve Energy Access in Palma de Mallorca, Spain, Dr. Jatin Nathwani and Ambika Opal facilitated an AE4H Innovation Lab. Approximately 75 AE4H members as well as prospective members attended the Lab. During the event, participants were split into three groups: Economy, Social, and Technology, and given a case study about a real community in Vanuatu. The teams were asked to co-develop a renewable energy solution and business case that would address the

energy access needs for the Vanuatu community members. The event was successful in engaging AE4H members in using their expertise in a practical setting, and in building collaboration amongst members. WISE would like to thank Trama TecnoAmbiental for providing data for the Innovation Lab case study.

2. Design of a Green Building in Ibadan, Nigeria

Through the WISE Capstone Mentorship Program, WISE often provides mentorship, connections, and resources for fourth-year engineering student groups undertaking their Capstone project. In 2022-23 WISE connected an Environmental Engineering Capstone group with AE4H partner Green Growth Africa based in Nigeria, to design a green building. This green building is built using waste plastic water bottles, based on Green Growth Africa's previous design and construction of school buildings, and their water bottle diversion program. The students designed solar energy and sustainable water systems for the building, and completed sustainability analyses and suggestions for further construction. Construction on the building commenced in early 2023 and is set to be finished later in the year.



WISE EVENTS

HYDROGEN WORKSHOP

May 9, 2022

WISE hosted a hydrogen workshop comprising speakers from academia, private sector, government agencies, and not-for-profit organizations. The workshop brought together an executive forum intended to encourage the exchange of ideas that would help create a roadmap to guide the future of green hydrogen and energy storage research in Canada. The workshop focus was on collaboration in hydrogen research, the exploration of opportunities for partnership, and the integration of efforts across stakeholder groups. The event engaged experts from engineering, social science, policy and economics, facilitating new network connections to create important insights and ideas on the future of hydrogen. The event anticipated inspired, wide-ranging discussions on all hydrogen related matters, from evidence-based decision making and policy planning to reduction of greenhouse gas (GHG) emissions and full-scale commercialization of fuel cells and hydrogen storage in the energy and transportation sector.

- › Panel 1: Fuel Cells and Future of Sustainable Mobility
- › Panel 2: Hydrogen and Ammonia Production
- › Panel 3: Hydrogen Storage



14TH INTERNATIONAL GREEN ENERGY CONFERENCE (IGEC-XIV)

July 4-8, 2022

The IGEC was a multi-disciplinary conference on energy systems and technologies with no/reduced environmental, economic and social impact, and provided a forum for the exchange of technical information, for the dissemination of high-quality research results, and for the debate and shaping of future directions and priorities in energy sustainability and security.



IREP'2022 SYMPOSIUM

July 25-30, 2022

The Conference was organized by the Waterloo Institute for Sustainable Energy of the University of Waterloo, and the University of Calgary. The International Institute of Research and Education in Power System Dynamics (IREP) International Steering Committee and the Local Organizing Committee cordially welcomed the power systems experts to the 11th Bulk Power Systems Dynamics and Control Symposium – IREP'2022 in Banff. The series of Bulk Power Systems Dynamics and Control Symposia was established by Les Fink in 1988 and is managed since 1994 by IREP. The IREP'2022 continued the outstanding and proud tradition, albeit delayed by the unfortunate and challenging world health crisis in 2020 and 2021, of previous and truly special meetings at Potosi (1988), Deep Creek Lake (1991), Davos (1994), Santorini (1998), Onomichi (2001), Cortina D'Ampezzo (2004), Charleston (2007), Buzios (2010), Rethymnon (2013), and Espinho (2017). The attendees to IREP'2022 from all over the world had the

opportunity to share their research work with a prominent technical audience, providing a venue for friendly and in-depth technical discussions of the presented work, which was a very unique characteristic and tradition of IREP symposia. The timely and relevant theme of the Banff Symposium was “A 100% Renewable Energy Source Bulk Power Grid: Opportunities and Challenges.” As with previous meetings and as part of IREP’s custom, there were many opportunities for distinctive social engagements and interactions amidst the exceptional and beautiful settings of the Canadian Rockies.



IREP 2022





WORKSHOP | INTRODUCTION TO FEEDBACK-BASED OPTIMIZATION AND APPLICATIONS TO ENERGY SYSTEMS

July 11, 2022

The focus of the workshop was on, how numerical optimization algorithms can be converted into feedback controllers to enable robust “closed-loop optimization”. The event reviewed different existing approaches of online optimization applied to problems in energy systems, with particular focus on microgrids, and discussed their pros and cons. The analysis was also on the various optimization algorithms to then show how they can be formulated as dynamical systems. The discussions also assessed, how to use the aforementioned background to design optimization algorithms in closed loop with physical systems, or feedback-based optimization algorithms, that steer the physical system towards the solution of an underlying constrained optimization problem. There was also an evaluation of a few specific applications of feedback optimization to the control and operation of microgrids, and also other possible applications of feedback optimization to energy systems.



SUSTAINABLE FUTURES INITIATIVE (SFI)

September 19, 2022

The Sustainable Futures Initiative aimed to make the University of Waterloo a global leader in sustainability research, education and innovation for the benefit of the environment, economy and society. The initiative would build on and elevate the research, education and innovation activities taking place within and across three of Waterloo’s research institutes: the Waterloo Climate Institute, the Waterloo Institute for Sustainable Energy and the Water Institute. The initiative would catalyze new collaborations that will unlock solutions for greater impact and provide a more holistic approach to achieving the United Nation’s Sustainable Development Goals in Canada and elsewhere.



CCS LAW AND REGULATION

October 13, 2022

A one-day workshop, organized by WISE, to discuss legal and regulatory regime for geological CO₂ storage in Ontario. The discussion included:

- › Clarification of subsurface property rights in geological formations
- › Integration with greenhouse gas mitigation requirements, including reporting and accounting requirements
- › Responsibilities for long-term liability for stored carbon dioxide
- › Identification of other regulatory obstacles and requirements



HARD TO ABATE CLUB WORKSHOP

November 4, 2022

NRCan and the University of Waterloo hosted a periodic workshop for heavy industry in Southern Ontario including the steel, cement, gas-fired power, oil refining and petrochemical sectors. These are known as the hard-to-abate industries with respect to abatement of CO2 emissions. The 'Hard-to-Abate Club' will provide (i) expert presentations on topics involving carbon capture, utilization and storage, electricity grids, transmission pipelines and other topics that these industries

find important, and (ii) networking to develop industrial synergies to allow them to meet the 2030 GHG goals of the Federal Government and the 2050 Net Zero goal. Such a forum should ultimately led to improved environmental and economic performance by these hard-to-abate industries that were threatened with paying high carbon taxes and being penalized by border adjustment tariffs. The objectives of the workshop were to listen to experts on the technologies of Carbon Capture, Utilization, and Storage (CCUS) and to encourage networking among Hard-to-Abate industries in Southwestern Ontario.



WISE SPECIAL LECTURE | NUCLEAR ENERGY FOR A SUSTAINABLE FUTURE: SMALL MODULAR AND ADVANCED REACTORS

February 13, 2023

WISE presented this special lecture in collaboration with the Office of Research at University of Waterloo. This lecture explored the role of nuclear energy in decarbonizing and achieving net-zero economies in Canada. The world is facing an urgent need to decarbonize and reach net-zero emissions to address the impacts of climate change. Nuclear energy has a critical role to play in this transition, providing a reliable and low-carbon energy solution. The discussion was on the current landscape in Canada, some of the advantages and limitations of nuclear energy compared to other energy sources and the potential impact of small modular reactors and advanced reactors. This lecture was intended for university students studying sustainable energy and included a summary of the range of relevant research underway at Canadian Nuclear Laboratories (CNL).



NET-ZERO WORKSHOP

April 20, 2023

WISE along with WCI, WISA, and Water Institute, hosted a day-long Net-Zero workshop to highlight key projects and research related to Net-Zero. University of Waterloo professors, researchers, and industry partners presented their projects and research in three panels:

- › Panel 1: Renewable Energy Technologies
- › Panel 2: Net-Zero Communities
- › Panel 3: Sustainable Transportation

There were also student poster sessions that highlighted student research in this area. This workshop brought together an executive forum intended to encourage the exchange of ideas that would help create a roadmap to guide the future of net-zero research and initiatives in Canada. The workshop focus was on collaboration in net-zero research and projects, the exploration of opportunities for partnership, and the integration of efforts across stakeholder groups.

WISE PARTICIPATION



5TH ANNUAL CANADA'S INNOVATION CORRIDOR SUMMIT TITLED "HYDROGEN PRODUCTION, STORAGE, AND DISTRIBUTION FOR NET-ZERO TRANSITION"

June 29, 2022

Professor XiaoYu Wu (Mechanical and Mechatronics Engineering) participated in the summit. Under the theme, Transition to Net-Zero, the 5th annual Canada's Innovation Corridor Summit highlighted and identified where the Corridor could utilize its strengths and talents to lead Canada's transitional economy and ensure our region takes on a global leadership position in providing and commercializing solutions. Specifically, programming focused on the challenges and opportunities that decarbonization will bring within the following key themes: industry, infrastructure, transportation, and research.

WISA SUSTAINABLE AERONAUTICS SUMMIT

October 4-5, 2022



The Waterloo Sustainable Aeronautics (WISA) summit was held at the Region of Waterloo International Airport Operations Centre. The

summit brought together more than 200 researchers and leaders from academia, industry and government. Experts discussed solutions to build a sustainable future for air travel and advance the aeronautics industry. WISE participated in this event as an exhibitor and showcases its R&D activities in the power and energy area.

MUNICIPAL NET-ZERO ACTION RESEARCH PARTNERSHIP (N-ZAP) PROJECT COMMITTEE MEETING

October, 2022



N-ZAP is a five-year action research partnership/project led by the University of Waterloo with Professor Amelia Clarke as the PI, the Federation of Canadian Municipalities, and ICLEI Canada. It is funded by the Government of Canada through the Climate Action and Awareness Fund (CAAF). The focus was to analyze different strategies to support the Canadian municipalities to monitor, measure and achieve net-zero (GHG) mitigation goals. The aim was to ensure emissions reduction projects, policies and programs were aligned with Canada's national reduction commitments. The discussion was on creating improved measurement, analysis and monitoring systems for both municipal and community-wide GHG emissions to advance the quantification of GHG emissions, enable the application of methods to identify mitigation opportunities and evaluate their effectiveness. This would augment national reporting processes and align with international practice. The meeting was the first in-person meeting at the University of Waterloo in October of 2022.



DISTRICT ENERGY SYSTEM (DES) RESEARCHER OPEN HOUSE

November 3, 2022

As Waterloo continued to advance its Shift: Neutral climate and energy action plan, the University has undertaken a study to determine how it could decarbonize the campus district energy system, which accounted for around 75% of its emissions. The project was led by the Sustainability Office and Plant Operations, and is being completed by Doherty Engineering. The Sustainability Office and Plant Operations had partnered with Waterloo Climate Institute and Waterloo Institute for Sustainable Energy to host a special open house for researchers with interest and expertise in sustainable energy technologies and policy, climate action planning in an organizational context, or district energy systems. The focus was on: reviewing summary information on the project; reflecting on initial assessments of potential technology solutions and implementation strategies; speaking to the project team members; and submitting thoughts, ideas, and suggestions on technologies and strategies.



2022 WORLD FUEL CELL CONFERENCE (WFCC2022)

December 12-15, 2022

It was held at the National Fuel Cell Research Center, the University of California Irvine. Professor Xianguo Li (Mechanical and Mechatronics Engineering) served as the conference co-chair. It was a multi-disciplinary conference that covered the latest developments and advancements in fuel cells, from fundamentals, to advanced materials, design, engineering, products, and applications. It was of a particular value and interest to those in the relevant fields.



VELOCITY INNOVATION CHALLENGE

January 20-February 6, 2023

Ambika Opal was invited as a guest presenter and judge for the Velocity Innovation Challenge, ran by Velocity. Three global challenges were presented to student participants: energy, food, and health. Ambika led the energy challenge. She conducted a presentation on energy access challenges and technologies to the students teams, including access to electricity, access to clean cooking fuels and technologies, and global statistics on energy access. Four teams chose to focus on the energy challenge, developing solutions such as clean cookstoves, lighting efficiency education programs, and renewable energy policy improvements for specific countries. The overall winner of the event was an energy team who designed a new clean cookstove and venting process to reduce indoor air pollution.



SOUP AND BANNOCK LUNCH

February 16, 2023

WISE along with Cooperative and Experiential Education ran a Soup and Bannock Lunch for the Waterloo Indigenous Student Centre. WISE staff prepared two soups for WISC staff and students, and presented information about internships and co-op placements with AE4H partners.



FEDERATION OF CANADIAN MUNICIPALITIES SUSTAINABLE COMMUNITIES CONFERENCE

February 7-10, 2023

Professor Amelia Clarke presented the Municipal Net-Zero Action Research Partnership (N-ZAP) poster at the Federation of Canadian Municipalities Sustainable Communities Conference in February of 2023.



SDG IMPACT CHALLENGE

March 9-10, 2023

WISE, along with Impact Alliance (a student club) and Cooperative and Experiential Education ran a two-day collaborative hackathon for students of all disciplines and years of study. At the hackathon, Rajnish Jain, founder of Avani Bio Energy, presented two real-life sustainability challenges his India-based organization is facing. One challenge was focused on calculations to develop a business case for selling carbon offsets as a revenue stream for Avani, and the other challenge was focused on the development of a resource centre or library to scale the work that Avani does.



11TH ANNUAL CLEAN ENERGY EXPO

February 23, 2023

Every year, the Centre for Urban Energy at Toronto Metropolitan University (TMU) opens its doors to the public for Clean Energy Expo. The event highlights included:

listening to high-profile guest speakers; meeting the researchers and graduate students addressing important energy challenges in energy storage, smart grid, renewables and more; student research awards ceremony sponsored by Toronto Hydro; tour of the one-of-a-kind Schneider Electric Smart Grid Laboratory and learn how to test your products, prototypes and technologies; learning about the professional development programs, including the Professional Master's Diploma in Energy and Innovation and our Electrical Engineering 101 Series; meeting with the Clean Energy Zone startups; and networking with professionals from across the energy sector. randomly as it was not a competitive event.



SDG MENTORSHIP WEEK

March 6-10, 2023

Sustainable Development Goal week was held in March 2023, at universities across Canada. Impact Alliance, an SDG-focused student club at the University of Waterloo, ran an SDG Mentorship Week to give students access to education and experts related to the SDGs. Impact Alliance invited Ambika Opal to conduct a mentorship week session on SDG 7: Affordable and Clean Energy on March 7th, 2023. Ambika presented the challenges of access to energy, projects that WISE works on regarding SDG 7, and inspired students to see the connections between SDG 7 and other SDGs such as No Poverty, Good Health and Wellbeing, and Quality Education.



AE4H GUEST LECTURES

March 9-10, 2023

In March 2023, AE4H member Rajnish Jain from Avani Bio Energy in Uttarakhand, India, conducted two guest lectures in an Environment and Business class taught by Professor Sean Geobey, and an International Development class taught by Professor Simron Singh. Rajnish shared the work of his social enterprise and discussed corporate social responsibility in the Environment and Business class, and progress towards sustainable development goals in the International Development class.



THE 4TH INTERNATIONAL CONFERENCE ON SOLAR TECHNOLOGIES AND HYBRID MINI GRIDS TO IMPROVE ENERGY ACCESS

April 26-29, 2023

The 4th International Conference on Solar Technologies & Hybrid Mini Grids to improve energy access, known in short as the S-@ccess conference, occurred from April 26-29, 2023. This conference was run by Trama TecnoAmbiental and the University of the Balearic Islands in Palma, Spain, and WISE was one of the conference partners, sponsors, and on the organizing committee. Prof. Jatin Nathwani, the founding Executive Director and a WISE member, was also on the conference scientific committee. Throughout the 2022-23 year, WISE supported the organization of the conference, and Prof. Nathwani and Ambika Opal attended the conference as representatives from the University of Waterloo.

ENGINEERING SCIENCE QUEST – ENVIRONMENTAL ENGINEERING WEEK

April 11, 2023



Engineering Science Quest is a program run by the Faculty of Engineering for high school and elementary school students to get involved in science and engineering. One program is a weekly after school session for students in grades 9-11. Ambika Opal and Professor Jatin Nathwani were invited to conduct a presentation on access to energy for environmental engineering week. Students learned about the Sustainable Development Goals, access to electricity and clean cooking, learned about WISE and AE4H partners and projects, and had a meaningful discussion on how they can contribute to sustainable energy and energy access goals.



URBAN LOGISTICS AND SUSTAINABLE TRANSPORTATION WORKSHOP

May 18, 2023

Professor Bissan Ghaddar (Management Sciences) was invited as a speaker at the University of Bergamo to present her research work in the area of optimization under uncertainty and machine learning. The focus of the workshop was to discuss the modeling and solving of realistic and timely urban goods transportation problems, while explicitly considering their uncertain dimensions, such as Customer Demand (CD), Travel Times (TT), Presence of Customers (PC). The aim of the models would be to facilitate the identification and design of sustainable local authority policies aimed at supporting livability, connectivity, and sustainability.

HIGH SCHOOL STUDENT TOURS

May 15-16, 2023



WISE conducted three information sessions and tours of the Evolv1 building for local high school student groups from Grand River Collegiate Institute, St. John's-Kilmarnock School, and Laurel Heights Secondary School. Students were working on projects regarding sustainable energy and reached out to WISE for more information. WISE invited them for a tour of the Evolv1 building and an information session on sustainable energy. During these tours, WISE provided information on the passive and active solar technologies, geothermal energy, psychological elements of sustainability, sustainable water systems, living wall, and architectural elements of the Evolv1 building, as well as a demo of WISE staff members' electric vehicles.

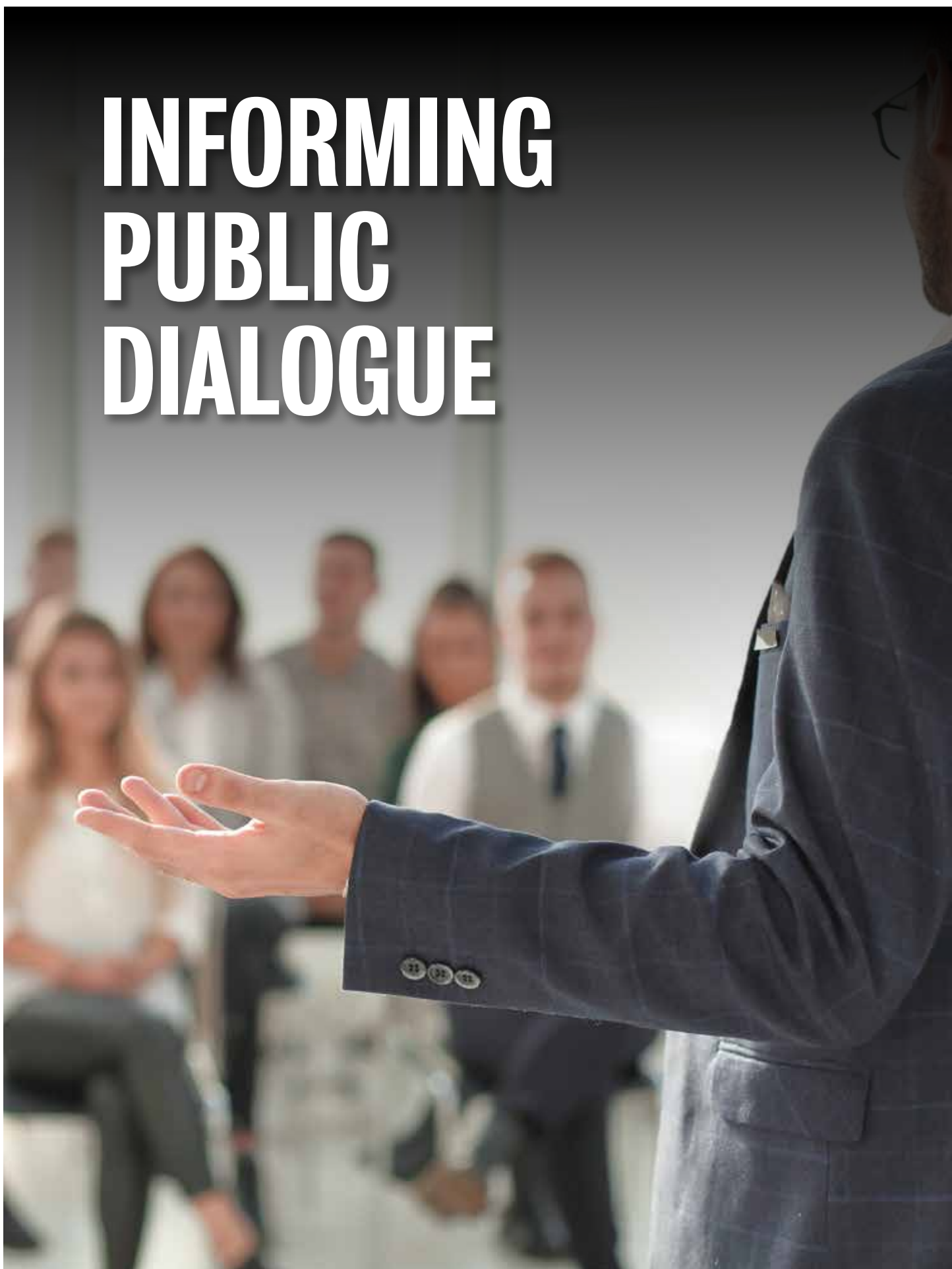


INFLUENCE

Our research shapes public attitudes, informs energy policies and improves quality of life at home and around the globe. By publicizing our work, organizing events and participating in important forums, we give governments, businesses and non-governmental organizations the information they need to advance new ideas and implement innovative concepts that benefit society as a whole.



INFORMING PUBLIC DIALOGUE



PUBLIC LECTURE SERIES

JUNE 2022

Daniel Eduardo Olivares Quero

Associate Professor,
Faculty of Engineering and
Sciences, and Director,
Center for Energy Transition
(CENTRA), Universidad
Adolfo Ibáñez (UAI)

Decarbonization
Pathways and Flexibility
Requirements in the
Chilean Electric
Power System

DECEMBER 2022

Dr. Eng. Mohamed M. Elkadragy

Technical Manager for
Battery and Energy Storage
at one of the leading
German Renewable
Energy companies

Battery Fundamentals and
Applications as Electrical
Vehicles: State-of-the-art
and Future Trends

FEBRUARY 2023

Ali Siddiqui

Head of Directorate,
Advanced Reactors,
Canadian Nuclear
Laboratories (CNL)

Nuclear Energy for a
Sustainable Future:
Small Modular and
Advanced Reactors

Nelson Leite

Chief Operating Officer,
FuelPositive

FuelPositive's
Containerized Green
Ammonia Systems:
Prioritizing Farmers
and Food Security

APRIL 2023

Faisal Kazi

President and CEO,
Siemens Canada Limited

The Grid of the Future:
How smart grids,
decentralized energy
resources, and new
business models can
help us reach a Net
Zero Grid by 2035



RESEARCH SPOTLIGHTS

WISE research spotlights showcase the advances our members are making to **deliver** energy more intelligently, **enable** smart policies and planning and **conserve** energy through greater efficiency. As a result, we've helped WISE researchers gain prominence with a wider audience in government, business and industry.



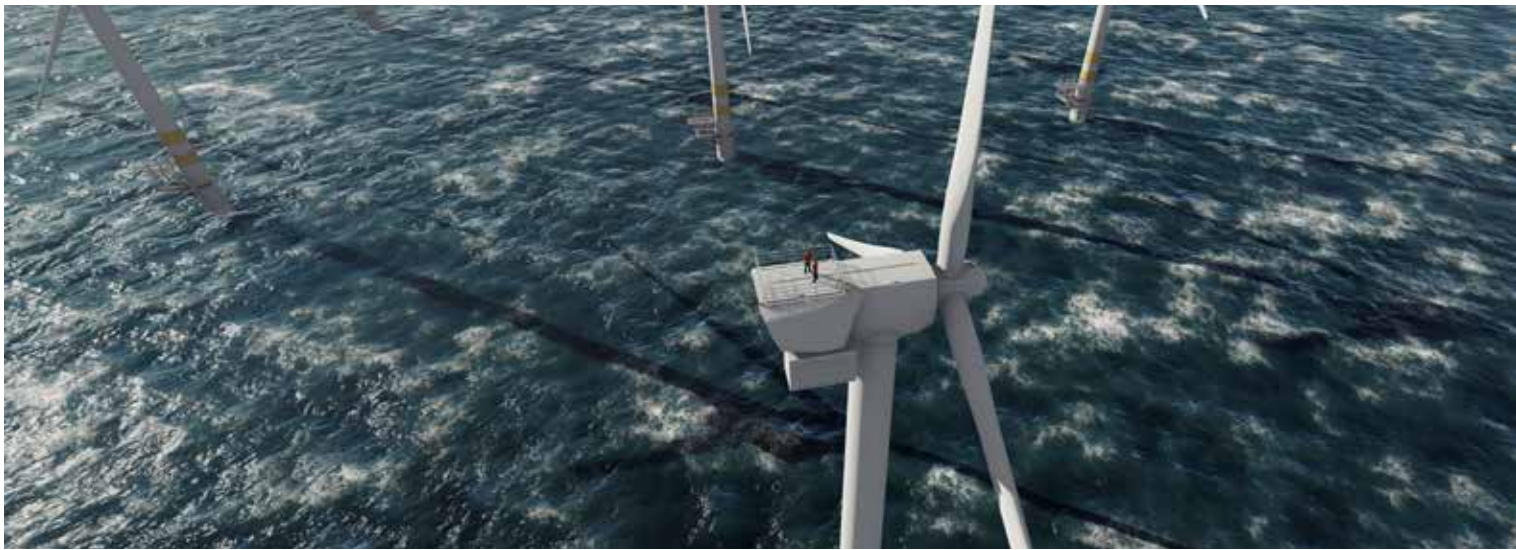
GAME THEORY IN THE ENERGY STORAGE MARKET

RESEARCHERS: Magdy Salama, Maria Hanna and Mostafa Shaaban

August 2022

Energy storage systems like batteries, supercapacitors and flywheels play an important role in the world of renewables. When the sun isn't shining or the wind isn't blowing, these devices ensure customers have reliable power. This has sparked interest in privately owned energy storage hubs that could sell power to customers as they need it. To find out how this might play out in the marketplace, WISE researcher Magdy Salama and his colleagues applied game theory, a method that models competition, interdependence, conflicts of interest and real-life decision making. Their study examined how interactions between an energy hub owner and a collection of customers – electric grids, residential customers and industrial customers – might play out under two different approaches.

RESEARCH SPOTLIGHTS



MAKING OFFSHORE WIND FARMS LEAN AND GREEN

RESEARCHERS: Prof. Mehrdad Kazerani and Marten Pape

September 2022

As the number of offshore wind farms around the world grows, so do efforts to make them more cost-effective and efficient. One way to do that is to avoid oversizing the power electronic converters that transform the variable-frequency electricity produced by the turbines into a fixed frequency suitable for the grid. In series-connected, single-string DC transmission systems – the most efficient way to transmit the electricity from distant turbines – operation of each converter is influenced by those of all the other wind turbines in the farm. But traditional methods for sizing converters don't account for those interdependencies. WISE researchers Marten Pape and Mehrdad Kazerani decided to tackle that problem. They developed a framework for determining the optimal sizes of converters for offshore wind farms that use HVdc transmission. Their model considered a slew of parameters, from wind speeds and fault handling to turbine startup requirements and more.

ANALYZING THE ECONOMIC POTENTIAL OF ELECTRIFIED AMMONIA PRODUCTION

RESEARCHERS: Prof. Xiao-Yu Wu, Milind Jain, Rithu Muthalathu

November 2022

Today, new technologies are emerging that use electricity to produce low-carbon ammonia – a versatile commodity that can be sold locally as fertilizer, traded as an export good or used to temporarily store electricity when supply exceeds demand. It's an enticing idea for energy producers, who often sell their excess electricity to neighbouring markets at a significant loss. But do the numbers add up? To find out, WISE researcher XiaoYu Wu and his colleagues carried out detailed analyses on the potential economic risks and benefits. As a model, the team used a Haber-Bosch ammonia plant powered by Ontario's electricity grid. They started by calculating the plant's lifetime production costs per tonne of ammonia under different scenarios, incorporating capital and operating costs, capacity factors, plant sizes and more.

PROLONGING THE LIFE OF WIND FARM TRANSFORMERS

RESEARCHERS: Prof. Shesha Jayaram, Mahdi Khanali and Anurag Devadiga

December 2022

Transformers are a crucial – and expensive – part of wind farm infrastructure, boosting the low-voltage output from turbine generators to the higher voltage required by the grid. But too often, they fail prematurely. That's because standard transformers aren't designed to handle spikes in high-frequency energy that are common in wind farms, where vacuum circuit breakers and switching devices often create transient voltages. As a result, they can break down the transformer's insulation, putting it out of commission. WISE researcher Dr. Shesha Jayaram and two of her grad students set out to analyze the problem. Mahdi Khanali began by developing and verifying a scaled model, since working with large power transformers is complex and time-consuming. He also developed a chemical method to detect the impact of partial discharges (PDs) – as directly measuring the PD activities is difficult electromagnetically in windfarm connected transformers.

RESEARCH SPOTLIGHTS



BUILDING BATTERIES TO GET FLYING CARS OFF THE GROUND

RESEARCHERS: Prof. Michael Fowler, Yueqi Wang, Dan Dan, Yangjun Zhang, Yuping Qian, Satyam Panchal, Weifeng Li, Manh-Kien Tran, Yi Xie

January 2023

Flying cars are no longer reserved for sci-fi novels, with groups like Boeing, Toyota and NASA working to move electric vehicles into the skies. One of the key challenges is ensuring the power batteries in these airborne automobiles don't overheat during takeoff and landing, when discharge rates peak. Flat heat pipe (FHP) technology offers a promising solution. Thanks to its high heat conductivity and large surface area, it can effectively dissipate the heat from battery packs and ensure uniform temperatures within them. So WISE researcher Michael Fowler and his colleagues set out to explore its potential in battery thermal management systems for flying cars. They started by developing a thermal model of the batteries that allowed them to examine how the state of charge, battery temperature and current affect the amount of heat produced.

INSIGHTS INTO CHINA'S ENERGY STORAGE

RESEARCHERS: Ian Rowlands and Yixin Chen

February 2023

Socio-political factors can make or break the large-scale deployment of virtually any new technology. Energy storage (e.g., batteries, pumped hydro, and compressed air) is one such technology, requiring broad social acceptance if it is to play an essential role for a sustainable energy transition. So how are those factors affecting energy storage deployment in China – the world's largest greenhouse gas emitter? Because Chinese media outlets typically reflect government positions and further shape public perceptions, WISE researchers Yixin (Candice) Chen and Ian Rowlands decided to investigate. They scrutinized two of the nation's top circulating mainstream newspapers – the People's Daily and China Daily – for relevant articles between 2017 and 2019. These years marked significant growth in energy storage and public debates over it, driven by China's 13th Five-Year Plan for Energy Development and other official policies related to energy storage.

OPTIMIZING OPERATIONS IN NET-ZERO BUILDINGS

RESEARCHERS: Paul Parker, Monika Mikhail, David Mather, and Costa Kapsis

March 2023

Today, buildings account for nearly a third of global energy consumption. Net-zero energy structures aim to decarbonize the sector by generating as much electricity on site as they use each year. But what happens when their actual energy consumption is initially higher than intended? In the case of a 100,000-square-foot office building recently constructed in Waterloo, Ontario, closing that performance gap required a complex process of optimizing the HVAC systems. WISE researchers were there to assess the results. Paul Parker, Monika Mikhail, David Mather and Costa Kapsis used data from the building's 43 energy meters to compare consumption during 2019 – the initial year of operation – with the first six months of 2022 and analyze the impact of different commissioning activities. They also interviewed the building operator and energy advisor for additional insights into operational decisions.

PUBLICATIONS

SELECTED MEMBER PUBLICATIONS [2022-2023]

- Alghamdi, B., & **Cañizares, C.** (2022). Frequency and voltage coordinated control of a grid of AC/DC microgrids. *Applied Energy*, 310, 118427. doi:10.1016/j.apenergy.2021.118427
- Ayad, A., Khalaf, M., **Salama, M.**, & El-Saadany, E. F. (2022). Mitigation of false data injection attacks on automatic generation control considering nonlinearities. *Electric Power Systems Research*, 209, 107958. doi:10.1016/j.epr.2022.107958
- Cabrera, G., Dickson, A., **Nimubona, A.**, & Quigley, J. (2022). Carbon capture, utilisation and storage: Incentives, effects and policy. *International Journal of Greenhouse Gas Control*, 120, 103756. doi:10.1016/j.ijggc.2022.103756
- Chang, H., **Ghaddar, B.**, & **Nathwani, J.** (2022). Shared community energy storage allocation and optimization. *Applied Energy*, 318, 119160. doi:10.1016/j.apenergy.2022.119160
- Chen, Z., Wang, X., Wang, L., & **Wu, Y.** (2022). Ag@Pd bimetallic structures for enhanced electrocatalytic CO₂ conversion to CO: an interplay between the strain effect and ligand effect. *Nanoscale*, 14(31), 11187-11196. doi:10.1039/d2nr03079a
- Cunanan, C. J., Elorza Casas, C. A., Yorke, M., **Fowler, M.**, & **Wu, X.** (2022). Design and Analysis of an Offshore Wind Power to Ammonia Production System in Nova Scotia. *Energies (Basel)*, 15(24), 9558. doi:10.3390/en15249558
- Dordí, T., Gehricke, S. A., Naef, A., & **Weber, O.** (2022). Ten financial actors can accelerate a transition away from fossil fuels. *Environmental Innovation and Societal Transitions*, 44, 60-78. doi:10.1016/j.eist.2022.05.006
- Guzman, N. S., **Cañizares, C. A.**, **Bhattacharya, K.**, & Sohm, D. (2022). Marginal Rate of Technical Substitution curves for frequency regulation services. *Electric Power Systems Research*, 212, 108550. doi:10.1016/j.epr.2022.108550
- Ibrahim, K., Sharkawy, R. M., Temraz, H. K., & **Salama, M. M. A.** (2022). Reliability calculations based on an enhanced transformer life expectancy model. *Ain Shams Engineering Journal*, 13(4), 101661. doi:10.1016/j.asej.2021.101661
- Jain, M., Muthalathu, R., & **Wu, X.** (2022). Electrified ammonia production as a commodity and energy storage medium to connect the food, energy, and trade sectors. *iScience*, 25(8), 104724. doi:10.1016/j.isci.2022.104724
- Kirakosyan, A., El-Saadany, E. F., Moursi, M. S. E., & **Salama, M. M. A.** (2022). An Improved Frequency Support Algorithm for MT-HVDC Systems. *IEEE Transactions on Power Delivery*, 37(3), 1916-1929. doi:10.1109/TPWRD.2021.3101144
- Li, C., Jin, S., Archer, L. A., & **Nazar, L. F.** (2022). Toward practical aqueous zinc-ion batteries for electrochemical energy storage. *Joule*, 6(8), 1733-1738. doi:10.1016/j.joule.2022.06.002

Li, X., Zhao, J., Duan, J., Panchal, S., Yuan, J., **Fraser, R., Fowler, M.,** & Chen, M. (2022). Simulation of cooling plate effect on a battery module with different channel arrangement. *Journal of Energy Storage*, 49, 104113. doi:10.1016/j.est.2022.104113

Lin, B., **Ghaddar, B.,** & **Nathwani, J.** (2022). Deep Reinforcement Learning for the Electric Vehicle Routing Problem With Time Windows. *IEEE Transactions on Intelligent Transportation Systems*, 23(8), 11528-11538. doi:10.1109/TITS.2021.3105232

Lotfi, A., & **Pirnia, M.** (2022). Constraint-guided Deep Neural Network for solving Optimal Power Flow. *Electric Power Systems Research*, 211, 108353. doi:10.1016/j.epr.2022.108353

Ma, J., & Venkatesh, B. (2022). New Real-Time Demand Response Market Co-Optimized With Conventional Energy Market. *IEEE Systems Journal*, 16(4), 1-12. doi:10.1109/JSYST.2021.3132786

Madadi Avargani, V., Zendehboudi, S., Cata Saady, N. M., & **Dusseault, M. B.** (2022). A comprehensive review on hydrogen production and utilization in North America: Prospects and challenges. *Energy Conversion and Management*, 269, 115927. doi:10.1016/j.enconman.2022.115927

Martín-Chivelet, N., **Kapsis, K.,** Wilson, H. R., Delisle, V., Yang, R., Olivieri, L., Polo, J., Eisenlohr, J., Roy, B., Maturi, L., Otnes, G., Dallapiccola, M., & Upalakshi Wijeratne, W. M. P. (2022). Building-Integrated Photovoltaic (BIPV) products and systems: A review of energy-related behavior. *Energy and Buildings*, 262, 111998. doi:10.1016/j.enbuild.2022.111998

McDiarmid, H., & **Parker, P.** (2022). Accelerating the 1.5°C energy transition for Canadian residential buildings through selective direct electrification with heat pumps. *The Canadian Geographer*, 66(4), 756-768. doi:10.1111/cag.12786

Muazzam, Y., Yousaf, M., Zaman, M., **Elkamel, A.,** Mahmood, A., Rizwan, M., & Adnan, M. (2022). Thermo-Economic Analysis of Integrated Hydrogen, Methanol and Dimethyl Ether Production Using Water Electrolyzed Hydrogen. *Resources (Basel)*, 11(10), 85. doi:10.3390/resources11100085

Pirnia, M., Elsarague, M., Beylunioglu, F. C., Ahmed, M., & **Nathwani, J.** (2022). Impact of COVID-19 on Ontario's electricity market: Load, generation, emissions. *The Electricity Journal*, 35(4), 107111. doi:10.1016/j.tej.2022.107111

Sakib, M. N., **Azad, S. P.,** & **Kazerani, M.** (2022a). A Critical Review of Modular Multilevel Converter Configurations and Submodule Topologies from DC Fault Blocking and Ride-Through Capabilities Viewpoints for HVDC Applications. *Energies (Basel)*, 15(11), 4176. doi:10.3390/en15114176

Sakib, M. N., **Azad, S. P.,** & **Kazerani, M.** (2022b). Fast DC Fault Current Suppression and Fault Ride-Through in Full-Bridge MMCs via Reverse SM Capacitor Discharge. *Energies (Basel)*, 15(13), 4595. doi:10.3390/en15134595

Sekhar, R., Shah, P., Panchal, S., **Fowler, M.,** & **Fraser, R.** (2022). Distance to empty soft sensor for ford escape electric vehicle. *Results in Control and Optimization*, 9, 100168. doi:10.1016/j.rico.2022.100168

Soltani, M., Moradi Kashkooli, F., Alian Fini, M., Gharapetian, D., **Nathwani, J.,** & **Dusseault, M. B.** (2022). A review of nanotechnology fluid applications in geothermal energy systems. *Renewable & Sustainable Energy Reviews*, 167, 112729. doi:10.1016/j.rser.2022.112729

Taqvi, S. T., Almansoori, A., Maroufmashat, A., & **Elkamel, A.** (2022). Utilizing Rooftop Renewable Energy Potential for Electric Vehicle Charging Infrastructure Using Multi-Energy Hub Approach. *Energies (Basel)*, 15(24), 9572. doi:10.3390/en15249572

Tran, M., Mevawalla, A., Aziz, A., Panchal, S., Xie, Y., & **Fowler, M.** (2022). A Review of Lithium-Ion Battery Thermal Runaway Modeling and Diagnosis Approaches. *Processes*, 10(6), 1192. doi:10.3390/pr10061192

Yazdavar, A. H., Eajal, A. A., Azzouz, M. A., **Salama, M. M. A.**, & El-Saadany, E. F. (2022). Harmonic Analysis of Droop-Based Islanded Microgrids. *IEEE Transactions on Smart Grid*, 13(4), 2589–2600. doi:10.1109/TSG.2022.3155710

Ye, W., Herdem, M., Li, J., **Nathwani, J.**, & **Wen, J.** (2022). Formulation and Data-Driven Optimization for Maximizing the Photovoltaic Power with Tilt Angle Adjustment. *Energies (Basel)*, 15(22), 8578. doi:10.3390/en15228578

Zhuang, Y., & **Simakov, D.** (2022). Autothermal CO₂ hydrogenation reactor for renewable natural gas generation: experimental proof-of-concept. *Reaction Chemistry & Engineering*, 7(11), 2285–2297. doi:10.1039/d2re00236a

2023

Ahmadloo, F., & **Azad, S.** (2023). Grid interaction of multi VSC systems for renewable energy integration. *IET Renewable Power Generation*, 17(5), 1212–1223. doi:10.1049/rpg2.12676

Alkatheri, M., Alhameli, F., Betancourt-Torcat, A., Almansoori, A., & **Elkamel, A.** (2023). Clustering Approach for the Efficient Solution of Multiscale Stochastic Programming Problems: Application to Energy Hub Design and Operation under Uncertainty. *Processes*, 11(4), 1046. doi:10.3390/pr11041046

Beigzadeh, A., Alabbad, M., Liu, D., Aljohani, K., Hakimov, K., Kashif, T. A., Zanganesh, K., **Croiset, E.**, & Farooq, A. (2023). Reaction kinetics for high pressure hydrogen oxy-combustion in the presence of high levels of H₂O and CO₂. *Combustion and Flame*, 247, 112498. doi:10.1016/j.combustflame.2022.112498

Chun Yuen Kwok, Xu, S., Kochetkov, I., Zhou, L., & **Nazar, L.** (2023). High-performance all-solid-state Li₂S batteries using an interfacial redox mediator. *Energy & Environmental Science*, 16(2), 610–618. doi:10.1039/d2ee03297j

Esmaeilion, F., Soltani, M., **Dusseault, M. B.**, & Rosen, M. A. (2023). Performance investigation of a novel polygeneration system based on liquid air energy storage. *Energy Conversion and Management*, 277, 116615. doi:10.1016/j.enconman.2022.116615

Espina, E., Cárdenas-Dobson, R., Simpson-Porco, J. W., **Kazerani, M.**, & Sáez, D. (2023). A Consensus-Based Distributed Secondary Control Optimization Strategy for Hybrid Microgrids. *IEEE Transactions on Smart Grid*, 1–14. doi:10.1109/TSG.2023.3263107

Hamouda, M. R., Nassar, M. E., & **Salama, M. M. A.** (2023). Blockchain-based sequential market-clearing platform for enabling energy trading in Interconnected Microgrids. *International Journal of Electrical Power & Energy Systems*, 144, 108550. doi:10.1016/j.ijepes.2022.108550

Iqbal, M. W., Yu, Y., & **Simakov, D. S. A.** (2023). Enhancing the surface area stability of the cerium oxide reverse water gas shift nanocatalyst via reverse microemulsion synthesis. *Catalysis Today*, 407, 230–243. doi:10.1016/j.cattod.2021.11.029

Kirakosyan, A., Ameli, A., El-Fouly, T. H., El Moursi, M. S., **Salama, M.**, & El-Saadany, E. F. (2023). A Novel Control Technique for Enhancing the Operation of MTDC Grids. *IEEE Transactions on Power Systems*, 38(1), 1. doi:10.1109/TPWRS.2022.3155692

- Li, J., Herdem, M. S., **Nathwani, J.**, & **Wen, J. Z.** (2023). Methods and applications for Artificial Intelligence, Big Data, Internet of Things, and Blockchain in smart energy management. *Energy and AI*, 11, 100208. doi:10.1016/j.egyai.2022.100208
- Mashhadimoslem, H., Ghaemi, A., Maleki, A., & **Elkamel, A.** (2023). Enhancement of oxygen adsorption using biomass-based oxidized porous carbon. *Journal of Environmental Chemical Engineering*, 11(2), 109300. doi:10.1016/j.jece.2023.109300
- Maurer, J., Tschuch, N., Krebs, S., **Bhattacharya, K.**, **Cañizares, C.**, & Hohmann, S. (2023). Toward transactive control of coupled electric power and district heating networks. *Applied Energy*, 332, 120460. doi:10.1016/j.apenergy.2022.120460
- Mikhail, M., Mather, D., **Parker, P.**, & **Kapsis, K.** (2023). Net-positive office commissioning and performance gap assessment: Empirical insights. *Energy and Buildings*, 279, 112717. doi:10.1016/j.enbuild.2022.112717
- Mustafa, A. M., Nassar, M. E., **Salama, M. M. A.**, & Hamouda, M. R. (2023). Voltage-sag mitigation by stability-constrained partitioning scheme. *Ain Shams Engineering Journal*, 14(2), 101867. doi:10.1016/j.asej.2022.101867
- Ogbe, E., Almansoori, A., **Fowler, M.**, & **Elkamel, A.** (2023). Optimizing Renewable Injection in Integrated Natural Gas Pipeline Networks Using a Multi-Period Programming Approach. *Energies (Basel)*, 16(6), 2631. doi:10.3390/en16062631
- Sarmast, S., Rouindej, K., **Fraser, R. A.**, & **Dusseault, M. B.** (2023). Sizing-design method for compressed air energy storage (CAES) systems: A case study based on power grid in Ontario. *Energy Conversion and Management*, 277, 116656. doi:10.1016/j.enconman.2023.116656
- Soltani, H., Soltani, M., & **Nathwani, J.** (2023). Optimization of thermal energy storage: Evaluation of natural convection and melting-solidification time of eccentricity for a rotational shell-and-tube unit. *Journal of Energy Storage*, 58, 106423. doi:10.1016/j.est.2022.106423
- Usman, H. M., **EIShatshat, R.**, & El-Hag, A. H. (2023). Distribution Transformer Remaining Useful Life Estimation Considering Electric Vehicle Penetration. *IEEE Transactions on Power Delivery*, 1-12. doi:10.1109/TPWRD.2023.3265671
- Vera, E. G., **Cañizares, C. A.**, **Pirnia, M.**, Guedes, T. P., & Trujillo, J. D. M. (2023). Two-Stage Stochastic Optimization Model for Multi-Microgrid Planning. *IEEE Transactions on Smart Grid*, 14(3), 1723-1735. doi:10.1109/TSG.2022.3211449
- Vera, E. G., **Cañizares, C.**, & **Pirnia, M.** (2023). Geographic-information-based stochastic optimization model for multi-microgrid planning. *Applied Energy*, 340, 121020. doi:10.1016/j.apenergy.2023.121020
- Yang, L., Liu, H., Qiao, Z., Sun, P., Li, D., Jiang, R., Liu, S., Niu, Z., Zhang, Y., Lin, T., Zhang, Q., Gu, L., Wang, S., Cao, D., & **Chen, Z.** (2023). Highly Active and Durable Metal Free Carbon Catalysts for Anion Exchange Membrane Fuel Cells. *Advanced Energy Materials*, 13(20), n/a. doi:10.1002/aenm.202204390
- Yang, T., Luo, D., Liu, Y., Yu, A., & **Chen, Z.** (2023). Anode-free sodium metal batteries as rising stars for lithium-ion alternatives. *iScience*, 26(3), 105982. doi:10.1016/j.isci.2023.105982



AWARDS AND RECOGNITION

PROFESSOR PART OF \$24-MILLION ENERGY-STORAGE PROJECT

Professor **Yimin Wu** (Mechanical and Mechatronics Engineering) at Waterloo is part of an ambitious, \$24-million research project that received the green light from the federal government in April 2023. Prof. Wu is a co-applicant on CANSTOREnergy: Seasonal storage of renewable energy, a six-year initiative involving dozens of participants. Contributions from Prof. Wu will advance his work on an artificial leaf to convert carbon dioxide (CO₂) into alternative fuels and chemicals, climate-change research that attracted worldwide attention when it was published in a leading journal in 2019. He is expected to receive about \$1 million of the New Frontiers in Research Fund (NFRF) support for the overall project, which will be led by Prof. David Sinton of the University of Toronto. This funding will be a huge boost to his group as he continued his work in the CO₂ reduction field and move the technology closer to industrial adoption. Here, the primary focus is on the development of a renewable energy storage solution – essentially storing excess summer-generated renewable energy for use in the winter – that considers local concerns and displaces fossil fuels.

2022 E.W.R. STEACIE AWARD

Professor **Linda Nazar** (Chemistry) was awarded the 2022 E.W.R. Steacie Award by the Chemical Institute of Canada. The award is presented to “a scientist who has made a distinguished contribution to chemistry while working in Canada.” Prof. Nazar is an internationally recognized leader in the development of electrochemical energy storage devices and materials. Her team synthesizes new materials, determines their structures and investigates their electrochemical properties. In particular, she is interested in ion and electron transport in materials as these properties are central to solid state electrochemistry and energy storage batteries. During her distinguished career, to date Nazar has published more than 265 publications, which have been cited more than 58,000 times. She is an Officer of the Order of Canada and a Fellow of the Royal Society in both the UK and Canada. One of her research, published in *Nature Energy*, features a new lithium metal halide solid-state electrolyte. Its excellent conductivity properties meant that Nazar’s team could use this electrolyte to create an all-solid state battery with long cycle life that can operate at high voltages up to 4.8 V.

SARES 2022 SCIENCE AWARD

The International Sustainable Aviation and Energy Research Society (SARES) has given the 2022 Science Award to Professor **Paul Parker** (School of Environment, Enterprise and Development (SEED) and Geography and Environmental Management (GEM)) for his outstanding research and invaluable contributions to sustainable aviation globally. Parker is a sustainability researcher with a passion for solar powered flight. As a professor in the Faculty of Environment SEED and GEM, he has pursued both passions: sustainability and aviation. As an energy system researcher, he focused on improved efficiency and renewable sources of energy. Parker and his team have surveyed the different stakeholder groups and found a strong desire to try electric flight among students, instructors and manager/owners. Professor Parker’s next project is to compare the performance of an electric plane to conventional ones for flight training under Canadian conditions.

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22 Non-University
of Waterloo
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19 distinguished
awards and
honours

31
labs

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areas of
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Members of the Council comprise senior leaders from the business community engaged in the development of the energy sector and shaping its future directions. The Council members help guide our future initiatives, provide input to our strategic research directions and help to further the Institute's goals and mission.

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Shesha Jayaram
John Straube
XiaoYu Wu
Umair Shah
Costa Kapsis
Jatin Nathwani
Armughan Al-Haq
Sana Sadiq
Ambika Opal
Bernard Duncker
Adrian Blackwell
Jonathan Enns
Anna Klinkova ●
Adam Presslee
Adam Vitalis
Reem Roufail
Roberto Guglielmi
Michael Fisher
Gennaro Notomista
Jessie Ma
Tony Wirjanto
Juan Moreno-Cruz ●
Horatio Morgan
Amelia Clarke
Siby Samuel

- Canada Research Chair
- University Research Chair
- Distinguished Awards and Honours





AFFORDABLE ENERGY FOR HUMANITY

A Global Change Initiative

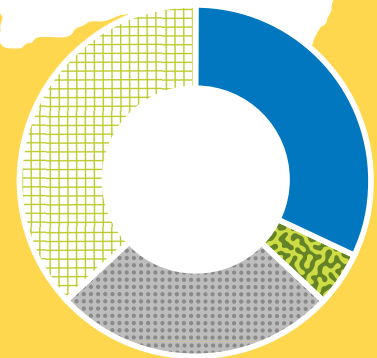


AE4H PARTICIPANTS

98 organizations in 37 countries are participating in the Global Change Initiative

98
organizations

37
countries



■ Private / 32%
■ Government / 5%
■ Non-Profit / 26%
■ Academic / 37%



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