Teaching Integrated Assessment Modeling for Sustainable Transitions: Lessons and Insights

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Abstract

Climate change and sustainability challenges are intricate and multifaceted, requiring an approach considering the entire complex interconnected system of resources. To untie some of this complexity, Integrated Assessment Models (IAMs) have been developed to provide a comprehensive and multidisciplinary framework for analyzing and solving problems in energy security, environmental degradation, economic growth, and social equality. In an educational setting, IAMs can be helpful tools because they help students build the critical thinking and systems-level perspective they will need to tackle sustainability issues and make well-informed decisions in the future. However, their complexity and abstraction mean that IAMs can be challenging to learn in one semester. This paper uses a toy model of the complex but powerful MESSAGEix IAM as a novel and practical pedagogical approach. Our analysis investigates how students approach complex problems and the methods to help them learn and understand complex concepts. In our evaluation, we consider the difficulties associated with imparting knowledge of complex IAMs to a wide range of learners. Finally, we discuss ways teachers might help students develop a systems perspective and an appreciation for the interconnectedness of

multiple social and environmental aspects through tools such as grading rubrics strategically designed to measure students' critical thinking skills. Because of the interdisciplinary nature of IAMs, students could pursue areas of study that particularly interested them, whether in the geographical, temporal, or sectoral aspects.

IAMs in Engineering Education: Enhancing Systems-Level Thinking

Climate change, depletion of natural resources, and environmental degradation are increasingly complex and multidimensional sustainability challenges that have emerged in recent decades (Steffen et al., 2015). Integrated assessment models (IAMs) are valuable tools for investigating these complex sustainability challenges because they can consider the relationships between different indices. IAMs bring together information from the physical, technological, and environmental realms, as well as policy, economics, and social systems, making them ideally suited for investigating issues such as climate change, energy systems, and water resource management. As such, IAMs have proven helpful to policymakers in assessing the effects of progressive approaches and are continuing to be valued as essential resources for the pursuit of sustainable development (Morgan & Dowlatabadi, 1996; Parson & Fisher-Vanden, 1997; Weyant, 2017; Yang et al., 2016).

Traditional engineering education has frequently emphasized specific technologies and technical solutions, reducing students' awareness of the broader context of sustainability challenges. Furthermore, engineering students are often segregated into disciplines, sometimes with little exposure to other disciplines or faculties. However, to prepare future engineers for the evolving sustainability challenges, engineering students must have a holistic comprehension of the interdisciplinary dimensions of these issues; they should have a thorough understanding of the complex interrelationships between the social, economic, technological, and environmental components of integrated system transitions. Engineering education must expand its curriculum to encompass the breadth of interrelated problems, such as climate change and its accompanying systems.

Using IAMs in engineering education can stimulate interdisciplinary thought, improve problem-solving abilities, and provide a deeper grasp of the complex relationships between systems. However, due to their innate complexity, IAMs can be challenging to teach to students without a solid technical background. Hence, novel and effective teaching approaches and procedures are necessary to facilitate the mastery of these models. One such approach is to use toy models. Toy models of IAMs are simplified versions of complex IAMs, making them lightweight and viable to teach in the context of a semester. This allows the students to think about and study IAMs without being overburdened by their complexity.

Additionally, evaluation of university courses and training workshops has demonstrated the effectiveness of using toy models to teach IAMs. For example, a study of an undergraduate course at MIT found that students who were taught using a toy model of the energy system could grasp critical concepts and develop a deeper understanding of the interactions between different systems (Sterman, 2000). Other case studies have demonstrated the effectiveness of using toy models to teach IAMs in various contexts, including climate change policy, renewable energy, and sustainable development (Weyant, 2017).

This article aims to investigate the function of IAMs in engineering education, emphasizing providing students with a thorough awareness of sustainability issues. The study proposes a perspective of teaching IAMs that is utilized within the framework of a semester to facilitate students' understanding of these models using the experience of a course taught at the University of Victoria. Additionally, the study addresses the cutting-edge modeling tools used to ensure the transparency and repeatability of outcomes for collaboration and version control. The following sections introduce the classroom setup for teaching IAMs, and some teaching tools used. Examples of exercises and case studies aiding in IAM comprehension are discussed in detail, as well as constraints of various levels of prerequisite knowledge in the students. Details of the toy model, and its applications in a classroom environment, are discussed. Finally, the conclusion summarizes how educators might aid students in establishing a systems-level perspective and an appreciation for the interconnection of numerous social and environmental factors.

Teaching IAM: A Flipped Classroom Approach

Instructors at the University of Victoria introduce engineering students to IAMs by teaching a course titled *Integrated Assessment Modeling for Energy System Transitions."* The course is designed to teach students the theory behind IAMs and the practical skills to model energy system changes, with a particular emphasis on IAM platforms. The course combines engineering, economic, policy, and historical views on energy system transformations and modeling. In order to create a robust theoretical background, students are given a historical overview of energy system transitions from biomass to coal, oil, natural gas, and electricity, as well as where we are currently situated in the decarbonization transition. The course then examines how the modeling landscape has changed due to these developments and how IAMs are utilized. The course aims to create a holistic perspective encompassing marginal and fundamental energy systems and modeling paradigm shifts.

This course's emphasis on integrated assessment modeling serves as a framework for students to evaluate broader implications for energy-climate activities. Throughout the course, students apply interdisciplinary principles through integrated assessment modeling both in a class setting and outside of class time. To do this, a partial flipped classroom method is utilized. This means that during class hours, content may be delivered by the instructor, but, in addition, there is structured work time and student-led lectures based on assigned readings. Research shows that a flipped classroom approach promotes active learning and enhances course outcomes, reflected by student attitudes (Awidi & Paynter, 2019; Butt, 2014; Danker, 2015). It has also been hypothesized that student-led lectures further improve flipped classrooms' benefits to students (Butt, 2014).

This course's in-class learning opportunities revolve around a specific IAM toy model: MESSAGEix. The MESSAGEix framework was developed by the International Institute of Applied Systems Analysis (IIASA) (Huppmann et al., 2019). The toy model is a Canadian country-level model with realistic parameterization using the country model generator mentioned in (Orthofer et al., 2019). The purpose of the toy model is to enable students to apply, utilize, and implement their ideas through a term project. The course was designed to allow students to select topics of interest, ranging from spatial and temporal dimensions to sectoral concerns. Given their various engineering backgrounds, students tend to focus on various economic and industry-specific problem sets. The course materials are hosted in a repository on GitHub or GitLab. The toy model is presented in the form of Jupyter notebooks, which are interactive notebooks that allow documentation and interactive coding. Learners are required to contribute to the GitHub repository in order to gain knowledge of collaborative tools and processes in addition to model creation.

In order to get the full benefits of a flipped classroom approach and promote higher-level thinking, in-class learning opportunities must be thoughtfully developed (Danker, 2015). This also presents an opportunity to facilitate controlled learning of the toy model through exploration periods and intermediate deliverables, ideally enhancing student understanding. This is done in four stages:

- The initial phase, *Getting Started,* ensures that everyone has installed and completed the tutorials. To evaluate a student's comprehension of the lessons, assignments may be offered.
- In the second step, *Planning the Project*, students investigate several concepts and engage in conversations with the instructor to establish their proposed project's viability. This phase is essential for verifying that the students' proposed projects match with the course learning outcomes.
- The third stage, *Implementation in the MESSAGE model*, entails the bulk of the effort, as students implement their concepts in the model. This phase includes the quantification of model assumptions, data processing, and other technical components.
- The fourth phase, *Reporting*, focuses on teaching students how to successfully report their data, construct visualizations, and convey their findings. This phase is essential for training students for professions in energy systems modelling and sustainability in the future.

This method has been useful for accommodating students with varied degrees of initial model comprehension. By dividing the project into four parts, students can concentrate on a single subject at a time and develop their comprehension gradually. Within the flipped classroom structure, the instructor can organically offer assistance throughout the process to ensure that students receive sufficient explanation and direction. Overall, this breakdown has assisted students in comprehending the model's intricacies and achieving course learning objectives.

Fostering Multidisciplinary Understanding and Transferable Skills in Engineering Education

Over the past three years, the IAM course at the University of Victoria has covered a wide range of topics, offering students an opportunity to explore different applications in which IAMs can be used. Moreover, students gained exposure to the application of complex models by utilizing state-of-the-art software tools. Students were instructed on how to interpret optimization models and constraints, as well as how to visualize model outputs using a range of graphs and maps. This enabled them to acquire transferable skills pertinent to a variety of disciplines, such as energy systems, environmental policy, and economics. This also assists students in understanding the usefulness of complex models in addressing real-world issues and informing policy decisions. Figure 1 shows a summary of the term project themes covered as an outcome of these course teachings. Students were also able to implement IAM concepts and tools in their term projects, thereby enhancing their learning experience and fostering innovation. We have detailed some outcomes from the course in this section.

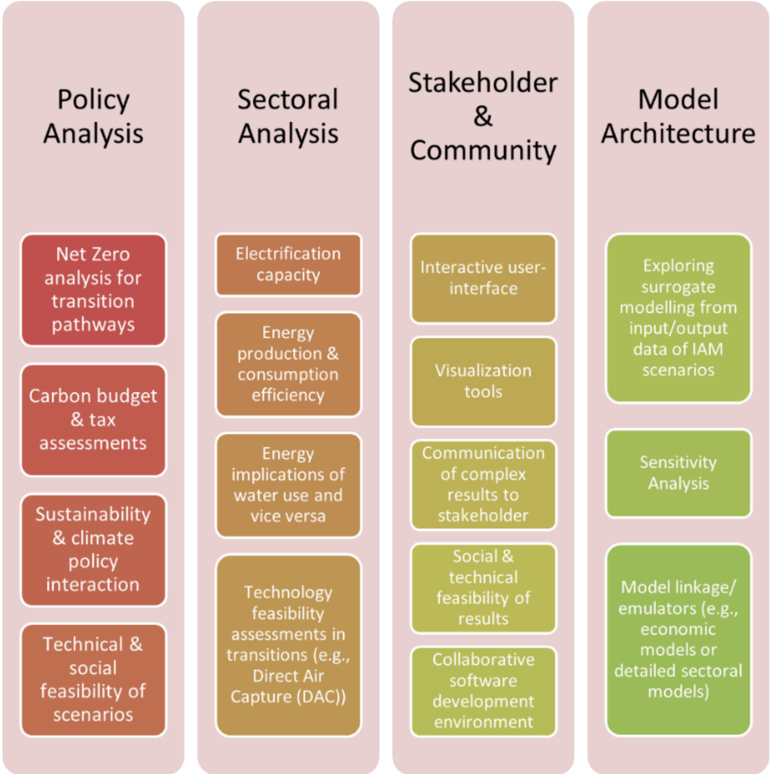

Fig 1. Aspects of IAMS covered by students during the course. These are general themes around which the students contributed to the course

Several students have investigated carbon budgeting and tax assessments; the practical aspects of climate policy implementation were explored by analyzing the allocation of carbon budgets and evaluating the economic implications of carbon taxation. Notably, a number of term projects analyzed mitigation and net zero pathways pertinent to the Canadian climate policy landscape. This included evaluating the efficacy of various policy options and comprehending their potential impacts on emissions reduction and sustainable development objectives. To demonstrate the practical application of these policy analyses, students evaluated carbon tax policies at various levels, from the federal to the provincial level. This hands-on experience enabled students to analyze the implications of various policy approaches, comprehend their potential economic and social impacts, and evaluate their efficacy in promoting emissions reduction and sustainability.

The course uncovered a further facet of the policy environment through an understanding of the complex relationships between sustainability and climate policies. Students have investigated the synergies, trade-offs, and potential conflicts that may result from investigating the interplay between policies aimed at promoting sustainable practices and addressing climate change. This all-encompassing approach equipped students with a thorough comprehension of the complexities of designing and implementing effective policy frameworks. A component of the policy analysis was the evaluation of scenarios' technical and social viability. Students have developed a nuanced comprehension of the real-world viability of proposed scenarios by evaluating the plausibility of various pathways and considering social acceptability and behavioral changes uniquely tailored to the Canadian context.

Evaluation of electrification capacity has been a significant component of sectoral analysis. The feasibility and repercussions of transitioning from fossil fuel-based systems to electrified solutions have also been a focus of term projects, typically approached by analyzing factors such as infrastructure investment requirements and technological advancements. In addition, there has been interest in investigating energy production and consumption efficacy in specific industries. In the context of emerging solutions such as direct air capture (DAC), assessing the technological viability has been an important aspect of sectoral analysis. The students assessed the technical viability, scalability, and potential impacts of technologies designed to reduce greenhouse gas emissions. Through this, students contributed to the ongoing discussion surrounding the deployment of innovative technologies and their role in attaining climate goals through comprehensive assessments. In addition, the significance of variable renewable energy sources at various dimensions within the energy system has been investigated.

Students have utilized capacity expansion models and other sectoral models (transport, buildings) to iterate on the model results with the MESSAGEix toy model. Some demand-side measures and assessments have also been covered in the outcome, such as aviation and electric vehicles in the transport sector or the electricity demand scenarios. These sector-specific analyses allowed students to assess the viability, ramifications, and potential pathways for sustainable transitions within these sectors. To understand the results of IAM scenarios and input/output data, machine learning topics were explored in some projects, where the students tried different machine learning methods in an effort to understand the use of surrogate modeling. By connecting IAMs with economic models or detailed sectoral models, students gained a deeper understanding of the potential applications of IAMs and their role in influencing policy decisions.

The course also emphasizes the importance of effective communication and collaboration in the policy-making process. Students have developed interactive user interfaces and visualization tools to effectively communicate complex results to stakeholders. From this, students developed the ability to interpret and translate complex narratives, which has enabled learners to bridge the gap between scientific analysis and practical policy applications. Additionally, collaborative development tools and transparent practices have been adopted to ensure the fairness, transparency, and accountability of the model development process. By emphasizing effective communication and stakeholder engagement, students equipped themselves with the skills necessary to facilitate informed decision-making and foster sustainable policy development.

Upon completion of the course, students have a greater comprehension of the highly intertwined nature of our energy-climate crisis and the transition to a sustainable future due to their hands-on modeling experiences. Students acquire a theoretical and practical appreciation for the significance of modeling in energy system transitions, including integrated assessment platforms. Students also learn how to apply their understanding of the existing modeling landscape to articulate future modeling needs, evaluate global climate policy from a systems perspective, and describe decarbonization pathways using an integrated assessment model. In addition, students gain fundamental skills in Python programming and data processing, preparing them for careers in energy systems modeling and sustainability. Through the course's emphasis on critical thinking, interdisciplinary collaboration, and problem-solving skills, students are endowed with the knowledge and skills necessary to address complex, interdisciplinary problems in the field of energy-climate transitions.

Concluding Thoughts

In conclusion, the incorporation of IAMs into engineering education provides students with a unique opportunity to apply their knowledge from multiple disciplines to address real-world sustainability challenges. IAMs offer a comprehensive approach by considering the interconnectedness of societal, economic, technological, and environmental factors. However, the complexity and cross-disciplinary nature of IAMs present challenges in teaching and understanding.

To overcome these obstacles, new methods of instruction should be considered. The use of toy models, case studies, and visualization tools can enhance students' understanding and engagement with IAMs. Toy models allow students to grasp the value and intricacies of IAMs, and a partial flipped classroom approach can be employed to effectively introduce and explore these models. Open-source models and collaborative technologies further promote transferable skills and encourage creative problem-solving across disciplines.

The key takeaway for instructors is that incorporating IAMs into engineering education can help students develop a deeper understanding of sustainability issues and cultivate the necessary skills to tackle complex, interdisciplinary challenges. IAMs foster analytical thinking, multidisciplinary perspectives, and practical expertise that can be applied in various contexts. It is essential for instructors to stay informed about new teaching methodologies that facilitate the effective communication of complex concepts to ensure student success.

By integrating IAMs into engineering education, students gain the valuable opportunity to address real-world problems and contribute to building a more sustainable future. Educators must embrace new instructional approaches to prepare the next generation to tackle the world's most pressing sustainability issues. By nurturing the analytical skills, multidisciplinary perspectives, and practical expertise fostered by IAMs, students will be well-equipped to navigate the complexities of sustainability and make meaningful contributions to creating a sustainable world.

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