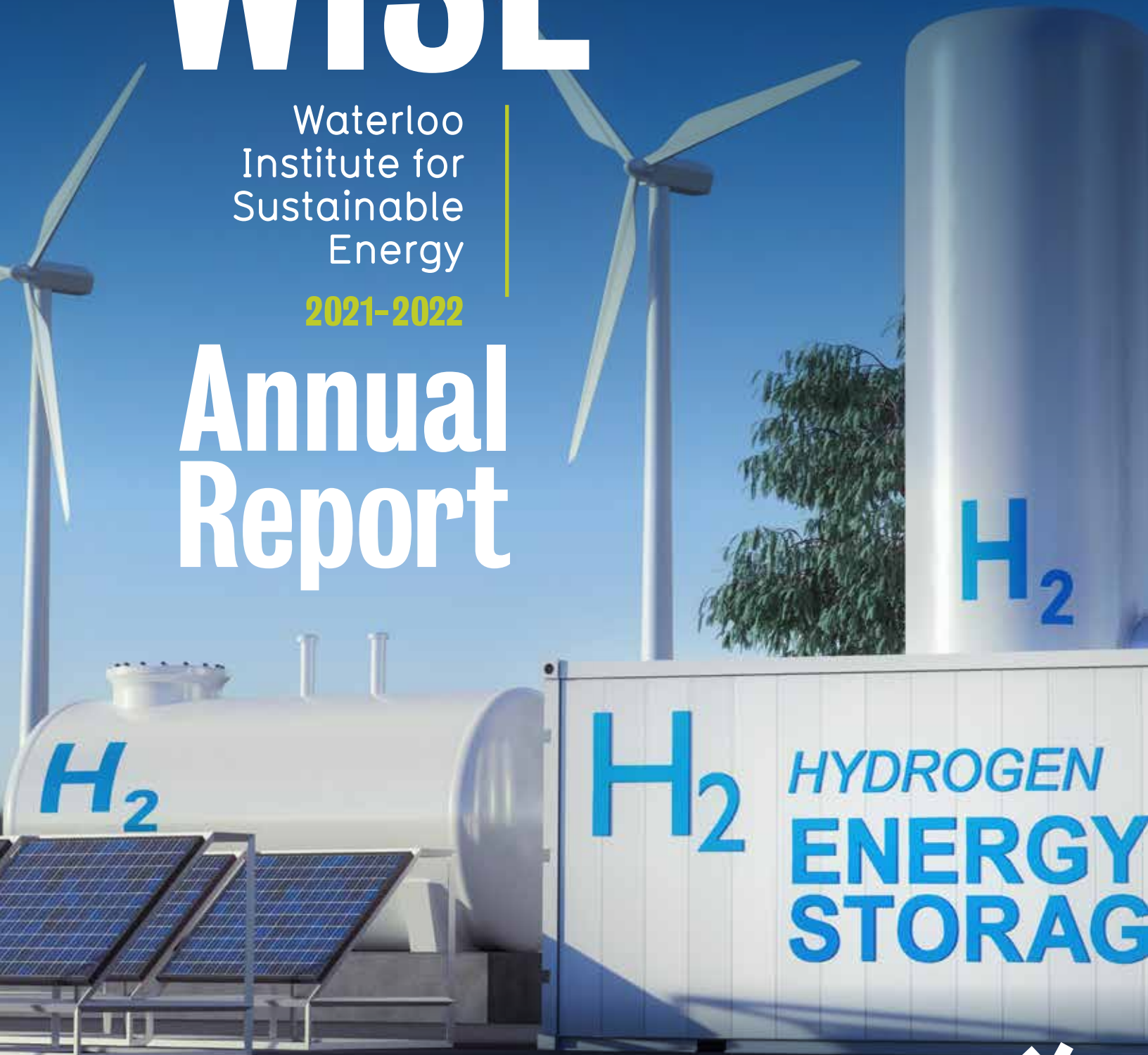


# WISE

Waterloo  
Institute for  
Sustainable  
Energy

2021-2022

## Annual Report

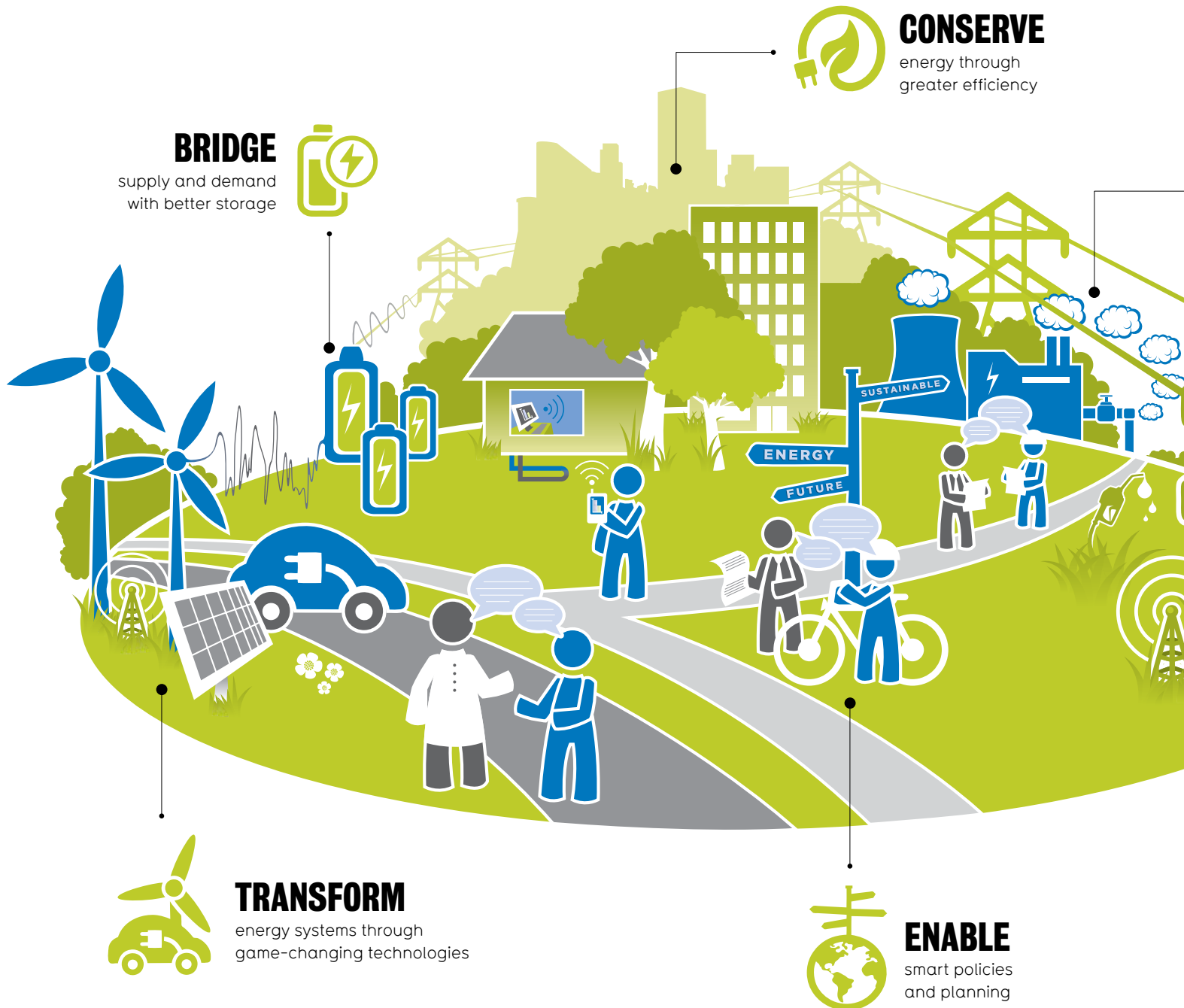


UNIVERSITY OF  
WATERLOO



WISE  
WATERLOO INSTITUTE  
FOR SUSTAINABLE ENERGY

# Waterloo Institute for Sustainable Energy



**IMPROVE**

conventional  
generation methods

**DELIVER**

energy more  
intelligently

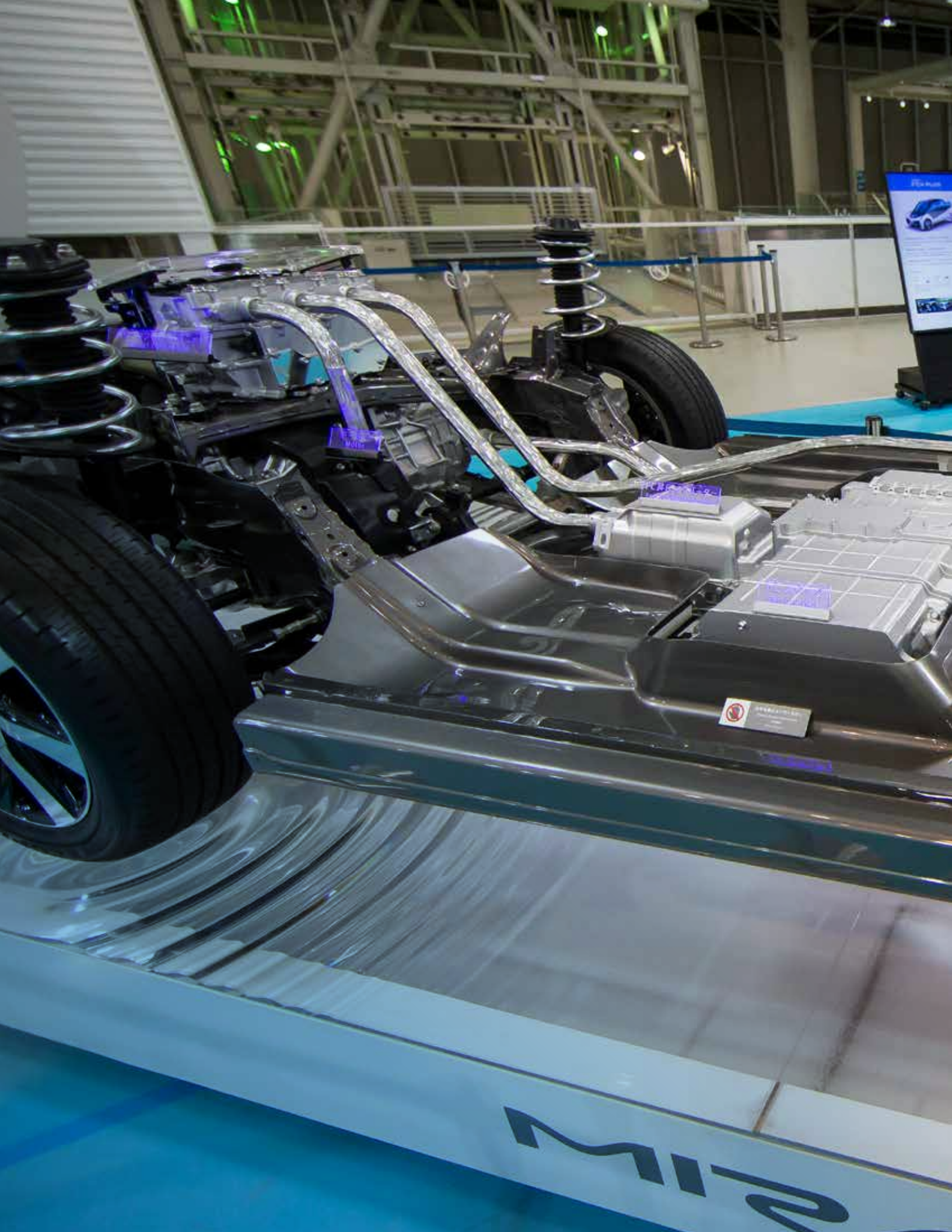
# VISION

**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**





2.1





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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.

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### REACH OUT

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

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### INFLUENCE

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



# A NOTE FROM THE EXECUTIVE DIRECTOR

As the incoming executive director of WISE, I express my strong support for the continued growth and success of the institute both nationally and globally. WISE works with multiple university departments, different faculty members, graduate students, industry partners, and governmental organizations in developing research initiatives specifically in the discipline of energy/renewable energy. The institute conducts research and develop innovative solutions and policies to help transform the energy system for long-term sustainability. WISE has a diversified portfolio of research projects, areas of expertise, and industry support. The advisory council of WISE comprises senior leaders from the business community who are engaged in the development of the energy sector and shaping its future directions. WISE has 30 state-of-the-art labs that can be used for applied research, technological development, and equipment testing. In the future, we aim to strengthen the existing and new coalitions and opportunities with all our stakeholders, achieving new heights of excellence in energy R&D and commercialization activities.

It is with honor and privilege I share the highlights of the WISE Annual Report 2021-2022. We have recognized the hard work of our members and the advancements they have made in the power and energy discipline. Our on-going ambition is to create accessible and affordable energy solutions for the privileged and underprivileged economies around the world for the social well-being of the humanity. Our “Affordable Energy for Humanity (AE4H) – A Global Change Initiative” is fully committed to support our faculty and student community regarding the initiation and execution of research projects, internships, and private sector alliances to scope and expand impactful interventions in the remote Indigenous communities of the Canadian Arctic.

I appreciate your time in reviewing the accomplishments of our members in the report. I look forward to our mutual engagement in creating new energy research initiatives.

A stylized, handwritten signature in black ink, appearing to read 'C. Cañizares'.

CLAUDIO CAÑIZARES, Executive Director



# NOTE FROM THE VICE PRESIDENT, RESEARCH AND INTERNATIONAL

I would like to welcome Professor Claudio Cañizares as the new incoming Executive Director at the Waterloo Institute for Sustainable Energy (WISE). Professor Cañizares is a University Professor and Hydro One Endowed Chair in the Department of Electrical & Computer Engineering (ECE) at Waterloo, where he has held various academic and administrative positions since 1993. His research activities focus on the study of stability, control, optimization, modeling, simulation, and computational issues in bulk power systems, microgrids, and energy systems in the context of competitive energy markets and smart grids. He has supervised/co-supervised over 170 research fellows and graduate students. He has authored/co-authored more than 360 publications with over 27,000 citations and a 75 h-index in Google Scholar, including journal and conference papers, several technical reports, book chapters, disclosures and patents. He has also led and been an integral part of securing many grants and contracts from government agencies and private companies worth over \$89 million in cash and in-kind, collaborating with multiple industry and university researchers in Canada and abroad in the areas of clean power and energy systems.

WISE provides a robust platform to undertake research, development, and training in the discipline of renewable energy and build innovative solutions to transform the energy system for long-term sustainability. Professor Cañizares has taken the responsibility to support the institute in its day-to-day business operations. He will be leading the institute during his tenure and continue to support fundamental research and industry-academic collaborations across numerous research disciplines. I wish Professor Cañizares all the best.



**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

Energy 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



# 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, CIVIL AND ENVIRONMENTAL ENGINEERING



Carl Haas is a Professor in and Chair of the Civil and Environmental Engineering department at the University of Waterloo. He is also a University Research Chair. Building on foundations in systems design and civil engineering, his research has grown to be multidisciplinary in nature with an emphasis on achieving sustainability and the circular economy in the built environment. It ranges from empirically based discovery to fundamental methods and processes that influence and improve practices. As a research catalyst, he collaborates with diverse colleagues toward achieving University of Waterloo's shared vision in a way that equitably contributes to fundamental advancement of knowledge and impact. By accomplishing Waterloo's vision and objectives, he contributed substantially to a better quality of life for all Canadians.

Prof. Haas along with his colleagues for one of his past projects has proposed a methodology based on Input-Output (IO) models for examining economic and energy impacts of substituting adaptive reuse for new building construction in Ontario. The research team concluded that adaptive reuse building construction may benefit Ontario's economy and reduce energy consumption under certain combinations of changes in supply and demand. The desired domain of adaptive reuse construction, where energy use decreases, while GDP and employment increases, is discerned for both the residential and non-residential building construction sectors in Ontario. This methodology may be used for other regions for which IO information exists. He also carried out another study in which it was found that the adaptive reuse of the building structure produces a considerable decrease in the environmental impacts and the construction building cost. Prof. Haas also led a project based on the quantitative comparison of adaptive reuse strategies of residential towers in northern climates.

The Department of Civil and Environmental Engineering has flourished and prospered under the governance of Prof. Haas since 2017. With 830 students enrolled in the undergraduate degree programs for architectural, civil, environmental and geological engineering, and 180 students in the graduate programs, the department attract curious, innovative and exceptional individuals from Canada and abroad who are looking to develop their theoretical and practical understanding of all aspects of the world around them – infrastructure and buildings, the natural environment, even soil and rocks. The 65 faculty and staff are experts in research areas as diverse as infrastructure management, drinking water treatment and structural rehabilitation, and the department pride itself on fostering a collaborative academic environment that is both challenging and fun. Profs. Basu, Cascante, Craig, Gracie, Kapsis, Lee, Pandey, Parker, Saari, Straube, and Tighe (Civil and Environmental Engineering) are top scientists in the field of clean energy infrastructure. Their contributions in the areas of geothermal energy, non-destructive testing of distribution grid infrastructure, energy & environment, hydrogen storage, solar & wind energy, bioenergy production, nuclear energy, climate policy, and green buildings have been generating powerful social and economic impressions on a global scale for the past several decades.

Civil and Environmental Engineering is one of the largest combined departments of civil, environmental, geological and architectural engineering in Canada. Many of the students and alumni pursue life-changing research and create successful entrepreneurial ventures by commercializing their research. The department has also created a vast association of industrial relationships in the energy sector that has led to a global standing in R&D and entrepreneurial activities in multidisciplinary areas.

**PROFESSOR CARL HASA, Civil and Environmental Engineering**

# 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 the Queen Elizabeth Scholarship foundation. Within this partnership, 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 remote international internship program that facilitates online co-op and field placements with AE4H partners around the world. Students work remotely from their homes for AE4H employers abroad, 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, the International Support Network for African Development, Pamir Energy, Jaza Energy, Badakhshon Energy, and ENVenture – New Energy Nexus Uganda who hosted students through the Energy Access Internship Program in 2021-2022.

## STUDENTS

The seven amazing students 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.

- › Chawthri Kanagarasa, Physics
- › Yelda Safi, English Rhetoric and Communication
- › Ayesha Asim, Environment and Business
- › Sean Tang, Math & Business Double Degree
- › Fibha Nazim, Master of Development Practice
- › Ahmad Danburam, Master of Development Practice
- › Aaesha Shehzad, Master of Arts in Global Governance



## CLEAN TECH HUB, NIGERIA

72% of Ugandans lack access to electricity. Rural cooperatives and Community Based Organizations (CBOs) created by members of the community know this problem well. Solar energy, non-electric water filters, improved biomass cookstoves, and fuel briquettes are all modern low-cost technologies that can solve rural and refugee settlement energy problems.

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.



## INTERNATIONAL SUPPORT NETWORK FOR AFRICAN DEVELOPMENT, NIGERIA

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## PAMIR ENERGY AND BADAKHSHON ENERGY, TAJIKISTAN AND AFGHANISTAN

Pamir Energy (Tajikistan) and Badakhshon Energy (Afghanistan) are social enterprises within the Aga Khan Development Network that work to provide access to energy in remote and mountainous areas of Tajikistan and Afghanistan. Many of these communities have never had access to electricity, and through Pamir and Badakhshon's work they are able to experience an improved quality of life and in turn, regional trade and cooperation have increased.



## JAZA ENERGY, TANZANIA

Jaza is an off-grid solar energy company that was founded in 2015. This company provides solar energy services to rural communities in Tanzania based on a “battery-swapping” business model. In each community that Jaza operates in, a small “solar hub” is built. These solar hubs are equipped with solar panels on the roof, and a number of portable batteries that can then be charged with the solar panels. Customers can come to the hub to rent a charged battery that can be carried to their homes to power lights and other electronics. Once a battery has been depleted, customers bring it back to the hub in exchange for a small fee.

– Laurel Pilon, co-op student Winter and Spring 2019



## ENVENTURE, UGANDA

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## COLLABORATE

## 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 Central Asia on meaningful and impactful tasks for companies who are working to provide electricity and improve lives in the remote villages of Tajikistan and Afghanistan, 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**

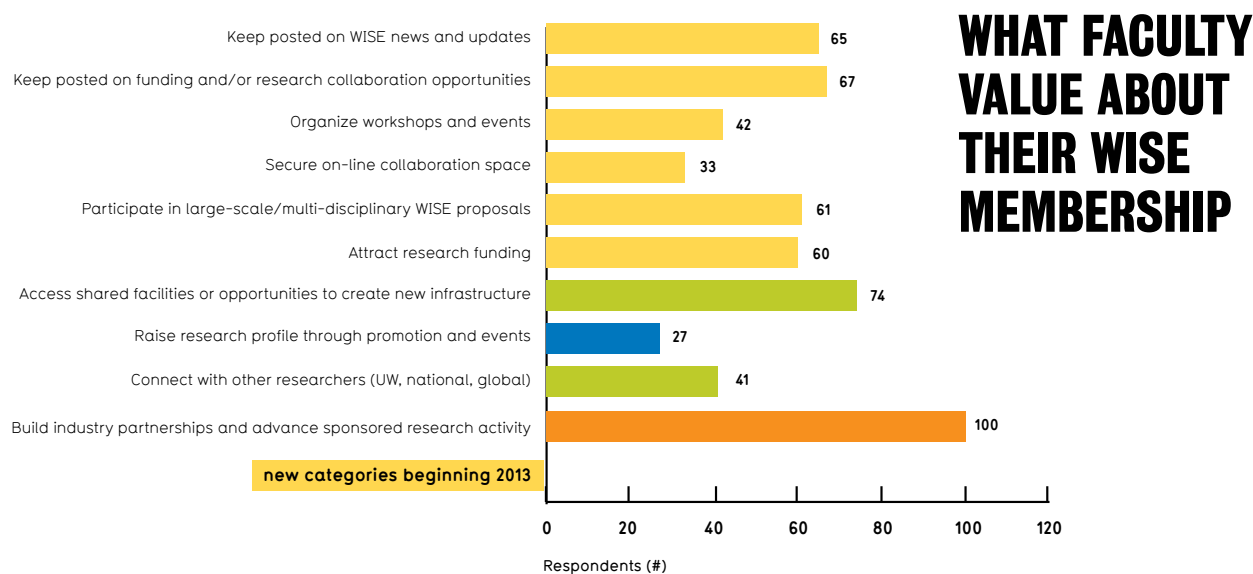
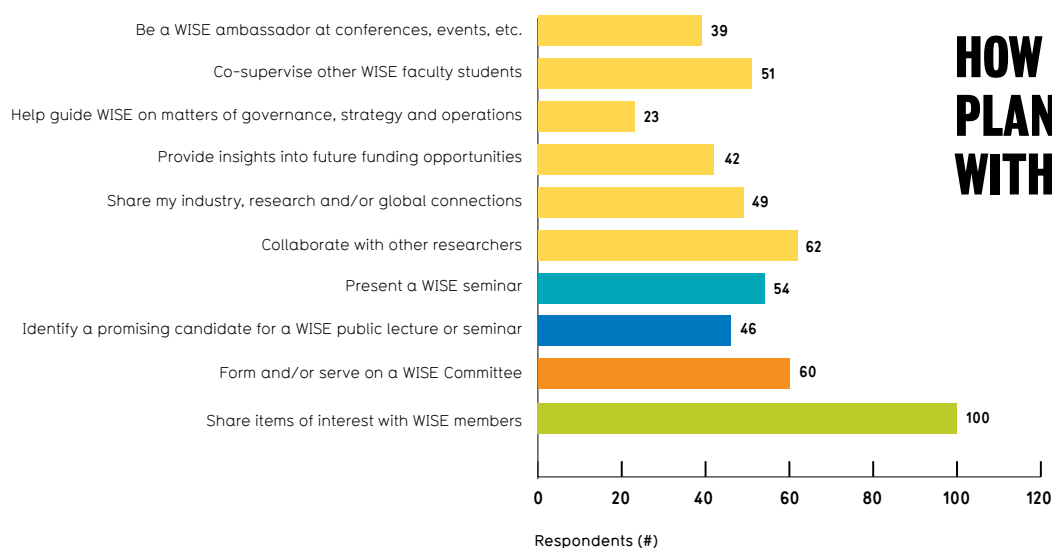
"This was my first international co-op term facilitated through WISE and it was an incredible learning experience. Not only did I get to learn more about sustainable energy and apply the skills I have developed through my undergrad, but I also got to learn more about energy initiatives in developing 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**



# RESEARCH INTERESTS OF OUR MEMBERS

Serving our members starts by understanding their needs and priorities. We do this through one-on-one meetings throughout the year, as well as enabling large-scale multi-disciplinary



# **\$25M+ IN FUNDING**

secured since 2010





**REACH OUT**



The background of the page features a blurred image of several wind turbines in a field, with solar panels visible in the lower foreground. A large, stylized star logo is positioned in the upper right quadrant. The star is composed of five points, with the central point being yellow and the four outer points being blue. The overall color palette is warm, with orange and yellow tones from the background image and the star's central point, contrasting with the blue of the star's outer points and the green of the grass at the bottom.

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:**

- › Hydrogen Production, Fuel Cell and Storage
- › Carbon Capture and Sequestration
- › Microgrids
- › Energy Policy, Transition and Economics
- › A Global Change Initiative – Affordable Energy for Humanity (AE4H)

# 1 HYDROGEN PRODUCTION, FUEL CELL AND STORAGE

The hydrogen and fuel cell industry has made significant advances in the past decade. The need for multi-megawatt fuel cell systems for electricity generation and utility-scale grid support applications is on the rise. Hydrogen can be produced using a variety of clean and renewable energy resources including biomass, hydro, wind, solar, nuclear, geothermal, and hydroelectric power to split water. It can also be generated through fossil fuels such as coal with carbon capture, utilization and storage, and natural gas. This diversity makes hydrogen a promising energy carrier and enables hydrogen production everywhere across the globe. Hydrogen is used in fuel cells to produce electricity by using a chemical reaction as opposed to combustion, which produces water and heat as by-products. Fuel cells can function at higher efficiencies compared to combustion engines. They can convert the chemical energy in the fuel directly to electrical energy with efficiencies greater than 60%. Fuel cells have zero emissions, which addresses the critical climate challenges as there are no carbon dioxide release. In addition, the concept of applying ammonia as a carrier for hydrogen delivery has gained a lot of attention in recent years because ammonia is much easier to liquify than hydrogen. Therefore, it can be easily stored and used for transportation.

Hydrogen can be stored in either a gas or liquid form. Storage as a gas usually requires high-pressure tanks whereas



**SXIAOYU WU**  
Professor, Mechanical  
and Mechatronics  
Engineering

storage as a liquid requires cryogenic temperatures due to the boiling point of hydrogen at one atmosphere pressure is below  $-252^{\circ}\text{C}$ . Hydrogen can also be stored on the surfaces of solids via the adsorption method or within solids via the absorption method.

Ammonia, a versatile chemical that is distributed and traded widely, can be used as an energy storage medium. **Professor Wu** (Mechanical & Mechatronics Engineering) carried out detailed analysis on the potential economic risks and benefits of using power-to-ammonia in three use pathways in the food, energy, and trade sectors, i.e., local sales, energy storage, and export under different levelized cost of ammonia (LCOA) scenarios. The base-case LCOA is lower than the market price, making local sales and export pathways profitable, and yet the energy storage pathway is at a loss unless ammonia-to-power efficiency is significantly improved. Four different combined use scenarios were also studied. Results show that under the base case LCOA and market assumptions, the combined use pathway leads to a loss of US\$30 million. But a combined use pathway can become more profitable when there are higher predicted ammonia prices, larger export demand for low-carbon ammonia, and technology development.

A shift towards a “hydrogen economy” can reduce carbon emissions, increase penetration of variable renewable power generation into the grid, and improve energy security. The deployment of hydrogen technologies

promises major contributions to fulfilling the economy’s significant energy needs while also reducing urban pollution emissions and the overall carbon footprint and moving towards a circular economy.

Using the Canadian province of Ontario as an example, **Professor Fowler** (Chemical Engineering) and **Professor Wu**



**MICHAEL FOWLER**  
Professor, Chemical  
Engineering



(Mechanical & Mechatronics Engineering) prioritizes certain recommendations for near-term policy actions, setting the stage for long-term progress to reach the zero-emissions target by 2050. To roll out hydrogen technologies in Ontario, they recommended promptly channeling efforts into deployment through several short-, mid-, and long-term strategies. Hydrogen refueling infrastructure on Highway 401 and 400 Corridors, electrolysis for the industrial sector, rail infrastructure and hydrogen locomotives, and hydrogen infrastructure for energy hubs and microgrids were included in strategies for the near term. With this infrastructure, more Class 8 large and heavy vehicles would be ready to be converted into hydrogen fuel cell power in the mid-term. Long-term actions such as Power-to-Gas, hydrogen-enriched natural

gas, hydrogen as feedstock for products (e.g., ammonia and methanol), and seasonal and underground storage of hydrogen would require immediate financial and policy support for research and technology development.



**XIANGUO LI**  
Professor, Mechanical  
and Mechatronics  
Engineering

**Professor Li** (Mechanical & Mechatronics Engineering) and **Professor Klinkova** (Chemistry) have examined the durability in the polymer



**ANNA KLINKOVA**  
Professor, Chemistry

electrolyte membrane (PEM) fuel cells. Durability is one of the main obstacles that prevents the commercialization of (PEM) fuel cells for transport applications. The reason being the microstructure of the catalyst layers (CLs)

deteriorates under dynamic loading operation. In their study, CLs' naturally random porous structure was simplified to be a random three-phase microstructure consisting of ionomers, catalyst agglomerates and pores, and the onset and growth of delamination process between the ionomer and catalyst agglomerate was investigated numerically by considering the catalyst agglomerate as elastic while the ionomer was elasto-viscoplastic, influenced by the cell assembly force arising from the cell clamping and variations in temperature and relative humidity. It was found that increasing clamping stress delays the delamination onset but has marginal effect on delamination propagation. The amplitude of hygrothermal cycles was the dominating factor in delamination and more frequent startup/shutdown of PEM fuel cells alleviates the delamination. Correlation between the rate of plastic strain accumulation in the ionomer and the interface delamination had been observed.

## 2 CARBON CAPTURE AND SEQUESTRATION

Canada has committed to a massive GHG emissions reduction by 2030 (i.e., CO<sub>2</sub> emissions abatement). Ontario heavy industry (steel, cement, chemicals, oil refining, automotive...) will be transitioning to low-CO<sub>2</sub> technology over the next 20–30 years, but to meet emissions goals identified by the Federal Government for 2030, action must be taken now. As Carbon taxes increase to \$170/tonne by 2030, and as the USA considers carbon border tariff adjustments, actions that can be economically achieved to reduce emissions will help Ontario's heavy industry remain sustainable.

The southwestern Ontario CO<sub>2</sub> emitters plants are the industrial backbone of Ontario without which its economy would be unsustainable. Carbon capture and storage (CCS) in the sedimentary rocks of southwest Ontario is an important option requiring immediate assessment before infrastructure on the ground can be located. With the exception of depleted oil and gas reservoirs, the most promising reservoirs for CO<sub>2</sub> sequestration are poorly understood. These deep saline aquifers only now have intrinsic value because of the need for CCS.

The recent Global CCS Institute's report for the Government of Alberta identified five "barriers" to CCS investment. Four of the five are policy responses,



**MAURICE DUSSEAULT**  
Professor, Earth and Environmental Sciences

e.g., a bankable value of CO<sub>2</sub> emissions and investment in transportation and storage networks. However, one is overwhelmingly a technical issue that has been the principal concern of the researchers, **Professor Maurice Dusseault** and **Professor Richard Jackson** (Earth and Environmental Sciences), at the University of Waterloo and other organizations in the private sector, i.e., Supporting detailed appraisal of prospective storage resources and adoption of the most appropriate capture technologies.



**ROBERT GRACIE**  
Professor, Civil and Environmental Engineering

Carbon sequestration in deep saline aquifers has been proposed for long-term storage of CO<sub>2</sub> as an alternative to the release of CO<sub>2</sub> into the atmosphere. **Professor Gracie** (Civil and Environmental Engineering) assessed a computationally efficient numerical model based on a sequentially coupled Finite Element Method (FEM) and Streamlined Upwind Finite Element Method (SU-FEM)–Finite Difference Method (FDM). An adaptive timestep strategy was implemented which allows computationally efficient and stable solutions as time progresses. The computational efficiency of the formulation is demonstrated by four examples that consider nonuniform permeability, multiple injection wells, an upsloping aquifer, and a dome-shaped aquifer. The adaptive timesteps reduced the computational cost by 75–82% compared to constant timesteps in the



four examples considered. The proposed formulation was compared against a benchmark study where eleven different simulators were used to determine the arrival time of the CO<sub>2</sub> plume at a leaky well. The original benchmark study did not include an FEM-based discretization of the reduced order equations. To the research teams' best knowledge, this work was the first FEM based implementation of reduced order (vertically averaged) multiphase flow equations evaluated against this benchmark. The proposed formulation was in good general agreement with the results from the various simulators studied in the benchmark, and excellent agreement with an FDM discretization of the vertically averaged governing equations.

Carbon dioxide (CO<sub>2</sub>) sequestration is considered to be one of the most effective technologies of mitigating greenhouse gas emissions. In this technology, single phase supercritical CO<sub>2</sub> is injected into an underground geological formation such as a deep saline aquifer. Existing sequestration projects demonstrate that successful implementations are possible; however, significant uncertainties associated with the risks of leakage remain an obstacle for broader use of this technology. The security of underground disposal could be considerably increased by dissolving the CO<sub>2</sub> in a brine produced from the aquifer, then re-injecting the mixture underground. The dissolution process occurs before the mixture reaches the aquifer; this significantly reduces or completely eliminates the risks of CO<sub>2</sub> leakage. This technique can drastically extend the



amount of worldwide aquifers available for carbon sequestration. As was previously shown, complete dissolution could be achieved in a surface pipeline operating under the pressure of a target aquifer,

where CO<sub>2</sub> is injected. **Professor Leonenko**

(Earth and Environmental Sciences)

presented a comprehensive model of CO<sub>2</sub> droplet dissolution in a vertical injection well. The model accounts for droplet breakup, coalescence, and dissolution processes as well as temperature and pressure variations

over well depth. The corresponding

computational code was written in MATLAB. The advection-diffusion population balance equation was solved using the finite difference method.

Distributions of droplet holdups and mean Sauter diameters computed in a vertical pipeline were compared with those in horizontal pipelines. The computations showed that the dissolution rate in a vertical pipe flow is higher than that in a horizontal flow due to an increase in CO<sub>2</sub> solubility with an increase in pressure. The pressure in a vertical pipe increases with well depth due to hydrostatics. However, it is important to emphasize that the dissolution enhancement in a vertical flow in comparison to a horizontal flow is relatively small and does not dramatically affect the dissolution process in a pipe. Both horizontal and vertical tubings are technically feasible to completely dissolve dispersed phase CO<sub>2</sub> before it reaches the target aquifer, but the latter could be more economical because it allows the utilization of depleted hydrocarbon wells.

# 3 MICROGRIDS

Climate change is a powerful driving force for reducing use of fossil fuels and associated greenhouse gas emissions. An emerging global trend is the development of distributed energy resources (DERs) with low carbon attributes as part of an integrated set of microgrid technologies for cost effective delivery of energy services to the end user. A microgrid comprises a local energy grid with control capabilities, i.e., it can be disconnected from the traditional electric grid and function autonomously. A micro-grid can be powered by DERs such as solar Photovoltaic (PV), wind, hydro, bioenergy, geothermal and storage technologies such as batteries, fuel-cells and Electric Vehicles (EVs). These clean energy technologies will play a significant role in the decarbonization of the energy sector.

A microgrid has the potential to operate independently from the grid and may also be used as a backup for the grid in case of emergencies, including natural disasters, allowing communities to be more energy independent and environmentally friendly. Microgrids can create economic and social opportunities for communities by lowering electricity costs, especially for remote Indigenous communities that are subsidized by the government of Canada. The electricity needs in the remote communities of the Canadian Arctic are met through diesel-based electricity generators. The cost of producing off-grid electricity from diesel generators can be up to ten times more than the electricity produced on

the main grid. The diesel fuel is usually flown in, shipped in, or driven in on winter roads that leads to high transportation costs and significantly adds to high energy expenses. In these communities, the entire life cycle cost of delivering electricity through diesel-based generation acts as a deterrent for socio-economic development. Reducing diesel dependency in Northern communities is a critical component of Canada's energy transition plan. With the price of oil reaching its highest levels and transmission expansion costs rapidly increasing, combined with the desire to reduce carbon dioxide emissions, renewable energy has become an important alternative for energy supply in remote communities. Also, the advent of Zero Emission Vehicles (ZEVs) and increasing use of intermittent RES impose complex challenges on power grid development, particularly with regard to energy storage in microgrids through batteries, hydrogen, and thermal systems. Renewable energy projects are being designed and deployed in Northern and remote power systems across the Canadian territories to reduce their reliance on diesel fuel.

Microgrid applications provide several benefits such as superior combined heat and power efficiency, improved reliability, and reduced carbon emissions. The technical challenges associated with microgrid applications include power quality, voltage/frequency changes, synchronized operation of numerous distributed generators,

power management and stability, grid connection/disconnection, and economic operation. Due to the low-inertia and significant renewable generation variability in isolated microgrids, short time-scale fluctuations in the order of

seconds can have a large impact on a microgrid's frequency regulation performance.

**Professor Cañizares**  
(Electrical and  
Computer Engineering)



**CLAUDIO CAÑIZARES**  
Professor, Electrical and  
Computer Engineering

developed a  
mathematical  
model for an Energy

Management System (EMS) that takes into account the operational impact of the short-term fluctuations stemming from renewable generation rapid changes, and the role that renewable curtailment and batteries, including their degradation, can play to counter-balance these variations. Computational experiments on the real Kasabonika Lake First Nation microgrid and CIGRE benchmark test system showed the operational benefits of the proposed EMS, highlighting the need to properly model short-term fluctuations and battery degradation in EMS for isolated microgrids with significant renewable integration.

Microgrids have the ability to function in islanded or grid-connected modes of operation. The increased

penetration of inverter-based DERs in the system promotes the concept of partitioning the system into self-governing and self-adequate microgrids. Most of the partitioning techniques determine virtual boundaries and did not consider the survivability of the constructed microgrids. **Professor Salama** (Electrical and Computer Engineering) has proposed a stability-constrained partitioning scheme based on small-signal stability to ensure microgrids' survivability when physically partitioned. Moreover, a sensitivity analysis of active power droop gain was utilized to define a novel index for the microgrid's marginal stability. The application targeted in this project

was the mitigation of voltage-sag events

caused by low impedance faults. The system was partitioned into clusters of survivable microgrids during faults to isolate the faulted zone that caused the voltage-sag event. By isolating the voltage-sag origin from the rest of

the system, voltage-sag mitigation was

accomplished. Also, a microgrid re-connection

method was suggested. This method allowed multiple droop-controlled DERs to adjust the frequency, phase, and magnitude of their output voltages to facilitate seamless re-connection of microgrids. Simulation results showed a seamless re-connection of two different microgrids when the recommended method was utilized. The effectiveness of the anticipated mitigation algorithm was validated using a modified IEEE 33-bus distribution system simulated on MATLAB/SIMULINK platform.



**MAGDY SALAMA**  
Professor, Electrical and  
Computer Engineering

# 4 ENERGY POLICY, TRANSITION AND ECONOMICS

Energy policies should be viewed as being implanted in a socio-technical system in which technical, economic, political, and social factors intermingle. Energy policy is a crucial element in economic development. As a result, energy policy in developed countries is a vital part of the overall regulatory framework that governs the growth in global appeal and the amalgamation of the private business sector. Global competitiveness includes the liberalization of the power sector and gas marketplaces and also the sharing of power generation, transmission, and distribution. Renewable energy sources are natural and can consequently assist to decrease reliance on oil imports, transition to a low carbon energy economy, and improve safety of supply. Canada has numerous policy measures in place to accomplish its energy and climate targets, consisting of a striving carbon-pricing scheme, clean fuel rules & regulations, deployment of renewable energy systems, a pledge to phase out persistent coal use by 2030, nuclear plant expansions, upstream methane protocols, energy efficiency programmes, and procedures to decarbonise the transport sector. In Canada, the electricity supply is among the cleanest in the world due to the large stocks of hydro power and the important role of nuclear power plants. There is a need of bigger interconnections among provinces and territories to safeguard balanced



development towards national goals for decarbonizing the power and energy sector. Sharper emissions reductions are still required in other sectors, especially oil and gas production, transport and industry.

In the presence of a global pandemic (COVID-19), the relentless pressure on global decisionmakers is to ensure a balancing of health (reduce mortality impacts), economic goals (income for livelihood

sustenance), and environmental sustainability

(stabilize GHG emissions long term). The

global energy supply system is a dominant

contributor to the GHG burden and

deeply embedded in the economy

with its current share of 85%, use of

fossil fuels has remained unchanged

over 3 decades. **Professor Nathwani**

(Management Sciences) presented a unique

approach to harmonizing the goals of human

safety, economic development, and climate risk,

respectively, through an operational tool that provides

clear guidance to decision-makers in support of

policy interventions for decarbonization. Improving

climate change performance as an integral part

of meeting human development goals allows the

achievement of a country's environmental, social, and

economic well-being to be tracked and monitored.

A primary contribution of this project was to allow

a transparent accounting of national performance

highlighting the goals of enhancing human safety in





concert with mitigation of climate risks. A measure of a country's overall performance, combined as the Development and Climate Change Performance Index (DCI), was derived from two standardized indexes, the development index H and the Climate Change Performance Index CCPI. Data were analyzed for 55 countries comprising 65 percent of the world's population. Through active management and monitoring, the proposed DCI could illustrate national performance to highlight a country's current standing, rates of improvement over time, and a historical profile of progress of nations by bringing climate risk mitigation and economic well-being into better alignment.

Limiting global warming to 1.5–2.0°C in line with our climate commitments will require decarbonization and transition 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



**PAUL PARKER**  
Professor, School of  
Environment, Enterprise  
and Development

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 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, his team 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. The policy of electrification of heating, ventilation, and air conditioning (HVAC) systems could play a substantial role in the transition to net zero – and heat pumps are emerging as a solution.

# 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 34 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

**150**  
members

**34**  
countries



to 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 2020–21, this included remote international co-op placements for UW students, an energy project mentorship program, energy access publications, and several new or completed partnership initiatives with AE4H members.

## AE4H PARTNERSHIP INITIATIVES

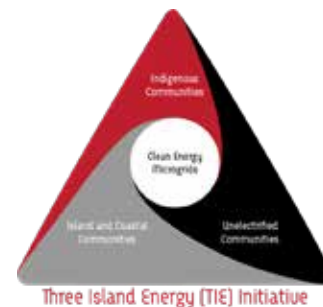
The greatest strength of the Affordable Energy for Humanity Initiative is its diverse and impactful partners. We are pleased to partner with AE4H members on initiatives that promote awareness, capacity, and research regarding access to energy. Here are three partnership initiatives that were either initiated or completed in 2021-22.

### 1. The Worldwide Teach-in on Climate Justiced decentralized System Data Analysis Platform (OSDAP)

**Bard**

The Worldwide Teach-in on Climate and Justice ([www.worldwideteachin.org](http://www.worldwideteachin.org)) 2022 was a global

event that engaged more than 50,000 people, in-person and online, in learning about climate solutions and justice in March 2022. The Waterloo Institute for Sustainable Energy (WISE) co-led the Worldwide Teach on Climate and Justice in partnership with Bard College Center for Environmental Policy in New York. WISE is the regional partner for Africa and South Asia, and worked with its AE4H partners to scale this event across these regions. Through the Teach-in, Bard College and the University of Waterloo are collaborating to build a global community of climate educators.



### 2. Three Island Energy

Three Island Energy is a program led by Indigenous Clean Energy that seeks to support global Indigenous, islanded, and coastal communities in the development and scaling of clean energy microgrids. WISE, under the AE4H initiative, was invited as a core partner in the initiative and supported research initiatives regarding microgrids and three island communities. WISE co-conducted a survey of AE4H members to learn about the use of microgrids in islanded, Indigenous, and coastal communities, and developed a presentation at COP26 to share the results.

### 3. S-@ccess Innovation Lab

The 3rd International Conference on Solar Technologies & Hybrid Mini Grids to improve energy access, known as the S-@ccess conference, occurred in September 2021. This conference is run by Trama TecnoAmbiental and the University of the Balearic Islands in Palma, Spain, and WISE has been a core conference partner for several years. Dr. Jatin Nathwani and Ambika Opal prepared a case study of a refugee settlement in northern Uganda and presented this case to participants of the conference through an Innovation Lab. Participants worked together to design renewable energy systems and a business case to solve the energy access challenges in this community.

# WISE EVENTS



## WORLD FORUM ON CLIMATE JUSTICE

September 21-23, 2021

Ambika Opal conducted a presentation at the World Forum on Climate Justice along with other regional co-leaders of the Worldwide Teach-in on Climate Justice. Ambika shared how energy access is an intrinsic part of climate justice, and how AE4H members are working towards climate justice.



## S-@CCESS INTERNATIONAL CONFERENCE ON SOLAR TECHNOLOGIES AND HYBRID MINI-GRIDS TO IMPROVE ENERGY ACCESS 2021

September 15-17, 2021

In September 2021, Dr. Jatin Nathwani and Ambika Opal facilitated an Innovation Lab for approximately 40 participants of the S-@ccess conference. This Innovation Lab saw experts working together across disciplines to design solutions to real global challenges regarding energy access.



## VISIONARY WORKSHOP: CCS PLANNING FOR SOUTHWESTERN ONTARIO FOR 2030

October 27, 2021

The Waterloo Institute for Sustainable Energy (WISE) of the University of Waterloo — hosted a Visioning Workshop on the issues related to the capture (i.e., processing), transportation, and subsurface storage of CO<sub>2</sub> in southwestern Ontario.

- › Panel 1: CO<sub>2</sub> Perspectives on Industrial Carbon Capture & Sequestration by 2030
- › Panel 2: Transportation and CO<sub>2</sub> Processing for Sequestration
- › Panel 3: The CO<sub>2</sub> Sequestration Potential of SW Ontario





## COP26: GLASGOW

November 4, 2021

Ambika Opal, Manager of Global Programs and Initiatives at WISE participated in a side event at COP26 run by Indigenous Clean Energy, titled “Indigenous Renewable Energy Microgrids for Energy Transition ‘Just Climate Energy’”. Ambika shared highlights of how remote, islanded, coastal, and Indigenous communities are using renewable microgrids as a solution for community energy needs.

## UW-IIT DELHI INNOVATION LAB

November 27 and October 30, 2021



In this two-part event series in October and November 2021, 20 students from the Indian Institute of Technology Delhi and the University of Waterloo worked together to solve real-world energy access case studies in both India and Canada. Students participated in an 'Innovation Lab' style workshop where they worked together to solve a sustainable energy challenge for remote communities in Canada and India. Professors from both institutions attended as advisors and judges. This event was conducted in partnership between Waterloo International and the Waterloo Institute for Sustainable Energy.



## WORLDWIDE TEACH-IN ON CLIMATE JUSTICE

March 23-24, 2022

On March 23 and 24, 2022, WISE conducted five panel discussions as part of the Worldwide Teach-in on Climate Justice, engaging more than 100 students from the University of Waterloo. WISE facilitated over 30 Teach-in events across Africa and South Asia through AE4H partners, that occurred between February and July 2022.



## RENEWABLES IN REMOTE COMMUNITIES

April 28, 2022

Ambika Opal presented at the Pembina Institute's Renewables in Remote Communities conference in April 2022. The topic of her presentation was Global Community Energy Stories. She used examples of communities in the AE4H initiative and compared energy access challenges to those in remote communities in Canada.

# WISE PARTICIPATION

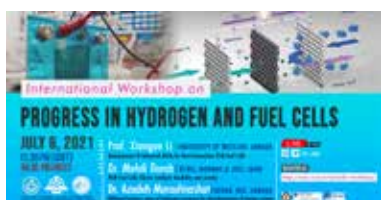


## LG ENERGY SOLUTION INNOVATION FORUM 2021

June 21-22, 2021

Professor Nazar (Chemistry) participated as a panelist along with a number of acclaimed scholars to discuss the current and future developments in the electrochemical energy and battery sector.

The forum fostered discussions on the next-generation batteries as well as the lithium-ion battery cells. The demand for the next-generation batteries have been on a steady rise over its key features of light weight and greater energy density. Lithium-ion batteries are widely being used as the power source for electric vehicles around the world. The open forum invited general public into the discussion on the newest trends, product developments and solutions.



## INTERNATIONAL WORKSHOP ON PROGRESS IN HYDROGEN AND FUEL CELLS

July 6, 2021

Professor Li (Mechanical and Mechatronics Engineering) gave a talk on “Development of advanced MEAs for next-generation PEM fuel cells”.

This workshop held in collaboration with the School of Mechanical Engineering, University of Tehran and the Engineering Skills Development Center (ESDC).



## 31<sup>ST</sup> EUROPEAN CONFERENCE ON OPERATIONAL RESEARCH

Athens, Greece | July 11-14, 2021

Professor. Ghaddar (Management Sciences) has given a keynote talk on “Polynomial optimization in power and water network operations”. She discussed several challenging optimization problems in power and water networks involving both operational decisions and non-linear models of the underlying physics described by the network. However, these networks exhibit a nice sparse structure. This talk provided an overview of approaches that combined recent advances in conic relaxations of polynomial optimization problems along with exploiting structure of the underlying problem. These approaches were demonstrated on applications arising in power and water networks.



## 2021 WORLD FUEL CELL CONFERENCE

August 16-20, 2021

Professor Li (Mechanical and Mechatronics Engineering) served as the President of Fuel Cell Division, International Association for Hydrogen Energy (IAHE), and Fuel Cell Division that organized the 2021 World Fuel Cell Conference (WFCC).

The WFCC is a multidisciplinary conference on the latest development and advancement of hydrogen and fuel cells, and provides a forum for the exchange of the latest scientific and technical information, for the dissemination of high-quality research results, and for the debate and shaping of future directions and priorities in hydrogen fuel cell science, technology, engineering, application and commercialization. This conference is targeting technical issues and interconnections between fuel cells and hydrogen.



## 2021 MOLECULAR FOUNDRY USER MEETING

August 19–20, 2021

Professor Nazar (Chemistry) discussed “Electrochemical energy storage using lithium sulfur conversion chemistry with liquid and solid state electrolytes” at the meeting.

The Molecular Foundry is a nanoscience research facility that provides visiting researchers (“users”) with access to cutting-edge expertise and instrumentation in a collaborative, multidisciplinary environment. The Molecular Foundry’s 2021 Annual User Meeting will be hosted virtually with free registration to bring our scientific community together in a safe and accessible format. This annual conference focuses on frontier research topics of interest to that community of users, providing a forum to share results and exchange ideas, and bringing together leading researchers, junior scientists, postdocs, and students.



## IBA 2021 ANNUAL MEETING

Xiamen, China | October 24–29, 2021

Professor Nazar (Chemistry) attended the meeting organized by the “International Battery Materials Association (IBA)”. Her presentation was on “Creating and understanding stable cathode-electrolyte interfaces for solid state batteries”.

The meeting focused on the latest findings that had led to battery materials of enhanced performance and safety, and to deepened understanding of the electrode processes that determine and dictate the electrochemical performance. Scientists and researchers of battery community around the world participated to share recent advances in battery materials and electrolytes for lithium ion batteries and beyond.



## THE 10<sup>TH</sup> ANNUAL AIN SHAMS UNIVERSITY INTERNATIONAL CONFERENCE

March 29–31, 2022

Professor Ponnambalam (Systems Design Engineering) delivered a talk on “New trends and technology advancement in Environmental systems and their effect on nations and societies towards Sustainability”.

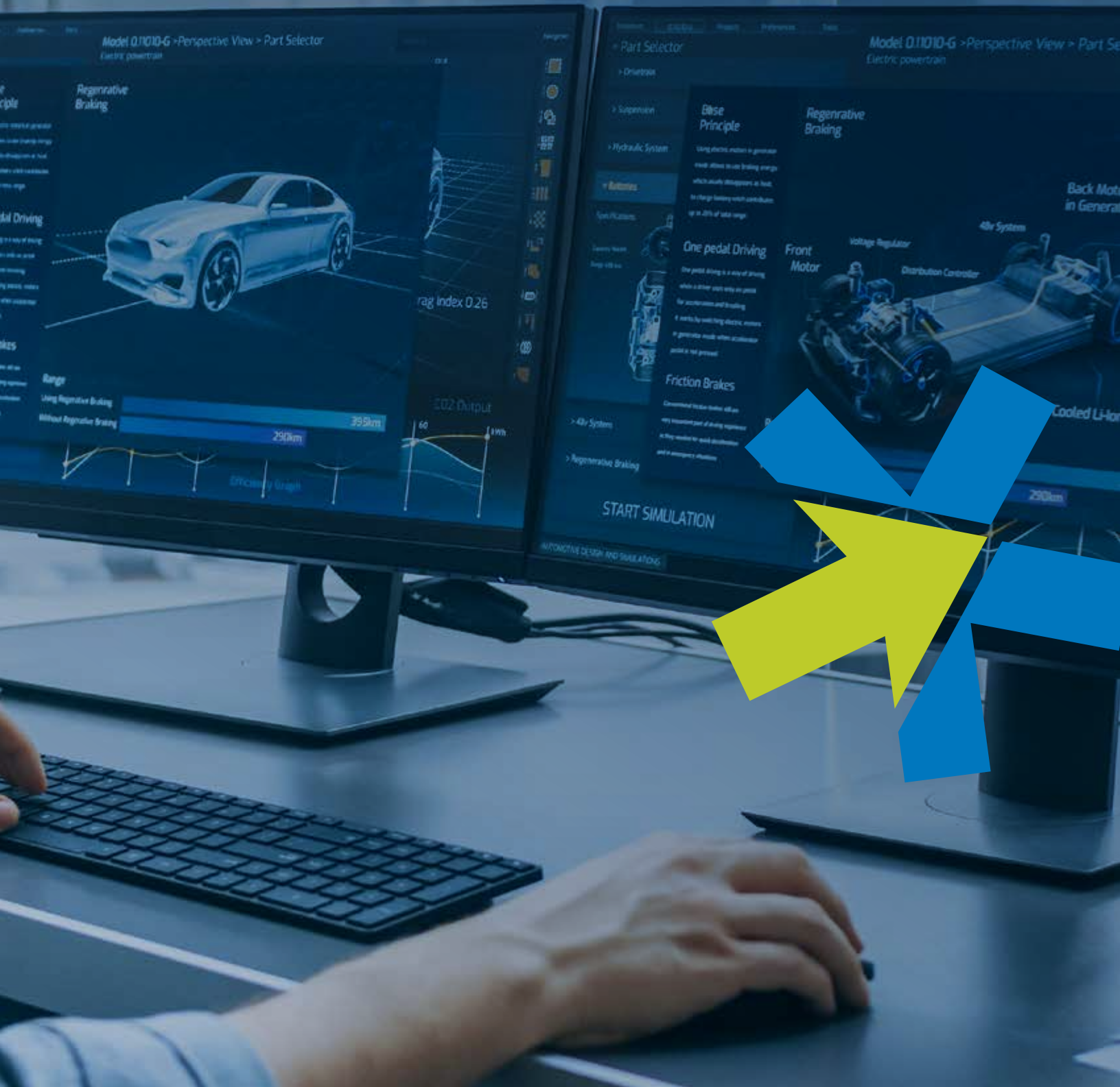
The conference addressed challenges and issues related to the artificial intelligence technologies, cloud computing, internet of things, quality of life, green and sustainable universities, cyber security, automation robotics, autonomous vehicles, environmental engineering, renewable energy, and water resources management under the cluster of engineering and technological sector.



# 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

A man in a blue suit is seen from the back, addressing a large, blurred crowd. He is holding a microphone in his right hand. The background is dark and out of focus, suggesting a large indoor event or conference.

## PUBLIC LECTURE SERIES

### MAY 2021

Philip Manyi Omenge

PhD Candidate,  
Egerton University

Environmental and Social  
Impact Assessment  
procedural steps  
that underpin conflict  
identification: Reference  
to renewable energy  
resource development  
in Kenya

### SEPTEMBER 2021

Ali Golriz

Lead, System & Sector  
Development, Innovation  
and R&D, Independent  
Electricity System  
Operator (IESO)

Integrating DERs in  
Wholesale Markets and  
Creating Distribution  
Markets

### FEBRUARY 2022

Dr. Sohrab Zendeboudi

Associate Professor,  
Department of  
Process Engineering,  
Memorial University of  
Newfoundland, Canada

Decarbonization Strategies  
in Canada: Challenges  
and Future Prospects

### NOVEMBER

Steven Wong

Research Advisor in  
the Renewable Energy  
Integration Group, PhD  
in Electrical Engineering  
from the University of  
Waterloo

Local Energy Flexibility in  
Future Power Systems

### MARCH 2022

Dr. Fabrizio Sossan

Associate Professor,  
MINES  
ParisTech – PSL  
Universities, France

Stress-informed model  
predictive control of  
hybrid hydropower



# RESEARCH SPOTLIGHTS

zero emission  $H_2$



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.



## PLOTTING THE PATH TO A HYDROGEN ECONOMY

**LEAD RESEARCHERS:** Matheus F. Michael Fowler, Xiao-Yu Wu, Faris Elmanakhly, Andre DaCosta, Brittany Berry, and Robert Stasko

July 2021

When you burn fossil fuels, the by-products are greenhouse gases and particulates. When you burn hydrogen, the by-product is water.

This versatile gas can serve as fuel for transportation and heating, as a way to store energy, and as a feedstock for many products such as ammonia and methanol. It's easy to transport via pipelines, trucks or tankers, and if you generate hydrogen using renewable energy, it can even be net-zero.

But how do you shift from fossil fuels to this greener alternative? WISE researchers teamed up with the Hydrogen Business Council of Canada to examine the situation in Ontario. Together, they identified the most appropriate applications for hydrogen technology and recommended policies to drive their adoption

The first leverages a Robust Optimization (RO) approach, which maximizes profit under worst-case scenarios, while the second uses Affine Arithmetic (AA) techniques. To hedge against price uncertainties, both approaches consider a wide range of parameters, including the thermodynamic characteristics of CAES, variable operational costs, air flow rates and more.

# RESEARCH SPOTLIGHTS





## OVERCOMING SHORT-CIRCUIT SHORTCOMINGS ON WIND FARMS

**RESEARCHERS:** Sahar Azad and Javad Zare

January 2022

Wind farms contribute an ever-growing share of the energy flowing through the world's electricity grids. Because those grids have to be stable and reliable, wind farms are required to stay connected even if a short circuit causes the voltage to drop. This prevents a short circuit from knocking out other generators and causing widespread outages.

However, current approaches to doing that can significantly affect the operation of relay devices that protect the transmission lines connecting the wind farm to the grid. To find a better way, WISE researcher Sahar Azad and recent master's student Javad Zare looked at the issue in a common type of wind farm: doubly fed induction generator (DFIG) systems.



## PARTICIPATING PROFITABLY: HOW COMPRESSED AIR ENERGY STORAGE CAN MAKE THE MOST OF ELECTRICITY MARKETS

**LEAD RESEARCHERS:** Matheus F. Zambroni de Souza, Claudio A. Cañizares and Kankar Bhattacharya

March 2022

In Compressed air energy storage (CAES) facilities offer an attractive way for bulk power systems to buffer the intermittent nature of renewable energy, storing excess energy when it's not needed and retrieving it during peak demand. But few studies have examined their operation in electricity markets.

For WISE researchers Claudio Cañizares, Kankar Bhattacharya and Matheus Zambroni de Souza, the question was how to maximize daily profits for these facilities. To find out, they developed two mathematical models to determine the optimum schedule for dispatching power to electricity markets.

# PUBLICATIONS

## SELECTED MEMBER PUBLICATIONS

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# **AWARDS AND RECOGNITION**



### EXCELLENCE IN GRADUATE SUPERVISION AWARD

Professor Claudio Cañizares (Electrical and Computer Engineering) has been selected to receive the prestigious Award of Excellence in Graduate Supervision. Graduate student supervision requires complex interaction between graduate students and the graduate supervisor. Graduate Studies and Postdoctoral Affairs (GSPA), in collaboration with the Graduate Student Association (GSA), established this award to recognize exemplary faculty members who have demonstrated excellence in graduate student supervision, through being a mentor, advisor, role model, humanist and a strategist who exemplifies a high level of energy and ingenuity.

### FACULTY OF ENGINEERING AWARD OF EXCELLENCE IN GRADUATE SUPERVISION

Professor Claudio Cañizares (Electrical and Computer Engineering) has been selected to be a recipient of the Faculty of Engineering Award of Excellence in Graduate Supervision.

Graduate student supervision requires complex interaction with graduate students. Students were asked to nominate supervisors who excelled in the role of a supervisor, as a mentor, advisor, role model, humanist and strategist — someone who exemplifies a high level of energy and ingenuity. These roles and characteristics among supervising faculty are integral to the success of Engineering Graduate Studies programs at the University of Waterloo.

### CANADA RESEARCH CHAIR (RENEWAL)

Professor James Craig (Civil and Environmental Engineering) has his research chair in Hydrological Modelling and Analysis renewed for another five years by the federal government. He will receive \$500,000 over five years to continue his work.

The award is one of 188 new and renewed chairs at 43 post-secondary institutions across the country selected for over \$151 million in funding. Canada Research Chairs are some of the world's brightest scholars and scientists who contribute to new discoveries and help to make sense of the world we live in. Professor Craig's expertise is in numerical and analytical modelling of water resource systems, with a focus on surface water hydrology, regional-scale groundwater flow, and subsurface heat transfer/phase change simulation.

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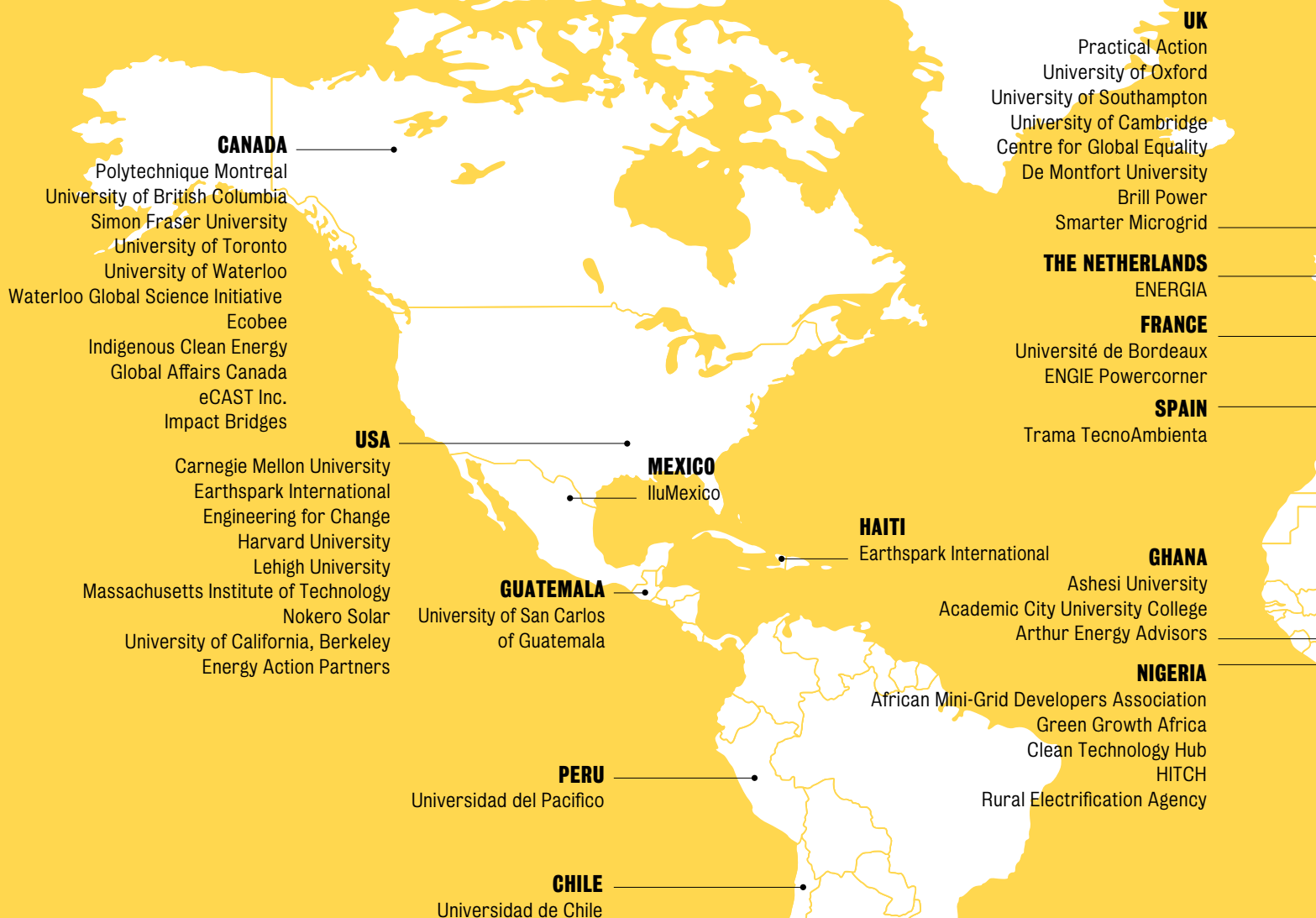
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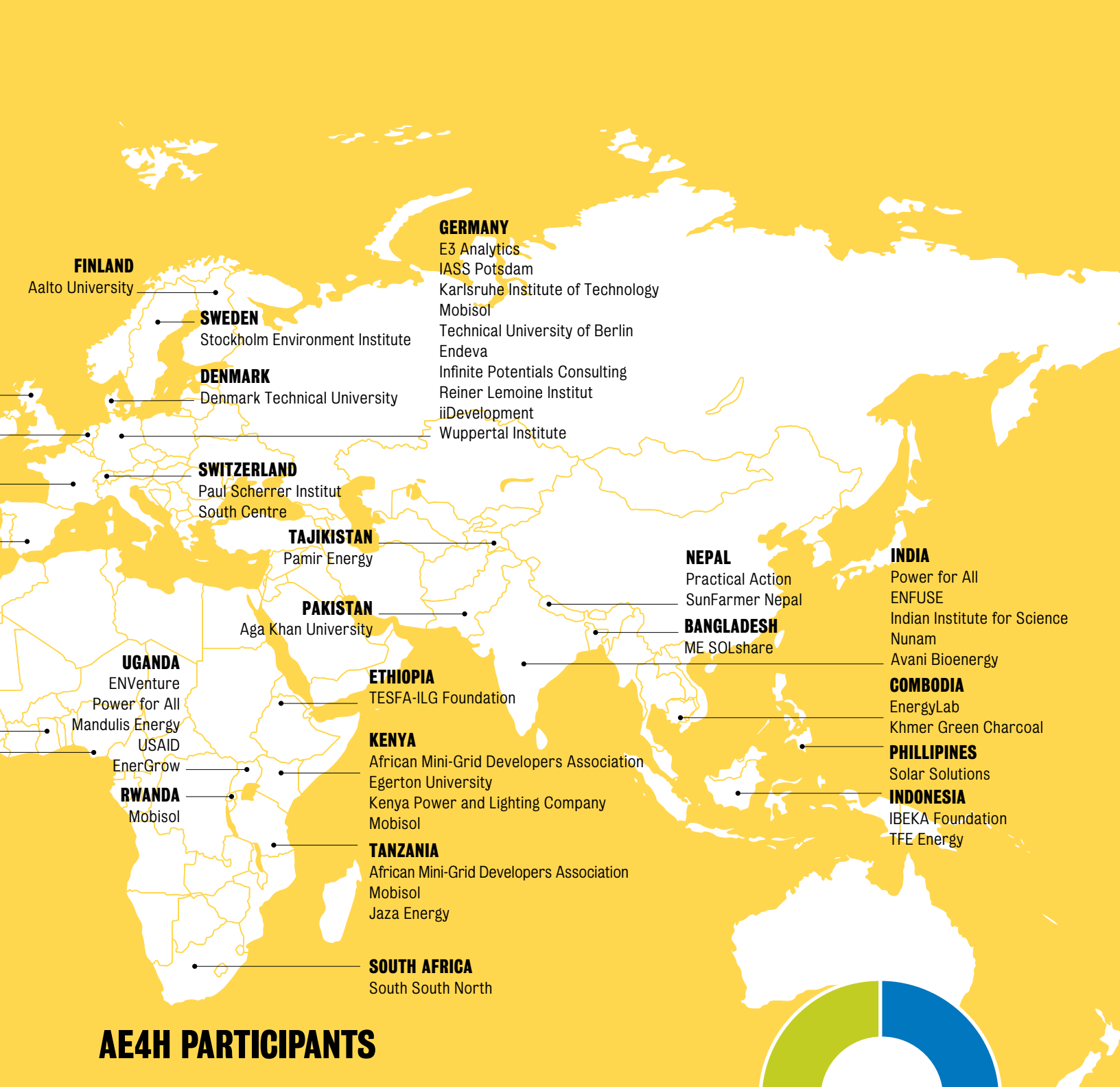
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