UNIVERSITY OF ALBERTA

FUTURE ENERGY SYSTEMS

$75 Million from the Canada First Research Excellence Fund (2016-2023) | **9+** University of Alberta faculties | **100+** individual research projects | **135+** University of Alberta researchers | **650+** students & post-doctoral fellows

SHAPING THE FUTURE OF ENERGY

As it travels from the place where it is generated to the place where we use it, energy moves through a system. For more than a century, that system has been dominated by large-scale, hydrocarbon-driven generation technologies and the transmission of energy in only one direction. Small-scale renewable energy technologies, energy storage, and flexible smart grids can diversify this system, enabling our transition to a low-carbon economy and shaping our energy future.

Future Energy Systems (FES) funds researchers working in multidisciplinary teams to develop new energy technologies and facilitate their introduction into our current energy system. It supports researchers seeking to mitigate the environmental impacts of current and future energy systems, and those seeking to understand the influence of energy transition on our environment, economy, and society. FES includes four research areas.

- Developing Hydrocarbons Responsibly
- Improving Environmental Performance
- Enabling Sustainability
- System Wide Enablers

IMPACTING OUR WORLD

- More than **2,300** research outputs from FES researchers on FES projects
- **167** masters and **249** doctoral students trained through FES research
- **115** masters and doctoral graduates to date
- **619** publications by program researchers
- **335** peer reviewed journal articles published in journals with an average impact factor of **5.128**
- **3,055** citations of published research
- **47%** of all peer reviewed articles feature FES graduate students and post-doctoral fellows as lead authors
- UofA continues to rank **number 1** in Canada for both publications and citations related to energy
- UofA ranks in the **top 3** globally for publications and citations related to hydrocarbon energy

FUTURE ENERGY SYSTEMS

Scientific Overview and Midterm Report 2017 - 2020

ENERGY EXISTS IN A SYSTEM

Energy is vital to our world, from enabling the basic necessities of life, to supporting modern conveniences and technologies. It can be generated in many ways, including hydro, nuclear, solar, wind, geothermal, and biomass. Yet most of today's energy originates from hydrocarbon sources (oil, coal, gas), as they are readily accessible and provide excellent energy density. However, with climate change, greenhouse gas emissions, and environmental disturbances impacting our world, we now understand their serious side effects. An energy transition to net-zero carbon emissions is necessary to change this trajectory for a sustainable future.

Changing our energy use trajectory is not simply a matter of changing energy sources. We must address the systems that connect each energy source to our daily lives. We must answer fundamental and applied technical questions about energy generation, uses, transportation, and regulation; and their environmental, economic, and societal impacts. Discoveries will be most meaningful and possible through coordinated efforts from researchers in numerous disciplines, each applying their specific expertise to the complex whole.

FUTURE ENERGY SYSTEMS

Launched in 2017 though the Canada First Research Excellence Fund (CFREF), Future Energy Systems (FES) built a broad, deep, and integrated research program to unite researchers from different disciplines to share expertise and tackle the hard but critically important questions. At its midpoint, FES encompasses 102 projects over 9 faculties; and its 135 researchers and 652 graduate students, post-doctoral fellows, and other highly-qualified personnel (HQP), generated more than 2,300 research outputs. Outputs include 619 publications, with 335 in peer reviewed journals with a median impact factor of 5.128, cited 3,055 times. These publications ensure UofA continues to rank number 1 in Canada for publications and citations related to energy, and in the top 3 globally for publications and citations related to hydrocarbon energy. Output quality and relevance have fostered strong international relationships with peers in China, Germany, and Mexico.

FES researchers share their expertise with decision makers and the public. Dozens of informal interactions have taken place between research and government personnel, with 11 contributions to development of policy and regulation reported, including direct policy advice to the federal cabinet. Outreach includes partnerships with public organizations such as Ingenium, Canada's museums of science and innovation, private organizations such as TELUS World of Science Edmonton, and community organizations such as the Edmonton Public Library.

FES contributes funds to training students at masters (167) and doctoral (249) levels. Of these, 114 have graduated, and 302 are training as researchers in FES. FES graduate students and post-doctoral fellows are highly qualified, being lead authors on 47% of peer reviewed journal articles published by program researchers.

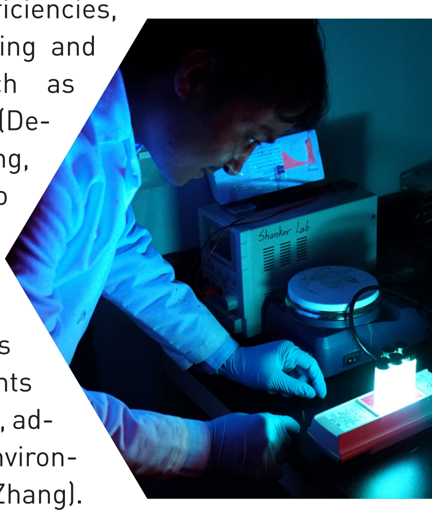
The significant milestones, scholarly contributions, and impacts of FES research on the energy transition can be summarized from the

perspective of energy systems. The system can be broadly divided into four chronologically based steps: energy generation, harvesting, and production; transport, storage, and access; use, impact, and regulation; monitoring, management, and mitigation.

ENERGY GENERATION

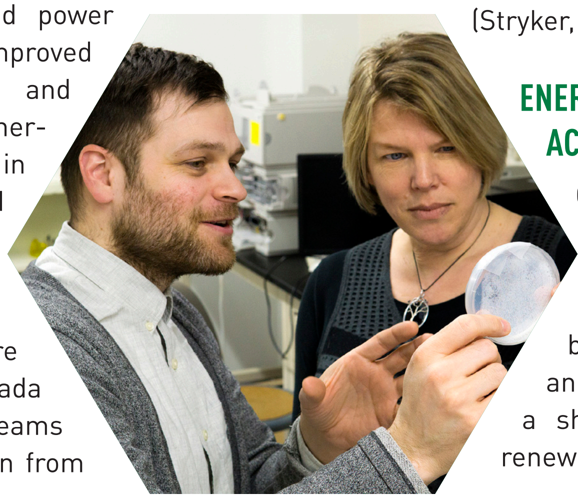
Regardless of origin, energy generation results from harvesting an energy source or energy releasing process and bringing that energy into a usable form for society. FES research encompasses heavy oil and renewables including solar, wind, geothermal, and biomass. With traditional, carbon based sources, FES research generates new technologies to reduce necessary inputs, decrease emissions, and mitigate potential environmental wastes and other impacts. In emerging renewables fields, a key goal is increasing efficiency while improving stability and reliability of new technologies to be economically competitive with established processes.

FES research on energy generation from renewable sources is significant. Machine learning is leveraged to increase organic photovoltaic cell efficiency (Buriak, Mar), and viable new materials such as carbon-nitrides and perovskites are being developed for solar applications (Gibbs, Michaelis, Shankar). Wind power generation is leading to improved turbine design (Ghaemi) and cost reduction (Zuo). Geothermal energy opportunities in Canada are being explored and catalogued (Banks, Unsworth), and new technologies prototyped to convert low temperature gradients typical in Canada into viable energy streams (Nobes). Energy generation from waste biomass to produce fuel is making use of forest and agricultural waste (Bressler, Kumar, Mushrif, Mussone), single carbon gas transformations are being studied with microorganisms and chemical catalysis (Sauvageau, Luo), and anaerobic digestion is being improved (Dhar).



Hydrocarbon based energy research includes technologies to improve efficiencies, through well site engineering and extraction processes such as those leveraging solvents (Dehghanpour, Kantzas, Leung, Nouri), and computation to support essential process design and operation (Li, Sacchi, Trivedi). Non-aqueous extraction techniques will lower water requirements of many technical processes, addressing a current major environmental concern (Liu, Zeng, Zhang).

As the oil and gas industry is relatively mature, much work in that area explores fundamental concepts which could be transformative in multiple sectors. This includes machine learning applications (Mar, Rajendran, Trivedi), optimization techniques (Dehghanpour, Leung, Li, Liu, Nouri), systems engineering and controls (Daneshmand, Gu, Mousavi, Sacchi), and fundamental exploration of physical properties (Leung, Waghmare, Zhang), including interfacial properties of asphaltenes in pipelines (Stryker, Zeng).



ENERGY TRANSPORT AND ACCESS

Once harvested, energy is not always easily available for use. From the point of generation, energy must be transported efficiently, and safely integrated into a shared infrastructure. With renewables, this energy must

be successfully stored to facilitate usage where and when required.

Storage options using vanadium, a waste material from oil sands operations, are being tested in partnership with the Government of Alberta (Musilek). Research is being conducted to optimize lithium batteries (Jin, Li, Sang), and on potential alternative materials for chemical battery production (Veinot, Wang). Storage and transport of conventional energy sources are being studied (Olfert, Stryker), including fundamental catalysis that could lead to using carbon dioxide gas as a storage solution for solar power (Bergens), and optimization of bitumen pipelines using novel internal geometry to reduce wear (Hemmati).

Research includes independent technologies for general applications, and add-on technologies to improve storage and transport. Storage solutions such as mechanical flywheels are being considered for small and specialized distributed uses, such as electric bus depots (Mertiny), while larger, utility scale operations are being addressed with solutions such as hydrogen power (Secanell).

Determining how these power sources and storage solutions can safely integrate into the energy grid is crucial. This challenge is applicable to wind farms and natural gas fields seeking to sell energy into an existing power grid. Poor integration mechanisms could destabilize the grid, leading to damaged infrastructure and brownouts. Smart grids capable of managing any potential renewable or conventional input are being developed (Ardakanian, Fleck, Li, Musilek), with work encompassing software control systems, and the actual design, prototyping, and testing of control equipment in partnership with utilities and energy producers.

ENERGY USE AND REGULATION

As energy systems change, long established knowledge of societal impacts of energy must evolve, including regulation and policy, and ways in which projects are conceived, consulted about, and implemented. If small communities could use new, small scale renewable energy generation technologies without involvement of large governments or private sector interests, social and economic impacts could complement environmental benefits. Understanding interconnected relevance of new energy technology, and the transition from previously profitable technologies, is essential to understanding and planning for the continuing transition.

Research is evaluating energy availability, such as the impact of existing energy systems on homelessness in northern Indigenous communities (Agrawal), and availability of geothermal energy to Indigenous communities in Alberta and the Northwest Territories (Unsworth, Lefsrud). Assessments are being conducted of economic feasibility and user compatibility of biomass sourced energy into existing systems (Koch, Luckert), determining impacts of wind generation integration (Hemmati) and how it will impact markets (Eckert), and how solar energy will impact markets and the grid (Brown). Market impact is a necessary focus to reduce potentially dangerous disruption in energy transition (Adamowicz, Leach). What communities may benefit from what types of energy transitions (Parkins), and political pathways that could support the transition (Thorlakson) are being addressed.

UNIVERSITY OF ALBERTA FUTURE ENERGY SYSTEMS
CANADA FIRST RESEARCH EXCELLENCE FUND

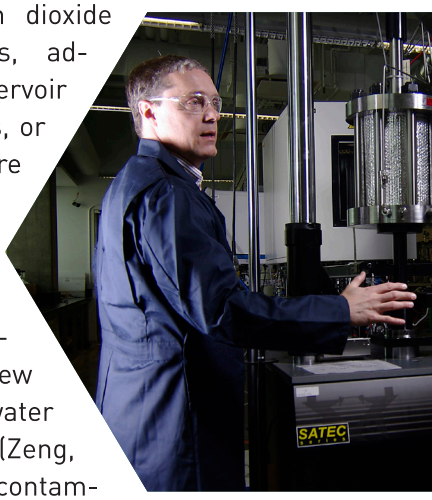
Impacts of the rise of renewable energy on the labour market in Alberta and in Canada are being assessed (Marchand), and processes and tools are being developed to help those who commission renewable projects to manage their construction (Robinson Fayek). Systems models are being developed and refined to assist policy makers in understanding potential wide ranging economic and societal impacts of transition (Davies, Kumar).

Community level impacts of energy systems and potential opportunities and limitations for Canadian municipalities are being addressed (Agrawal). Broader societal questions are being explored, such as energy justice, and how knowledge systems and social constructs can be significantly impacted by current and future energy systems, and have impact on those systems (Gehman, Simpson, Wichmann, Wilson).

ENERGY MONITORING, MITIGATION, AND RECLAMATION

Any energy system's long term sustainability depends on appropriate, thorough, consistent, and innovative monitoring techniques and mitigation strategies that keep pace with new technologies and regulatory requirements. Although all energy systems cause some environmental disturbances, technologies can be developed and protocols implemented to adequately assess potential disturbance and reduce or eliminate current and future impacts.

FES projects are significantly contributing to capturing and storing carbon dioxide. Open source machine learning tools have been developed to significantly reduce time to identify and implement lower cost carbon capture materials and processes (Rajendran). Technology development for carbon dioxide conversion to useful products (Luo) and streamlining carbon monitoring, storage, and utilization (Meldrum) are underway. Fundamental research on carbon capture chemistry, physics, energetics, and storage is being pursued (Kostiuk, Maeda, Tsai, Zhang). Long-term carbon dioxide storage feasibility studies, addressing wellbore and reservoir processes, thermal impacts, or consequences of salinity are ongoing (Chalaturnyk).



Land and water reclamation is vital to any energy system to reduce environmental impacts. From new strategies for process water and wastewater treatment (Zeng, Zhang), to advanced water contamination sensors (Serpe), and use of innovative materials such as chicken feathers or biochar for water decontamination (Chang, Gamal El-Din, Siddique, Ullah), returning water to the environment in a clean state is necessary to avert the path of waste materials to landfills. Reclaimed land and water systems must be resilient, necessitating best practices for soil reclamation, soil contaminant remediation, and revegetation; and new metrics of measuring reclamation success (Naeth).

Assessment of technology impacts is critical, including determining environmental footprints, scope of biomass waste production, and broad life cycle assessment of energy transition technologies (Kumar). Future energy systems will rely heavily on advanced mitigation, utilizing novel management strategies, being developed for new microgrids (Khazaei) and distributed energy systems (Ardakanian). New methods of monitoring heavy oil processes (Daneshmand, Gu) and treatment of waste products of

non-aqueous oil extraction (Choi) are important in new energy systems.

Use of technologies such as wirelessly powered sensors have potential to improve process management of various energy generation technologies. Work was conducted by FES researchers Mojgan Daneshmand and Pedram Mousavi, who tragically perished over Tehran in January 2020 aboard Ukrainian International Airlines flight 752. Their novel and advanced research continues (Iyer, Mirzavand).

INTERDISCIPLINARY COLLABORATIONS

Interdisciplinary collaborations are embedded in FES research projects, with numerous instances of mutual support and collaboration among researchers in different disciplines. To date, 47 FES publications have authors from different UofA faculties, signaling high interdisciplinarity.

Some collaborations began during the design phase of existing projects. The team identifying geothermal potential for Indigenous communities in Alberta and the Northwest territories is led by an engineer (Lefsrud), and includes a geological scientist, and an anthropologist to address both technical and social science aspects of energy projects. Biomass research using microorganisms to convert potential methane emissions into usable fuel precursors (Sauvageau) requires microbiological expertise to understand the function of methanotrophic bacteria at a genetic level, and process engineering for an economically viable process.

Other collaborations emerged as research evolved during the first half of the FES program. One group (Mar) used machine learning to increase efficiency of another's (Buriak) organic solar cells by approximately 30% in a few months, using design of experiment techniques. An engineering group (Rajendran) used machine learning to develop tools for chemists for rapid screening of potential materials (zeolites, metal organic frameworks) and processes for carbon capture technologies.

A civil and environmental engineering group (Robinson Fayek) gathering data on small scale renewable energy projects in Canada discovered through a graduate student presentation that an environmental sociologist (Parkins) had collected this data as part of their investigation into ownership structures for community based energy projects. The data were shared, accelerating the engineering team's ability to develop tools for use in the construction industry. In the land and water theme, scientific expertise and business theory came together in a project (Jennings) investigating public engagement to better support scientifically sound wetland reclamation strategies.

PARTNERSHIPS

The FES program is strongly focused on research outcomes to benefit Canadian and global society, through partnerships and collaborations with private industries, government, and other institutions. FES is currently engaged with 369 such partnerships. Collectively, these partnerships and collaborations ensure that FES research is routinely connected to academic peers, industry users, academic institutions, and government regulators.

FES has a strong partnership with the Global Research Initiative in Sustainable Low Carbon Unconventional Resources (GRI) at the University of Calgary addressing complex problems with expertise of researchers at both institutions. Research on system wide consequences of a green energy transition from

multiple perspectives is being conducted, including life cycle analysis of energy transition pathways (Kumar), and assessment of political pathways for energy (Thorlakson). Research is addressing carbon dioxide conversion to useful chemicals and fuels (Luo), carbon dioxide storage strategies and impacts (Chalaturnyk), and monitoring sequestration sites (Gu); partial upgrading of extracted bitumen to improve pipeline transport (Stryker) and oil well monitoring (Sacchi); optimization of deep, poorly accessible oil wells, and specific molecular behaviour of oil reservoir components to improve oil flow (Leung); and computational modeling and techniques to optimize well operations and reservoir management, reducing harmful environmental impacts (Trivedi).

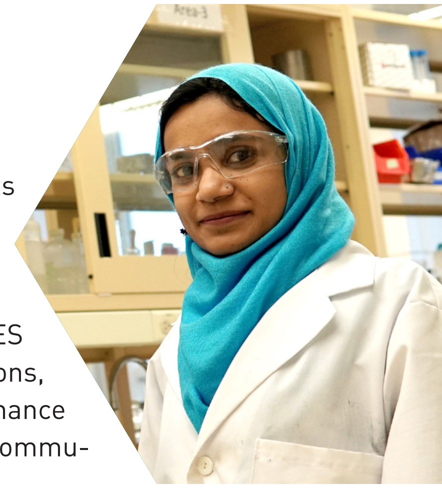
In 2017 the UofA and Tsinghua University in Beijing China founded the Joint Research Centre for Future Energy and Environment, bringing global perspectives to understanding how global energy transition might optimally occur. The partnership funded 11 projects, with topics from wastewater treatment and water reclamation (Yu, El-Din, Zhang, Zeng), carbon dioxide capture and utilization (Zhang, Chalaturnyk), lithium ion batteries (Li, Jin), shale condensate reservoirs (Li), wind energy generation (Zuo), and assessment of biomass resources (Kumar).

FES research with breakthrough technology significantly impacts the strength and resilience of stakeholders in future energy systems. These are bolstered by partnerships with companies in the oil and gas sector, such as Cenovus Energy (Leung) and start-up companies across energy systems including Mango Materials (Sauvageau). Other collaborations are with peoples directly affected by current and future energy systems, including the Tłıcho Government in Northwest Territories and Edmonton community leagues (Agrawal), aiming to understand and serve the collaborators in question. FES partnerships often include industrial research chairs, companies such as EPCOR, and groups such as the Canadian Oil Sands Innovation Alliance (COSIA) and the Clean Resource Innovation Network (CRIN). Global organizations such as the Worldwide Universities Network (WUN), which UofA hosted for a summer school on energy systems in 2019, and the Worldwide Energy University Network (WEUN) provide opportunities focused on student learning.

FES works closely with the Government of Alberta. Collaboration with the ministry for Economic Development and Tradehas led to specific information sessions and invitations for researchers to participate in funding competitions. The program also works with Alberta Innovates, the corporation responsible for significant provincial research funding.

FES researchers collaborate on numerous endeavours around energy, including a panel at the International Conference of the Fuel Science Center at RWTH Aachen University in Germany; a joint doctoral program with 3 Institutes of Technology in India; co-funded biomass and redox flow battery projects with the Fraunhofer Society in Germany, including involvement of several Alberta government units and WestJet; shared research and potential trilateral partnerships with Tecnológico de Monterrey in Mexico and the University of Texas at Austin, USA.

EQUITY, DIVERSITY, AND INCLUSIVITY

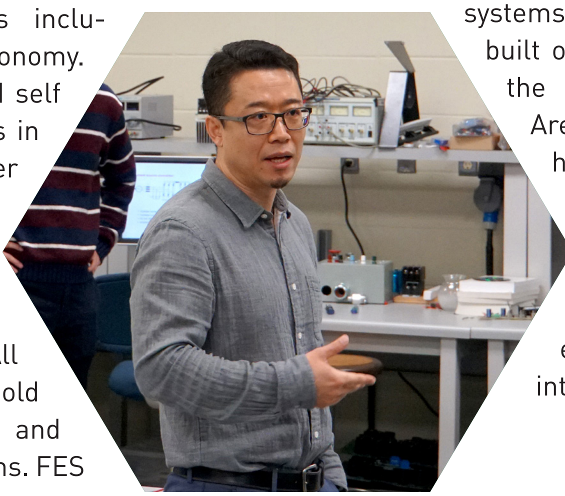


FES strongly affirms its pursuit of excellence aligns with a vision of increased equity, diversity, and inclusivity (EDI). FES considers EDI in all operations, from formation of governance and advisory bodies to commu-

nications activities, seeking to end misconceptions that the research environment is only appropriate for specific types of individuals, representing specific groups, and reinforce that diverse points of view strengthen research outcomes. The FES plan to expand awareness of EDI knowledge and strategies, and better support disadvantaged or under represented groups is structured to invite collaboration and insight from the FES community. It consists of five initiatives, providing resources and encouraging participation in developing safe spaces for all, including accommodations for personal, cultural, or religious reasons.

Expanding representation in science, technology, engineering, and mathematics is a FES priority. A FES sponsored stipend through the UofA Undergraduate Research Initiative, supports women, visible minorities, Indigenous persons, and persons with disabilities in pursuing energy research. A recent survey of FES researchers and HQP received 277 self identifications. Among the respondents, 25% identified as female, 35% as being part of a minority, and 1% as Indigenous persons. These identifications are one step on the path to a more representative research environment.

FES supports Indigenous inclusion in research and autonomy. Indigenous land rights and self governance are key drivers in many FES projects, whether considering access to energy resources, impacts of regulation and implementation, or determining needs and desires. All researchers commit to uphold Indigenous sovereignty and dignity in their collaborations. FES focuses on removing barriers and educating our members and the public to support inclusion of marginalized peoples, including Indigenous researchers in the program, and to communicate Indigenous perspectives in energy systems and academic research.



LOOKING FORWARD

FES will build upon a foundation of diverse, strong, world leading research, and address the energy systems questions of a changing, post-pandemic world. With COVID-19 altering individual and collective perspectives on the importance of travel, desirability of large urban centres, and viability of telecommuting, new forms of decentralized energy have strong potential to be increasingly in demand. Impactful contributions to energy transition during this period of significant societal change will be made by identifying successes within the projects already underway, seeking academic, industry, and government partners for whom those successes are relevant, and developing large scale, transformative projects that can move research from campus to the world in meaningful ways. It is being done by identifying gaps within the energy systems research program that are required to advance the successful research done in the first half of FES.

The breadth, depth, and diversity of FES research is being leveraged to have lasting impacts on Canada's current and future energy systems. With a continuity plan built on a strong foundation from the Energy Systems Signature Area, the University of Alberta has created the pathway for Future Energy Systems to ensure that the institution will continue advancing as a global leader in energy systems research well into the future.