Enabling Transdisciplinary Education for Energy Systems Transitions

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Anthropogenic climate change caused by greenhouse gas (GHG) emissions related to energy production is advancing at an accelerating rate threatening the stability of industries, economies, and societies. In 2016, 194 countries adopted the Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) [1] agreeing to, among other things, reduce global GHG emissions and begin transitioning to renewable energy production. This massive undertaking requires a significant paradigm shift in technologies, economics, and socio-politics. As industrial and technological leaders, engineers will be at the forefront of this transition thus requiring a holistic approach to the energy transition problem. This approach to education is herein termed the E^3-systems approach referring to the need for engineering students to understand systems in the domains of energy engineering, ecological sciences, and socio-economics.

Germany's "Energiewende" provides an interesting case study in the need for an E^3-systems approach. This policy is one of the only widely successful energy transition policies to come out of the European Energy Council's 2011 renewable energy directive [2]. It guaranteed feed-in tariffs without limits for installed renewable energy capacity for 20 years. This policy proved quite successful with prices dropping for consumers, installation cost for wind and photovoltaics decreasing, and a growth of renewables as a share of the global energy production market [3]. From a technical and economic perspective this program was quite successful, however from a socio-political perspective this policy was marred with failures. Pressure from traditional energy suppliers and other stakeholders led to the general public's perception that government programs resulted in reduced power quality, skyrocketing costs, and unemployment. The "Energiewende" program can be seen as an archetypal example of the complex interaction between technology, economic, and socio-political domains requiring an E^3-systems thinking.

To date, traditional engineering education is still ill-prepared to accommodate transdisciplinary concepts and content. Nearly 40 year ago, Linstone et al. [4] described the need for a multiple perspectives approach in their seminal paper "The Multiple Perspective Concept". Adams et al. [5] discussed the struggles of "engaging future engineers" and prepare them for "'real engineering work". Contemporary engineering education is stifled by "a focus on acquiring technical knowledge over preparing for professional practice, coverage of technical concepts over deep learning, narrow and discipline-focused programs" [5]. The situation is exacerbated by comprehensive curricula driven accreditation requirements, placing taxing time and intellectual demands on students. In response to these challenges, an international group of educators that span engineering, economics, social science, and environmental fields joined forces and created a training concept that fosters learning and transdisciplinary thinking in groups of international students from diverse program backgrounds, and different levels of seniority. An 8-day immersive summer school was created to facilitate the transdisciplinary education needed for the E^3-systems approach. With this approach, engineering students will be better equipped to recognize and address the complex interactions between the energy engineering, ecological, and socio-economic domains to facilitate energy transition goals and GHG emission reduction targets outlined in treaties like the UNFCCC.

The ABBY-Net E^3 approach to graduate student training

Inspired and initiated by a scientific delegation visit of Bavarian (German) academics to Alberta (Canada) in 2011, the Alberta-Bavaria research network (ABBY-Net) emerged as a collaborative cross-national research consortium dedicated to the study of energy systems and transition processes including relevant issues of natural resource management, energy system engineering and socio-economics under changing and contrasting environmental conditions in both countries. The resulting E^3-systems approach was designed to exercise interdisciplinary systems thinking across core disciplines of engineering, environmental sciences, socio-economics, and computing science as the integrating data-driven research facilitator. Figure 1 charts this research framework graphically as the E^3 research space, in which each research domain contributes its own disciplinary perspective to the common subject of energy systems and transition innovation. The graduate color circle represents the transdisciplinary nature of the E^3 research space where disciplines are not distinct entities but are blended at the fringes. Computing science, with its indispensable expertise in data analysis and systems integration, provides the novel tools and standards required to formalize systems interactions, as well as the interface required to functionally connect disciplinary knowledge in a data-drive manner. Thus, computing science adds a fourth dimension to this integrative research space.

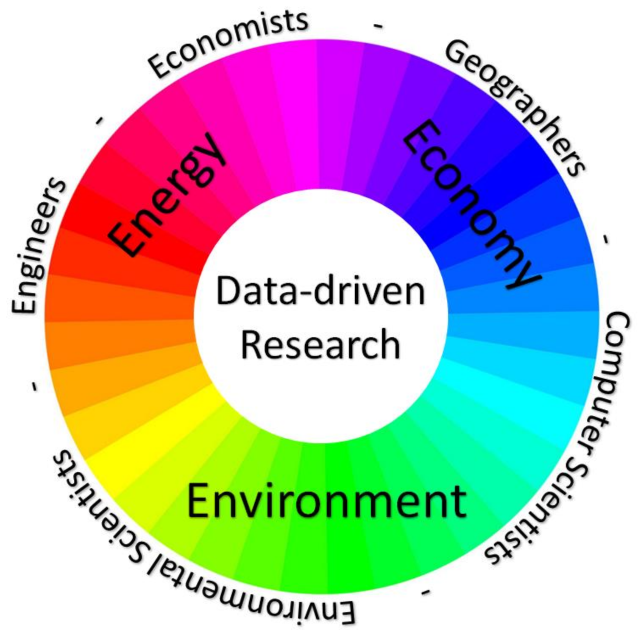

Figure 1. Schematic depicting the E³ research space with blended domain boundaries and data-driven analysis and systems integration at its center.

The focus of the ABBY-Net consortium around relevant disciplinary excellence allows participating researchers to jointly develop and assess energy technology and system designs including broader, often spatially explicit, environmental socio-economic consideration typically outside traditional engineering project procedures. Thus, the environmental and socio-economic drivers, barriers, and impacts typically and directly linked to energy technology development, and its industrial and societal acceptance, becomes an integral part of research with the common goal of developing and evaluating consistent scenarios and pathways for energy systems and transitions. Alongside fruitful academic research collaborations within the ABBY-Net consortium, over the years the group has developed a graduate training concept and program, born out of a research workshop back in 2011 in Munich, Germany. Among the key outcomes of this workshop was the decision to fill a gap in the training of the next generation of engineers and scientists by holding annual graduate training summer school events designed to bring together Masters- and PhD-level students with senior researchers and guest lecturers from academia, industry, and regulatory stakeholders to discuss current issues in energy and energy transitions. What started as an exchange of knowledge and experiences between energy trends in Germany under its “Energiewende” and the volatility of markets for the Western Canadian oil and gas sector, has since grown into a model for interdisciplinary and international graduate training for engineers and energy-related disciplines outside of traditional classroom formats. Having completed seven years of ABBY-net summer schools that alternate between Germany and Alberta, ABBY-Net has trained more than 180 graduate students across multiple disciplines, many of which are now part of an active alumni network. Figure 2 depicts the breakdown of the student participants over the years with respect to their discipline and university geographical affiliation. It can be observed that the composition of the summer school participants varies in terms of the disciplines that students represent, with students from engineering and environmental science having a strong showing over the years.

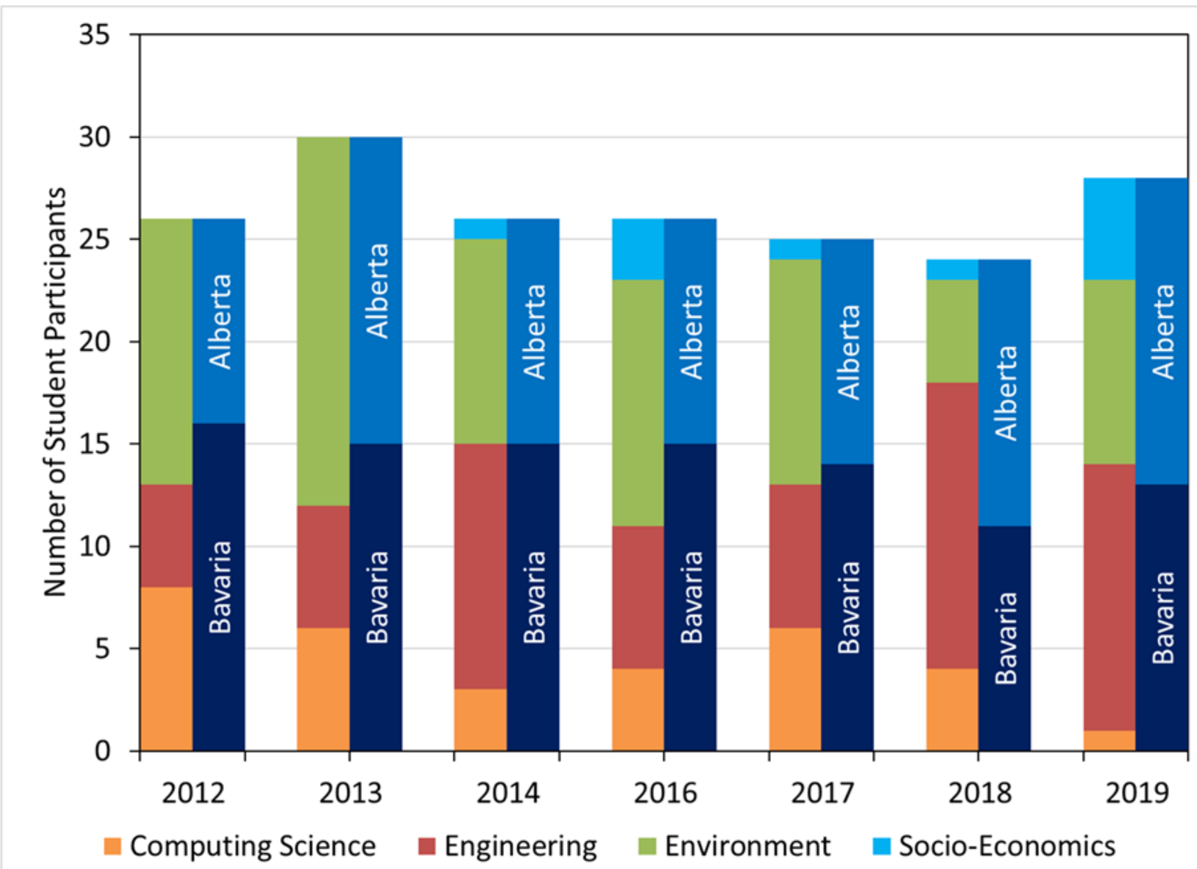

Figure 2. Annual breakdown of student participants with respect to disciplines and university geographical affiliation.

The week-long ABBY-Net summer schools are structured to educate and engage interdisciplinary groups of graduate students on the issues and analytical techniques required to deliver effective, science-based solutions to key energy systems and transitions issues with specific reference to the geo-spatial and political environments of Alberta (Canada) and Bavaria (Germany). The program's delivery and approach are divided roughly into four stages: (i) lectures covering fundamental concepts and specific background knowledge across engineering, environmental science, socio-economics, and data science as the basis for (ii) seminars and discussions designed to help students learn more about specific topics and basic analytical procedures from other disciplines; (iii) field excursions designed to provide hands-on understanding of local ecosystems, energy technology installations and related resource-management topics. Finally, (iv) interdisciplinary groups of summer school students are tasked to develop possible research project proposals following specific formats, such as the Alliance Grant model by the Natural Sciences and Engineering Research Council that brings together university researchers and industry and NGO stakeholders addressing interdisciplinary challenges of direct relevance to industry partners. A sample summer school curriculum is shown in Figure 3, where the four stages are highlighted accordingly. Note that modules M0 to M10 shown in Figure 3 relate to thematic, disciplinary and activity groupings.

The development and writing of joint grant proposals is a learning and development process that spans the entire summer school experience, exposing graduate students to the many challenges of working and communicating across disciplinary boundaries while working toward achieving a common objective. Besides the value of engineering and scientific research topics, the ABBY-Net training approach aims at training the next generation of engineers and scientists by exposing graduate students to explore new scientific grounds in their own discipline, while also gaining domain-knowledge from collaborating with other disciplines within the energy system and transition space.

Time / Date	One Month Before	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
07:00-08:00		Travel to Summer School location	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast
Morning	**M0** Webinar	Orientation and Registration	**M2** Energy Systems (*Instructor*) Coffee **M2** (cont.) Seminar Exercise	**M4** Field Tour Prep Lecture	**M5** Data Science (*Instructor*) Coffee **M5** (cont.) Seminar Exercise	**M7** Field Tour Prep Lecture	**M9** Policy Perspective (*Guest Speaker 1*) Coffee **M9** (cont.) Government Agency Perspective (*Guest Speaker 2*)	**M10** (cont.) Group Work	**M10** Group Presentations: Student Groups to Provide Formal Presentations to Instructor Panel
12:00 - 13:00		Lunch	Lunch		Lunch		Lunch	Lunch	Farewell
Afternoon		**M1** Introductions and Course Overview, (*Instructor*) Energy Transitions (*Instructors*) Seminar Exercise (*Instructors*) Free Time	**M3** Environ-mental Systems (*Instructor*) Coffee **M3** (cont.) Seminar Exercise	**M4** (cont.) Field Tour: Local Ecosystem (*Instructor*)	**M6** Energy Economics (*Instructor*) Coffee **M6** (cont.) Seminar Exercise	**M7** (cont.) Field Tour: Local Technology Installations **(*Instructors*)**	**M9** (cont.) Industry Perspective (*Guest Speaker 3*) Coffee **M10** Group Work (*Instructor*)	**M10** (cont.) Group Work	Return Travel
18:00 - 19:00		Icebreaker	Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	
Evening		**"Fireplace Talk"** (*Instructor*)	Free Time	**M4** (cont.) Discussion: Field Tour Debrief	**Discussion**: German "Energiewende"	**M8** Lecture: Inter-disciplinary Research Proposals (*Instructors*)	**M10** (cont.) Group Work	**M10** (cont.) Group Work	

Figure 3. Sample summer school curriculum structured into four stages of learning: (blue) lectures conveying fundamental concepts and specific background knowledge, (orange) seminars promoting transdisciplinary domain awareness and understanding; (green) field excursions providing hands-on understanding, and (purple) interdisciplinary collaborative group work.

The ABBY-Net summer school advantage and its innovation in the context of graduate training in engineering therefore lies in the highly integrative research experience. Learning of scientific competences from disciplines relevant to energy systems and transitions outside of the traditional engineering curriculum in an intense yet relaxed learning environment with immediate access to field experts, online and offline resources. This environment has been proven to challenge participants to give their best, while forming interdisciplinary network linkages and expanding horizons in research and teaching. Akin to similar collaborative learning experiences [6] a high level of motivation was observed in student participants, leading to rapid learning and high student engagement.

Interdisciplinary information exchange is a common topic of conversation during ABBY-Net summer schools. One student from engineering working in a group studying geothermal potential commented on the state of geothermal well adoption. He said, based on the work the group had completed to that point, the engineering for geothermal wells was not the biggest issue to resolve, but actually the economic and social issues were the more challenging problems to solve. He said he found this surprising because of the inherent benefits of geothermal energy generation. This anecdote was given to one of the author's near the end of the 2019 summer school. This anecdote underlines the impact of the Abby-Net summer schools as they create an enlightening environment where students can engage with each other to gain an understanding of topics outside their own discipline.

To facilitate the exchange of information, participants are divided into peer groups of approximately five students, preferably with at least one group members representing each of the E^3 domains, i.e., socio-economics, environmental science, engineering, and computer science. The participants approach each stage of the summer school as a group allowing them to develop a broader understanding of the issues they are faced with as well as transdisciplinary solutions to those challenges. The interdisciplinary research proposals, stage (iv) discussed above, presented and submitted upon conclusion of the 2019 summer school, provide compelling testament to suggest the program does facilitate transdisciplinary education within the E^3 framework. Representative examples of the program results will be drawn from these reports in the following.

Case Study: Reduction and analysis of heterogeneous data:

The E^3-systems approach significantly increases the complexity of data analysis due to the diversity of available data. Technical and economic research produces various types of quantifiable data which themselves can be difficult to concatenate. This is compounded by socio-economic research, including stakeholder preferences, adoption behavior and political opinions, which has the potential to generate both qualitative and quantitative data. For example, the report of one participating group identified electricity market prices, hydropower generation potential, impacts on local ecosystems, and stakeholder acceptance as potential forms of data. Processing and understanding these heterogeneous datasets is best facilitated through methods from data-science, including emerging techniques such as artificial intelligence. Upon identifying the challenges related to data analysis, the group specifically designated the position of a 'data-science researcher' in their team. This is a common approach to address complexities encountered during the project experience, i.e., students seek domain knowledge through collaborative learning and peer education. Students find support in these situations from the team of instructors, who are present throughout the summer school to provide domain-specific knowledge and study resources.

Case Study: Identification of barriers to technology adoptions:

The research proposals typically explore gaps in the available literature and/or significant potential benefit to the energy transition process. One group created a proposal focusing on repurposing oil and gas wells as geothermal wells. In this process they identified knowledge gaps in all three key areas of the E^3 framework. From an energy systems perspective the group stated, "Previous studies have shown that there are at least 69,000 existing oil and gas wells that have the potential to produce some amount of geothermal energy based on their heat gradient. Of those wells, 53,000 wells can be used for direct heating systems, 7,200 can be used for industrial heating, and 500 wells have the potential to be used for electricity generation," then goes on to state "Companies are hesitant to invest in geothermal in Canada due to a lack of experience in geothermal energy investments, especially in comparison to the mature energy sector already established..." One of the primary research objectives of this report was to investigate potential methods to reduce the technical and economic barriers limiting repurposing of decommissioned oil and gas wells. Clearly, this group demonstrated research needs in the energy systems engineering and economic disciplines, i.e., lack of technological maturity and investment experience, respectively.

Case Study: Appreciation of multidisciplinary research exigencies:

Designing interdisciplinary research projects is not trivial and requires long term organization of research tasks and an understanding of the interconnectedness of those objectives. A representative example of this planning can be seen in a proposal on the potential of hydroelectric energy generation along the North Saskatchewan River (NSR) basin in central Alberta, Canada. This group proposed a five year timeline with multiple stages and clear objectives at each stage. An example of these objectives, considering the E^3 framework, is “Design and build hydrological model...that can predict the future of hydro[electric] in NSR basin,” “[Investigate] potential ecosystem shifts under different scenarios,” and “Survey political, social, and market acceptance of building new [hydro plants] or upgrading existing hydro plants, and propose mechanisms to mitigate stakeholder concerns.” This group also identified a potential research team consisting of three doctoral students and five masters students from engineering, environmental science and geography, and socio-economic disciplines. Through the long term organization of the project as well as the clear interdisciplinary objectives the students demonstrated a deeper understanding of the disciplinary challenges and their dynamics in a temporal and cognitive context. Further, the diversity of stated research objectives and the composition of the proposed research team indicates an understanding of the relationships between the key research fields, i.e., an understanding of the E^3 system.

Discussion and Conclusions

In light of global threats to traditional energy technology and systems, rapidly advancing data science and varying societal acceptance of technological solutions to global issues, contemporary engineering education appears ill-prepared to cope with the transdisciplinary challenges posed by energy futures and other related topics. With its focus on excellence on technical expertise and constraints posed by narrow disciplinary accreditation requirements, many current engineering programs fail to equip especially its graduate professionals with the necessary skills to work and communicate across disciplinary boundaries.

In an attempt to tackle this educational challenge, an international group of educators in engineering, economics, environmental and data scientists joined forces to create and implement a summer school training program that has transdisciplinary engineering education at its heart.

Building on the familiar concept of the summer school, the ABBY-Net research consortium’s program actively fosters transdisciplinary learning and network-building using the topic of energy systems and transition as the unifying challenge to participants independent of their field. The value of its approach lies first and foremost in creating student awareness of the transdisciplinary nature of many issues and as a means to overcome disciplinary language and cultural barriers. The summer school's mix of methods is then focused on collaborative and experiential learning among soon-to-be graduate professionals. While innovative summer school programs are certainly not the solution to advancing engineering education in North America, the ABBY-Net example is a showcase for avenues in which educators can be role models in enabling transdisciplinary education for energy systems transitions.

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