

EMERGING UNDERGRADUATE SUSTAINABLE ENERGY ENGINEERING PROGRAMS IN CANADA AND BEYOND: A REVIEW AND ANALYTIC COMPARISON

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Abstract: Faced with global climate change and many other challenges, our energy system is transforming from a centralized, fossil-fuel dependent, utility-dominated infrastructure system to a decentralized, sustainable, “smart” network. As this transition clarifies, academics and practitioners from multiple disciplines are rethinking the way society frames, delivers, and uses energy. Successfully navigating this transformation calls for systems-thinkers who are capable of diagnosing increasingly complex energy problems and delivering robust, integrated, interdisciplinary solutions. As leaders in education innovation, universities have a distinct role in cultivating a new education framework and generation of systems-thinkers. Hiring committees, educators, and students alike are responding to this call, resulting in the emergence of novel undergraduate sustainable energy engineering programs. In particular, engineers’ training in thermodynamics and electrical principles provides the technical foundation of energy systems, which could be augmented with broader sustainable energy proficiency: for example through discourse around the economic and political factors that govern the energy system and the society in which the energy system resides. Each of these emerging programs has a unique specialization, set of learning outcomes, and organizational structure, inviting reflection on their relative strengths and weaknesses.

We compare several of these programs, including the University of Toronto’s Energy Program, Carleton University’s Sustainable and Renewable Energy Engineering Degree, the University of British Columbia’s Electrical Energy Systems Option, and the University of Calgary’s Energy and Environment Specialization. Our objective is to understand the drivers that can enrich discipline-oriented curricula with socially relevant, problem-oriented literacy. We devise a series of metrics to analyze these programs, including the program structure, the scope of the curriculum, access to application and research opportunities, and the institutional energy research community. Data is gathered primarily through reviewing program documentation and websites. Finally we evaluate each program’s effectiveness in cultivating the “T-shaped” engineer using a multi-criteria framework, designed to measure education outcomes. The program comparison shows that even with the immense constraints imposed on active curriculum development including accreditation requirements, budgets, and faculty availability, there is tremendous opportunity and design flexibility regarding how to integrate sustainable energy systems-thinking into energy engineering education; seizing this opportunity now, while developing a culture of continuous improvement and adaptation, is imperative to our evolution as educators and engineers.

1 INTRODUCTION

The sustainable energy industry is growing rapidly due to a culmination of environmental, energy security, public health and (in some jurisdictions) economic rationales. In Canada, wind, solar, run-of-river, and biomass generating capacity increased 93% between 2009 and 2013 (Clean Energy Canada, 2014).

Targeted sustainable energy policies, ranging from feed-in tariff programs for renewably generated electricity to energy efficiency subsidies, as well as declining costs have led to a growing demand for sustainable energy specialists. While traditional engineering programs provide some energy specific training, such as studies in thermodynamics and electromagnetism, energy-related courses are often offered through traditional engineering departments and lack specific sustainability concepts. In addition, the shift to a sustainable energy system requires new solution frameworks, calling for a set of learning outcomes that are largely absent in conventional engineering education. In response, there have been numerous initiatives for new courses and programs intended to prepare engineers for work in sustainable energy industries. For example, the Centre for Sustainable Engineering was established in 2005 as a partnership between Carnegie Mellon University, the University of Texas at Austin, and Arizona State University, to assist engineering faculty in incorporating sustainable development into their curricula (Davidson et al., 2010); an early review of renewable energy education at the university level is provided in (Bhattacharya, 2001). Although this call applies to multiple education disciplines and levels, the focus of this paper is on engineering education at the undergraduate level. For the purposes of this analysis, we use a broad working definition of sustainable energy, including energy consumers (building science, industrial processes, transportation) to energy systems (grid security, self-sufficiency, electricity distribution) to energy generation (renewable electricity, heating and cooling).

Four undergraduate engineering programs with an energy focus have been chosen here for comparison: the University of Toronto's (Toronto) Energy Program, Carleton University's (Carleton) Sustainable and Renewable Energy Engineering Degree, the University of British Columbia's (UBC) Electrical Energy Systems Option, and the University of Calgary's (Calgary) Energy and Environment Specialization. Several aspects of institutional characteristics impact the programs themselves as well as the wider institutional metrics. Firstly, our curriculum evaluation relies heavily on the availability of courses offered to students in the respective energy program. The size of each institution, specifically in the engineering school, inevitably impacts the institutions' range of courses due to faculty availability and student enrolment, as well as the breadth of the (sustainable) energy research. As a result, both our curriculum evaluation and research community evaluation are (perhaps unfairly) biased towards larger institutions. The 2013 undergraduate engineering enrolment in each of program are 4,560 at Toronto, 3,699 at UBC, 3,189 at Calgary and 3,228 at Carleton (Prism Economics and Analysis, 2014). Full time equivalent faculty members (professors and instructors/lecturers) in 2013 include 241 at Toronto, 180 at UBC, 161 at Calgary, and 147 at Carleton (Prism Economics and Analysis, 2014). Maclean's categorizes universities according to institutional type in three ways: as (i) primarily undergraduate focused, (ii) comprehensive including undergraduate, graduate, and professional degrees, or (iii) medical/doctoral universities offering a broad range of research including medical sciences (Dwyer, 2013). Toronto, UBC, and Calgary are categorized as medical/doctoral universities, while Carleton is a comprehensive university. Finally, a crucial consideration, given the proposed comparison, is that each program is accredited and therefore subject to the same set of constraints imposed by the Canadian Engineering Accreditation Board. Although this is not an exhaustive list of every undergraduate engineering program with a specialization, minor, or major in energy offered in Canada, it represents a cross-section of program structure and specialization that invites reflection, given that graduates of each of these programs will work in Canada's energy sector. For practical reasons, numerous undergraduate energy engineering programs or specializations in Canada were excluded from this analysis, such as those hosted at the University of Ontario Institute of Technology, Queen's University, the University of Alberta, and the University of New Brunswick, to name a few.

2 DATA AND METHOD

The primary objective of this analysis is to understand how engineering students can develop system-level, problem-oriented literacy with respect to sustainable energy systems. To do so, we devise a series of comparative metrics, including the program organization structure, the scope of the curriculum, students' access to application and research opportunities, and the institutional energy research community. These metrics, which admittedly are only a small subset, are used within a multi-criteria framework to evaluate each program's effectiveness in developing sustainable energy engineers. Data was primarily collected through curriculum documentation, and program and institutional websites.

2.1 Program Structure

Each of the four energy engineering undergraduate programs under review has a unique organizational structure. Several organizational factors distinguish the programs, including the year of opting into the of energy specialization, the cohort of eligible students, and the energy specialization designation as either a major or minor/specialization, as summarized in Table 1. Carleton’s energy program begins in first year so that Carleton students choose their specialization at a very early stage in their career, enabling them to focus on energy for their entire undergraduate degree. Calgary offers its Energy and Environment specialization to students starting second year in chemical, civil, electrical, geomatics and mechanical engineering. Finally both the Toronto and the UBC energy specializations begin in third year. Toronto’s Energy Option is offered to students enrolled in the Engineering Science program; UBC’s Energy Systems Option is offered to electrical engineering students. Carleton’ students receive a BEng in Sustainable and Renewable Energy Engineering, while Toronto’s students earn a major in energy within the engineering science degree. Calgary and UBC graduates earn a conventional engineering bachelor with a specialization in Energy and Environment or Energy Systems.

Table 1: Comparison of Program Structure

	Carleton	Toronto	Calgary	UBC
Energy-specialization	1 st -4 th year	3 rd -4 th year	2 nd -4 th Year	3 rd -4 th year
Eligible students	Accepted first year students	Engineering science students	Chemical, civil, electrical, geomatics, and mechanical engineering students	Electrical engineering students
Specialization or core designation	Major designation with two additional specialization streams	Major in Energy	Minor/ specialization in Energy and Environment	Minor/ specialization in Energy Systems
Accredited	Yes	Yes	Yes	Yes

*Citations: (Carleton University, 2013), (University of Toronto, 2011), (University of Calgary, 2015), (University of British Columbia, 2015), (Prism Economics and Analysis, 2014)

The presumptive advantage of Carleton’s four-year energy focus is that students should be exposed to more energy content and at an earlier stage in their career. Disadvantageously, by deciding to specialize in sustainable energy at such an early stage, the program may exclude at least some undecided students. Interestingly, Carleton’s curriculum only has one sustainable energy course in the first two years, probably due to the significant accreditation obligations that consume much of the first and second year curricula to ensure coverage of fundamental depth and breadth courses. With only one sustainable energy course offered during the first two years, the disadvantages of having to specialize so early in one’s career may well balance out the advantages of early specialization. On the other hand, students who identify as “energy specialists” may pursue a hidden curriculum by engaging in opportunities outside of the course curriculum and relating foundations courses to energy systems.

Calgary offers their energy specialization to the widest breadth of students including those in chemical, civil, geomatics and mechanical engineering. Calgary excludes computer and software engineering students, as well as those in electrical and oil & gas engineering fields. Conversely, UBC limits its energy option to electrical engineering students. On the one hand, the energy courses offered at UBC may be easier to develop and teach since students would have a similar educational background. On the other hand, the breadth of students’ experiences in Calgary’s energy courses may result in more interdisciplinary breadth. Simply through defining the eligibility of students in each program differently, Calgary and UBC have differentiated the scope of energy subject learning outcomes. Calgary has set up a program structure that could cover our entire working definition of sustainable energy, while UBC has

inherently reduced its program coverage to electrical subjects. The degree to which each program delves into the sustainable energy subjects is discussed further in the curriculum evaluation section.

Carleton offers the most specialized program by focusing on sustainable and renewable energy. Although less specific, Toronto students earn a major in energy that is distinct from any conventional engineering degree. UBC and Calgary students, by contrast, earn a bachelor's degree in one of the conventional engineering subjects, with a minor or specialization in energy. The degree of program specialization has obvious implications for the employability of its graduates, which may depend on the long-term health of the sustainable energy industry. From a larger perspective, the degree of program specialization touches on a wider debate about the role of undergraduate engineering education and universities. Although it is often argued that university education should create broadly educated, analytical problem solvers, given the increasing complexity of today's system, and perhaps particularly the energy system, students may have to specialize earlier to be effective employees.

2.2 Curriculum Evaluation

A program's curriculum has a critical role in determining the degree to which students obtain a technical foundation in conventional engineering principles as well as broader sustainable energy proficiency. Information regarding each program's curriculum was primarily derived from the following sources, which are referred to throughout this section: Toronto (University of Toronto, 2011), Carleton (Carleton University, 2013), Calgary (University of Calgary, 2015) and UBC (University of British Columbia, 2015). All four programs offer a similar suite of foundational engineering courses including an introduction to engineering design; math courses including calculus, linear algebra, and probability/statistics; programming courses; science courses including a mechanics and/or dynamics; an engineering economics course; and electrical engineering courses including electromagnetisms and circuits. In addition to these core courses, all four universities offer a range of electives in science, engineering, humanities, and/or social sciences. As such, we conclude that all four programs offer similar foundational training in engineering principles, which is a reflection of accreditation requirements and typical university definitions of foundational engineering curricula, ensuring coverage in mathematics, natural science, engineering science, engineering design, and complementary studies.

The programs differentiate themselves by the range of energy courses they offer. To understand the scope of energy related courses, we have relied on three overlapping categorizations of energy systems: energy subjects, economic sectors, and sustainability. The subject categorization parallels conventional engineering disciplines by dividing energy systems into thermodynamics, electrical, or nuclear. Alternatively, the economic sector categorization is based on Canada's four largest GHG emitting sectors: transportation (24%), oil and gas (23%), electricity (13%), and buildings (12%) (Environment Canada, 2013). Finally, energy systems can be categorized as conventional or sustainable; here we rely on an assertion from the literature.

Each school offers a different degree of breadth in energy subjects. All four programs offer (at least one) thermodynamics course, as well as a range of electrical courses such as power electronics, power systems, and circuits. Interestingly, Toronto is the only school that offers courses on nuclear or fusion energy, including a total of five courses (University of Toronto, 2011). From energy subject perspective, only Toronto offers courses in all three broad subject areas. Calgary, UBC, and Carleton only offer courses in two of the three subject areas.

Energy courses can also be categorized according to their economic sector. While none of the energy programs offer courses that focus specifically on the transport sector, transportation technologies and fuels are embedded within a range courses. For example, Toronto offers courses in combustion and fuels, bio refinery, fuel cells, and energy storage and generation (including a module on batteries) (University of Toronto, 2011). Carleton offers a course on thermofluids in energy systems, which integrates fluid mechanics, thermodynamics a heat transfer into the design of transport conversion technologies including internal combustion engines, fuel cells, and batteries; in addition Carleton offers an efficient energy conversion course which includes a module on fuel cells (Carleton University, 2013). Aside from thermodynamics courses, transport-related courses were not found in specific energy

programs at the Calgary (University of Calgary, 2015) or UBC (University of British Columbia, 2015) curriculum. Toronto and Calgary both offer courses that focus explicitly on oil and gas sector. Like transportation, building studies may be integrated into many different courses. Only the Toronto program offers courses in building science and sustainable buildings. In addition Toronto and Calgary offer a course on lighting. Building-related courses were not found in the Carleton or UBC curriculum, however Carleton's efficient energy conversion course, which focuses on electric power generation, could theoretically be expanded to include a buildings component. All four universities offer several courses on transmission and/or distribution, electrical energy conversion, and power systems/electronics. The electrical energy sector is the primary economic sector focus at all four universities. Toronto offers the widest selection of courses from different energy sectors including transportation, oil and gas, electricity, and buildings. In addition to the electric sector, Carleton offers a module on transport, and Calgary offers a course on buildings (lighting) as well as oil and gas. Carleton's omission of the oil and gas and building sectors, Calgary's omission of the transport sector, and UBC's omission of all three non-electric sectors, is understandable due their disciplinary background but results in gaps of large percentages of Canada's GHG emissions. These omissions are often implicit in the program name and design. For example UBC's exclusive focus on the electric sector is natural given the program's roots in electrical engineering. Carleton's omission of the oil and gas sector is natural given the program's explicit focus on sustainable and renewable energy types. Beyond program design, the limited range of course in these areas may be a reflection that development in the oil and gas, transport, and building sectors is occurring within industry rather than academia.

Our final curriculum evaluation explores the degree to which sustainability has been explicitly enveloped into the curriculum. Jennings asserts that "modern renewable energy education includes a study of the technology, resources, system design, economics, industry structure and policies in an integrated package" (Jennings, 2009). Although Jennings is referring specifically to renewable energy education, a similarly integrated approach, with exposure to both the systems level as well as their components, applies to both renewable and conventional energy systems. The sustainability of a system is partially determined by how components of the system come together. As such, we apply Jennings' (2009) assertion in a broader energy context. Although Carleton is the only program that designates "sustainability" directly in the program title, Carleton, Toronto and Calgary offer introductory courses on sustainable energy; UBC does not. In addition, Carleton and Toronto offer courses in specific renewable energy technologies, including solar cells/ photonic devices Carleton and Toronto), hydro and wind plants (Toronto), bio energy (Toronto), as well as modules within courses in solar thermal (Carleton) or geothermal (Carleton). Toronto addresses the connection between energy and the larger environmental system through a course entitled "Terrestrial energy systems". Since renewable energy solutions and sustainable development are closely linked, a firm grounding in the concept of sustainability is imperative; multiple courses have modules on sustainability, but no program offers an entire course dedicated exclusively to sustainability. Carleton and Toronto introduce energy systems thinking through Carleton's "Sustainable Energy Systems Design" and Toronto's "Introduction to Energy Systems". Carleton and Toronto also address the interaction between energy systems and society at large through Carleton's "Energy Economy, Reliability, and Risk" and Toronto's "Energy Policy". Carleton, Toronto, and Calgary offer some courses on the environment, ranging from risk assessment, pollution, modeling, and life-cycle assessment. None of the four programs reviewed here offer a curriculum that matches Jennings' (2009) notion of a complete modern renewable energy education. For example, UBC's program could benefit from at least an introduction to sustainable energy. UBC and Calgary programs could benefit from renewable energy technology specific courses, an energy systems course, and a course linking energy systems to the wider context. Carleton, Calgary, and UBC programs could benefit from course on energy policy, and connection to natural system. While Toronto arguably had the broadest coverage of energy topics, the electrical courses tend to be core, while building and transport courses tend to be electives; Toronto's energy program may ultimately benefit from two distinct streams to enable more depth in non-electrical energy subjects.

2.3 Professional Engineering Experience Opportunities and Curriculum

Undergraduate engineering graduates pursue both industrial/commercial and graduate positions; for every two undergraduate degree granted in 2013, one masters or PhD degree was granted (Prism

Economics and Analysis, 2014). From an undergraduate perspective, preparation for both industry and post-graduate (research) positions are important. All four programs offer an optional opportunity to acquire professional experience: Calgary and Toronto host internship programs while Carleton and UBC host co-op programs (Prism Economics and Analysis, 2014). Each program also offers courses on engineering design and practice, as well as capstone project courses. In addition Carleton, Calgary, and UBC offer an engineering professional practice course, while Carleton and UBC offer communication courses, and Toronto, Calgary, and UBC offer courses regarding engineers' role in the broader society. As a result, all four programs provide professional skills courses and (optional) experience. These engineering design, professional practice, and engineers' role courses may be a natural place to embed sustainability concepts, as part of a larger across-the-curriculum approach.

2.4 Access to Research Opportunities and the Sustainable Energy Research Community

For the significant portion of engineering undergraduates bound for post-graduate degrees, research experience in a wide breadth of energy areas is important. To provide access to research experience, Toronto has a mandatory thesis course, and UBC has an optional thesis course. Carleton and Calgary do not appear to offer undergraduate research thesis courses, however students may have the opportunity to work in research labs during their summers. Reviewing the complete host of sustainable energy research opportunities at each institution is beyond the scope of this analysis; as such membership in the institutional sustainable energy centre or institute is used as a somewhat limited proxy. Carleton hosts the Sustainable Energy Research Centre with over 50 energy-related engineering faculty members (Cruickshank, 2010), The University of Toronto houses the Institute for Sustainable Energy with almost 60 faculty members (University of Toronto, 2015), and UBC houses the Clean Energy Research Centre with over 60 faculty members (UBC Clean Energy Research Centre, 2011). Each of these centres or institutes include faculty in a range of energy areas including renewable energy technologies and fuels, non-renewable energy, energy systems, energy storage, energy materials, energy end-use, and carbon intensive communities. The University of Calgary started the Institute for Sustainable Energy, Environment and Economy, however, their website no longer appears to be active. The Institute became a source of media attention in early 2013 when its director stepped down due an allegation that private industry overreach into the university could be affecting research activities. In conclusion, Toronto and UBC offer student research opportunities (through thesis programs) and a well-developed sustainable energy research community. Although Carleton has a well-developed sustainable energy research community, they do not offer a thesis course in their curriculum, potentially hampering their students' ability to engage in research activities during their undergraduate program; this may be a reflection of Carleton's designation by Maclean's as a comprehensive university rather than a medical/doctoral university. Finally although Calgary undoubtedly has research activities in sustainable energy areas, as far as we could tell they are not currently organized into a centralized institute or centre.

3 EVALUATION FRAMEWORK AND RESULTS

Based on the discussion in the previous section, we have developed a multi-criteria framework, designed to guide evaluation of each programs effectiveness in cultivating undergraduate engineers well versed in energy topics and prepared for engineering or research careers. Among other limitations discussed in more detail below, this evaluation is limited to the documentation we could find through online sources. Collecting additional data, through conversations with stakeholders at each institution, would illuminate nuances that are not apparent in program documentation.

Table 2: Multi-criteria evaluation framework

		Carleton	Toronto	Calgary	UBC
Foundational Engineering Curriculum		Strongly present	Strongly present	Strongly present	Strongly present
Energy Coverage	Subject	Partially present	Strongly present	Partially present	Partially present
Energy Coverage	Sector	Partially present	Strongly present	Mostly present	Apparently weakly present
Sustainable Coverage	Energy	Mostly present	Mostly present	Partially present	Apparently absent
Engineering Experience and Curriculum		Strongly present	Strongly present	Strongly present	Strongly present
Research and Community	Experience	Partially present	Strongly present	Apparently absent	Strongly present

4 CANADA'S UNDERGRADUATE SUSTAINABLE ENERGY PROGRAMS IN A WIDER CONTEXT

Beyond Canada, there are multiple examples of undergraduate engineering energy programs, such as University of New South Wales' Bachelor of Engineering in Renewable Energy, or Murdoch University's Renewable Energy Bachelor of Engineering. Beyond the undergraduate level, there are a multitude of college, master's, and research level programs with an entirely different mandates. For example technician degrees in renewable/sustainable energy or energy systems are hosted at Durham College, Seneca Collage, Niagara College Canada, Conestoga, Fanshawe, Humber, and Chatham, to name a few in Ontario (Ontario Colleges .ca., 2015). Course-based masters programs or certificates focusing on sustainable energy are hosted at Carleton, UBC, Waterloo, and University of Toronto (upcoming). Finally there are many hundreds of university faculty members taking on graduate research students in energy-related fields. A deeper discussion around the distinct roles of technical, undergraduate, and masters programs in sustainable engineering education can be found in the literature, for example (Boyle, 2004).

5 LIMITATIONS OF THE ANALYSIS

There are several crucial limitations embodied in this analysis. Firstly, we only reviewed four programs, which limit the breadth and depth of our analysis; further work exploring programs outside of engineering or Canada are welcome. In addition, this work has focused on undergraduate university degrees; further analysis could explore the strengths and weaknesses of sustainable energy degrees at the college, master's and research levels. Secondly, the data collection was limited to content that was available on publicly published documents and websites; the analysis could be enriched by pursuing interviews with curricula designers, students, and alumni with a nuanced view of the curricula and student experiences. In particular, the curriculum evaluation relied on course names and brief course descriptions, which may have unfairly evaluated programs for missing content that was embedded in the course, but not mentioned in the course description. In addition, courses inevitably evolve over time and include special modules, and the course descriptions could be out of date. Finally, the curriculum evaluation is unfairly biased towards larger institutions and engineering departments with a larger breadth of courses on offer.

6 CONCLUSIONS

Broadly speaking, the undergraduate programs reviewed here can be categorized either as conventional engineering programs with a (sustainable) energy course add-on versus completely overhauled curricula focused on sustainable energy. Without any "apparently absent" criteria according to our definition, Carleton and Toronto's programs generally fit into the latter category, but do not score perfectly according

to our evaluation. The balance between educating broad engineering problem solvers versus renewable energy specialists remains an open debate. On the one hand, Jennings states that “attempts to add one or two units of study on renewables into traditional science and engineering degrees are unlikely to produce graduates with sufficient knowledge or understanding to use renewables effectively” (Jennings 2009). Conversely, the amount of foundational engineering coursework may limit the programs’ ability to offer inter-disciplinary courses inherent to sustainable energy system. As such, it may be more challenging to develop fulsome sustainable energy programs within undergraduate programs. Each of the four programs reviewed here have distinct specializations; Carleton focuses on renewable/sustainable energy; UBC focuses on electrical energy; Toronto offers a wide breadth of energy courses. Ultimately, sustainability education should extend well beyond the undergraduate degree itself, for example through a value-oriented perspective and systems-level literacy. Engineering programs that train students too specifically in current gaps in the sustainable energy system could risk becoming “flavour of the month” programs. However, there is no doubt that the quality of sustainable energy education closely tracks the development of the sustainable energy sector, either through enhancing society’s confidence, developing markets, training practitioners, conducting research, and developing policy.

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